Heuristic Analysis

1. Optimal Plans

Air Cargo Problem 1

Plan 1	Plan 2	Plan 3	Plan 4
Load(C2, P2, JFK)	Load(C1, P1, SFO)	Load(C2, P2, JFK)	Load(C1, P1, SFO)
Load(C1, P1, SFO)	Load(C2, P2, JFK)	Fly(P2, JFK, SFO)	Fly(P1, SFO, JFK)
Fly(P2, JFK, SFO)	Fly(P1, SFO, JFK)	Unload(C2, P2, SFO)	Load(C2, P2, JFK)
Unload(C2, P2, SFO)	Fly(P2, JFK, SFO)	Load(C1, P1, SFO)	Fly(P2, JFK, SFO)
Fly(P1, SFO, JFK)	Unload(C2, P2, SFO)	Fly(P1, SFO, JFK)	Unload(C2, P2, SFO)
Unload(C1, P1, JFK)	Unload(C1, P1, JFK)	Unload(C1, P1, JFK)	Unload(C1, P1, JFK)

Air Cargo Problem 2

Plan 1	Plan 2	Plan 3	Plan 4
Load(C3, P3, ATL)	Load(C1, P1, SFO)	Load(C3, P3, ATL)	Load(C1, P1, SFO)
Load(C2, P2, JFK)	Load(C2, P2, JFK)	Fly(P3, ATL, SFO)	Fly(P1, SFO, JFK)
Load(C1, P1, SFO)	Load(C3, P3, ATL)	Unload(C3, P3, SFO)	Load(C2, P2, JFK)
Fly(P3, ATL, SFO)	Fly(P1, SFO, JFK)	Load(C2, P2, JFK)	Fly(P2, JFK, SFO)
Unload(C3, P3, SFO)	Fly(P2, JFK, SFO)	Fly(P2, JFK, SFO)	Load(C3, P3, ATL)
Fly(P2, JFK, SFO)	Fly(P3, ATL, SFO)	Unload(C2, P2, SFO)	Fly(P3, ATL, SFO)
Unload(C2, P2, SFO)	Unload(C3, P3, SFO)	Load(C1, P1, SFO)	Unload(C3, P3, SFO)
Fly(P1, SFO, JFK)	Unload(C2, P2, SFO)	Fly(P1, SFO, JFK)	Unload(C2, P2, SFO)
Unload(C1, P1, JFK)	Unload(C1, P1, JFK)	Unload(C1, P1, JFK)	Unload(C1, P1, JFK)

Air Cargo Problem 3

Plan 1	Plan 2	Plan 3	Plan 4
Load(C2, P2, JFK)	Load(C1, P1, SFO)	Load(C2, P2, JFK)	Load(C1, P1, SFO)
Load(C1, P1, SFO)	Load(C2, P2, JFK)	Fly(P2, JFK, ORD)	Fly(P1, SFO, ATL)
Fly(P2, JFK, ORD)	Fly(P1, SFO, ATL)	Load(C4, P2, ORD)	Load(C3, P1, ATL)
Load(C4, P2, ORD)	Load(C3, P1, ATL)	Fly(P2, ORD, SFO)	Fly(P1, ATL, JFK)
Fly(P2, ORD, SFO)	Fly(P2, JFK, ORD)	Unload(C4, P2, SFO)	Load(C2, P2, JFK)
Unload(C2, P2, SFO)	Load(C4, P2, ORD)	Load(C1, P1, SFO)	Fly(P2, JFK, ORD)
Unload(C4, P2, SFO)	Fly(P1, ATL, JFK)	Fly(P1, SFO, ATL)	Load(C4, P2, ORD)
Fly(P1, SFO, ATL)	Fly(P2, ORD, SFO)	Load(C3, P1, ATL)	Fly(P2, ORD, SFO)
Load(C3, P1, ATL)	Unload(C4, P2, SFO)	Fly(P1, ATL, JFK)	Unload(C4, P2, SFO)
Fly(P1, ATL, JFK)	Unload(C3, P1, JFK)	Unload(C3, P1, JFK)	Unload(C3, P1, JFK)
Unload(C1, P1, JFK)	Unload(C2, P2, SFO)	Unload(C2, P2, SFO)	Unload(C2, P2, SFO)
Unload(C3, P1, JFK)	Unload(C1, P1, JFK)	Unload(C1, P1, JFK)	Unload(C1, P1, JFK)

2. Summary of Run Results

Air Cargo Problem 1

Algorithm / Heuristic	Expansion	Goal Test	New Node	Plan Length	Run Time (s	Optimal
Breadth-First Search	43	56	180	6	0.0581	TRUE
Breadth-First Tree Search	1458	1459	5960	6	1.9148	TRUE
Depth-First Graph Search	12	13	48	12	0.0150	FALSE
Depth-Limited Search	101	271	414	50	0.1567	FALSE
Uniform-Cost Search	55	57	224	6	0.0715	TRUE
Recursive Best-First Search	4229	4230	17029	6	5.5474	TRUE
Greedy Best-First Graph Search	7	9	28	6	0.0087	TRUE
A* Search (h_1)	55	57	224	6	0.0789	TRUE
A* Search (h_ignore_preconditions)	41	43	170	6	0.0660	TRUE
A* Search (h_pg_levelsum)	11	13	50	6	0.6745	TRUE

Air Cargo Problem 2

Algorithm / Heuristic	Expansion	Goal Test	New Node	Plan Length	Run Time (s	Optimal
Breadth-First Search	3401	4672	31049	9	14.7858	TRUE
Depth-First Graph Search	350	351	3142	346	2.3113	FALSE
Uniform-Cost Search	4761	4763	43206	9	22.2885	TRUE
Greedy Best-First Graph Search	550	552	4950	9	2.2927	TRUE
A* Search (h_1)	4761	4763	43206	9	20.6533	TRUE
A* Search (h_ignore_preconditions)	1450	1452	13303	9	7.2339	TRUE
A* Search (h_pg_levelsum)	86	88	841	9	56.3242	TRUE

Air Cargo Problem 3

Algorithm / Heuristic	Expansion	Goal Test	New Node	Plan Length	Run Time (s	Optimal
Breadth-First Search	14491	17947	128184	12	67.1867	TRUE
Depth-First Graph Search	1948	1949	16253	1878	27.4220	FALSE
Uniform-Cost Search	17783	17785	155920	12	84.5386	TRUE
Greedy Best-First Graph Search	4031	4033	35794	22	18.4641	FALSE
A* Search (h_1)	17783	17785	155920	12	84.5508	TRUE
A* Search (h_ignore_preconditions)	5003	5005	44586	12	27.5230	TRUE
A* Search (h_pg_levelsum)	311	313	2863	12	288.3614	TRUE

3. Discussion

For Air Cargo Problem 1, Greedy Best-First Graph Search turned out to be the best algorithm in terms of all criteria, beating all three heuristic A* Search algorithms with different heuristics. Recursive Best-First Search showed the worst performance in terms of the numbers of expansions, goal tests, and new nodes and run time, but nevertheless produced an optimal plan of length 6. Depth-Limited Search resulted in a non-optimal plan with the longest length of 50. Except Depth-Limited Search and Depth-First Graph Search, all the other algorithms produced an optimal plan of length 6.

For Air Cargo Problems 2 and 3, Breadth-First Tree Search, Depth-Limited Search, and Recursive Best-First Search algorithms, which showed significantly worse performance for Air Cargo Problem 1 in terms of the numbers of expansions, goal tests, and new nodes, have been excluded from comparison.

The results for Air Cargo Problem 2 and Air Cargo Problem 3 were quite similar. For both problems, A* Search algorithm with h_pg_levelsum heuristic showed the best performance and produced optimal plans of length 9 and 12, respectively, albeit with the longest run time in both cases. For both problems, Uniform-Cost Search and A* Search with h_1 heuristic (non-heuristic) showed the worst performance in terms of the numbers of expansions, goal tests, and new nodes, although both of them produced optimal plans. Curiously, the two algorithms resulted in the identical numbers of expansions, goal tests, and new nodes. For both problems, Depth-First Graph Search algorithm produced non-optimal plans of the longest lengths of 346 and 1878, respectively. Although it proved itself to be the best algorithm for Air Cargo Problem 1 and produced optimal plans for both Air Cargo Problem 1 and Air Cargo Problem 2, Greedy Best-First Graph Search algorithm nevertheless produced a non-optimal plan of length 22 for Air Cargo Problem 3.

Some takeaways from the experiment are as follows:

- A heuristic search algorithm may not always outperform non-heuristic search algorithms. For Air Cargo Problem 1, Greedy Best-First Search algorithm outperformed A* Search algorithms. This may indicate that, for relatively simpler problems, a greedy algorithm may produce an optimal plan more quickly and with fewer numbers of expansions, goal tests, and new nodes.
- In terms of run time, Greedy Best-Search algorithm may be the best algorithm across problems of different levels of complexity. However, the plan produced as a result is not guaranteed to be optimal. For Air Cargo Problem 3, the algorithm resulted in a non-optimal plan.
- Depth-First Graph Search algorithm, while being one of the fastest algorithms, does not produce optimal plans.
- A* Search algorithm with h_pg_levelsum heuristic can be expected to show the best (or closest-to-best) performance across different problems and produce optimal plans, however, at the cost of the longest run time (considering the algorithms compared for all three problems).