Heuristic Analysis

(AIND-Planning and Search)

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Optimal plans for problems

The problems are on air cargo domain where CARGO, PLANE and AIRPORT are the objects. The preconditions and actions LOAD, UNLOAD and FLY are defined as per the action schema given below in Listing 1.

```
Action(Load(c, p, a),
        PRECOND: At(c, a) ∧ At(p, a) ∧ Cargo(c) ∧ Plane(p) ∧ Airport(a)
        EFFECT: ¬ At(c, a) ∧ In(c, p))
Action(Unload(c, p, a),
        PRECOND: In(c, p) ∧ At(p, a) ∧ Cargo(c) ∧ Plane(p) ∧ Airport(a)
        EFFECT: At(c, a) ∧ ¬ In(c, p))
Action(Fly(p, from, to),
        PRECOND: At(p, from) ∧ Plane(p) ∧ Airport(from) ∧ Airport(to)
        EFFECT: ¬ At(p, from) ∧ At(p, to))
```

Listing 1: Air cargo Action schema

Problem 1: Problem 1 initial state and goal is as given in Listing 2.

```
Init(At(C1, SFO) ∧ At(C2, JFK)
        ∧ At(P1, SFO) ∧ At(P2, JFK)
        ∧ Cargo(C1) ∧ Cargo(C2)
        ∧ Plane(P1) ∧ Plane(P2)
        ∧ Airport(JFK) ∧ Airport(SFO))
Goal(At(C1, JFK) ∧ At(C2, SFO))
```

Listing 2: Problem 1 initial state and goal

An optimal plan consists of 6 actions as given in Listing 3. Planner cannot reason about the order of FLY and UNLOAD operation as enough data (such as time to fly) is not available for reasoning. Metrics collected for different planning strategies are given in Table 1 and Figure 1.

```
Load(C1, P1, SFO)
Load(C2, P2, JFK)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
```

Listing 3: Optimal plan for problem 1

Problem 2: Problem 2 initial state and goal is as given in Listing 4.

```
Init(At(C1, SFO) ∧ At(C2, JFK) ∧ At(C3, ATL)
        ∧ At(P1, SFO) ∧ At(P2, JFK) ∧ At(P3, ATL)
        ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3)
        ∧ Plane(P1) ∧ Plane(P2) ∧ Plane(P3)
        ∧ Airport(JFK) ∧ Airport(SFO) ∧ Airport(ATL))
Goal(At(C1, JFK) ∧ At(C2, SFO) ∧ At(C3, SFO))
```

Listing 4: Problem 2 initial state and goal

Optimal plan for problem 2 consists of 9 actions. The optimal plan computed is given in Listing 5. Metrics collected for different planning strategies are given in Table 2 and Figure 2.

```
Load(C3, P3, ATL)
Fly(P3, ATL, SFO)
Unload(C3, P3, SFO)
Load(C2, P2, JFK)
Fly(P2, JFK, SFO)
Unload(C2, P2, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, JFK)
Unload(C1, P1, JFK)
```

Listing 5: Problem 2 optimal plan

Problem 3: Problem 3 initial state and goal is as given in Listing 6.

```
Init(At(C1, SFO) ∧ At(C2, JFK) ∧ At(C3, ATL) ∧ At(C4, ORD)
        ∧ At(P1, SFO) ∧ At(P2, JFK)
        ∧ Cargo(C1) ∧ Cargo(C2) ∧ Cargo(C3) ∧ Cargo(C4)
        ∧ Plane(P1) ∧ Plane(P2)
        ∧ Airport(JFK) ∧ Airport(SFO) ∧ Airport(ATL) ∧ Airport(ORD))
Goal(At(C1, JFK) ∧ At(C3, JFK) ∧ At(C2, SFO) ∧ At(C4, SFO))
```

Listing 6: Problem 3 initial state and goal

Optimal plan for problem 3 consists of 12 actions. The optimal plan computed is given in Listing 7. Metrics collected for different planning strategies are given in Table 3 and Figure 3. Here plane P2 is loaded with cargos C2 and C4 respectively at JFK and ORD before flying to SFO to achieve the best plan.

```
Load(C2, P2, JFK)
Fly(P2, JFK, ORD)
Load(C4, P2, ORD)
Fly(P2, ORD, SFO)
Load(C1, P1, SFO)
Fly(P1, SFO, ATL)
Load(C3, P1, ATL)
Fly(P1, ATL, JFK)
Unload(C4, P2, SFO)
Unload(C3, P1, JFK)
Unload(C2, P2, SFO)
Unload(C1, P1, JFK)
```

Listing 7: Problem 3 optimal plan

Comparison of non-heuristic search

Non-heuristic search methods used to solve problems 1,2 and 3 were Breadth First, Depth First Graph and Uniform cost search.

Depth First Graph search gives faster results but the solution is not optimal as it consists of many hops (represented by path length). The plan lengths obtained using depth first are many orders of magnitude away from the optimal plan. Breadth First search and Uniform cost search gave almost similar results in terms of nodes expanded, path length and the time taken to search. For complex problems, like problem 3, uniform cost search was more efficient in terms of execution time. But, in terms of number of nodes expanded, breadth first search was better compared to uniform cost search.

Comparison of heuristic search

Heuristic search methods used to solve problems 1,2 and 3 were A* with constant cost (H1), A* with ignored preconditions and A* with planning graph level sum.

A* PG Levelsum explored very less number of nodes compared to other algorithms and always resulted in giving out optimal solutions. But, comparing to other A* strategies, the execution time is slightly higher. This may be because of the construction of planning graphs. The best algorithm among all these A* strategies is A* Ignore Preconditions in terms of execution time. But it resulted in higher number of nodes explored.

Comparison of all classes

If we are considering the number of node expansion, A* PG Levelsum is the best algorithms. It expands way less number of nodes compared to its counterparts. If execution time and optimal plan are in the consideration and we don't worry about the nodes expanded, then we should consider using A* with Ignore Preconditions.

Visual References

Air Cargo Problem 1					
Algorithm	**Expansions**	**Goal Tests**	**New Nodes**	**Length**	**Time (sec)**
Breadth First	43	56	180	6	2.85E-02
Depth First Graph	21	22	84	20	1.27E-02
Uniform cost	55	57	224	6	3.54E-02
A* H1	55	57	224	6	3.37E-02
A* Ignore Preconditions	41	43	170	6	3.60E-02
A* PG Levelsum	11	13	50	6	5.11E-01

Table 1: Metrics collected for Problem 1

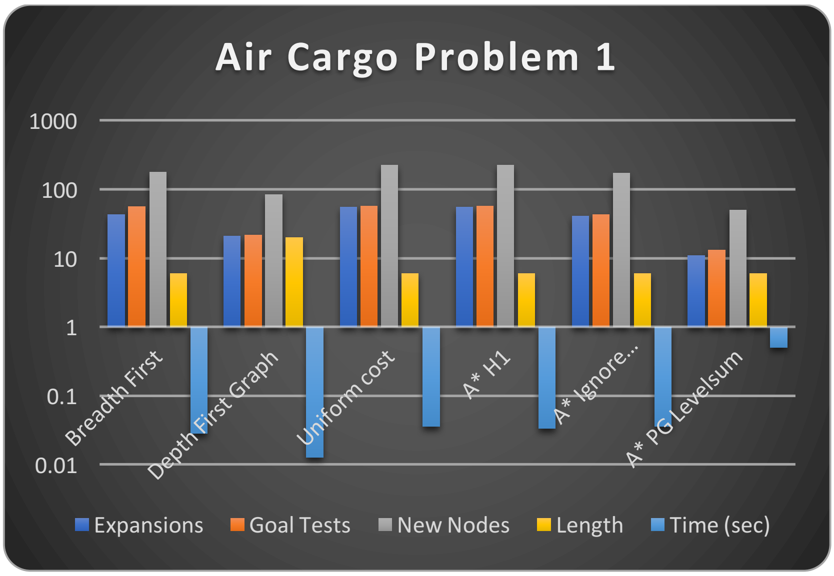

Figure 1: Plot of Metrics collected for Problem 1 in logarithmic scale

Air Cargo Problem 2					
Algorithm	**Expansions**	**Goal Tests**	**New Nodes**	**Length**	**Time (sec)**
Breadth First	3346	4612	30534	9	1.37E+01
Depth First Graph	107	108	959	105	4.33E-01
Uniform cost	4853	4855	44041	9	1.25E+01
A* H1	4853	4855	44041	9	1.20E+01
A* Ignore Preconditions	1450	1452	13303	9	4.47E+00
A* PG Levelsum	86	88	841	9	5.28E+01

Table 2: Metrics collected for Problem 2

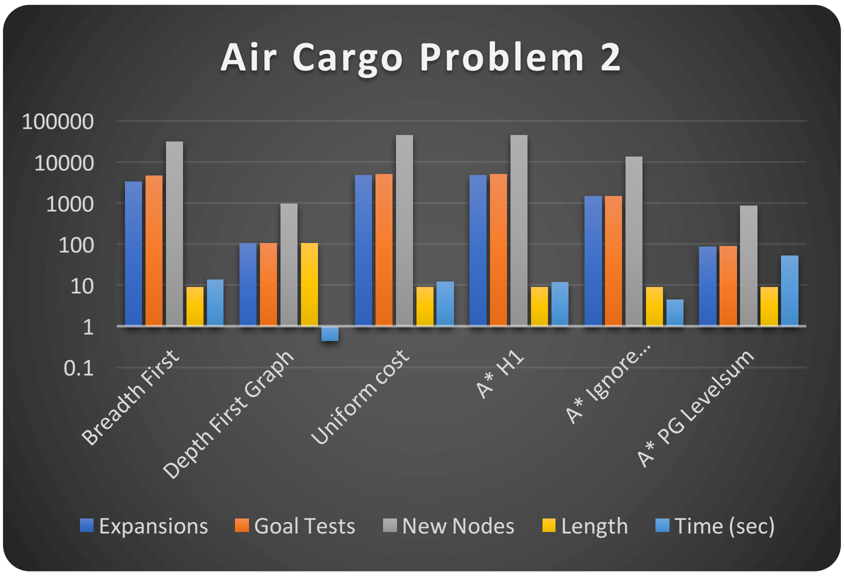

Figure 2: Plot of Metrics collected for Problem 2 in logarithmic scale

Air Cargo Problem 3					
Algorithm	**Expansions**	**Goal Tests**	**New Nodes**	**Length**	**Time (sec)**
Breadth First	14663	18098	129631	12	9.91E+01
Depth First Graph	408	409	3364	392	1.62E+00
Uniform cost	18223	18225	159618	12	4.80E+01
A* H1	18223	18225	159618	12	4.80E+01
A* Ignore Preconditions	5040	5042	44944	12	1.53E+01
A* PG Levelsum	325	327	3002	12	2.39E+02

Table 3: Metrics collected for Problem 3

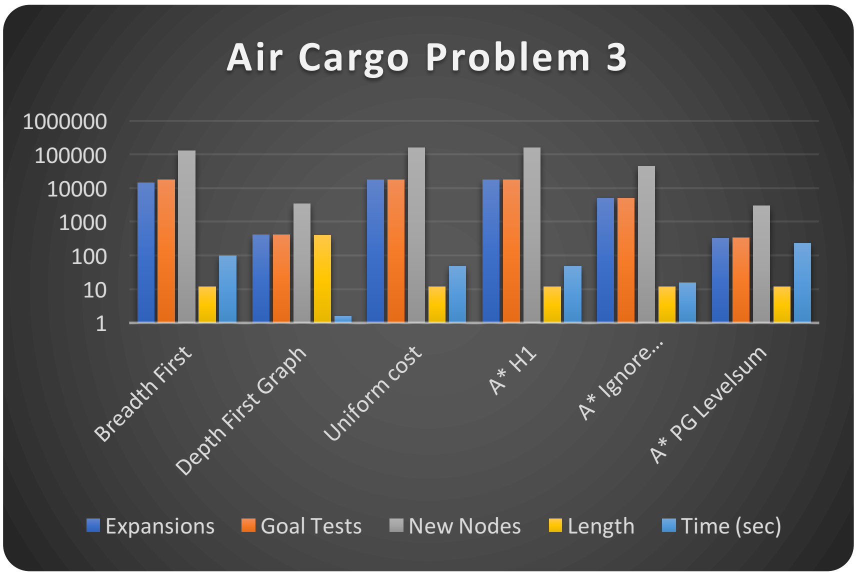

Figure 3: Plot of Metrics collected for Problem 3 in logarithmic scale