On the Relationship Between State-Dependent Action Costs and Conditional Effects in Planning

Robert Mattmüller       Florian Geißer
Benedict Wright        Bernhard Nebel

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Relaxations with State-Dependent Costs and Effects
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\[ x = \{ 1, 2, 3 \}, \quad \text{cost}((x), x) = 1, \quad \text{eff}((x), x) = \{ 2, 3, 4 \}, \quad \text{inc}((x)) \]

\[ x = \{ 1, 2, 3, 4, 5, 6 \}, \quad \text{cost}((x), x) = x, \quad \text{eff}((x), x) = \{ 2, 3, 4 \} \bigcup \]

Relaxations with State-Dependent Costs and Effects

\[ \text{cost}(\emptyset, x) = x \]

\[ \text{eff}(\emptyset, x) = \text{inc}(x) \]

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\[ x = 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \]

\[ x^+ = \{1, 2, 3\} \quad \text{cost}(\bullet, x^+) = 1 \quad (\text{min}) \]
\[ \text{eff}(\bullet, x^+) = \{2, 3, 4\} \quad (\text{U}) \]
Relaxations with State-Dependent Costs and Effects

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Relaxations with State-Dependent Costs and Effects

What happened?
- Cost-effect mismatch!
- Uninformative heuristic $h^+(x_1) = 5$ vs. $h^*(x_1) = 15$

What to do about it?
- Handle costs and effects in combination!
- How?
  - ✗ in tabular form? Exponential blow-up.
  - ✔ as decision diagram? Often compact.

$\leadsto$ edge-valued multi-valued decision diagrams (EVMDDs)
[Ciardo and Siminiceanu 2002; Lai, Pedram, and Vrudhula 1996]
Combined Representation using EVMDDs

Combined EVMDD for costs and effects

Consequence: effect $x' := 4$ now associated with cost 3.
EVMDD Construction
How to construct those EVMDDs?

Possible approach:

- Repeated application of apply procedure
  [Ciardo and Siminiceanu 2002; Lai, Pedram, and Vrudhula 1996]

Prerequisite:

✅ Generalize apply procedure beyond numbers.

Recursive construction:

- Build ASTs of normalized cost and effects, and their combination.
- Recursively run apply procedure on this AST.
EVMDD Construction

Example: cost $x + 2y + 1$ combined with effect $((x \lor y) \triangleright \neg z') \land \ldots$
EVMDD Construction

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EVMDD Construction

Example: cost
EVMDD Construction

Example: cost $x + 2y + 1$ combined with effect $((x \lor y) \triangleright \neg z') \land \ldots$
EVMDD Construction

Example: effects
EVMDD Construction

Example: cost $x + 2y + 1$ combined with effect $((x \lor y) \triangleright \neg z') \land \ldots$
EVMDD Construction

Example: cost and effect combined
Properties of the Construction

**Proposition**

If EVMDD $E_i$ represents function $f_i$ ($i = 1, 2$), then EVMDD $\text{apply}(\circ, E_1, E_2)$ represents $f(s) = f_1(s) \circ f_2(s)$.

E. g., $\circ = +, -, \lor, \land, \triangleright, \text{make\_pair}, \ldots$
Properties of the Construction

Corollary
Combined cost-effect EVMDD represents function $f$ with

$$f(s) = (\text{cost in } s, \text{ active effects in } s).$$
Properties of the Construction

Size of combined cost-effect EVMDD:

- **worst case**: product of factor sizes
- **best cases**: \( \frac{\max}{\sum} \) of factor sizes if
  - factors have identical structure:
  - or factors depend on disjoint variable sets:
Uses of Cost-Effect EVMDDs

- Efficient computation of relaxed semantics
- Heuristics based on that: $h^+(x_1) = 15$
- Compiling away state-dependent costs and effects
Empirical Results

Preliminary. Cost-based navigation domain.

**Heuristic values**: costs and effects *combined* vs. *separately*

**Representation size of combination**: (small instances, on avg)

- EVMDD-based: 58 nodes
- tabular: 1381 entries
Summary

- Informative heuristics wanted
  - combined treatment of state-dependent costs and effects
- Representation: cost and effect EVMDDs
- Construction: repeated apply