## Heuristic Analysis

To analyze the implementation of the planning graph and the heuristics, 3 air cargo problems with increasing complexity were run with the following ten search algorithms (Russel & Norvig, 2016):

* Breadth first search
* Breadth first tree search
* Depth first graph search
* Depth limited search
* Uniform cost search
* Recursive best first search with a pseudo heuristic (h1) returning a hardcoded constant
* Greedy best first graph search with h1
* A\* search with h1
* A\* search with ignore
* A\* search with level-sum heuristic

Table 1 lists the results for air cargo problem one, which was the only problem for which each algorithm found a plan in under 10 minutes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | #node expansions | #Goal tests | Time elapsed(sec) | New nodes | Plan  length |
| Breadth first | 43 | 56 | 0.32 | 180 | 6 |
| Breadth-first tree | 1458 | 1459 | 10.8 | 5960 | 6 |
| Depth-first  graph | 12 | 13 | 0.08 | 48 | 12 |
| Depth limited | 101 | 271 | 0.8 | 414 | 50 |
| Uniform cost | 55 | 57 | 0.4 | 224 | 6 |
| Recursive  Best first | 4229 | 4230 | 9.1 | 17029 | 6 |
| Greedy  Best first | 7 | 9 | 0.04 | 28 | 6 |
| A\* with h1 | 55 | 57 | 0.38 | 224 | 6 |
| A\* with ignore preconditions | 41 | 43 | 0.3 | 170 | 6 |
| A\* with levelsum | 55 | 57 | 54.3 | 224 | 6 |

Table Air cargo problem 1

The optimal plan for problem 1 consists of 6 actions:

Load(JFK, P2, C2)

Load(SFO, P1, C1)

Fly(P2, JFK, SFO)

Unload(SFO, P2, C2)

Fly(P1, SFO, JFK)

Unload(JFK, P1, C1)

All but two algorithms were able to find a plan with a length of six. *Greedy best first* clearly performed best in all 5 categories, with the lowest complexity in both time and space, by far. The three *A\** searches are close with respect to their space complexity. *A\* search with levelsum* has however a much higher running time than the other 2, which may be an indication of a non-optimal implementation.

Table 2 lists the results for all algorithms that could find a plan for air cargo problem 2 in fewer than 10 minutes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | #node expansions | #Goal tests | Time elapsed(sec) | New nodes | Plan  length |
| Breadth first | 3343 | 4609 | 153.92 | 30509 | 9 |
| Breadth-first tree |  |  |  |  |  |
| Depth-first  graph | 582 | 583 | 35.24 | 5211 | 575 |
| Depth limited |  |  |  |  |  |
| Uniform cost | 4853 | 4855 | 149.35 | 44041 | 9 |
| Recursive  Best first |  |  |  |  |  |
| Greedy  Best first | 998 | 1000 | 31.16 | 8982 | 21 |
| A\* with h1 | 4853 | 4855 | 155.27 | 44041 | 9 |
| A\* with ignore preconditions | 1450 | 1452 | 46.19 | 13303 | 9 |
| A\* with levelsum |  |  |  |  |  |

Table : Air cargo problem 2

The minimal plan for problem 2 consists of 9 actions:

Load(SFO, P1, C1)

Load(JFK, P2, C2)

Load(ATL, P3, C3)

Fly(P1, SFO, JFK)

Fly(P2, JFK, SFO)

Fly(P3, ATL, SFO)

Unload(SFO, P3, C3)

Unload(SFO, P2, C2)

Unload(JFK, P1, C1)

A plan of minimal length 9 was found by 4 algorithms, of which *A\* search with ignore preconditions* performed best in all 5 categories. *Greedy best first* which performed best for problem 1, failed to find the minimum plan for the more complex problem 2.

Table 3 lists the results for all algorithms which were able to find a plan for air cargo problem 3 in fewer than 10 minutes.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | #node expansions | #Goal tests | Time elapsed(sec) | New nodes | Plan  length |
| Breadth first |  |  |  |  |  |
| Breadth-first tree |  |  |  |  |  |
| Depth-first  graph | 627 | 628 | 38.29 | 5176 | 596 |
| Depth limited |  |  |  |  |  |
| Uniform cost |  |  |  |  |  |
| Recursive  Best first |  |  |  |  |  |
| Greedy  Best first | 5578 | 5580 | 211.61 | 49150 | 22 |
| A\* with h1 | 18223 | 18225 | 57.68 | 159618 | 12 |
| A\* with ignore preconditions | 5040 | 5042 | 192.06 | 44944 | 12 |
| A\* with levelsum |  |  |  |  |  |

Table : Air cargo problem 3

A minimal plan for problem 3 comprises 12 actions:

Load(SFO, P1, C1)

Load(JFK, P2, C2)

Fly(P1, SFO, ATL)

Load(ATL, P1, C3)

Fly(P2, JFK, ORD)

Load(ORD, P2, C4)

Fly(P2, ORD, SFO)

Fly(P1, ATL, JFK)

Unload(SFO, P2, C4)

Unload(JFK, P1, C3)

Unload(SFO, P2, C2)

Unload(JFK, P1, C1)

Again, the *A\** algorithms were able to find a plan with the minimal length of 12. While *A\** with *uniform cost* heuristic performed better in time, *A\* with ignore preconditions* required less memory. None of the other algorithms was able to find the minimal plan. *Greedy best first*,which performed best on problem one, came however close with, a plan length of 22. With a time and space complexity comparable to *A\* with ignore preconditions, Greedy best first* may be an interesting alternative in situation where good heuristics are not available.

# Literature

Russel, S., & Norvig, P. (2016). *Artificial Intelligence: A Modern Approach, Global Edition.* Pearson.