Automated Planning for Liner Shipping Fleet Repositioning

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In collaboration with:
Mikkel Muhldorff Sigurd and Shaun Long
Maersk Line
Motivation

• Globally: ~100 repositionings monthly
• Cost: From $200K - $1 million per vessel
• Maersk Line saved $100 million last year repositioning by hand.
Outline

1. Liner Shipping Fleet Repositioning
2. PDDL Domain
3. Solution methods
   a. Linear Temporal Optimization Planning
   b. POPF
   c. MIP
4. Computational Results
5. Conclusion & Future Work
Liner Shipping Services

Slot 1
- YOK (Sun.)
- YTN (Fri.)
- HKG (Sat.)
- XMN (Sun.)
- NGB (Tue.)
- SHA (Wed.)
- LZC (Sun.)
- BLB (Thu.)

Slot 2
- YOK (Sun.)
- YTN (Fri.)
- HKG (Sat.)
- XMN (Sun.)
- NGB (Tue.)
- LQN (Sun.)

Slot 3
- YOK (Sun.)
- YTN (Fri.)
Repositioning

Goal: Optimize cost!

- Sail on service
- Sail with equipment
- Slow steam
- Respect cargo flows

Yokohama to Los Angeles

$923k

$485k

193 hrs

483 hrs

Friday, June 29, 12
Repositioning

Difficulties:

- Vessel interactions (SOS & Phase-in)
- Action duration linked costs
- Hotel cost
PDDL 2.1 Domain

- **High level actions:** phase-out, phase-in, sail, sail-on-service, sail-equipment
- **Model aspects:**
  - **TILs:** Between 146 and 266

  (at 16  (vessel-may-phase-out vessel0 pMYTPP))
  (at 16.1 (not (vessel-may-phase-out vessel0 pMYTPP)))
  (at 504  (vessel-may-phase-in pPABLB))
  (at 504.1 (not (vessel-may-phase-in pPABLB)))

- **Hotel cost envelope actions**

  Hotel Cost Calc Phase Out Vessel1
  │
  │
  │ Sail Vessel1 PortFrom PortTo │
  │
  │ Phase–Out Vessel1 PortFrom │
  │
  │ Phase–In Vessel1 PortTo │
PDDL 2.1 Domain

- Model aspects:
  - Action costs that decline with duration

Yokohama to Los Angeles

<table>
<thead>
<tr>
<th>Duration (hrs)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
<td>$923k</td>
</tr>
<tr>
<td>483</td>
<td>$485k</td>
</tr>
</tbody>
</table>

- Required concurrency
## Related Work

<table>
<thead>
<tr>
<th>Sapa</th>
<th>Can’t model duration-dependent effects.</th>
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</thead>
<tbody>
<tr>
<td>(Do and Kambhampati 2003)</td>
<td></td>
</tr>
<tr>
<td><strong>LPG</strong></td>
<td></td>
</tr>
<tr>
<td>(Gerevini, Saetti, and Serina 2003 &amp; Gerevini and Saetti 2010)</td>
<td></td>
</tr>
<tr>
<td><strong>Net-benefit planners</strong></td>
<td></td>
</tr>
<tr>
<td>(HSP*, MIPS-XXL, Gamer)</td>
<td></td>
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<tr>
<td>(Helmert, Do, and Refanidis 2008)</td>
<td></td>
</tr>
<tr>
<td><strong>Kongming</strong></td>
<td>Does not allow multiple updates to a single variable.</td>
</tr>
<tr>
<td>(Li and Williams 2008)</td>
<td></td>
</tr>
<tr>
<td><strong>TM-LPSAT</strong></td>
<td>Does not optimize a plan metric.</td>
</tr>
<tr>
<td>(Shin and Davis 2005)</td>
<td></td>
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</tbody>
</table>
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Linear Temporal Optimization Planning

Partial-Order Planning + Linear Programming

Example: Sail Action

Objective:
\[ \min \alpha_v (x^e_v - x^s_v) \]

Constraints:
\[ 10 \leq x^e_v - x^s_v \leq 100 \]
\[ h^s_v \leq x^s_v \]

Pre:
- \( \text{at}(vessel) = \text{from} \)
- \( \text{state}(vessel) = \text{T} \)

Eff:
- \( \text{at}(vessel) = \text{to} \)

sail(vessel, from, to)

State variables

Optimization variables
LTOP Plans

Initial State ← Action 1

Action 1
Obj: \( s_1 + e_1 \)
s.t.: \( e_1 - s_1 \leq 40 \)
\( e_1, s_1 \geq 0 \)

Initial State ← Action 2

Action 2
Obj: \( 5e_2 - 3s_2 + 1.2v_2 \)
s.t.: \( 20 \leq e_2 - s_2 \leq 70 \)
\( 10 \leq 2v_2 - v_1 \leq 30 \)
\( s_2, e_2, v_2 \geq 0 \)

Initial State ← Action 3

Action 3
Obj: \( 2e_3 + s_3 - v_1 \)
s.t.: \( 10 \leq 5e_3 - s_3 \)
\( 2s_3 + v_1 \leq 34 \)
\( s_3, e_3, v_1 \geq 0 \)

Goal State

Goal State ← Action 1

Goal State ← Action 2

Goal State ← Action 3
LTOP Plans

Optimization Model

Obj: \( s_1 + e_1 + 5e_2 - 3s_2 + 1.2v_2 + 2e_3 + s_3 - v_1 \)

s.t.: 
- \( e_1 - s_1 \leq 40 \)
- \( 20 \leq e_2 - s_2 \leq 70 \)
- \( 10 \leq 2v_2 - v_1 \leq 30 \)
- \( 10 \leq 5e_3 - s_3 \)
- \( 2s_3 + v_1 \leq 34 \)
- \( e_3 - s_1 \leq 0 \)

More action ordering constraints...

\( s_1, e_1, s_2, e_2, s_3, e_3, v_1, v_2 \geq 0 \)
LTOP Branch & Bound

\[ \text{cost} \geq 600 \]
\[ UB = 600 \]

\[ \text{cost} \geq 650 \]

\[ \text{cost} \geq 500 \]

Prune
POPF

- Forward-chaining partial-order planner
- Satisficing planner, but can keep searching to improve quality

- Modifications:
  - TIL Handling: Modeled in a MIP (DTP)
  - Cost estimation action pruning

Coles, A. J.; Coles, A. I.; Fox, M.; and Long, D. Forward-chaining partial-order planning. ICAPS-10.

Coles, A. J.; Coles, A. I.; Clark, A.; and Gilmore, S. T. Cost-sensitive concurrent planning under duration uncertainty for service level agreements. ICAPS-11.
POPF TIL Handling

- POPF TIL handling: dummy actions
- New TIL handling in certain cases:
  - Leave choice of window to a MIP
  - DTP solver insufficient (continuous costs)
POPF TIL Handling

- $f$ added/deleted periodically

1. No action adds/deletes $f$

$$\sum_{k=0}^{n} f_k^+ w_k^i \leq \text{step}_i \leq \sum_{k=0}^{n} f_k^- w_k^i$$

$$\sum_{k=0}^{n} w_k^i = 1$$

2. No action adds $f$; actions with a precondition on $f$ delete $f$

$$\forall^n_{k=1} \sum_{i \in F} w_k^i \leq 1$$
MIP

Variables

\[ y_{a,b} \in \{0, 1\} \text{ – use edge } a \text{ to } b? \]
\[ w_a \in \{0, 1\} \text{ – use action } a? \]
\[ 0 \leq x^s_a \text{ – action begin} \]
\[ 0 \leq x^e_a \text{ – action end} \]
\[ 0 \leq h^s_v \text{ – hotel cost} \]
\[ 0 \leq h^e_v \text{ – hotel cost} \]

Activity Graph

(Phase-in actions)

(Phase-out actions)
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<table>
<thead>
<tr>
<th>Inst.</th>
<th>MIP</th>
<th></th>
<th></th>
<th></th>
<th>POPF (Optimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DLH</td>
<td>DL</td>
<td>LH</td>
<td>L</td>
</tr>
<tr>
<td>AC3_1_0</td>
<td>0.4</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td>AC3_2_0</td>
<td>9.3</td>
<td>51.0</td>
<td>51.5</td>
<td>50.4</td>
<td>53.5</td>
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<tr>
<td>AC3_3_0</td>
<td>23.0</td>
<td>188.3</td>
<td>196.8</td>
<td>193.3</td>
<td>202.0</td>
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<tr>
<td>AC3_1_1e</td>
<td>3.8</td>
<td>3.9</td>
<td>3.9</td>
<td>5.2</td>
<td>5.3</td>
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<tr>
<td>AC3_2_2ce</td>
<td>27.7</td>
<td>15.2</td>
<td>25.2</td>
<td>55.2</td>
<td>126.8</td>
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<tr>
<td>AC3_3_2c</td>
<td>250.5</td>
<td>203.2</td>
<td>362.2</td>
<td>2979.7</td>
<td>3715.8</td>
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<tr>
<td>AC3_3_2e</td>
<td>228.8</td>
<td>217.1</td>
<td>263.0</td>
<td>1453.1</td>
<td>2092.8</td>
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<td>AC3_3_2ce1</td>
<td>312.2</td>
<td>218.2</td>
<td>260.8</td>
<td>1451.6</td>
<td>2068.4</td>
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<td>AC3_3_2ce2</td>
<td>252.6</td>
<td>192.4</td>
<td>216.0</td>
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<tr>
<td>AC3_3_2ce3</td>
<td>706.5</td>
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<td>AC3_3_3</td>
<td>148.3</td>
<td>80.0</td>
<td>102.4</td>
<td>735.0</td>
<td>1140.8</td>
</tr>
</tbody>
</table>

CPU Time in seconds; 1 hour timeout
Instances all variations on our real-world case study
## Computational Results

<table>
<thead>
<tr>
<th>Inst.</th>
<th>POPF (Satisficing)</th>
<th></th>
<th>No MIP relax</th>
<th>No-TIL-Abs</th>
<th>Reversed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
<td>Makespan</td>
<td></td>
<td></td>
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<tr>
<td>AC3_1_0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC3_2_0</td>
<td>0.4 (0.0)</td>
<td>0.1 (1.7)</td>
<td>0.7 (0.0)</td>
<td>105.8 (0.0)</td>
<td>0.4 (0.0)</td>
</tr>
<tr>
<td>AC3_3_0</td>
<td>32.5 (0.0)</td>
<td>3.2 (1.6)</td>
<td>113.2 (0.0)</td>
<td>13.0 (0.1)</td>
<td>78.1 (0.0)</td>
</tr>
<tr>
<td>AC3_1_1e</td>
<td>1105.1 (0.0)</td>
<td>117.5 (2.3)</td>
<td>3041.6 (0.0)</td>
<td>88.2 (0.1)</td>
<td>39.2 (0.8)</td>
</tr>
<tr>
<td>AC3_2_2ce</td>
<td>1.7 (0.0)</td>
<td>0.1 (0.7)</td>
<td>2.3 (0.0)</td>
<td>1079.3 (0.3)</td>
<td>1.2 (1.2)</td>
</tr>
<tr>
<td>AC3_3_2c</td>
<td>1550.6 (0.3)</td>
<td>1.1 (19)</td>
<td>2284.2 (0.0)</td>
<td>31.3 (3.7)</td>
<td>892.5 (1.6)</td>
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<tr>
<td>AC3_3_2e</td>
<td>399.2 (0.2)</td>
<td>9.2 (7.3)</td>
<td>26.3 (1.4)</td>
<td>303.4 (1.3)</td>
<td>602.8 (1.1)</td>
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<tr>
<td>AC3_3_2ce</td>
<td>291.5 (1.3)</td>
<td>9.6 (11)</td>
<td>28.4 (2.4)</td>
<td>310.8 (2.3)</td>
<td>688.6 (1.9)</td>
</tr>
<tr>
<td>AC3_3_2ce1</td>
<td>303.9 (1.3)</td>
<td>9.7 (11)</td>
<td>28.4 (2.4)</td>
<td>314.5 (2.3)</td>
<td>697.2 (1.9)</td>
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<tr>
<td>AC3_3_2ce2</td>
<td>1464.2 (1.6)</td>
<td>10.0 (12)</td>
<td>204.9 (2.8)</td>
<td>303.4 (2.7)</td>
<td>690.1 (2.3)</td>
</tr>
<tr>
<td>AC3_3_2ce3</td>
<td>348.0 (1.1)</td>
<td>10.3 (8.7)</td>
<td>29.4 (1.9)</td>
<td>308.4 (1.7)</td>
<td>603.3 (1.5)</td>
</tr>
<tr>
<td>AC3_3_3</td>
<td>1975.5 (2.3)</td>
<td>10.1 (15)</td>
<td>226.0 (3.6)</td>
<td>352.6 (3.4)</td>
<td>699.6 (2.9)</td>
</tr>
</tbody>
</table>

**CPU Time in seconds (Optimality gap)**
Conclusion

• Question:
  • Should the LSFRP be modeled with a MIP or automated planning?

• Future work:
  • Investigate of planning vs. MIPs on variations of the LSFRP
  • Adding container flows (revenue) to the LSFRP
  • Download the LSFRP PDDL Domain:

http://www.decisionoptimizationlab.dk/datasets