Air Cargo Problem Heuristic Analysis

Part 1

Problem 1	Node expansions	Goal tests	Time elapsed	Planning length
breadth_first_search	43	56	0.032	6*
depth_first_graph_search	21	22	0.014	20
greedy_best_first_graph_search	7	9	0.006	6*

Problem 2	Node expansions	Goal tests	Time elapsed	Planning length
breadth_first_search	1,923	2,672	4.485	9*
depth_first_graph_search	82	83	0.166	77
greedy_best_first_graph_search	732	734	1.470	24

Problem 3	Node expansions	Goal tests	Time elapsed	Planning length
breadth_first_search	14,663	18,098	42.081	12*
depth_first_graph_search	408	409	1.709	392
greedy_best_first_graph_search	5,398	5,400	15.676	26

* Optimal solution

- Breadth_first_search always guarantees to find an optimal solution in all three problems (as explained in AIMA book, Peter Norvig, 3rd edition, pp84.) but this algorithm has the most number of node expansions, most number of goal tests and the longest search time;
- Depth_first_graph_search has the least number of node expansions and the least number of goal tests in all three problems, but has the shortest search time only in p2 and p3 (search time in p1 is slightly longer than greedy_best_first_graph_search, indicating that the short search time advantage of depth_first_graph_search is only obvious when problem size is large). The performance of this algorithm is the worst among the three algorithms in all three problems;
- Greedy_best_first_graph_search has significant less number of node expansions, the number of goal tests and search time compared to breadth_first_search in p2 and p3, but with only slightly worse-than-optimal solutions in p2 and p3 and much better solution compared to depth_first_graph_search. In p1, this algorithm even provided the same optimal solution as the breadth_first_search with half of the node expansions and goal tests and the least amount of search time.

The solutions (action sequence) of the three algorithms to these three problems are attached in the appendix, below only listed the optimal solutions to the three problems:

1. Problem 1
   - Load(C1, P1, SFO)
   - Load(C2, P2, JFK)
   - Fly(P1, SFO, JFK)
   - Fly(P2, JFK, SFO)
   - Unload(C1, P1, JFK)
   - Unload(C2, P2, SFO)
2. Problem 2
   - Load (C1, P1, SFO)
   - Load(C2, P2, JFK)
   - Fly(P2, JFK, ATL)
   - Load(C3, P2, ATL)
   - Fly(P1, SFO, JFK)
   - Fly(P2, ATL, SFO)
   - Unload(C1, P1, JFK)
   - Unload(C3, P2, SFO)
   - Unload(C2, P2, SFO)
3. Problem 3
   - Load(C1, P1, SFO)
   - Load(C2, P2, JFK)
   - Fly(P1, SFO, ATL)
   - Load(C3, P1, ATL)
   - Fly(P2, JFK, ORD)
   - Load(C4, P2, ORD)
   - Fly(P2, ORD, SFO)
   - Fly(P1, ATL, JFK)
   - Unload(C3, P1, JFK)
   - Unload(C1, P1, JFK)
   - Unload(C4, P2, SFO)
   - Unload(C2, P2, SFO)

Part 2

Problem 1	Node expansions	Goal tests	Time elapsed	Planning length
breadth_first_search	43	56	0.032	6*
depth_first_graph_search	21	22	0.014	20
greedy_best_first_graph_search	7	9	0.006	6*
astar_search_h1	55	57	0.038	6*
astar_search_h_ignore_preconditions	55	57	0.039	6*
astar_search_h_pg_levelsum	43	45	0.757	6*

Problem 2	Node expansions	Goal tests	Time elapsed	Planning length
breadth_first_search	1,923	2,672	4.485	9*
depth_first_graph_search	82	83	0.166	77
greedy_best_first_graph_search	732	734	1.470	24
astar_search_h1	2,724	2,726	6.146	9*
astar_search_h_ignore_preconditions	2,724	2,726	6.805	9*
astar_search_h_pg_levelsum	1,663	1,665	274.903	9*

Problem 3	Node expansions	Goal tests	Time elapsed	Planning length
breadth_first_search	14,663	18,098	42.081	12*
depth_first_graph_search	408	409	1.709	392
greedy_best_first_graph_search	5,398	5,400	15.676	26
astar_search_h1	18,164	18,166	52.220	12*
astar_search_h_ignore_preconditions	18,164	18,166	57.655	12*
astar_search_h_pg_levelsum	11,336	11,338	2907.603	12*

* Optimal solution

- All of the three heuristic algorithms (h1 is not a true heuristic algorithm) generated optimal solutions in all three problems. This is because the h cost used in these A* algorithms are less than the actual cost from any state to reach the goal (as explained in AIMA book, Peter Norvig, 3rd edition, pp94.).
- h1 and h_ignore_preconditions have almost identical performance in terms of node expansions, goal tests and time elapsed. h_ignore_preconditions has slight longer running time because h1 used a constant 1, while h_ignore_preconditions did extra calculations to find the minimum number of actions to reach the goal without preconditions (this algorithm started with the number of goals as a constant and continues to search if there are any actions that can lead to multiple fluent in the goal, so that the constant can be less than the number of goals (as explained in AIMA book, Peter Norvig, 3rd edition, pp376.), this additional search might lead to the slight longer run time compared to the h1 algorithm).

- h_pg_levelsum has the least node expansions and goal tests among A* heuristic algorithms and even compared to all three non-heuristic algorithms; however, it has significantly longer run time than the h_ignore_preconditions heuristic algorithm (almost 50 times longer) and longer than the three non-heuristic algorithms. Given that h_pg_levelsum has explored less nodes, the reasons why it took such a long time may be because of the planning graph construction and the extra steps to calculate the sum of levels, with more efficient code, this time might be reduced significantly.
- If running time is more important than nodes expansions and goal tests, h_ignore_preconditions is better than h_pg_levelsum because they both generated optimal solutions and h_ignore_preconditions has huge run time saving compared to h_pg_levelsum. However, it is not as good as the depth_first_graph_search algorithm because it explored more nodes, tested more goals and has longer running time. If the planning graph construction time can be minimized (so that the running time can be significantly reduced), h_pg_levelsum might be a better choice because it explored much less nodes and guarantees optimality.

Appendix

Solving Air Cargo Problem 1 using breadth_first_search...

Expansions   Goal Tests   New Nodes

   43   56   180

Plan length: 6 Time elapsed in seconds: 0.03192493827160494

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, SFO)

Unload(C2, P2, SFO)

Fly(P1, SFO, JFK)

Unload(C1, P1, JFK)

Solving Air Cargo Problem 1 using depth_first_graph_search...

Expansions   Goal Tests   New Nodes

   21   22   84

Plan length: 20 Time elapsed in seconds: 0.01441777777777778

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Load(C2, P1, JFK)

Fly(P1, JFK, SFO)

Fly(P2, SFO, JFK)

Unload(C2, P1, SFO)

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Load(C2, P2, SFO)

Fly(P1, JFK, SFO)

Load(C1, P2, SFO)

Fly(P2, SFO, JFK)

Fly(P1, SFO, JFK)

Unload(C2, P2, JFK)

Unload(C1, P2, JFK)

Fly(P2, JFK, SFO)

Load(C2, P1, JFK)

Fly(P1, JFK, SFO)

Fly(P2, SFO, JFK)

Unload(C2, P1, SFO)

Solving Air Cargo Problem 1 using greedy_best_first_graph_search with h_1...

Expansions	Goal Tests	New Nodes
7	9	28

Plan length: 6 Time elapsed in seconds: 0.0055672098765432165

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Unload(C1, P1, JFK)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 2 using breadth_first_search...

Expansions   Goal Tests   New Nodes

  1923   2672   15352

Plan length: 9 Time elapsed in seconds: 4.484940641975309

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, ATL)

Load(C3, P2, ATL)

Fly(P1, SFO, JFK)

Unload(C1, P1, JFK)

Fly(P2, ATL, SFO)

Unload(C2, P2, SFO)

Unload(C3, P2, SFO)

Solving Air Cargo Problem 2 using depth_first_graph_search...

Expansions   Goal Tests   New Nodes

  82   83   511

Plan length: 77 Time elapsed in seconds: 0.16614360493827185

Fly(P3, ATL, JFK)

Fly(P1, SFO, ATL)

Fly(P2, JFK, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C2, P1, JFK)

Fly(P2, SFO, JFK)

Fly(P1, JFK, ATL)

Fly(P2, JFK, ATL)

Fly(P1, ATL, SFO)

Unload(C2, P1, SFO)

Fly(P2, ATL, SFO)

Fly(P1, SFO, ATL)

Fly(P2, SFO, JFK)

Load(C3, P1, ATL)

Fly(P1, ATL, SFO)

Fly(P2, JFK, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C3, P1, JFK)

Fly(P2, SFO, JFK)

Fly(P1, JFK, ATL)

Fly(P2, JFK, ATL)

Fly(P1, ATL, SFO)

Load(C2, P1, SFO)

Fly(P2, ATL, SFO)

Fly(P1, SFO, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, JFK)

Unload(C2, P1, JFK)

Fly(P2, JFK, ATL)

Fly(P1, JFK, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Load(C1, P2, SFO)

Fly(P2, SFO, ATL)

Fly(P1, SFO, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C1, P2, JFK)

Fly(P2, JFK, ATL)

Load(C3, P1, JFK)

Fly(P2, ATL, SFO)

Fly(P1, JFK, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, SFO)

Unload(C3, P1, SFO)

Fly(P1, SFO, ATL)

Fly(P2, JFK, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C3, P2, SFO)

Fly(P2, SFO, ATL)

Fly(P1, JFK, ATL)

Fly(P2, ATL, JFK)

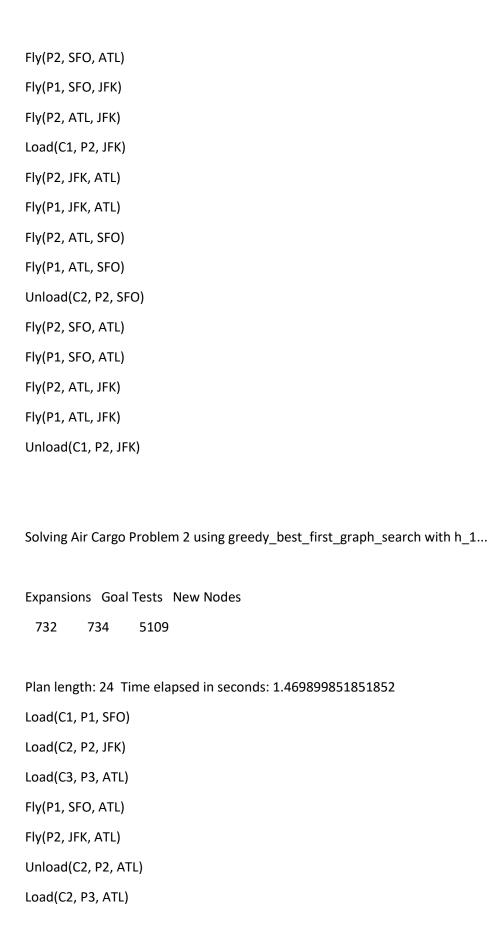Fly(P1, ATL, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, JFK)

Fly(P2, JFK, ATL)

Fly(P1, JFK, ATL)

Fly(P2, ATL, SFO)

Unload(C3, P2, SFO)

Fly(P1, ATL, SFO)

Fly(P2, SFO, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, JFK)

Load(C1, P2, JFK)

Fly(P2, JFK, ATL)

Fly(P1, JFK, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Unload(C2, P2, SFO)

Fly(P2, SFO, ATL)

Fly(P1, SFO, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C1, P2, JFK)

Solving Air Cargo Problem 2 using greedy_best_first_graph_search with h_1...

Expansions   Goal Tests   New Nodes

  732   734   5109

Plan length: 24 Time elapsed in seconds: 1.469899851851852

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Load(C3, P3, ATL)

Fly(P1, SFO, ATL)

Fly(P2, JFK, ATL)

Unload(C2, P2, ATL)

Load(C2, P3, ATL)

Unload(C1, P1, ATL)

Load(C1, P3, ATL)

Unload(C3, P3, ATL)

Load(C3, P2, ATL)

Unload(C1, P3, ATL)

Load(C1, P2, ATL)

Unload(C2, P3, ATL)

Fly(P3, ATL, JFK)

Load(C2, P2, ATL)

Unload(C1, P2, ATL)

Load(C1, P1, ATL)

Fly(P2, ATL, SFO)

Unload(C3, P2, SFO)

Unload(C2, P2, SFO)

Fly(P2, SFO, ATL)

Fly(P1, ATL, JFK)

Unload(C1, P1, JFK)

Solving Air Cargo Problem 3 using breadth_first_search...

Expansions   Goal Tests   New Nodes

 14663   18098   129631

Plan length: 12 Time elapsed in seconds: 42.08079130864198

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, ORD)

Load(C4, P2, ORD)

Fly(P1, SFO, ATL)

Load(C3, P1, ATL)

Fly(P1, ATL, JFK)

Unload(C1, P1, JFK)

Unload(C3, P1, JFK)

Fly(P2, ORD, SFO)

Unload(C2, P2, SFO)

Unload(C4, P2, SFO)

Solving Air Cargo Problem 3 using depth_first_graph_search...

Expansions	Goal Tests	New Nodes
408	409	3364

Plan length: 392 Time elapsed in seconds: 1.7092867160493839

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C2, P1, JFK)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Unload(C2, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C2, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Load(C3, P1, ATL)

Fly(P1, ATL, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, SFO)

Fly(P2, ORD, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C3, P1, JFK)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Unload(C2, P2, JFK)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C3, P1, JFK)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, SFO)

Fly(P2, ATL, JFK)

Unload(C3, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C3, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, SFO)

Load(C1, P1, SFO)

Fly(P2, ATL, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, JFK)

Unload(C3, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, SFO)

Unload(C1, P1, ATL)

Fly(P1, ATL, ORD)

Fly(P2, SFO, ORD)

Fly(P1, ORD, SFO)

Fly(P2, ORD, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, JFK)

Load(C3, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Unload(C3, P2, ATL)

Fly(P2, ATL, ORD)

Fly(P1, ATL, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ORD, SFO)

Fly(P2, SFO, JFK)

Fly(P1, SFO, JFK)

Load(C2, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Unload(C2, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Load(C3, P1, ATL)

Fly(P1, ATL, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, SFO)

Fly(P2, ORD, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C3, P1, JFK)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Load(C3, P2, JFK)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, SFO)

Fly(P1, ATL, JFK)

Fly(P2, SFO, ATL)

Load(C1, P2, ATL)

Fly(P2, ATL, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, SFO)

Unload(C3, P2, JFK)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, SFO)

Fly(P1, ATL, JFK)

Load(C3, P1, JFK)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Unload(C3, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Unload(C1, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Load(C3, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, JFK)

Fly(P2, ORD, ATL)

Unload(C3, P1, JFK)

Fly(P2, ATL, JFK)

Fly(P1, JFK, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Load(C4, P2, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ATL, ORD)

Fly(P2, ATL, SFO)

Fly(P1, ORD, SFO)

Fly(P2, SFO, JFK)

Fly(P1, SFO, JFK)

Unload(C4, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Load(C2, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C2, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Load(C1, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C1, P2, JFK)

Fly(P2, JFK, ORD)

Load(C4, P1, JFK)

Fly(P2, ORD, ATL)

Fly(P1, JFK, ORD)

Fly(P2, ATL, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, SFO)

Unload(C4, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C4, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Load(C3, P2, JFK)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Unload(C4, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Load(C2, P2, JFK)

Fly(P1, ATL, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, SFO)

Fly(P2, ORD, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C3, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, SFO)

Unload(C2, P2, JFK)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Load(C2, P1, JFK)

Fly(P2, ATL, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, SFO)

Unload(C2, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Load(C1, P1, JFK)

Fly(P2, ATL, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, SFO)

Unload(C1, P1, SFO)

Fly(P1, SFO, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, JFK)

Fly(P2, ATL, SFO)

Load(C4, P2, SFO)

Fly(P2, SFO, ATL)

Fly(P1, JFK, ORD)

Fly(P2, ATL, JFK)

Fly(P1, ORD, ATL)

Fly(P2, JFK, ORD)

Fly(P1, ATL, SFO)

Load(C3, P1, SFO)

Fly(P2, ORD, ATL)

Fly(P1, SFO, ORD)

Fly(P2, ATL, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Unload(C4, P2, JFK)

Fly(P1, ATL, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, SFO)

Fly(P2, ORD, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Load(C4, P1, JFK)

Fly(P2, SFO, ORD)

Fly(P1, JFK, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, ORD)

Unload(C3, P1, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ATL, ORD)

Fly(P1, ATL, SFO)

Fly(P2, ORD, SFO)

Fly(P1, SFO, JFK)

Fly(P2, SFO, JFK)

Unload(C4, P1, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, ORD)

Fly(P2, ATL, SFO)

Fly(P1, ORD, SFO)

Load(C2, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C2, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Load(C1, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C1, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Load(C3, P1, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ATL, ORD)

Fly(P1, ATL, SFO)

Fly(P2, ORD, SFO)

Fly(P1, SFO, JFK)

Load(C4, P1, JFK)

Fly(P2, SFO, JFK)

Fly(P1, JFK, ORD)

Fly(P2, JFK, ORD)

Fly(P1, ORD, ATL)

Fly(P2, ORD, ATL)

Fly(P1, ATL, SFO)

Unload(C4, P1, SFO)

Fly(P2, ATL, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ORD, ATL)

Fly(P2, SFO, JFK)

Fly(P1, ATL, JFK)

Load(C2, P2, JFK)

Fly(P2, JFK, ORD)

Fly(P1, JFK, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, SFO)

Fly(P1, ATL, SFO)

Unload(C2, P2, SFO)

Fly(P2, SFO, ORD)

Fly(P1, SFO, ORD)

Fly(P2, ORD, ATL)

Fly(P1, ORD, ATL)

Fly(P2, ATL, JFK)

Fly(P1, ATL, JFK)

Unload(C3, P1, JFK)

Solving Air Cargo Problem 3 using greedy_best_first_graph_search with h_1...

Expansions   Goal Tests   New Nodes

  5398   5400   47680

Plan length: 26 Time elapsed in seconds: 15.675959308641978

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, ORD)

Load(C4, P1, ORD)

Fly(P2, JFK, ATL)

Load(C3, P2, ATL)

Fly(P2, ATL, ORD)

Unload(C1, P1, ORD)

Load(C1, P2, ORD)

Fly(P1, ORD, ATL)

Unload(C4, P1, ATL)

Fly(P1, ATL, ORD)

Fly(P2, ORD, ATL)

Load(C4, P2, ATL)

Fly(P2, ATL, ORD)

Unload(C1, P2, ORD)

Load(C1, P1, ORD)

Unload(C3, P2, ORD)

Load(C3, P1, ORD)

Fly(P1, ORD, JFK)

Unload(C3, P1, JFK)

Unload(C1, P1, JFK)

Fly(P1, JFK, ORD)

Fly(P2, ORD, SFO)

Unload(C4, P2, SFO)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 1 using astar_search with h_1...

Expansions   Goal Tests   New Nodes

   55   57   224

Plan length: 6 Time elapsed in seconds: 0.037586172839506174

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Unload(C1, P1, JFK)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 1 using astar_search with h_ignore_preconditions...

Expansions   Goal Tests   New Nodes

   55   57   224

Plan length: 6 Time elapsed in seconds: 0.03916246913580247

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Unload(C1, P1, JFK)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 1 using astar_search with h_pg_levelsum...

Expansions   Goal Tests   New Nodes

   43   45   178

Plan length: 6 Time elapsed in seconds: 0.7569975308641975

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Unload(C1, P1, JFK)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 2 using astar_search with h_1...

Expansions   Goal Tests   New Nodes

   2724   2726   21377

Plan length: 9 Time elapsed in seconds: 6.1463691851851845

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, ATL)

Load(C3, P2, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C1, P1, JFK)

Unload(C3, P2, SFO)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 2 using astar_search with h_ignore_preconditions...

Expansions   Goal Tests   New Nodes

  2724   2726   21377

Plan length: 9 Time elapsed in seconds: 6.805276049382717

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, ATL)

Load(C3, P2, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C1, P1, JFK)

Unload(C3, P2, SFO)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 2 using astar_search with h_pg_levelsum...

Expansions   Goal Tests   New Nodes

1663   1665   13259

Plan length: 9 Time elapsed in seconds: 274.90340345679016

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P2, JFK, ATL)

Load(C3, P2, ATL)

Fly(P1, SFO, JFK)

Fly(P2, ATL, SFO)

Unload(C1, P1, JFK)

Unload(C3, P2, SFO)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 3 using astar_search with h_1...

Expansions   Goal Tests   New Nodes

 18164   18166   159147

Plan length: 12 Time elapsed in seconds: 52.22031644444445

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, ATL)

Load(C3, P1, ATL)

Fly(P2, JFK, ORD)

Load(C4, P2, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ATL, JFK)

Unload(C3, P1, JFK)

Unload(C1, P1, JFK)

Unload(C4, P2, SFO)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 3 using astar_search with h_ignore_preconditions...

Expansions   Goal Tests   New Nodes

 18164   18166   159147

Plan length: 12 Time elapsed in seconds: 57.654925432098764

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, ATL)

Load(C3, P1, ATL)

Fly(P2, JFK, ORD)

Load(C4, P2, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ATL, JFK)

Unload(C3, P1, JFK)

Unload(C1, P1, JFK)

Unload(C4, P2, SFO)

Unload(C2, P2, SFO)

Solving Air Cargo Problem 3 using astar_search with h_pg_levelsum...

Expansions   Goal Tests   New Nodes

 11336   11338   100920

Plan length: 12 Time elapsed in seconds: 2907.602612148148

Load(C1, P1, SFO)

Load(C2, P2, JFK)

Fly(P1, SFO, ATL)

Load(C3, P1, ATL)

Fly(P2, JFK, ORD)

Load(C4, P2, ORD)

Fly(P2, ORD, SFO)

Fly(P1, ATL, JFK)

Unload(C3, P1, JFK)

Unload(C1, P1, JFK)

Unload(C4, P2, SFO)

Unload(C2, P2, SFO)