Tests Ran OK

```
(aind) JC-AM-C02MT1UBFH05:2_Classical Planning jasoncarpenter$ python -m unittest -v
test_levelsum (tests.test_my_planning_graph.TestPlanningGraphHeuristics) ... ok
test_maxlevel (tests.test_my_planning_graph.TestPlanningGraphHeuristics) ... ok
test_setlevel (tests.test_my_planning_graph.TestPlanningGraphHeuristics) ... ok
test_competing_needs_mutex (tests.test_my_planning_graph.TestPlanningGraphMutex) ... ok
test_inconsistent_effects_mutex (tests.test_my_planning_graph.TestPlanningGraphMutex) ... ok
test_inconsistent_support_mutex (tests.test_my_planning_graph.TestPlanningGraphMutex) ... ok
test_interference_mutex (tests.test_my_planning_graph.TestPlanningGraphMutex) ... ok
test_negation_mutex (tests.test_my_planning_graph.TestPlanningGraphMutex) ... ok

----------------------------------------------------------------------
Ran 8 tests in 6.097s

OK
```

Air Cargo Problem 1

Problem	Section	Breadth First Search	depth_first_graph_search	uniform_cost_search
Air Cargo Problem 1	Actions	20	20	20
Air Cargo Problem 1	Expansions	43	21	60
Air Cargo Problem 1	Goal Tests	56	22	62
Air Cargo Problem 1	New Nodes	178	84	240
Air Cargo Problem 1	Plan Length:	6	20	6
Air Cargo Problem 1	Time Elapsed	0.006911131	0.003716114	0.010737047
Air Cargo Problem 1	Data	Load(C1, P1, SFO) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK)	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)	Load(C2, P2, JFK) Fly(P2, JFK, SFO) Load(C1, P2, SFO) Unload(C2, P2, SFO) Fly(P2, SFO, JFK) Unload(C1, P2, JFK)

greedy_best_first_graph_search with h_unmet_goals	greedy_best_first_graph_search with h_pg_levelsum	greedy_best_first_graph_search with h_pg_maxlevel	greedy_best_first_graph_search with h_pg_setlevel
20	20	20	20
7	6	12	6
9	8	14	8
29	28	51	28
6	6	7	6
0.0015929	0.385260295	0.270173572	0.904381468
Load(C1, P1, SFO) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK)	Load(C1, P1, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO)	Load(C1, P1, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK) Load(C2, P2, JFK) Fly(P1, JFK, SFO) Fly(P2, JFK, SFO) Unload(C2, P2, SFO)	Load(C1, P1, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO)

astar_search with h_unmet_goals	astar_search with h_pg_levelsum	astar_search with h_pg_maxlevel	astar_search with h_pg_setlevel
20	20	20	20
50	28	59	33
52	30	61	35
206	122	236	138
6	6	6	6
0.010021021	1.031393637	0.530486582	2.047613831
Load(C2, P2, JFK)	Load(C2, P2, JFK)	Load(C2, P2, JFK)	Load(C2, P2, JFK)
Fly(P2, JFK, SFO)	Fly(P2, JFK, SFO)	Fly(P2, JFK, SFO)	Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)	Unload(C2, P2, SFO)	Unload(C2, P2, SFO)	Unload(C2, P2, SFO)
Load(C1, P2, SFO)	Load(C1, P2, SFO)	Load(C1, P2, SFO)	Load(C1, P2, SFO)
Fly(P2, SFO, JFK)	Fly(P2, SFO, JFK)	Fly(P2, SFO, JFK)	Fly(P2, SFO, JFK)
Unload(C1, P2, JFK)	Unload(C1, P2, JFK)	Unload(C1, P2, JFK)	Unload(C1, P2, JFK)

Air Cargo Problem 2

Problem	Section	Breadth First Search	depth_first_graph_search	uniform_cost_search
Air Cargo Problem 2	Actions	72	72	72
Air Cargo Problem 2	Expansions	3343	624	5154
Air Cargo Problem 2	Goal Tests	4609	625	5156
Air Cargo Problem 2	New Nodes	30503	5602	46618
Air Cargo Problem 2	Plan Length:	9	619	9
Air Cargo Problem 2	Time Elapsed	2.082911204	2.794446356	3.766881431
Air Cargo Problem 2	Data	Load(C1, P1, SFO) Load(C2, P2, JFK) Load(C3, P3, ATL) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK) Fly(P3, ATL, SFO) Unload(C3, P3, SFO)	Fly(P3, ATL, SFO) Fly(P1, SFO, ATL) Fly(P3, SFO, JFK) Fly(P1, ATL, JFK) Fly(P2, JFK, ATL) Fly(P3, JFK, ATL) Fly(P2, ATL, SFO) Fly(P3, ATL, SFO) Load(C2, P1, JFK) Fly(P2, SFO, ATL) Fly(P1, JFK, ATL) Fly(P2, ATL, JFK) Fly(P1, ATL, SFO) Fly(P3, SFO, ATL) Fly(P1, SFO, JFK) Load(C3, P3, ATL) Fly(P3, ATL, SFO) Fly(P2, JFK, ATL) Fly(P3, SFO, JFK) Fly(P2, ATL, SFO) Fly(P1, JFK, ATL) Fly(P2, SFO, JFK) Fly(P1, ATL, SFO) Unload(C3, P3, JFK) Fly(P1, SFO, JFK) Fly(P3, JFK, ATL)	Load(C3, P3, ATL) Fly(P3, ATL, SFO) Load(C1, P3, SFO) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C3, P3, SFO) Fly(P3, SFO, JFK) Unload(C2, P2, SFO) Unload(C1, P3, JFK)

greedy_best_first_graph_search with h_unmet_goals	greedy_best_first_graph_search with h_pg_levelsum	greedy_best_first_graph_search with h_pg_maxlevel	greedy_best_first_graph_search with h_pg_setlevel
72	72	72	72
17	9	121	9
19	11	123	11
170	86	1091	84
9	9	11	9
0.022531278	9.140934102	17.25033423	29.65538577
Load(C1, P1, SFO) Load(C2, P2, JFK) Load(C3, P3, ATL) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Fly(P3, ATL, SFO) Unload(C3, P3, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK)	Load(C1, P1, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Load(C3, P3, ATL) Fly(P3, ATL, SFO) Unload(C3, P3, SFO)	Load(C1, P1, SFO) Load(C2, P2, JFK) Load(C3, P3, ATL) Fly(P2, JFK, SFO) Fly(P3, ATL, SFO) Unload(C3, P3, SFO) Unload(C2, P2, SFO) Unload(C1, P1, SFO) Load(C1, P3, SFO) Fly(P3, SFO, JFK) Unload(C1, P3, JFK)	Load(C1, P1, SFO) Load(C2, P2, JFK) Load(C3, P3, ATL) Fly(P2, JFK, SFO) Fly(P3, ATL, SFO) Fly(P1, SFO, JFK) Unload(C3, P3, SFO) Unload(C2, P2, SFO) Unload(C1, P1, JFK)

astar_search with h_unmet_goals	astar_search with h_pg_levelsum	astar_search with h_pg_maxlevel	astar_search with h_pg_setlevel
72	72	72	72
2467	357	3393	1037
2469	359	3395	1039
22522	3426	30955	9605
9	9	9	9
2.351478326	258.525172	1157.207995	2547.580143
Load(C3, P3, ATL)	Load(C2, P2, JFK)	Load(C2, P2, JFK)	Load(C2, P2, JFK)
Fly(P3, ATL, SFO)	Fly(P2, JFK, SFO)	Load(C3, P3, ATL)	Load(C3, P3, ATL)
Unload(C3, P3, SFO)	Load(C3, P3, ATL)	Fly(P2, JFK, SFO)	Fly(P2, JFK, SFO)
Load(C2, P2, JFK)	Fly(P3, ATL, SFO)	Fly(P3, ATL, SFO)	Fly(P3, ATL, SFO)
Fly(P2, JFK, SFO)	Unload(C3, P3, SFO)	Unload(C3, P3, SFO)	Unload(C3, P3, SFO)
Unload(C2, P2, SFO)	Load(C1, P3, SFO)	Unload(C2, P2, SFO)	Unload(C2, P2, SFO)
Load(C1, P3, SFO)	Fly(P3, SFO, JFK)	Load(C1, P3, SFO)	Load(C1, P3, SFO)
Fly(P3, SFO, JFK)	Unload(C2, P2, SFO)	Fly(P3, SFO, JFK)	Fly(P3, SFO, JFK)
Unload(C1, P3, JFK)	Unload(C1, P3, JFK)	Unload(C1, P3, JFK)	Unload(C1, P3, JFK)

Air Cargo Problem 3

Problem	Section	Breadth First Search	greedy_best_first_graph_search with h_unmet_goals
Air Cargo Problem 3	Actions	88	88
Air Cargo Problem 3	Expansions	14663	25
Air Cargo Problem 3	Goal Tests	18098	27
Air Cargo Problem 3	New Nodes	129625	230
Air Cargo Problem 3	Plan Length:	12	15
Air Cargo Problem 3	Time Elapsed	11.19259433	0.037588578
Air Cargo Problem 3	Data	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)	Load(C1, P1, SFO) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Fly(P2, SFO, ORD) Load(C4, P2, ORD) Fly(P2, ORD, SFO) Unload(C4, P2, SFO) Fly(P2, SFO, ATL) Load(C3, P2, ATL) Fly(P2, ATL, JFK) Unload(C3, P2, JFK) Fly(P2, JFK, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK)

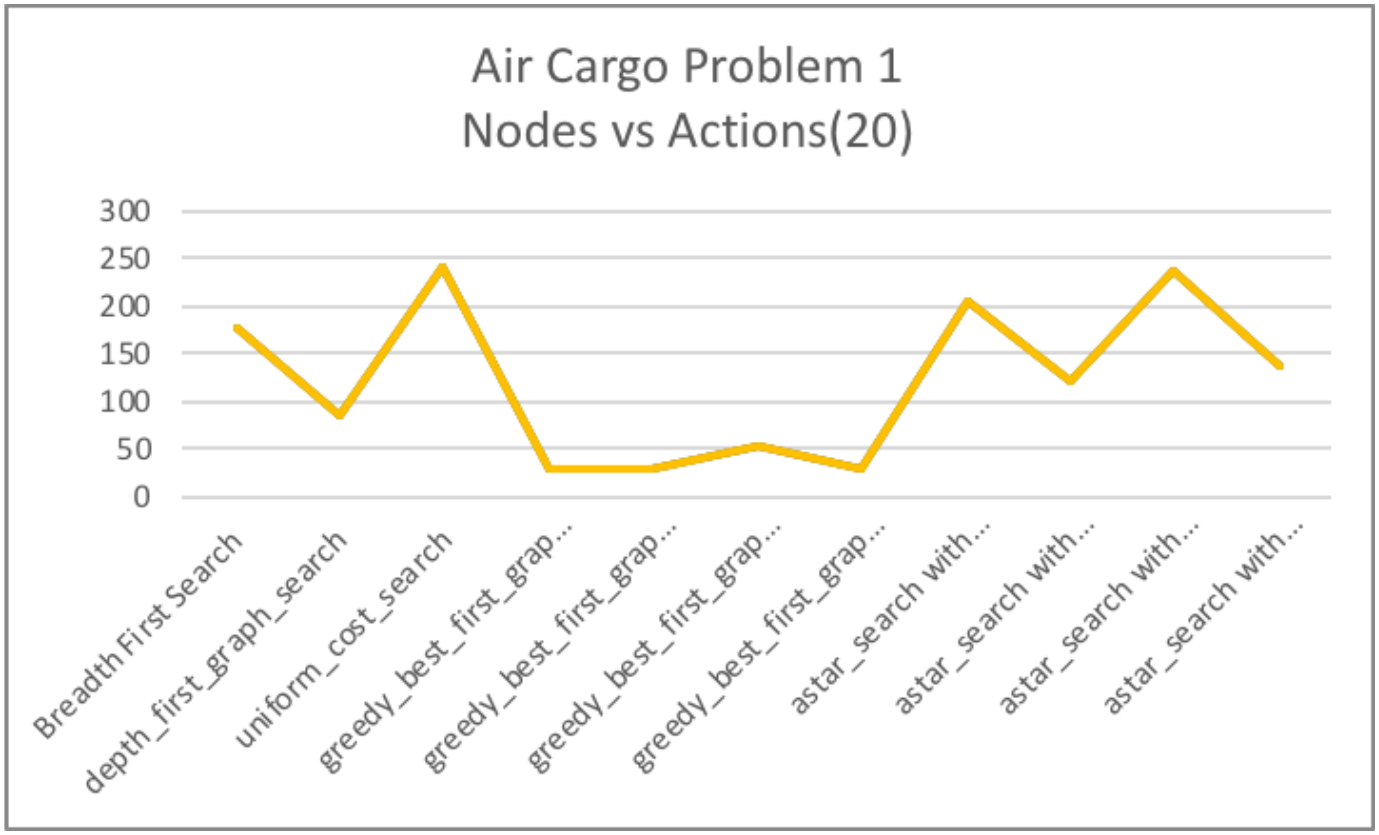
greedy_best_first_graph_search with h_pg_setlevel	astar_search with h_unmet_goals	astar_search with h_pg_levelsum
88	88	88
35	7388	369
37	7390	371
345	65711	3403
17	12	12
179.4124734	9.000550936	425.4928982
Load(C1, P1, SFO)		
Fly(P1, SFO, ORD)		
Load(C2, P2, JFK)		
Fly(P2, JFK, ATL)		
Load(C3, P2, ATL)		Load(C1, P1, SFO)
Load(C4, P1, ORD)	Load(C2, P2, JFK)	Fly(P1, SFO, ATL)
Fly(P1, ORD, SFO)	Fly(P2, JFK, ATL)	Load(C3, P1, ATL)
Fly(P2, ATL, SFO)	Load(C3, P2, ATL)	Fly(P1, ATL, JFK)
Unload(C4, P1, SFO)	Fly(P2, ATL, ORD)	Load(C2, P2, JFK)
Fly(P1, SFO, JFK)	Load(C4, P2, ORD)	Fly(P2, JFK, ORD)
Load(C4, P2, SFO)	Fly(P2, ORD, SFO)	Load(C4, P2, ORD)
Fly(P2, SFO, JFK)	Unload(C4, P2, SFO)	Fly(P2, ORD, SFO)
Unload(C3, P2, JFK)	Unload(C2, P2, SFO)	Unload(C4, P2, SFO)
Fly(P2, JFK, SFO)	Load(C1, P2, SFO)	Unload(C3, P1, JFK)
Unload(C4, P2, SFO)	Fly(P2, SFO, JFK)	Unload(C2, P2, SFO)
Unload(C2, P2, SFO)	Unload(C3, P2, JFK)	Unload(C1, P1, JFK)
Unload(C1, P1, JFK)	Unload(C1, P2, JFK)	

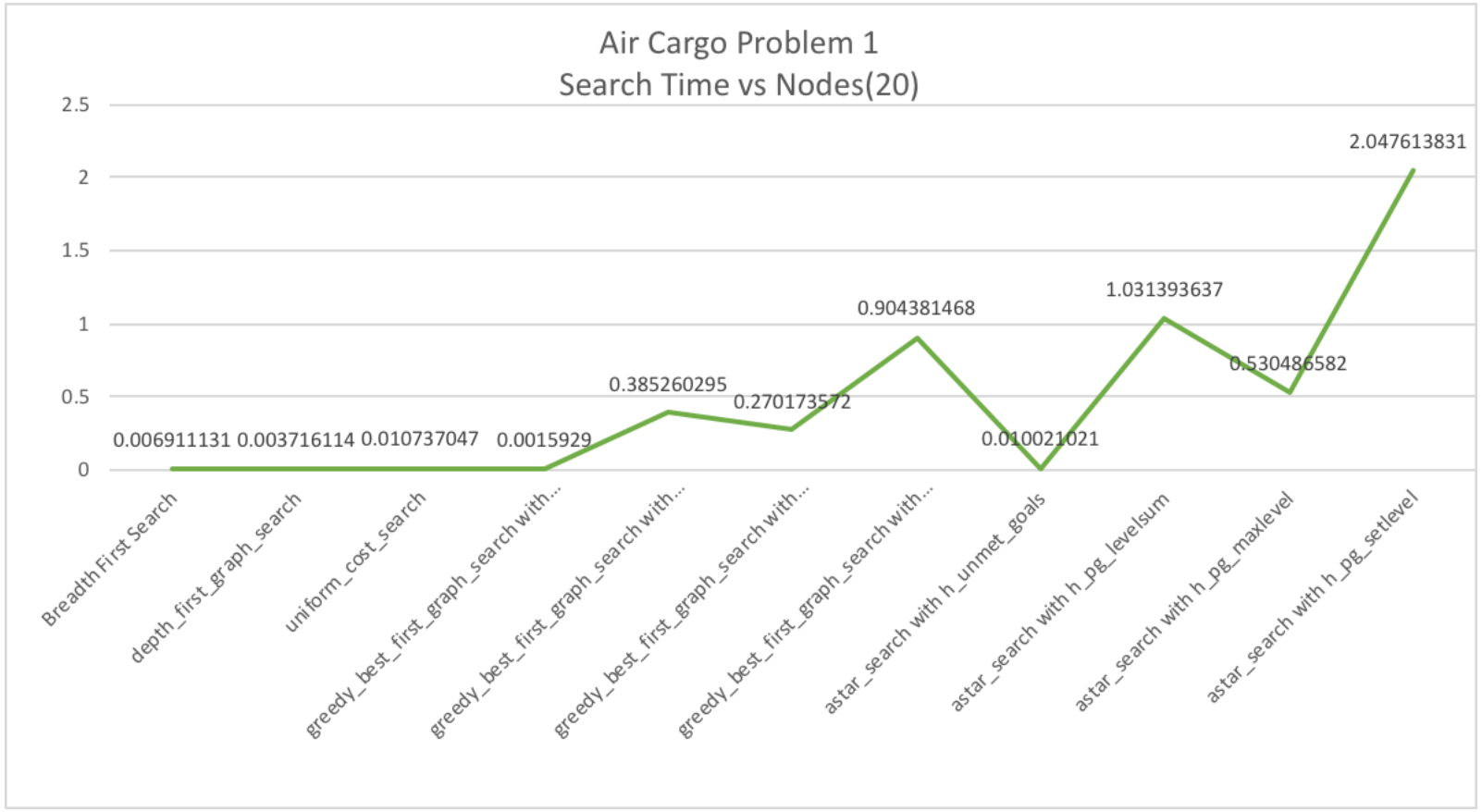
Air Cargo Problem 4

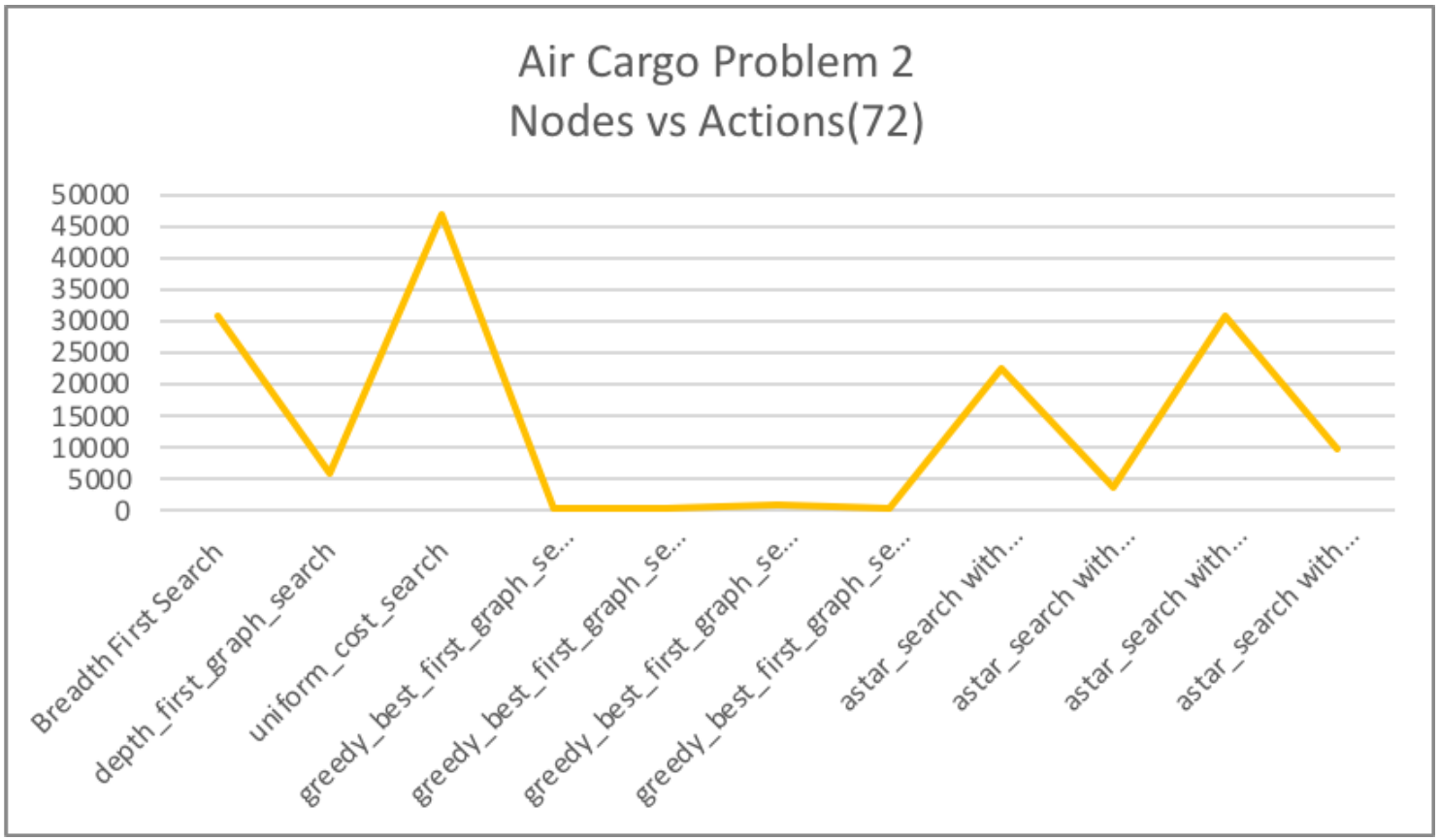
Problem	Section	Breadth First Search	greedy_best_first_graph_search with h_unmet_goals
Air Cargo Problem 4	Actions	104	104
	Expansions	99736	29
	Goal Tests	114953	31
	New Nodes	944130	280
	Plan Length:	14	18
	Time Elapsed	102.1062493	0.062874794
	Data	Load(C1, P1, SFO) Fly(P1, SFO, ATL) Load(C3, P1, ATL) Fly(P1, ATL, ORD) Load(C4, P1, ORD) Load(C5, P1, ORD) Fly(P1, ORD, JFK) Load(C2, P1, JFK) Unload(C1, P1, JFK) Unload(C3, P1, JFK) Unload(C5, P1, JFK) Fly(P1, JFK, SFO) Unload(C2, P1, SFO) Unload(C4, P1, SFO)	Load(C1, P1, SFO) Load(C2, P2, JFK) Fly(P2, JFK, SFO) Unload(C2, P2, SFO) Fly(P2, SFO, ORD) Load(C4, P2, ORD) Load(C5, P2, ORD) Fly(P2, ORD, SFO) Unload(C4, P2, SFO) Fly(P2, SFO, JFK) Unload(C5, P2, JFK) Fly(P2, JFK, ATL) Load(C3, P2, ATL) Fly(P2, ATL, JFK) Unload(C3, P2, JFK) Fly(P2, JFK, SFO) Fly(P1, SFO, JFK) Unload(C1, P1, JFK)

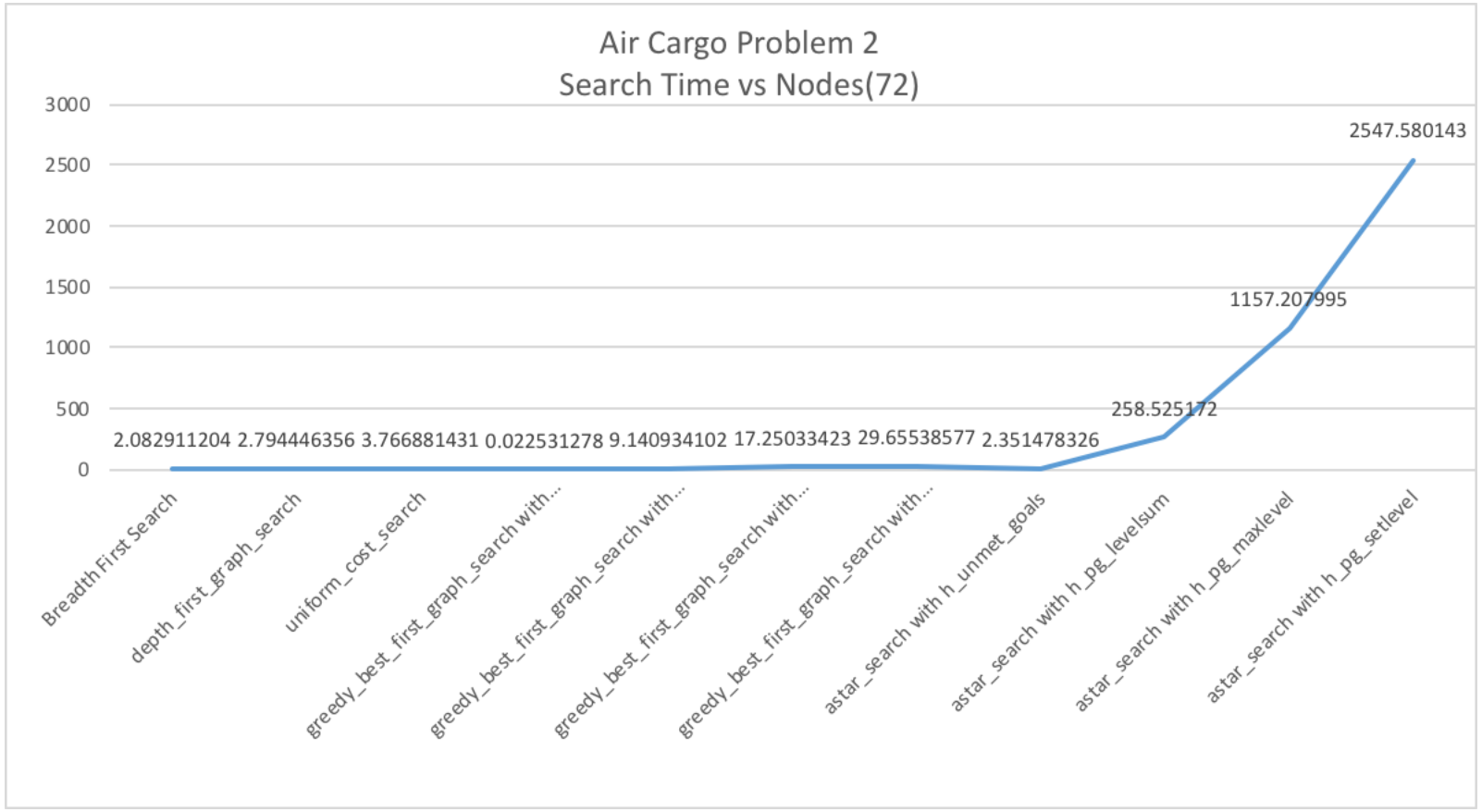
greedy_best_first_graph_search with h_pg_setlevel	astar_search with h_unmet_goals	astar_search with h_pg_levelsum
104	104	104
107	34330	1208
109	34332	1210
1164	328509	12210
23	14	15
952.247023	59.22744523	2294.919114
Load(C1, P1, SFO)		
Fly(P1, SFO, ORD)		
Load(C2, P2, JFK)		
Load(C4, P1, ORD)		
Fly(P2, JFK, ATL)		
Load(C3, P2, ATL)		
Load(C5, P1, ORD)		
Fly(P1, ORD, SFO)		
Fly(P2, ATL, SFO)		Load(C1, P1, SFO)
Unload(C5, P1, SFO)	Load(C2, P2, JFK)	Fly(P1, SFO, ORD)
Load(C5, P2, SFO)	Fly(P2, JFK, ATL)	Load(C4, P1, ORD)
Unload(C4, P1, SFO)	Load(C3, P2, ATL)	Load(C5, P1, ORD)
Fly(P1, SFO, JFK)	Fly(P2, ATL, ORD)	Fly(P1, ORD, JFK)
Load(C4, P2, SFO)	Load(C4, P2, ORD)	Unload(C5, P1, JFK)
Fly(P2, SFO, JFK)	Load(C5, P2, ORD)	Unload(C1, P1, JFK)
Unload(C3, P2, JFK)	Fly(P2, ORD, SFO)	Load(C2, P1, JFK)
Load(C3, P1, JFK)	Unload(C4, P2, SFO)	Fly(P1, JFK, SFO)
Unload(C5, P2, JFK)	Unload(C2, P2, SFO)	Fly(P2, JFK, ATL)
Fly(P2, JFK, SFO)	Load(C1, P2, SFO)	Load(C3, P2, ATL)
Unload(C4, P2, SFO)	Fly(P2, SFO, JFK)	Fly(P2, ATL, JFK)
Unload(C3, P1, JFK)	Unload(C5, P2, JFK)	Unload(C4, P1, SFO)
Unload(C2, P2, SFO)	Unload(C3, P2, JFK)	Unload(C3, P2, JFK)
Unload(C1, P1, JFK)	Unload(C1, P2, JFK)	Unload(C2, P1, SFO)

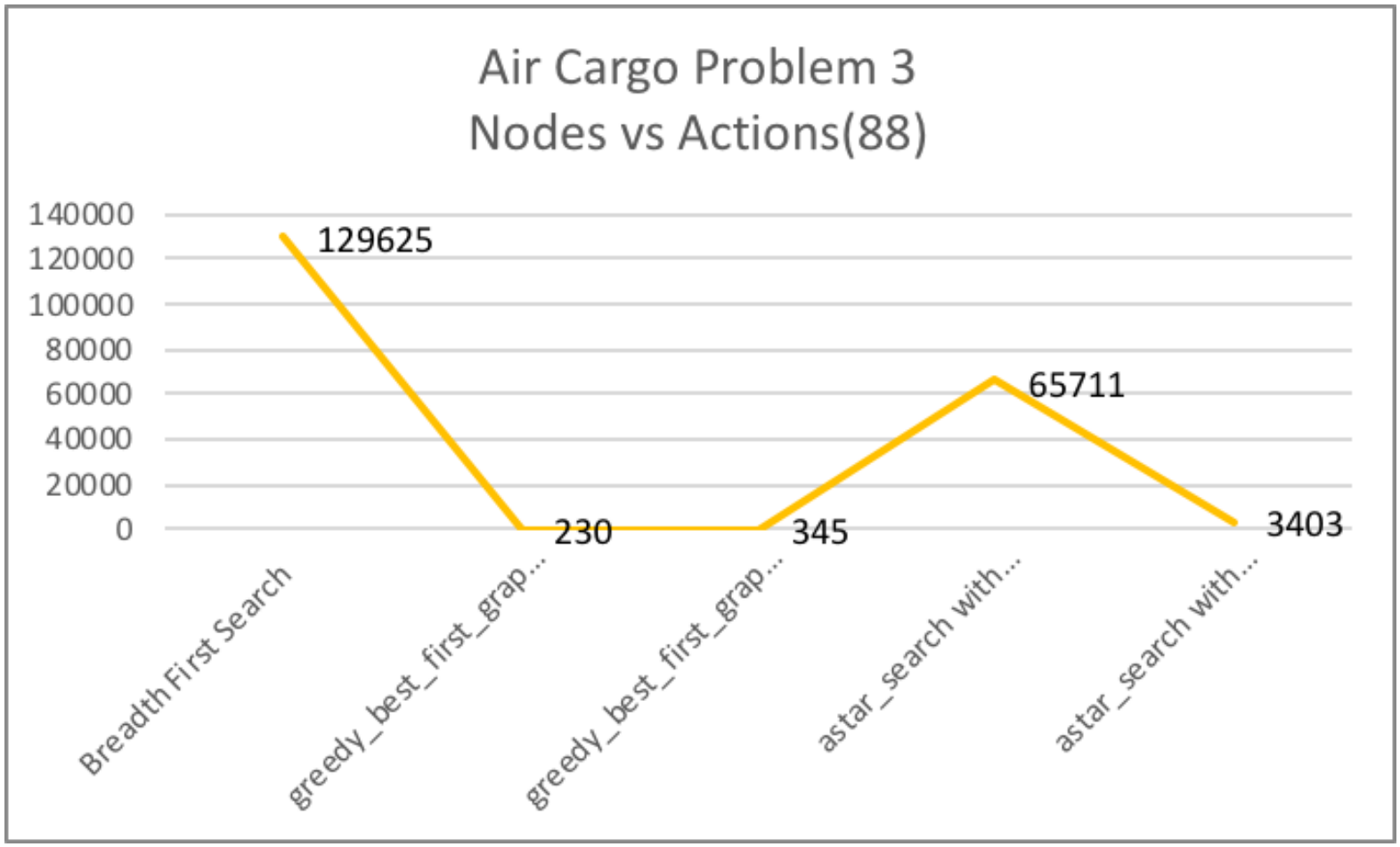
Use a table or chart to analyze the number of nodes expanded against number of actions in the domain

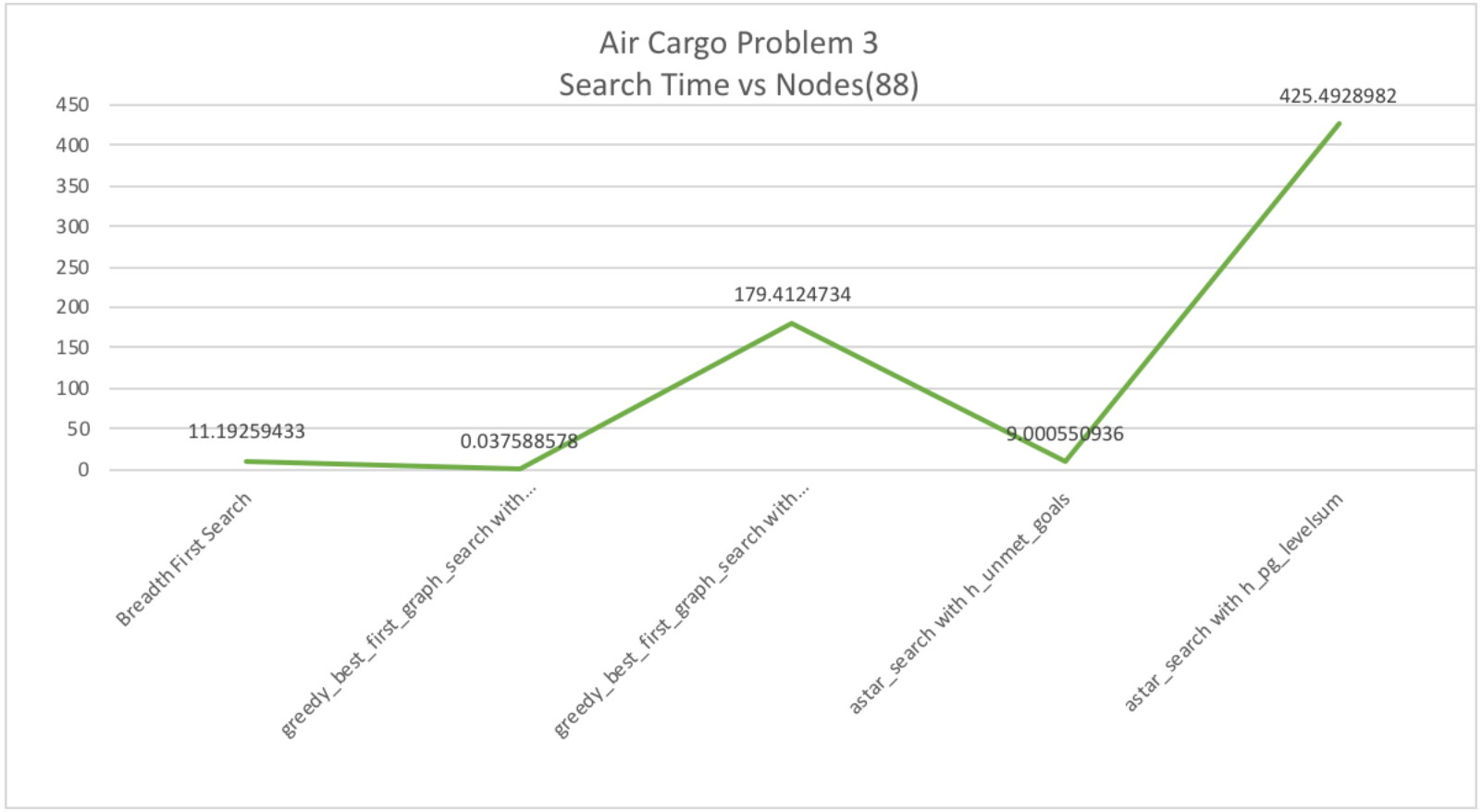


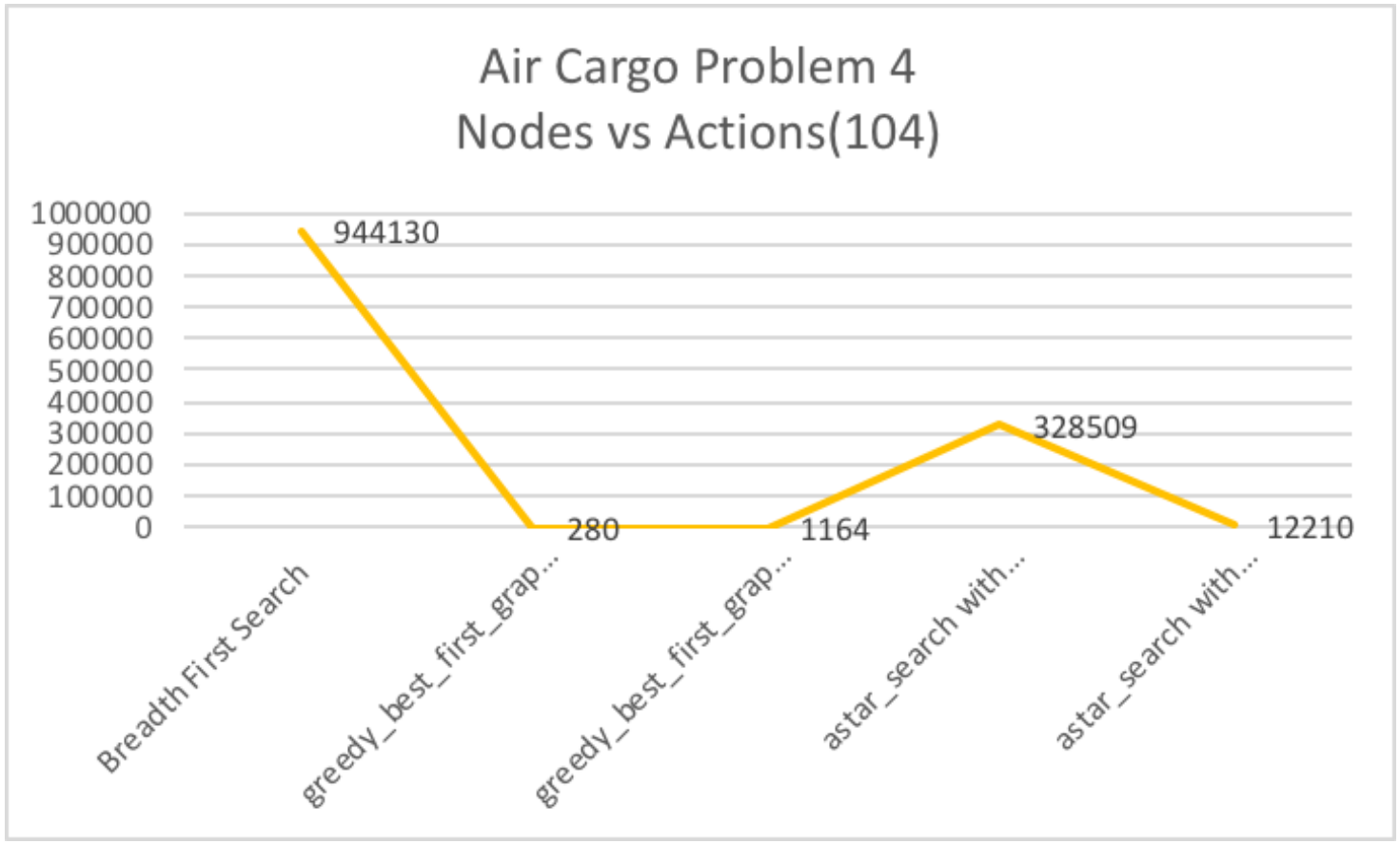

Air Cargo Problem 1
Search Time vs Nodes(20)
2.5
2
1.5
1
0.5
0
0.006911131
0.003716114
0.010737047
0.0015929
0.385260295
0.270173572
0.904381468
0.010021021
1.031393637
0.530486582
2.047613831
Breadth First Search
depth_first_graph_search
uniform_cost_search
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
astar_search with h_unmet_goals
astar_search with h_pg_levelsum
astar_search with h_pg_maxlevel
astar_search with h_pg_setlevel

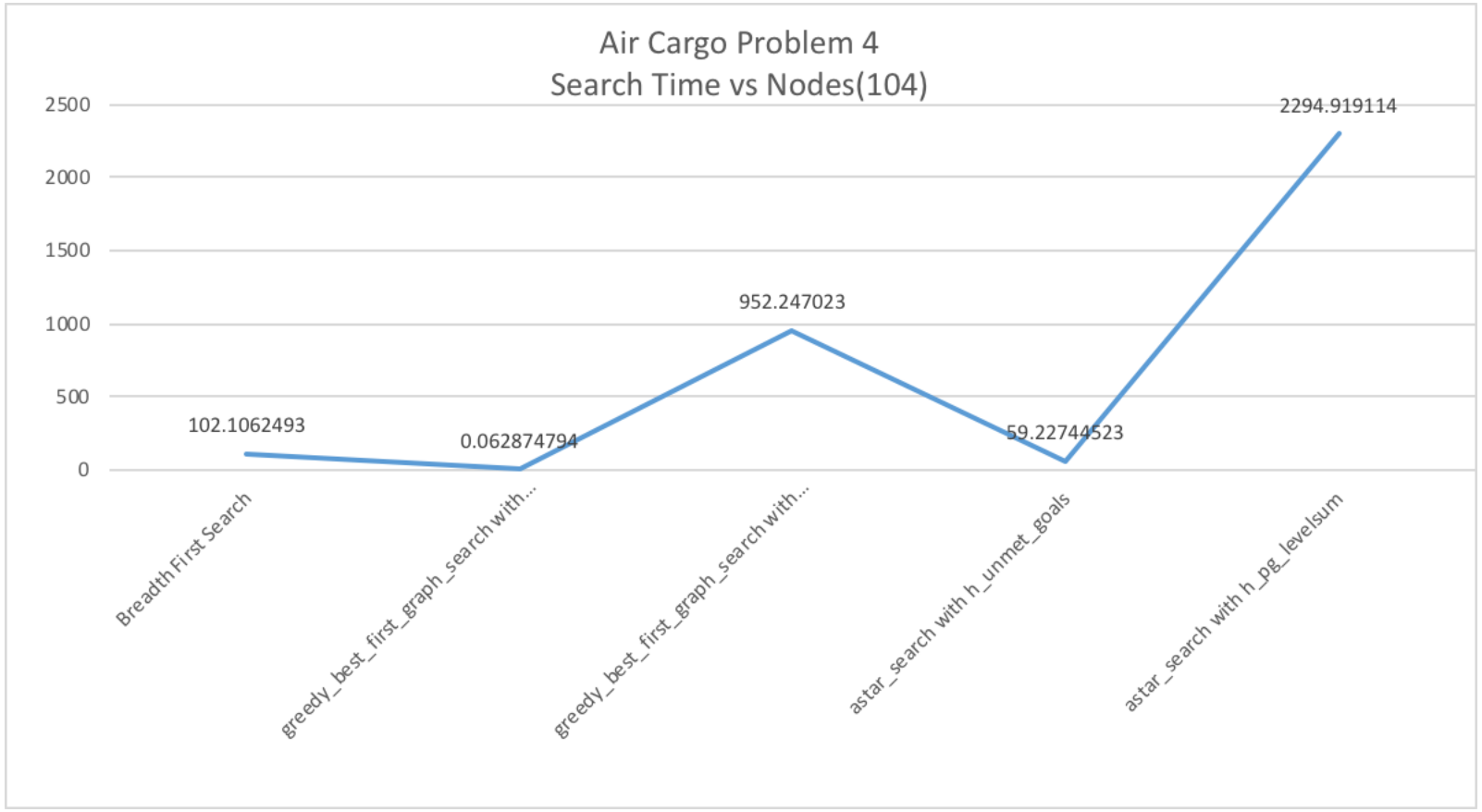

Air Cargo Problem 2
Nodes vs Actions(72)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Breadth First Search
depth_first_graph_search
uniform_cost_search
greedy_best_first_graph_se...
greedy_best_first_graph_se...
greedy_best_first_graph_se...
greedy_best_first_graph_se...
astar_search with...
astar_search with...
astar_search with...
astar_search with...

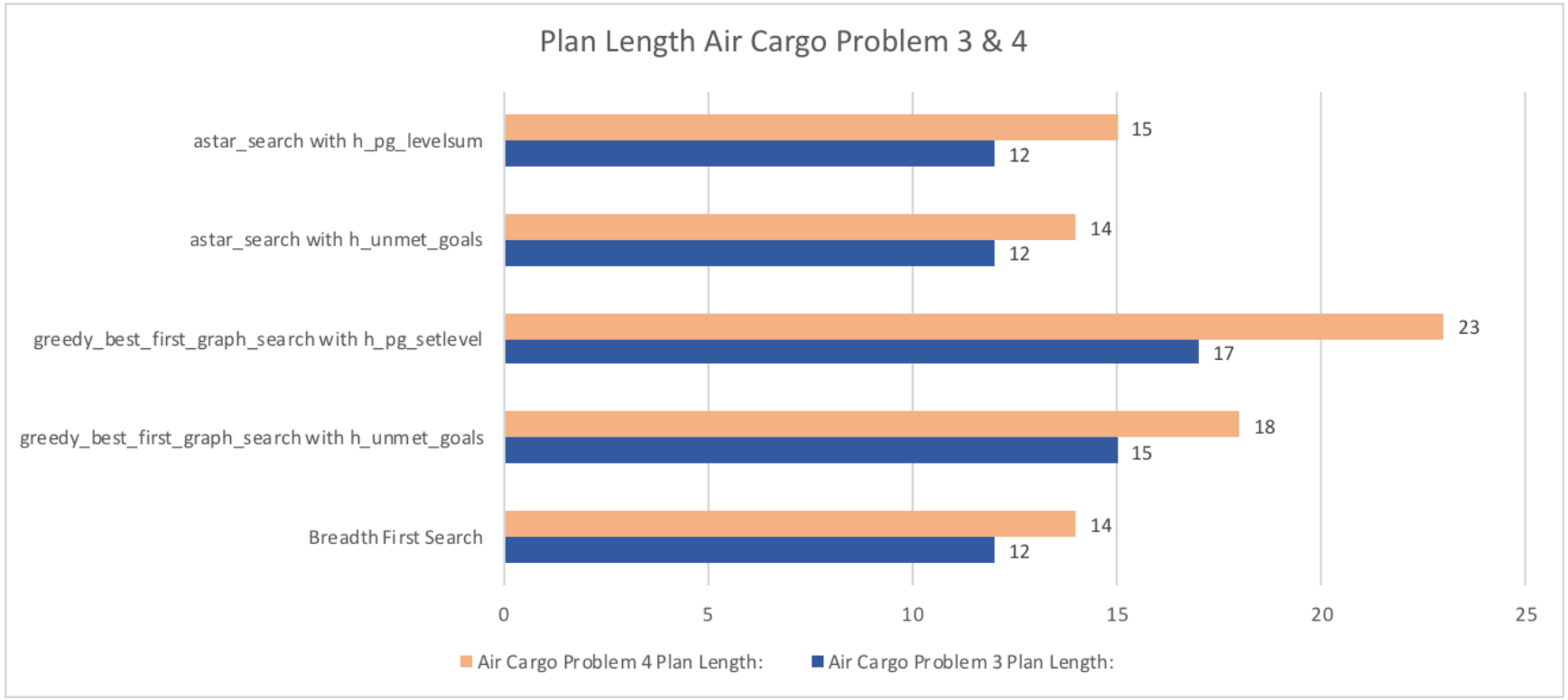

Air Cargo Problem 2
Search Time vs Nodes(72)
3000
2500
2000
1500
1000
500
0
2.082911204
2.794446356
3.766881431
0.022531278
9.140934102
17.25033423
29.65538577
2.351478326
258.525172
1157.207995
2547.580143
Breadth First Search
depth_first_graph_search
uniform_cost_search
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
astar_search with h_unmet_goals
astar_search with h_pg_levelsum
astar_search with h_pg_maxlevel
astar_search with h_pg_setlevel

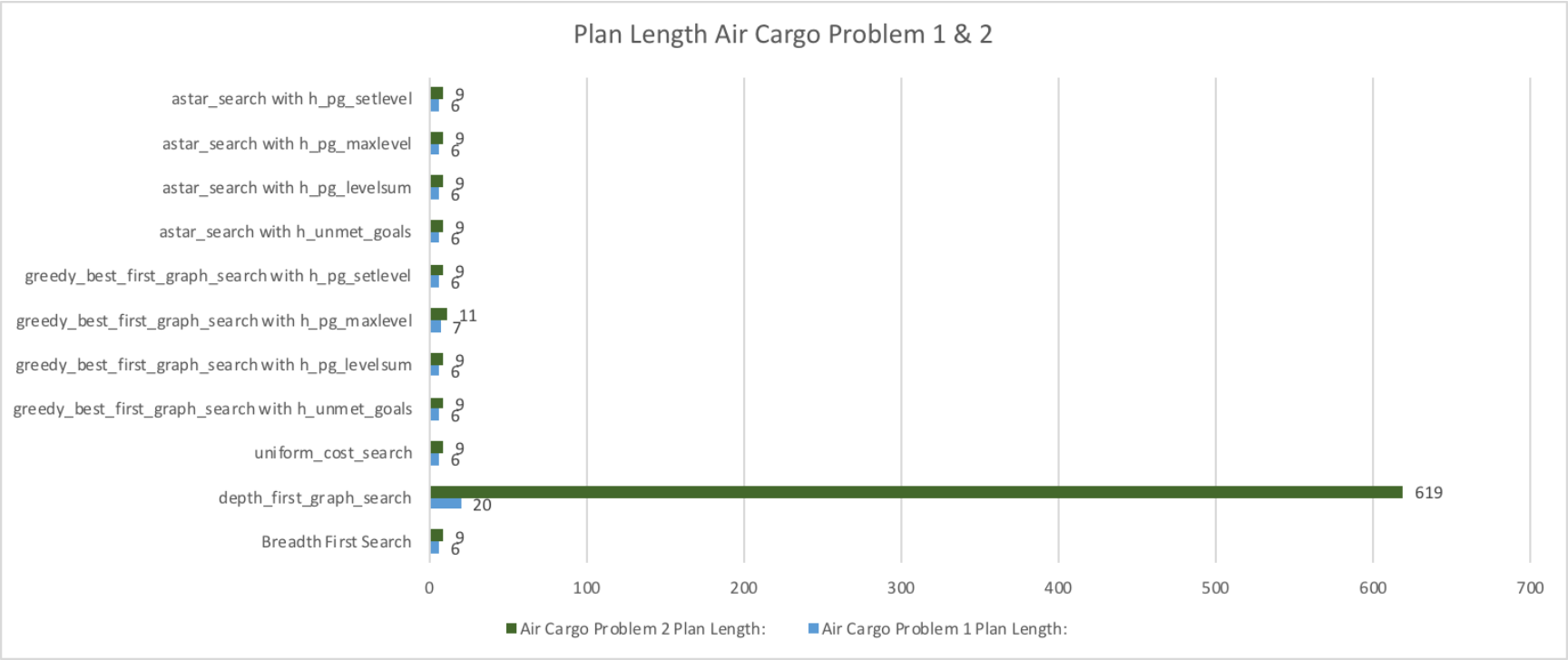

Air Cargo Problem 3
Nodes vs Actions(88)
140000
120000
100000
80000
60000
40000
20000
0
129625
230
345
65711
3403
Breadth First Search
greedy_best_first_grap...
greedy_best_first_grap...
astar_search with...
astar_search with...


Air Cargo Problem 3
Search Time vs Nodes(88)
450
400
350
300
250
200
150
100
50
0
11.19259433
0.037588578
179.4124734
9.000550936
425.4928982
Breadth First Search
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
astar_search with h_unmet_goals
astar_search with h_pg_levelsum


Air Cargo Problem 4
Nodes vs Actions(104)
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
944130
280
1164
328509
12210
Breadth First Search
greedy_best_first_grap...
greedy_best_first_grap...
astar_search with...
astar_search with...


Air Cargo Problem 4
Search Time vs Nodes(104)
2500
2000
1500
1000
500
0
102.1062493
0.062874794
952.247023
59.22744523
2294.919114
Breadth First Search
greedy_best_first_graph_search with...
greedy_best_first_graph_search with...
astar_search with h_unmet_goals
astar_search with h_pg_levelsum


Plan Length Air Cargo Problem 3 & 4
astar_search with h_pg_levelsum
astar_search with h_unmet_goals
greedy_best_first_graph_search with h_pg_setlevel
greedy_best_first_graph_search with h_unmet_goals
Breadth First Search
15
12
14
12
23
17
18
15
14
12
0
5
10
15
20
25
Air Cargo Problem 4 Plan Length:
Air Cargo Problem 3 Plan Length:



We can see based on the graphs that as nodes increase so does time required to determine the plan. While each algorithm goes up, certain algorithms such as A* goes up even more. This depends on the amount of work required. Heuristics often provide more accuracy but can cause longer times depending on the settings for the algorithm. We can see each problem has different nodes and different times based on the algorithm chosen for that particular problem. That's why no specific algorithm can win at all problems.

Which algorithm or algorithms would be most appropriate for planning in a very restricted domain (i.e., one that has only a few actions) and needs to operate in real time?

In a restricted domain, with a few actions similar to problem 1, there is very little difference between each algorithim so we need to focus more on the real time operation. An example would be greedy_best_first_graph_search with h_unmet_goals with its 0.0001 time and minimal plans (6) seems to be appropriate for this environment.

Which algorithm or algorithms would be most appropriate for planning in very large domains (e.g., planning delivery routes for all UPS drivers in the U.S. on a given day)

Looking over the problems with larger nodes, some of them (such as astar_search with h_pg_levelsum) take an inordinate amount of time to figure out the plan. While astar_search with h_unmet_goals & greedy_best_first_graph_search with h_unmet_goals are quick enough even in larger domains.

Which algorithm or algorithms would be most appropriate for planning problems where it is important to find only optimal plans?

Greedy plans cannot guarantee optimal plans, neither can depth first search. However, a* searches will find an optimal plan depending on the heuristics because it keeps looking until no better path is found. Breadth first cost search and uniform cost search will find the optimal plan as well.