LP-based Heuristics for Cost-optimal Planning

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A Framework for LP-based Heuristics

- Operator-counting constraint
  - Linear constraints
  - Operator-counting variable Y_o for each operator ("*Number of times o is used in a plan*")
  - Satisfied by occurrences in any plan
  - Example: $Y_{o_1} \geq 2Y_{o_2}$ ("*o_1 must occur at least twice as often as o_2*")
- IP/LP heuristics
  - Minimize $\sum_{o \in \mathcal{O}} \mathrm{cost}(o) \cdot Y_o$ subject to some operator-counting constraints
  - LP relaxation solvable in polynomial time
  - Admissible heuristics

Example 1: Disjunctive Action Landmarks

- Landmark constraints

$$\sum_{o \in L} Y_o \geq 1$$

- Existing heuristic
  - Optimal cost partitioning for landmarks (Karpas and Domshlak 2009)
  - cf. Keyder, Richter, and Helmert (2010) and Bonet and Helmert (2010)

Example 2: Net change

- Net change for a fact f
  - Operators produce (make true) or consume (make false) f
  - Number of producers and consumers must balance out
  - Lower bound estimation for operators that sometimes produce/consume f
- Net change constraints

$$\sum_{\substack{o \text{ guaranteed to} \\ \text{produce } f}} Y_o + \sum_{\substack{o \text{ sometimes} \\ \text{produces } f}} Y_o - \sum_{\substack{o \text{ guaranteed to} \\ \text{consume } f}} Y_o \geq LB(f)$$

- Existing heuristic
  - State-equation heuristic (van den Briel et al. 2007, Bonet 2013, Bonet and van den Briel 2014)

Example 3: Pattern databases

- Pattern databases
  - Admissible heuristic, only influenced by subset of operators
- Post-hoc optimization constraints

$$h^P(s) \leq \sum_{o \text{ relevant for } P} \mathrm{cost}(o) \cdot Y_o$$

- Existing heuristic
  - Post-hoc optimization (Pommerening, Röger, and Helmert 2013)

Example 4: Explicit State Abstractions

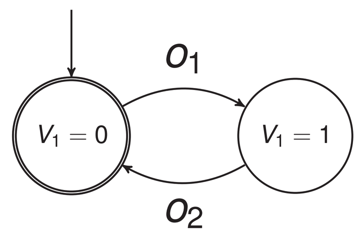
- Abstractions with explicit transition system
  - Examples: Pattern databases, Merge&Shrink, CEGAR
- Existing heuristic
  - Optimal cost partitioning heuristic (Katz and Domshlak 2010)
  - Dual formulation fits our framework
- OCP constraints
  - Transitions start or end in abstract states
  - Used transitions must balance out
  - Operator count must support all used transitions

Combination of Heuristic Values

Theorem

The LP heuristic for a set of operator-counting constraints dominates the maximum over LP heuristics for the individual constraints

- Better way to combine different sources of information
- Dominance can be strict:



$L = \{o_1\}$

State-equation heuristic $h^{\mathrm{SEQ}}(s) = 0$ — Landmark constraint $h^{\{L\}}(s) = 1$

$$\max\{h^{\mathrm{SEQ}}(s), h^{\{L\}}(s)\} = 1 < h^{\mathrm{SEQ}+\{L\}}(s) = 2$$

Dominance of heuristics

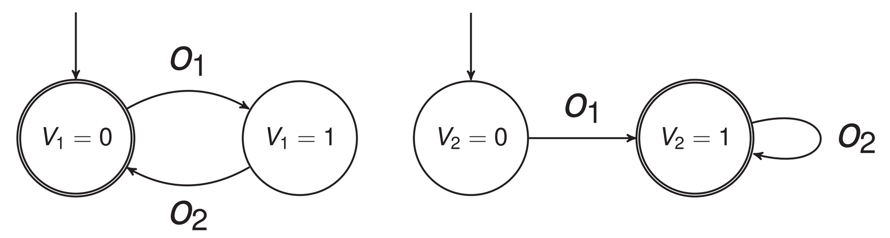
- LP heuristics as analytic tool
- General scheme to show dominance of h_1 over h_2
  1. h_1 is the LP heuristic with constraints C_1
  2. h_2 is the LP heuristic with constraints C_2
  3. Every solution of C_1 satisfies constraints in C_2
  4. $h_1 \geq h_2$

Theorem

The state-equation heuristic dominates optimal cost partitioning over projections to goal variables

$$h^{\mathrm{OCP}}_{\mathrm{Sys}_1} \leq h^{\mathrm{SEQ}}$$

- A counter-example shows $h^{\mathrm{SEQ}} \not\leq h^{\mathrm{OCP}}_{\mathrm{Sys}_1}$



Implied constraints

- Safety-based improvement of the state-equation heuristic (Bonet 2013)
  - Net change constraints contain lower bound estimation
  - Corresponding upper bound estimation can be added
  - Some inequalities become equalities
  - Constraint implied by all lower bound net change constraints

Theorem

The safety-based improvement cannot increase the heuristic value of the state-equation heuristic.

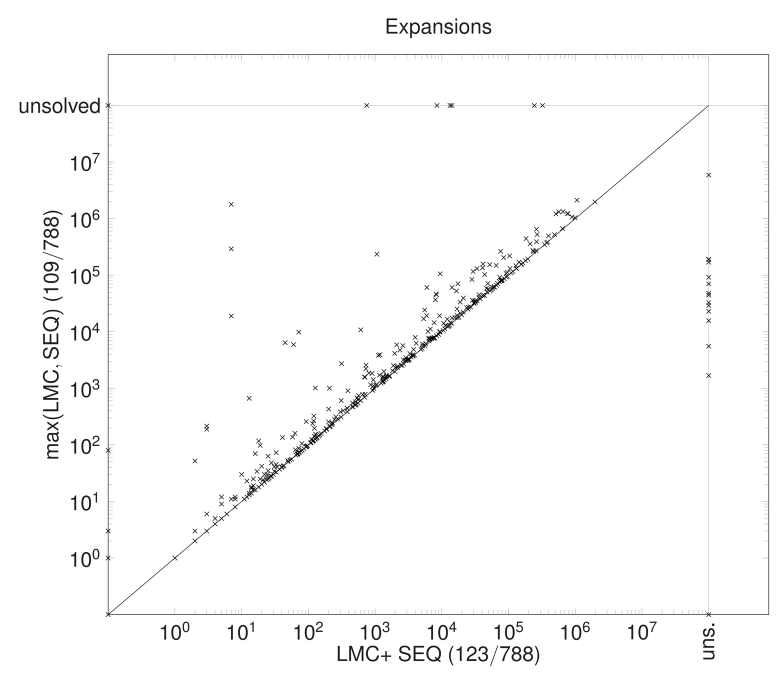
- Caveat: only if *all* lower bound net change constraints are present

Empirical Results

	SEQ	PhO-Sys^1	PhO-Sys^2	LMC	OPT-Sys^1	LMC+ PhO-Sys^2	LMC+ SEQ	PhO-Sys^2+ SEQ	LMC+ PhO-Sys^2+ SEQ	$h^{\text{LM-Cut}}$
barman (20)	4	4	4	4	4	4	4	4	4	4
elevators (20)	7	9	16	16	4	17	16	15	16	**18**
floortile (20)	4	2	2	6	2	6	6	4	6	**7**
nomystery (20)	10	11	**16**	14	8	**16**	12	14	14	14
openstacks (20)	11	**14**	**14**	**14**	5	**14**	11	11	11	**14**
parcprinter (20)	**20**	11	13	13	7	14	**20**	**20**	**20**	13
parking (20)	3	**5**	1	2	1	1	2	1	1	3
pegsol (20)	**18**	17	17	17	10	17	**18**	17	16	17
scanalyzer (20)	11	9	4	11	7	10	10	10	8	**12**
sokoban (20)	16	19	**20**	**20**	13	**20**	**20**	**20**	19	**20**
tidybot (20)	7	13	**14**	**14**	4	**14**	10	8	10	**14**
transport (20)	**6**	**6**	**6**	**6**	4	**6**	**6**	5	**6**	**6**
visitall (20)	17	16	16	10	15	17	**19**	17	18	11
woodworking (20)	9	5	10	11	2	13	**16**	10	**16**	12
Sum IPC 2011 (280)	143	141	153	158	86	169	**170**	156	165	165
IPC 1998–2008 (1116)	487	446	478	586	357	589	**618**	516	598	598
Sum (1396)	630	587	631	744	443	758	**788**	672	763	763

- Individual Constraints
  - LM-cut constraints have highest coverage
  - Optimization of LM-cut landmarks does not pay off
  - State-equation and PhO heuristic similar coverage
  - Computation of optimal cost partitioning too expensive
- Combination of Constraints
  - Clear improvement over individual constraints
  - State-equation heuristic with LM-cut constraints exceeds coverage of $h^{\text{LM-cut}}$
  - Combining all three sources does not pay off

Interaction of Constraints



- Comparing combination in LP with maximum
- Coverage is unchanged
- Stronger heuristic estimates (synergy)
  - Fewer expansions
  - More tasks solved with perfect heuristic