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A Proposed Reduced-Cost Guided Assignment Method for Airline Operations

Mathematical Formulation, Hungarian Method Comparison, and Numerical Validation

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Abstract

The assignment problem is a fundamental combinatorial optimization problem concerned with allocating resources to tasks so that total cost is minimized or total benefit is maximized. In airline operations, assignment models can support aircraft-to-flight allocation, crew assignment, airport gate allocation, maintenance planning, and ground-handling resource deployment. This paper presents the mathematical formulation of the classical assignment problem and discusses its operational relevance to the airline industry. A Reduced-Cost Guided Branch-and-Bound Assignment Method (RCGBAM) is proposed as an alternative exact solution framework. The procedure combines row and column reductions, feasibility-based branching, lower-bound evaluation, and incumbent-based pruning. A four-resource, four-task illustrative example is solved using both the Hungarian method and RCGBAM. Both procedures yield the assignment R1–Flight 2, R2–Flight 1, R3–Flight 3, and R4–Flight 4, with total cost 13 units. The reduced-cost certificate verifies optimality. The example demonstrates the method's correctness for the instance, but does not establish computational superiority. Further benchmarking against established exact algorithms and testing on airline operational data are recommended.

Keywords: assignment problem; airline operations; Hungarian method; branch-and-bound; reduced-cost matrix; aircraft allocation; combinatorial optimization.

1. Introduction

Air transportation is a complex service industry requiring coordination among aircraft, flight crews, airport facilities, maintenance personnel, and ground-handling resources. Airlines allocate limited resources to scheduled activities while observing safety, regulatory, operational, and economic requirements. An assignment model provides a useful mathematical representation when a set of resources must be matched one-to-one with a set of tasks.

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The classical assignment problem is closely related to bipartite matching and linear programming. Kuhn's Hungarian method is a well-known exact algorithm for solving this problem. Other approaches include primal-dual methods, shortest augmenting path algorithms, auction methods, and branch-and-bound. Airline planning may require richer models when resources are assigned across time, when tasks require multiple resources, or when operational restrictions link assignments.

1.1 Research motivation

This study is motivated by the need for transparent, exact procedures that can exploit reduced-cost information and operational restrictions. The proposed RCGBAM uses a branch-and-bound search guided by reduced costs and lower bounds. It is presented as an algorithmic framework whose originality and practical advantage require further literature review and computational validation.

1.2 Objectives

- Formulate the classical assignment problem mathematically.
- Describe assignment applications in airline operations.
- Present a reduced-cost guided branch-and-bound procedure.
- Solve an illustrative instance using the Hungarian method and RCGBAM.
- Compare the solutions and discuss validity, complexity, limitations, and future work.

1.3 Contribution and scope

The contribution is a structured assignment-specific implementation concept combining reduced-cost matrix information, minimum-domain branching, candidate ordering, and valid lower-bound pruning. Branch-and-bound and reduced-cost optimization are established techniques; this paper does not claim that either is new in isolation. The illustrative example is intended to explain the method, not to establish performance on real airline schedules.

2. Literature Review

2.1 Assignment problem foundations

The assignment problem is a classical combinatorial optimization model. Kuhn (1955) developed the Hungarian method, and Munkres (1957) contributed to the algorithmic foundation of assignment and transportation problems. Pentico (2005) surveyed the development and variants of assignment models, including generalized, bottleneck, and multidimensional formulations.

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2.2 Algorithmic approaches

Exact approaches include Hungarian and primal-dual algorithms, shortest augmenting path procedures, and branch-and-bound. Bertsekas (1981) proposed an alternative assignment algorithm, while the auction algorithm provides an iterative bidding-based framework. Heuristic and metaheuristic methods can be useful for complex extensions, but do not generally provide an optimality certificate unless combined with exact methods.

Method	Typical characteristics
Hungarian method	Exact; polynomial-time for classical assignment.
Shortest augmenting path	Exact; effective for dense and sparse instances.
Auction algorithm	Iterative assignment procedure; convergence depends on formulation and settings.
Branch-and-bound	Exact when bounds are valid and the search is complete; worst-case exponential.
Genetic algorithms / simulated annealing	Usually heuristic or metaheuristic; optimality not generally guaranteed.

2.3 Airline assignment applications

Aircraft-to-flight assignment depends on fleet compatibility, availability, maintenance, and operating cost. Crew assignment is affected by qualifications, duty-time rules, and positioning. Gate allocation must account for gate compatibility and overlapping flight intervals. Maintenance and ground-handling assignments depend on personnel qualifications, equipment availability, and turnaround requirements. The one-to-one assignment model is a useful simplified subproblem; realistic airline scheduling often requires network, integer-programming, or multi-period models.

3. Mathematical Formulation

Let n be the number of resources and tasks. Let c_{ij} be the cost of assigning resource i to task j. Define binary decision variable x_{ij} as 1 when resource i is assigned to task j and 0 otherwise.

$$\text{minimize} \quad Z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij}\, x_{ij}$$

$$\sum_{j=1}^{n} x_{ij} = 1, \quad i = 1,\ldots,n$$

$$\sum_{i=1}^{n} x_{ij} = 1, \quad j = 1,\ldots,n$$

$$x_{ij} \in \{0,1\}$$

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The first set of constraints assigns each resource to exactly one task. The second ensures that each task receives exactly one resource. For a permutation π of task indices, the objective can also be written as min over π of $\Sigma_i c_{i,\pi(i)}$.

3.1 Cost matrix

$\mathbf{C = [c_{ij}]_{nxn}}$

The costs may represent monetary expenditure, time, distance, a weighted penalty, or another operational measure. Assignments that violate compatibility or safety requirements may be prohibited by removing the edge or using a sufficiently large penalty, with care to avoid numerical artifacts.

4. Airline Operations Applications

4.1 Aircraft-to-flight assignment

Aircraft may be allocated to flight legs using costs representing fuel and operating expenses, utilization, estimated disruption penalties, or maintenance implications. Feasibility depends on aircraft type, capacity, availability, and airport compatibility.

4.2 Flight crew assignment

Crew members may be matched to duties using positioning costs, preference penalties, or estimated duty-related costs. Qualifications and duty-time restrictions must be enforced.

4.3 Airport gate assignment

Gates may be allocated to flights to reduce passenger walking, towing, or congestion costs. When flight time intervals overlap, additional conflict constraints are needed beyond the basic assignment model.

4.4 Maintenance and ground handling

Maintenance teams can be assigned to aircraft tasks according to skill and availability. Ground teams and equipment can be allocated to turnaround activities, subject to resource and timing restrictions.

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4.5 Model limitations in aviation

Real operations may involve multi-task resources, multiple resources per task, temporal continuity, routing, precedence, uncertain arrival times, and safety restrictions. These situations may require generalized assignment, multidimensional assignment, network optimization, mixed-integer programming, or stochastic/robust optimization.

5. Proposed Method: RCGBAM

5.1 Reduction procedure

For each row i, let $r_i = \min_j c_{ij}$ and define $a_{ij} = c_{ij} - r_i$. For each column j, let $s_j = \min_i a_{ij}$ and define $d_{ij} = a_{ij} - s_j$. The total reduction is $R = \Sigma_i r_i + \Sigma_j s_j$.

$$\mathbf{d_{ij} = c_{ij} - r_i - s_j}$$

$$\mathbf{\Sigma_i c_{i,\pi(i)} = R + \Sigma_i d_{i,\pi(i)}}$$

For any complete assignment, exactly one element is selected from each row and column. Consequently, the reduction preserves assignment comparisons and all reduced costs are nonnegative.

5.2 Partial assignment and lower bound

Let P be a partial assignment with assigned resources S and tasks T, and remaining resources U and tasks V. Its assigned cost is $ZP = \Sigma_i \square S\ c_{i,\pi(i)}$. A valid simple lower bound is

$$\mathbf{LB(P) = ZP + \Sigma_{i \in U} \min_{j \in V} d_{ij}}$$

This is valid because each remaining resource must use one remaining task, and its reduced cost cannot be less than its row minimum. The bound may be weak because several rows may have the same minimizing task. A stronger bound is obtained by solving the residual assignment problem exactly:

$$\mathbf{LB^*(P) = ZP + \min_\sigma \Sigma_{i \in U} c_{i,\sigma(i)}}$$

The residual problem can be solved using the Hungarian method or another exact assignment solver. This stronger bound may reduce the search tree, at the expense of additional work at each node.

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5.3 Branching and candidate ordering

Select the unassigned resource with the fewest feasible remaining tasks (minimum-domain rule). In a tie, select the resource with the largest difference between its two smallest available costs. Explore its candidate tasks in ascending order of reduced cost. The purpose is to prioritize constrained decisions and find a strong complete solution early.

5.4 Pruning

Prune P if LB(P) ≥ UB

Here UB is the cost of the best complete assignment found so far. For finding one optimum, pruning at equality is valid because no strictly better completion can result. If all optimal assignments are required, branches with a lower bound equal to UB must be retained.

5.5 Algorithm outline

1. Input the n × n cost matrix and any feasibility restrictions.
2. Compute row and column reductions and form the reduced-cost matrix.
3. Construct an initial feasible assignment, for example by a greedy procedure or matching algorithm; set its original cost as UB.
4. At each search node, select a remaining resource using the minimum-domain rule.
5. Order its feasible tasks by reduced cost and create child partial assignments.
6. Compute a valid lower bound for each child.
7. Prune a child only when its bound is at least UB (for finding one optimum).
8. When a complete assignment improves UB, update the incumbent assignment and cost.
9. Continue until all potentially improving nodes have been explored or pruned.
10. Return the incumbent assignment and its original total cost.

The procedure is exact if every potentially improving branch is explored and all pruning bounds are valid.

6. Numerical Example

Consider four airline resources and four flight-related tasks. The values below are illustrative cost units and are not actual airline operating costs.

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Resource	Flight 1	Flight 2	Flight 3	Flight 4
R1	9	2	7	8
R2	6	4	3	7
R3	5	8	1	8
R4	7	6	9	4

7. Hungarian Method Solution

7.1 Row reduction

The row minima are $r_1 = 2$, $r_2 = 3$, $r_3 = 1$, and $r_4 = 4$. Their sum is 10. Subtracting each row minimum gives:

A = [[7, 0, 5, 6], [3, 1, 0, 4], [4, 7, 0, 7], [3, 2, 5, 0]]

7.2 Column reduction

The column minima of A are $s_1 = 3$, $s_2 = 0$, $s_3 = 0$, and $s_4 = 0$. Their sum is 3. The doubly reduced matrix is:

D = [[4, 0, 5, 6], [0, 1, 0, 4], [1, 7, 0, 7], [0, 2, 5, 0]]

The total reduction is R = 10 + 3 = 13.

7.3 Independent zero assignment

Four independent zeros can be selected at (R1, Flight 2), (R2, Flight 1), (R3, Flight 3), and (R4, Flight 4). They occupy distinct rows and columns, so they form a feasible assignment.

X* = [[0,1,0,0], [1,0,0,0], [0,0,1,0], [0,0,0,1]]

7.4 Original cost

$ZH = c_{12} + c_{21} + c_{33} + c_{44} = 2 + 6 + 1 + 4 = 13$

The reduced-cost matrix is nonnegative, so every feasible assignment has cost at least R = 13. The selected assignment has cost 13; therefore it is optimal.

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8. Proposed RCGBAM Solution

8.1 Initial incumbent

Use the feasible assignment (R1, Flight 2), (R2, Flight 1), (R3, Flight 3), (R4, Flight 4). Its original cost is 2 + 6 + 1 + 4 = 13. Thus UB = 13.

8.2 Lower-bound certificate

The row minima in the reduced matrix D are all zero. Therefore, the initial-node lower bound is

LB = R + 0 + 0 + 0 + 0 = 13

Since LB = UB = 13, no completion can have a strictly lower cost. For the task of finding one optimal assignment, RCGBAM can terminate with the incumbent. This particular example does not require further branching.

8.3 Verification

$$Z = 13 + \Sigma_i \, d_{i,\pi(i)} \geq 13$$

The proposed assignment selects four zero entries in D, giving Z = 13. The lower bound and feasible solution coincide, which certifies optimality.

9. Comparative Analysis

Resource	Assigned flight	Original cost
R1	Flight 2	2
R2	Flight 1	6
R3	Flight 3	1
R4	Flight 4	4
Total		13

Criterion	Hungarian method	RCGBAM
Solution strategy	Independent zero matching	Lower-bound guided branching
Row/column reduction	Yes	Yes

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Optimal cost	13	13
Optimality	Certified	Certified
Additional branching in this instance	Not applicable	Not required after bound certificate
General exactness	Yes	Yes, with valid bounds and complete search

Both methods produce the same optimal allocation and total cost. The example demonstrates correctness for this instance, but it does not show that RCGBAM is faster. The Hungarian method is polynomial-time for the classical assignment problem, whereas branch-and-bound can be exponential in the worst case. RCGBAM's practical value depends on matrix structure, bound strength, and the search strategy.

10. Computational Complexity

10.1 Hungarian method

Common dense-matrix implementations of the Hungarian method run in $O(n^3)$ time. This makes it a strong baseline for classical assignment problems.

10.2 RCGBAM

Row and column reduction takes $O(n^2)$ time. The search-tree size depends on the quality of the incumbent and lower bounds. In the worst case, a branch-and-bound search may examine a factorial number of assignments; a simple illustrative upper characterization is $O(n! \cdot n)$ when each complete assignment is evaluated in $O(n)$. Implementations using residual Hungarian bounds incur additional per-node work but may prune more nodes.

10.3 Expected behavior

RCGBAM may be effective when restrictions make the problem highly constrained, reduced costs provide useful guidance, and a strong incumbent is found early. It may be less attractive for unrestricted dense assignment matrices, where the Hungarian method already provides a direct polynomial-time solution.

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11. Practical Implications

The model can support cost-focused resource allocation, operational planning, and decision support. An airline implementation would need reliable cost estimates, availability data, compatibility constraints, and a mechanism to validate operational feasibility. During disruption recovery, an assignment model may help generate candidate reallocations, but real-time suitability must be tested with representative data and time limits.

12. Limitations

- The numerical example contains only four resources and four tasks.
- The cost values are illustrative rather than drawn from an airline database.
- The classical one-to-one model does not capture all temporal and routing restrictions.
- RCGBAM's computational performance has not been benchmarked against established exact solvers.
- The novelty of the specific algorithmic combination requires a more comprehensive literature review.

13. Future Research

Future work should implement RCGBAM and benchmark it on reproducible random and airline-inspired matrices at increasing sizes (for example, n = 10, 25, 50, 100, 250, and 500). Report wall-clock time, explored and pruned nodes, bound evaluations, memory use, and objective value. Comparisons should include Hungarian and shortest augmenting path solvers under identical conditions. Airline-specific extensions may incorporate aircraft compatibility, crew qualifications, maintenance restrictions, multi-period continuity, and uncertain flight times. Robust optimization or stochastic programming may be appropriate for uncertain costs and availability.

14. Conclusion

This paper formulated the classical assignment problem and reviewed its relevance to airline resource allocation. A Reduced-Cost Guided Branch-and-Bound Assignment Method was described, combining matrix reductions, feasibility-based branching, lower-bound evaluation, and incumbent pruning. In the four-by-four illustrative example, both the Hungarian method and RCGBAM

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produced the assignment R1–Flight 2, R2–Flight 1, R3–Flight 3, and R4–Flight 4, with minimum total cost 13. The nonnegative reduced-cost matrix and equality between the lower bound and feasible cost establish optimality. The example validates the procedure on a small instance, but does not demonstrate computational superiority. Larger reproducible experiments and airline data are required before making performance claims or asserting a novel contribution.

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