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A COMPARISON OF PARALLEL BRANCH AND BOUND ALGORITHMS FOR LOCATION-TRANSPORTATION PROBLEMS IN HUMANITARIAN RELIEF

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ABSTRACT: This paper studies the effect of branching rules (BR) and heuristic algorithms (HA) to find feasible solutions for a branch and bound (BB) algorithm used to solve sub-problems in a parallel two-phase branch and bound (PTBB) approach. The nine PTBB algorithms, which are developed by varying 3^2 combinations of BR and HA strategies, are tested on the facility location-transportation problem for disaster response (FLTDR). The mathematical model for the problem determines the number and location of distribution centres in a relief network, the amount of relief supplies to be stocked at each distribution centre and the vehicles to take the supplies in order to maximize the percentage of needs coverage of disaster victims under capacity restriction, transportation and budgetary constraints. To examine the performance of the algorithms, computational experiments are conducted on the various sizes of generated problems. Three strategies of BR and HA provided in the "intlinprog" function of MATLAB were applied for these problems. The objective function values and the computational times of all algorithms were collected and analyzed. The results showed that all PTBB algorithms can solve problem sizes of four candidate locations with fifteen demand points without premature termination by time. The PTBB algorithm using "maxfun" branching rules and "rss" heuristic to find a feasible solution is recommended for FLTDR because of the least computational time usage.

Keywords: Disaster Response, Facility Location, Transportation, Humanitarian Relief

1. INTRODUCTION

Disaster operations management has been a popular issue for decades because of the increase in the number and severity of natural disasters. During 2007-2011, natural disasters killed 23.64% more people and there was a 59.21% increase in economic damage when compared with 2002-2006 [1]. The life cycle of disaster operations management comprises four phases, which are the mitigation phase, the preparedness phase, the response phase, and the recovery phase [2]. The first two phases are pre-positioning phases that need to be performed prior to the onset of a disaster. The other two are post-disaster phases. The period of time of each phase depends on the type of disaster (a quick-onset or a slow-onset disaster). The disaster response is a crucial phase. The objective of disaster response in the humanitarian relief chain is to rapidly provide relief (emergency food, water, medicine, shelter, and supplies) to areas affected by large-scale emergencies, so as to minimize human suffering and death. Relief logistics play an important role in this phase. The scope of relief logistics relates to ten subsystems, which are planning, inventory distribution, transportation, procurement, maintenance, control, human resources, information and communication, and administration subsystems [3]. The first three subsystems have been intensively studied under the following topics: facility location problems, inventory problems, transportation/routing problems and scheduling problems. Both individual analyses and the integration of these four problems have been researched. Moreover, most research topics have emphasized designing a disaster management framework, such as the study appearing in [4]. Few research papers have focused on constructing a disaster response operation framework and application, which aims to determine a solution based on numerical data by using a mathematical method, such as [5] and [6].

The facility location-transportation problem for disaster response (FLTDR) relates to solving both location and transportation problems simultaneously. The location problem requires determining the number, the position and the mission of a humanitarian aid distribution centre within the disaster region. The transportation problem deals with the distribution of humanitarian aid from the distribution centre to demand points [6]. Most of the mathematical models for FLTDR are Mixed Integer Linear Programming (MIP) problems with complex constraint structures [7].

The traditional Branch and Bound (BB) algorithm is currently the only general tool available for finding optimal solutions to these difficult formulations [8]. However, finding an optimal solution for a complex and large size FLTDR using a BB takes excessive computing time. Parallel computing is one of the most efficient alternatives that has been used since the beginning of the twenty-first century. The use of parallelism to speed up the execution of a typical (sequential) BB algorithm is widely known as a Parallel Branch and Bound (PBB) algorithm. There are three main approaches of PBB algorithms according to the degree of parallelism of the search tree. Parallelism of type 1 introduces parallelism when performing the operations on generated sub-problems (e.g., bounding computations). In the type 2 approach, the search tree is built in parallel by performing operations on several sub-problems simultaneously. In the parallelism of type 3, several trees are explored concurrently [9]. Both the selection of computer architectures and PBB approaches for a particular MIP problem affect the computational performance. Much of the research in the PBB approach area has emphasized developing new or improving the existing computer architectures such as [10]-[12]. Little research has focused on developing new or improving PBB approaches such as [13]. However, the various strategies of the BB algorithm, which are used in sub-problem solving in the PBB algorithm and affect the branching sequence of the PBB algorithm, have not been studied. Therefore, this research intends to determine the impact of these strategies, which are BR and HA, on computational time and quality of solutions (in the case of premature termination). The goal of this research is to determine the best strategy for the PBB algorithms.

2. RESEARCH METHODOLOGY

2.1 Problem Description

The FLTDR in this study focuses on calculating the number of distribution centres to be constructed; determining the locations of distribution centres (y_l); identifying the quantity of relief items to be stored (p_{jl}) and determining the assignment of vehicles (X_{ilhkv}) and quantities of the humanitarian aid (Q_{ilhkv}) to serve demand points in order to maximize the relief item coverage under the following assumptions. Each particular house or building within the affected area could require humanitarian aid and is thus a potential demand point. The demand quantities are estimated by a homeland security organisation or experts. The demand quantities can only be satisfied by the distribution centre, which is assumed to stock and distribute multiple types of relief item. The relief items are divided with respect to their response time criticalities and target response time intervals.

The amount of stock to be held at the distribution centre depends on the number and location of distribution centres in the network as well as the assignment of demand locations to the distribution centres, while distribution centre location and assignment decisions are affected by the quantity of relief items to be stocked at each distribution centre. Each distribution candidate site has a global and a per product capacity that fixes the maximum quantity to be stored within the site. The location candidates and the capacity of distribution centres are considered in the pre-disaster phase based on the demand locations and quantities. Both location and stock decisions are limited by pre-disaster budgetary restrictions.

The vehicles available at candidate sites are of various types and there are different numbers of available vehicles. The different docking times of each vehicle type at each site and the time needed for loading and unloading one unit of each product for each vehicle type are considered. The traveling time from a distribution centre to a demand location is determined corresponding to distance and vehicle type. There are also some restrictions on the total weight and the total volume of vehicles. A maximum daily work time for each vehicle type is imposed. A given vehicle can perform as many trips as needed during a day as long as the corresponding work time limit is respected. Each vehicle trip is assumed to visit only one demand point at a time. One demand point may be visited many times. However, because of the maximum daily work time, the number of trips to a specific delivery point by a particular vehicle will be limited to a maximum value, which is set at two. Finally, shipping costs from distribution centres to demand points are restricted by post-disaster budgetary restrictions. The mathematical model formulation of this problem refers to [13]. The parameters and decision variables are defined as follows.

I	Set of demand points; $I = \{1, \ldots, n\}$
J	Set of items; $J = \{1, \ldots, p\}$
L	Set of candidate sites; $L = \{1, \ldots, u\}$
H	Set of vehicle types at site l; $H = \{1, \ldots, m_l\}$
K	Set of number of vehicles for each vehicle type at site l; $K = \{1, \ldots, u_{hl}\}$
V	Set of vehicle trip; $V = \{1, 2\}$
d_{ij}	Demand for item type j at demand point i
s_{jl}	Capacity of site l for item type j
S_l	Capacity of site l for all item
Q_h	Weight capacity of a vehicle of type h
V_h	Volume capacity of a vehicle of type h
τ_{lh}	Docking time for a vehicle of type h at site l

t_{ilh} Travel time from site l to demand point i by vehicle type h
α_{jh} Time of loading and unloading one unit of item type j into a vehicle of type h
D_h Maximum daily work time for a vehicle of type h
w_j Weight of one unit of item type j
v_j Volume of one unit of item type j
F_l Fixed cost of establishing distribution centre j
g_{jl} Unit cost of acquiring and storing item type j at distribution centre l
c_{ilh} Unit cost of shipping items from distribution centre l to demand point i by vehicle type h
B_0 Emergency relief budgets allocated for pre-positioning relief supplies
B_1 Emergency relief budgets allocated for post-disaster distribution

Decision variables

$$y_l = \begin{cases} 1 & \text{if a distribution center is located at site } l \\ 0 & \text{otherwise} \end{cases}$$

$$X_{ilhkv} = \begin{cases} 1 & \text{If demand point } i \text{ is visited from distribution center } l \text{ with the } k^{th} \text{vehicle of type } h \text{ on its } v^{th} \text{trip} \\ 0 & \text{otherwise} \end{cases}$$

Q_{ijlhkv} = Quantity of item type j delivered to point i from distribution center l with the k^{th} vehicle of type h on its v^{th} trip

p_{jl} = Quantity of item type j provided at site l

Mathematical Model

$$Max \;\; Z = \sum_{i\in I}\sum_{j\in J}\frac{1}{d_{ij}}\sum_{l\in L}\sum_{h\in H}\sum_{k\in K}\sum_{v\in V} Q_{ijlhkv} \quad (1)$$

subject to

$$\sum_{l\in L}\sum_{h\in H}\sum_{k\in K}\sum_{v\in V} Q_{ijlhkv} \le d_{ij} \quad \forall i\in I, j\in J \quad (2)$$

$$\sum_{i\in I}\sum_{h\in H}\sum_{k\in K}\sum_{v\in V} Q_{ijlhkv} \le p_{jl} \quad \forall j\in J, l\in L \quad (3)$$

$$\sum_{i\in I}\sum_{k\in K}\sum_{v\in V}\left((2t_{ilh}+\tau_{lh}) X_{ilhkv} + \sum_{j\in J}\alpha_{jh} Q_{ijlhkv} \right) \le D_h y_l \quad \forall h\in H, l\in L \quad (4)$$

$$\sum_{j\in J} w_j Q_{ijlhkv} \le Q_h X_{ilhkv} \quad \forall i\in I, l\in L, h\in H, k\in K, v\in V \quad (5)$$

$$\sum_{j\in J} v_j Q_{ijlhkv} \le V_h X_{ilhkv} \quad \forall i\in I, l\in L, h\in H, k\in K, v\in V \quad (6)$$

$$\sum_{j\in J} p_{jl} \le S_l y_l \quad \forall l\in L \quad (7)$$

$$p_{jl} \le s_{jl} \quad \forall j\in J, l\in L \quad (8)$$

$$\sum_{l\in L} F_l y_l + \sum_{j\in J}\sum_{l\in L} g_{jl} p_{jl} \le B_0 \quad (9)$$

$$\sum_{i\in I}\sum_{l\in L}\sum_{h\in H}\sum_{k\in K}\sum_{v\in V} X_{ilhkv} c_{ilh} \le B_1 \quad (10)$$

$$y_l \in \{0,1\} \quad (11)$$

$$X_{ilhkv} \in \{0,1\} \quad (12)$$

$$Q_{ijlhkv} \ge 0, integer \quad (13)$$

$$p_{jl} \ge 0, integer \quad (14)$$

The objective function Eq. (1) maximizes the total fraction of demand covered by the established distribution centres. Constraint set Eq. (2) guarantees that the quantity of item j delivered for each demand point i does not exceed its demand. Constraint set Eq. (3) ensures that the total quantity of a given item type j delivered from a distribution centre l does not exceed the quantity of item type j available in this distribution centre. Constraint set Eq. (4) requires that the maximum daily work time restriction related to each vehicle k of type h located at a distribution centre l is not exceeded. These constraints also prohibit trips from unopened sites. Constraint sets Eq. (5) and Eq. (6) express the vehicle capacity constraints for each trip in terms of weight and volume. Constraint set Eq. (7) and Eq. (8), respectively, insure that the total and the per item capacity of the distribution centre are satisfied. Constraint Eq. (9) requires that the pre-disaster expenditure related to establishing a distribution centre and holding inventory does not exceed the pre-disaster budget. Constraint Eq. (10) ensures that the total transportation costs do not exceed the post-disaster budget. Finally, constraint sets Eq. (11) - Eq. (14) define the nature of decision variables used in the model.

2.2 Parallel Branch and Bound Algorithms

In order to analyse the effect of BR and HA on the performance of the PTBB1 algorithm, which is an PBB approach that was proposed in [13], for various sizes of FLTDR, a 3^4 full factorial design with single replication is used to carry out the numerical experiments. Two following hypotheses are tested. The first hypothesis is to test whether treatments, which are the parameter of the problem (the number of demand points n and the number of candidate locations of distribution centres u) and the options of the BB algorithm (BR and HA), affect the responses. The other hypothesis is to test whether a treatment interaction affects the responses. Three generated problems are tested in each combination of treatments. The response is the average computational time. Each treatment is composed of three levels, which are shown in Table 1. The levels of BR and HA are options of BB that are provided in the "intlinprog" function in MATLAB. For BR, the rules that choose the fractional component with a maximal corresponding component in the absolute value of the objective function (maxfun); the fractional component with maximum pseudocost (maxpscost); and the component whose fractional part is closest to 0.5 (mostfractional) to be branched are carried out. Three levels of HA are used to enhance bound tightening as follows. For the first level or strategy (none), there is no search for a feasible point. Any feasible point that is encountered in the BB search is taken. The second strategy (rss) applies a hybrid procedure that combines searching the neighbourhood of the current best integer feasible solution point (if available) and local branching to find a new and better solution. The last strategy (round) takes the linear programming (LP) solution to the relaxed problem at a node. It rounds the integer components in a way that attempts to maintain feasibility. Therefore, the nine PTBB algorithms are developed by applying 3^2 combinations of BR and HA strategies for the PTBB1 algorithm. These algorithms are tested on nine problem cases.

The PTBB1 proposed in [13] is composed of 10 steps as follows. Parallel computing is applied in steps 2 to 10 using the "*parfor*" function in MATLAB. The nine strategies of the BB algorithm are implemented in step 6.

Step 1: Calculate the upper bound of the number of distribution centres to be located (ub_{NumDC}) using the budgetary constraint. Let the set of current solutions (y_l, X_{ilhkv}, p_{jl} and Q_{ilhkv}) be an empty set and the current objective function (Z_{cur}) is zero.

Step 2: Set the current number of distribution centres to be located ($NumDC_{cur}$) at 1.

Step 3: Find all possible patterns of selecting $NumDC_{cur}$ locations out of u candidate locations. Now all possible sets of decision variables y_l corresponding to $NumDC_{cur}$ are created. Let the number of all possible patterns corresponding to $NumDC_{cur}$ be $NumPat_{cur}$.

Step 4: Set the current pattern (Pat_{cur}) at 1.

Step 5: Select the set of decision variables y_l relating to $NumDC_{cur}$ and Pat_{cur} .

Step 6: Solve a transportation sub-problem relating to y_l using a BB algorithm. At this step the solutions for variables X_{ilhkv}, Q_{ilhkv}, and p_{jl} are found and the objective function *(Z)* corresponding to y_l is known.

Step 7: Update the set of current solutions and Z_{cur} by employing a new solution and a new Z obtained from step 6 if the Z is better (more) than Z_{cur}. Otherwise, go to step 8.

Step 8: Set $Pat_{cur} = Pat_{cur}+1$. If $Pat_{cur} \leq NumPat_{cur}$ go to step 9. Otherwise, go to step 10.

Step 9: Select the set of decision variables y_l relating to a new Pat_{cur}. Solve the LP relaxation problem of the transportation sub-problem using an interior point algorithm. If $Z > Z_{cur}$, go to step 6. Otherwise, go to step 8.

Step 10: Set $NumDC_{cur} = NumDC_{cur}+1$. If $NumDC_{cur} \leq ub_{NumDC}$ go to step 3. Otherwise, stop the iterative process.

All PTBB algorithms are coded with MATLAB. The numerical experiments are implemented on an asynchronous shared memory system, which is constructed from a workstation with a CPU Intel Core i7-5820K 3.30 GHz 6-core processor with 16 GB RAM. The data sets of nine problem cases with the specific n and u in [13] are used. All algorithms are set to be prematurely terminated at 28,800 sec. or 8 hrs. in order to limit the computational time for large-size problems. The percentage of weight demand coverage, computational time and the solutions of the decision variables are recorded. The results of the experiments are statistically analysed by using analysis of variance (ANOVA) at a level of significance $\alpha = 0.10$ with MINITAB.

3. RESULTS

Since there is no premature termination by time; only the average computational time of all combinations or algorithms is shown in Table 2. All nine strategies of BR and HA give the optimum solution. To statistically analyse the effect of four factors (n, u, BR, and HA) on the average computational time, ANOVA is carried out using MINITAB. Four-factor interaction effects are ignored. The ANOVA table is shown in Table 3. Before drawing any conclusions from the ANOVA table, the assumption of experimental or residual error, which is normally and independently distributed, should be examined by analysing the residual plots illustrated in Fig. 1. From Fig. 1, the Normal Probability Plot shows that the residuals are in linear form. It can be concluded that the data distribution is a normal distribution. Likewise, the Histogram shape also shows that the data distribution is normal. The other two graphs show

Table 1 The levels of all treatments

Treatment	n	u	Branching rules	Heuristic for finding feasible solutions
Low level	5	1	maxfun	none
Intermediate level	10	2	maxpscost	rss
High level	15	4	mostfractional	round

Table 2 Average computational time of all treatment combinations (unit: seconds)

n	Functions	u = 1			u = 2			u = 4		
		none	rss	round	none	rss	round	none	rss	round
5	maxfun	2.75	2.74	2.74	2195.40	2166.10	2156.70	23110.90	13099.10	13098.70
	maxpscost	905.52	883.69	878.36	3723.50	3733.80	3733.40	12415.10	12991.80	12975.10
	mostfractional	1.42	1.42	1.41	3322.20	3346.60	3332.20	15800.35	15817.50	15849.50
10	maxfun	902.78	906.63	1962.30	5097.00	3159.50	3148.20	5450.40	5431.50	5410.50
	maxpscost	3689.56	3875.15	4138.40	5396.70	5394.90	5371.10	11921.00	13998.00	12092.00
	mostfractional	2879.67	2987.35	3170.60	5201.04	5178.25	5124.90	8970.87	8991.50	8931.00
15	maxfun	5190.74	5720.61	4840.17	7319.20	7008.91	7201.00	26730.17	24711.03	23548.00
	maxpscost	3050.82	2080.04	2610.83	3456.10	2437.20	2640.70	27192.78	24920.10	28801.68
	mostfractional	3410.38	3060.36	3100.21	8001.49	7013.41	7201.00	27610.90	23450.00	25548.00

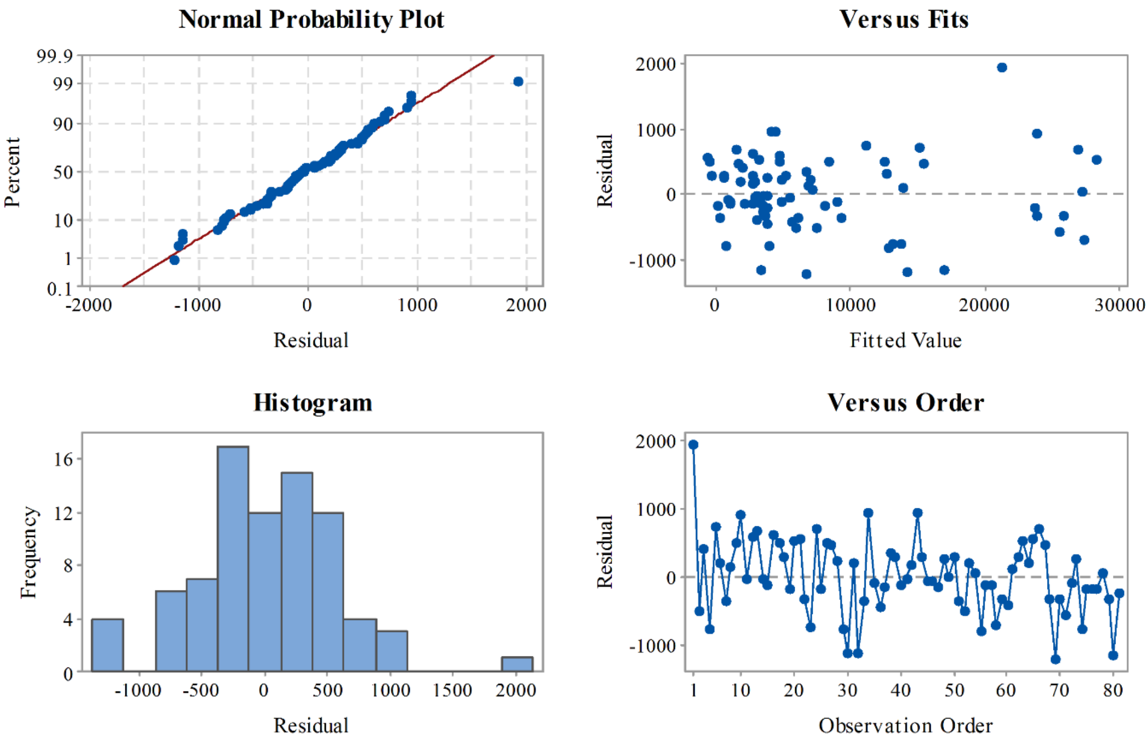


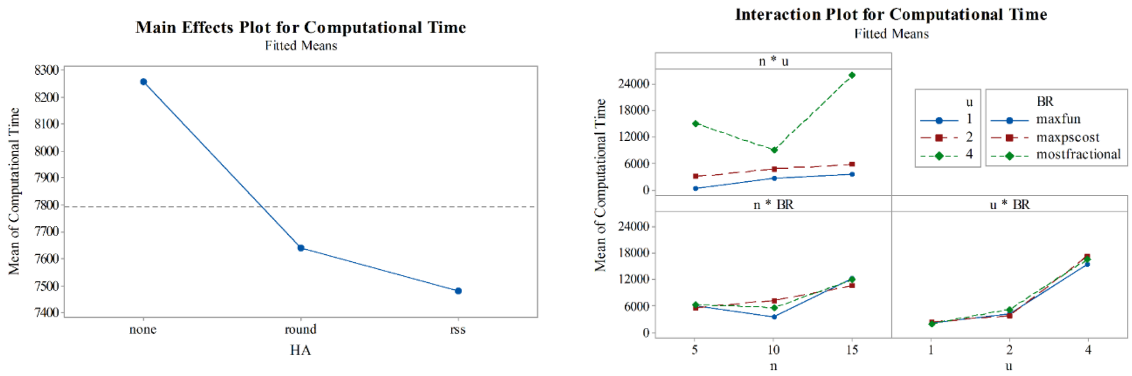
Fig. 1 Residual plots for computational time data

that the residual is independently distributed because the plotted data is distributed randomly. Thus, it can be concluded that the residual is normal and independently distributed.

From Table 3, the factors n, u, HA, the n*u interaction and n*BR interaction, the u*BR interaction, and the n*u*BR interaction significantly affect the response because the p-values are less than the level of significance α = 0.10. According to Table 3, factor u has a greater effect on the computational time than n because it has a higher F-value. Moreover, the combination of these two factors, which leads the numerous decision variables and problem size, shows a nonlinear impact on the computational time. Because the n*u*BR interaction has a significant effect, only the three-factor interaction plots of n, u and BR (shown in Fig. 2) are used and the main effect plots of n, u and BR are ignored to interpret the results and to set the levels of these factors. To set the appropriate HA strategy, the main effect plot of HA (shown in Fig. 2) is considered.

Table 3 ANOVA for the computational time data

Source of Variation	Degrees of Freedom	Adjusted Sum of Squares	Adjusted Mean Square	F-Value	P-Value
n	2	643906702	321953351	213.80	0.000
u	2	3230007029	1615003515	1072.47	0.000
BR	2	6889907	3444954	2.29	0.134
HA	2	9088131	4544065	3.02	0.077
n*u	4	753671742	188417935	125.12	0.000
n*BR	4	74963016	18740754	12.45	0.000
n*HA	4	5580682	1395170	0.93	0.473
u*BR	4	18863426	4715856	3.13	0.044
u*HA	4	8259167	2064792	1.37	0.288
BR*HA	4	8213325	2053331	1.36	0.290
n*u*BR	8	77731263	9716408	6.45	0.001
n*u*HA	8	12449772	1556222	1.03	0.452
n*BR*HA	8	13052877	1631610	1.08	0.422
u*BR*HA	8	16062604	2007825	1.33	0.296
Error	16	24093874	1505867		
Total	80	4902833518			



(a) (b)

Fig. 2 Main effect plot of HA (a) and three-factor interactions of n, u and BR for computational time (b)

According to the main effect plot of HA, the efficient option of HA is the “rss” option because it gives the least computational time. The bottom-left graph and the bottom-right graph of the interaction plots indicate that BR should be set at the “maxfun” option. The top-left graph of the interaction plots show that the least values of n and u (the smallest size problem) use the least computational time.

4. CONCLUSION

Both BR and HA impact the computational time of PTBB algorithms. The selection of BR options affect the computational time of PTBB1 in a nonlinear relation corresponding to n and u. The most efficient BR and HA for the PTBB algorithms to solve the generated FLTDR are the “maxfun” and “rss” options, respectively. This is because the “maxfun” option just looks for and picks up the fractional component with the maximal corresponding component in the absolute value of the objective function without much calculation. Unlike the “maxfun” option, the “maxpscost” option takes time to calculate the pseudocost in selecting the component to be branched while the “mostfractional function” option needs to search and compare the values of all possible pairs of variables. These two options may help to reduce the number of branches to be visited, but this advantage cannot be observed in this study. The “rss” option, which uses a hybrid procedure to find a new and better solution, is more efficient than the “round” option, which just rounds the integer components in a way that attempts to maintain feasibility. This result shows that it is worthwhile to take time to find the best quality feasible solution and tightening bound. This is because it can help PTBB algorithms to fathom a number of inferior branches to be visited. Therefore, the PTBB algorithm using "maxfun" branching rules and "rss" heuristic to find a feasible solution is recommended for FLTDR because it can deliver the optimum solution with the least computational time.

For future research, other strategies of BR and HA or other factors such as node selection rules should be investigated. Moreover, to extend the performance of the PTBB algorithms and computer architecture to develop a parallel computing machine should also be considered.

5. ACKNOWLEDGEMENTS

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