Hybrid Planning Heuristics based on Task Decomposition Graphs

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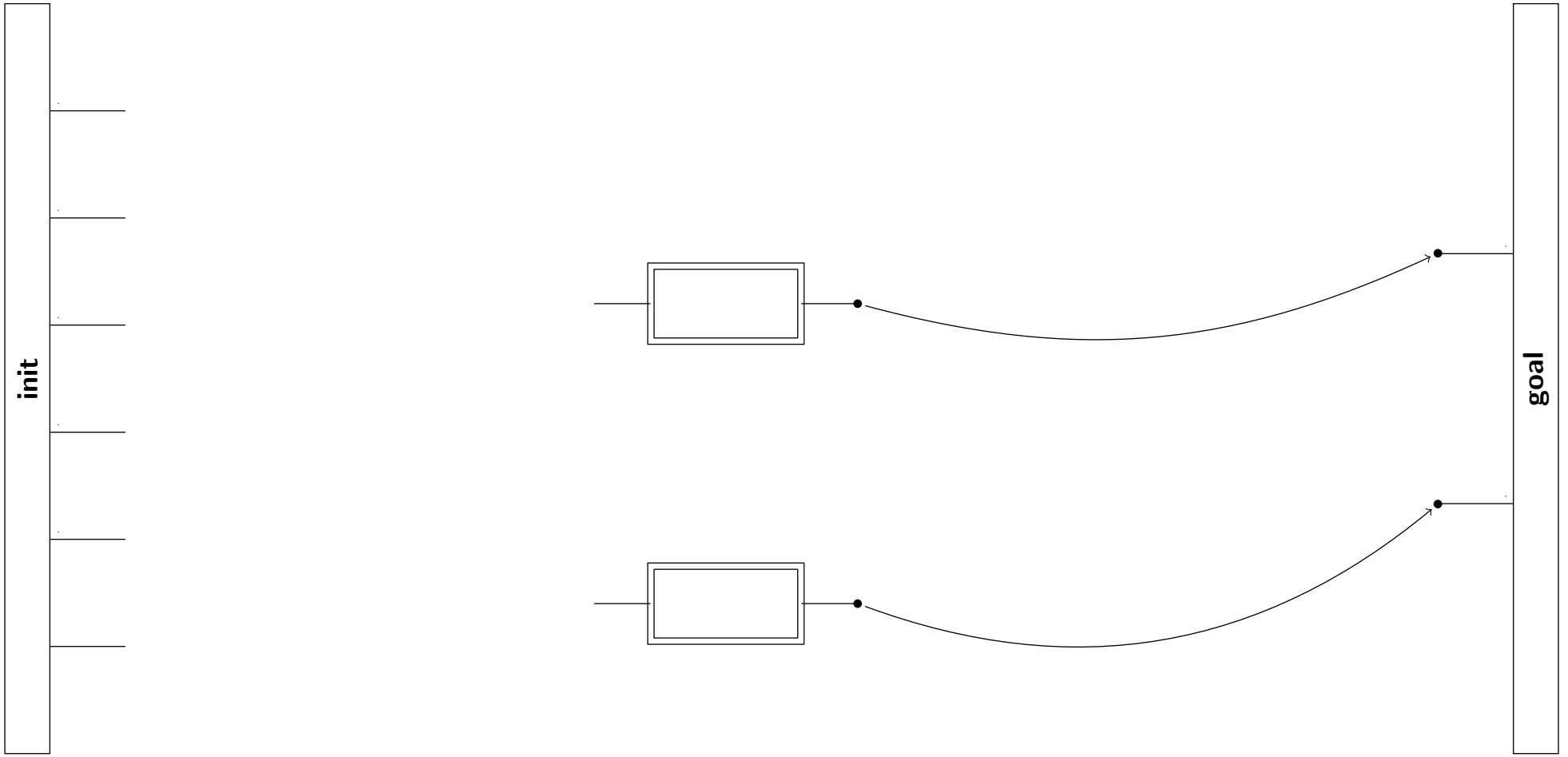
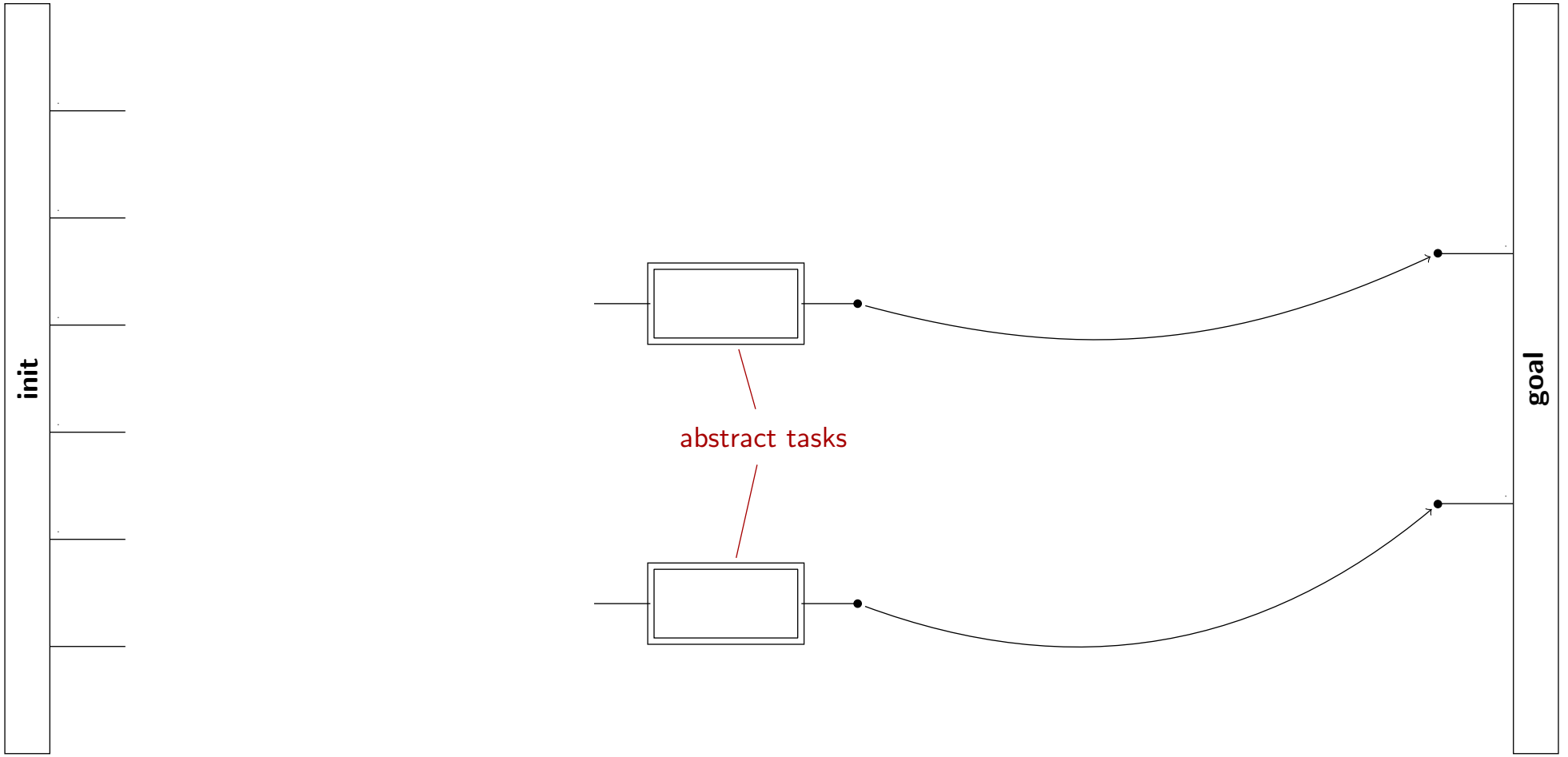
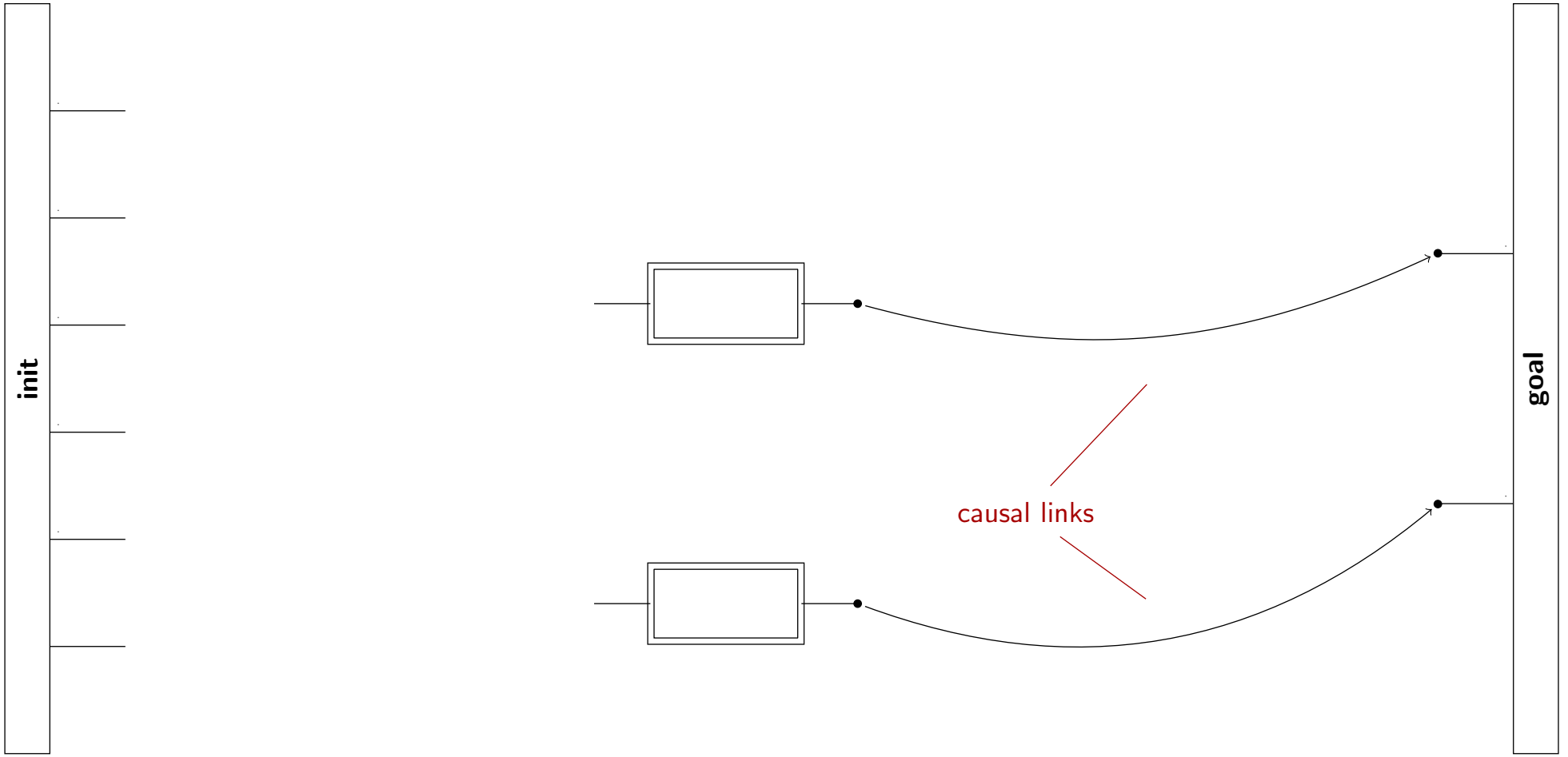
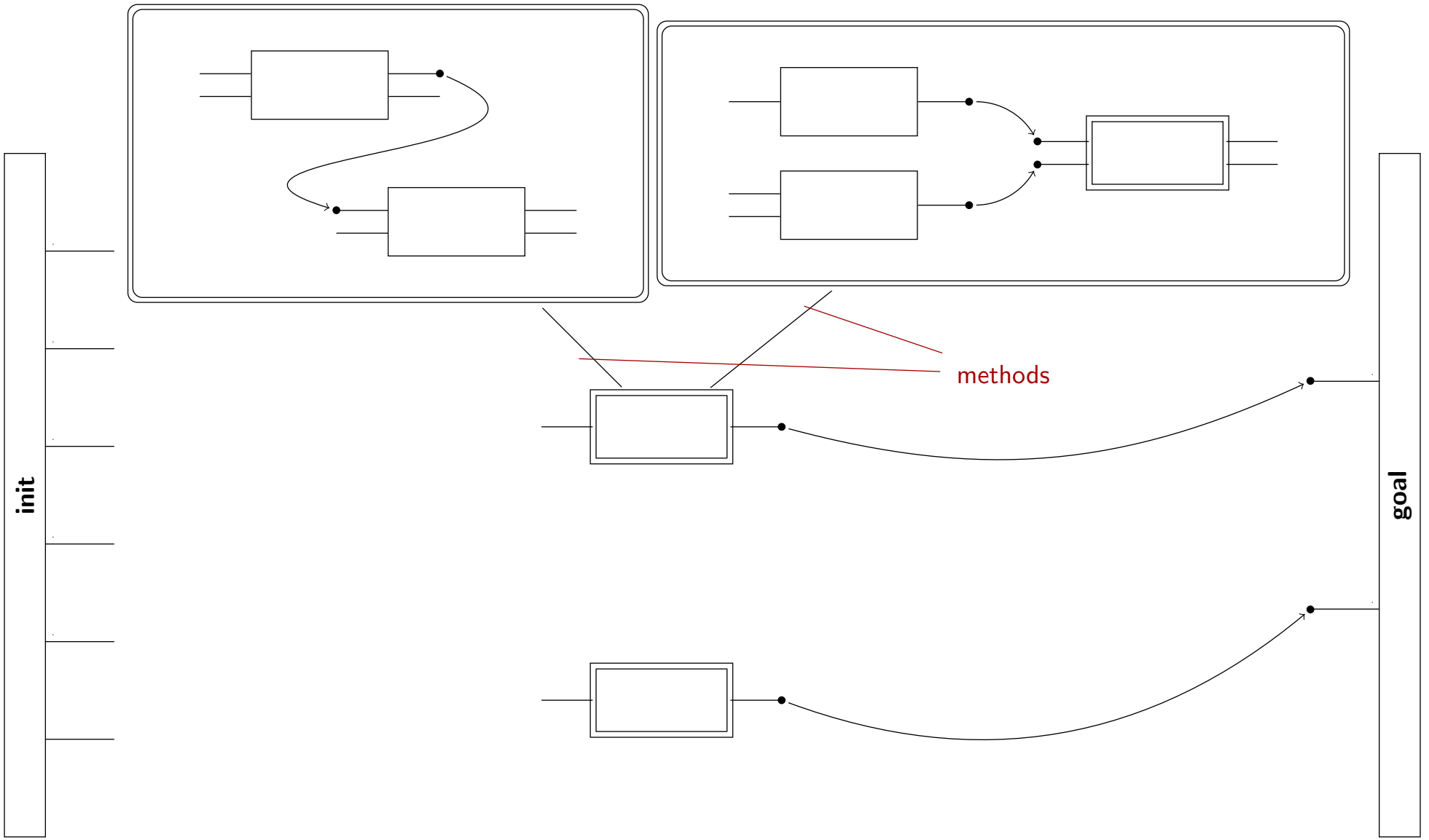
Hybrid Planning:

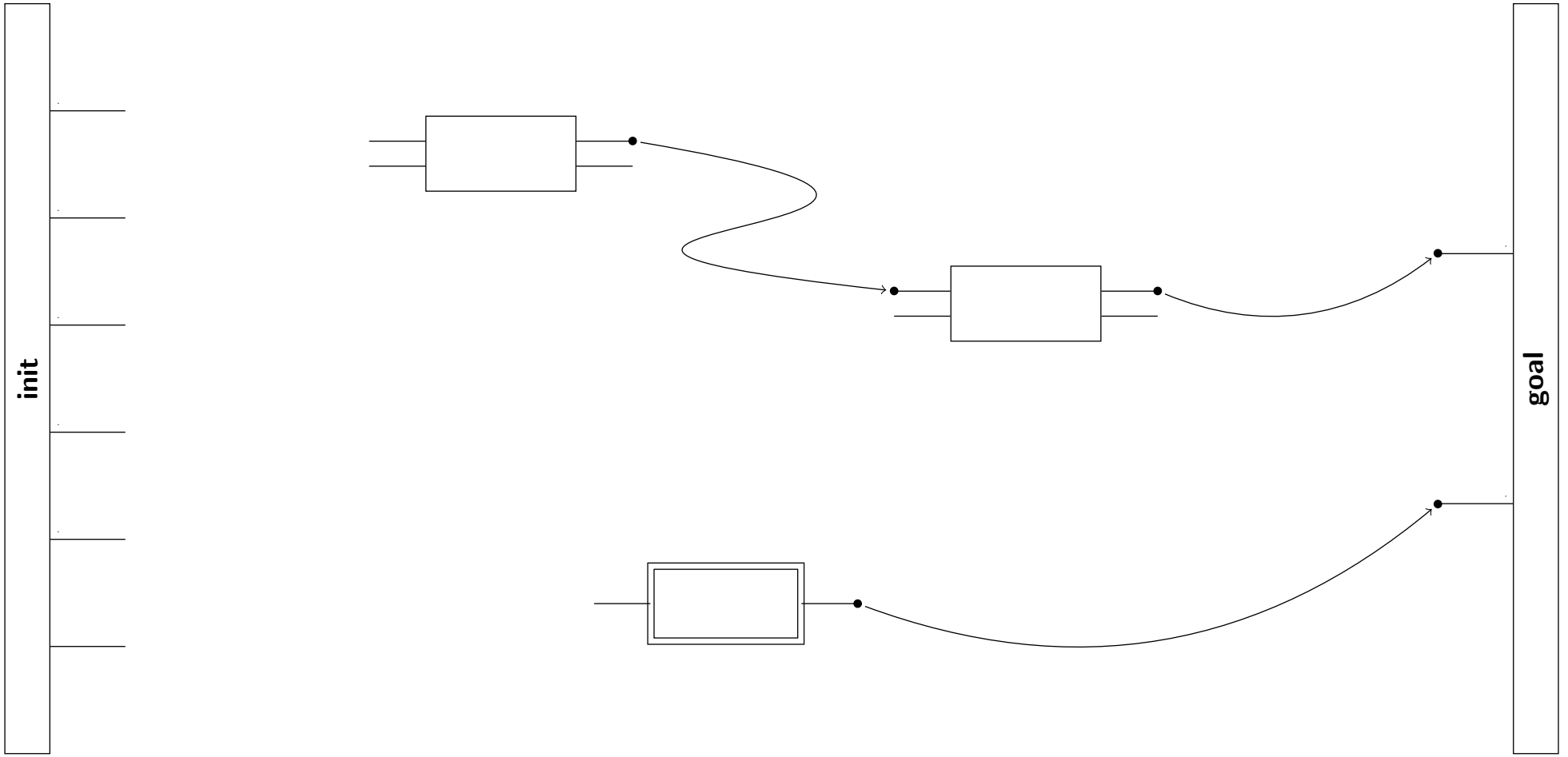
- approach fusing Hierarchical Task Network (HTN) Planning with Partial-Order Causal-Link (POCL) Planning
- search in the space of partial plans
- refine the initial partial plan until it is executable

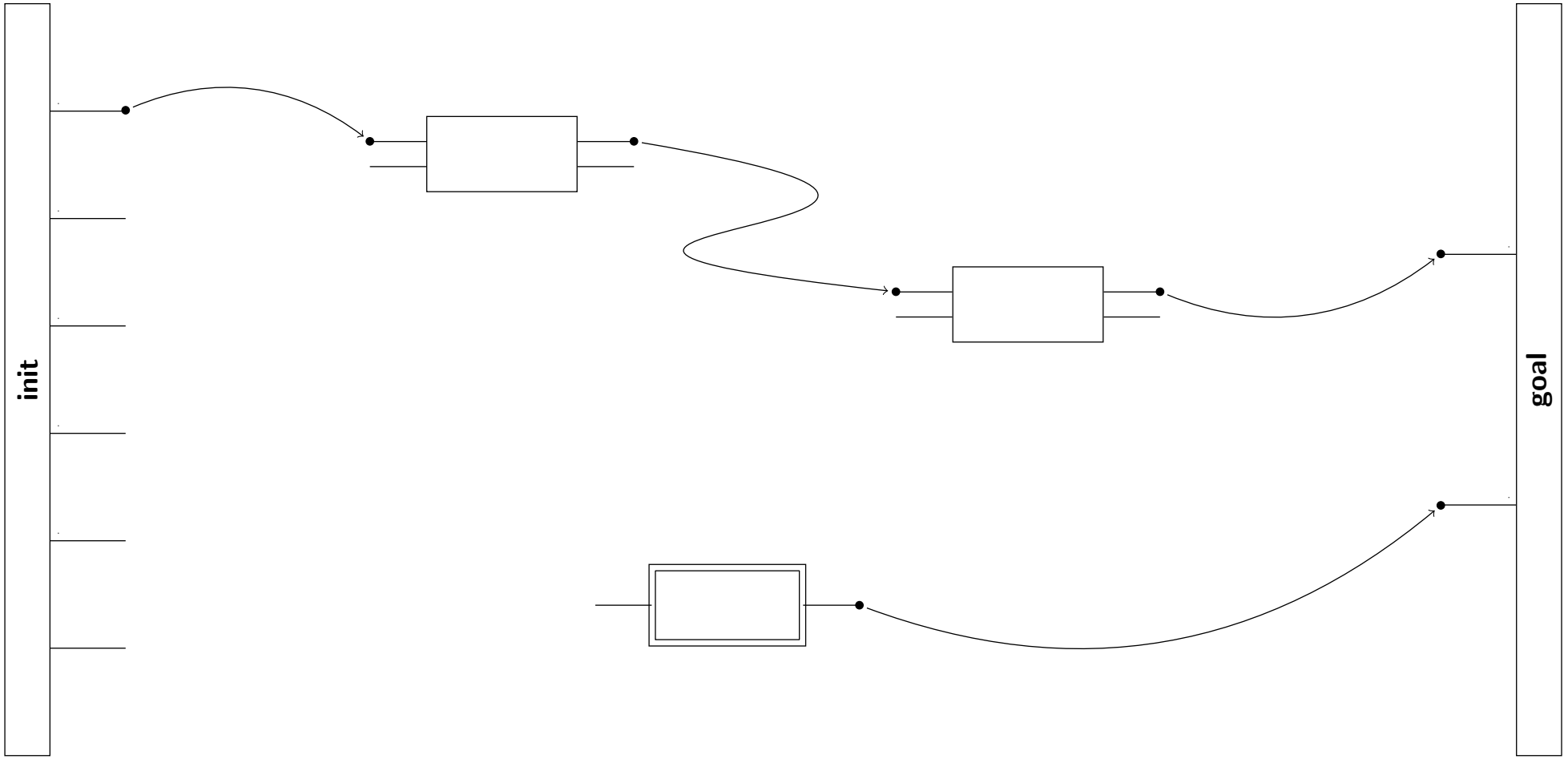

init
goal

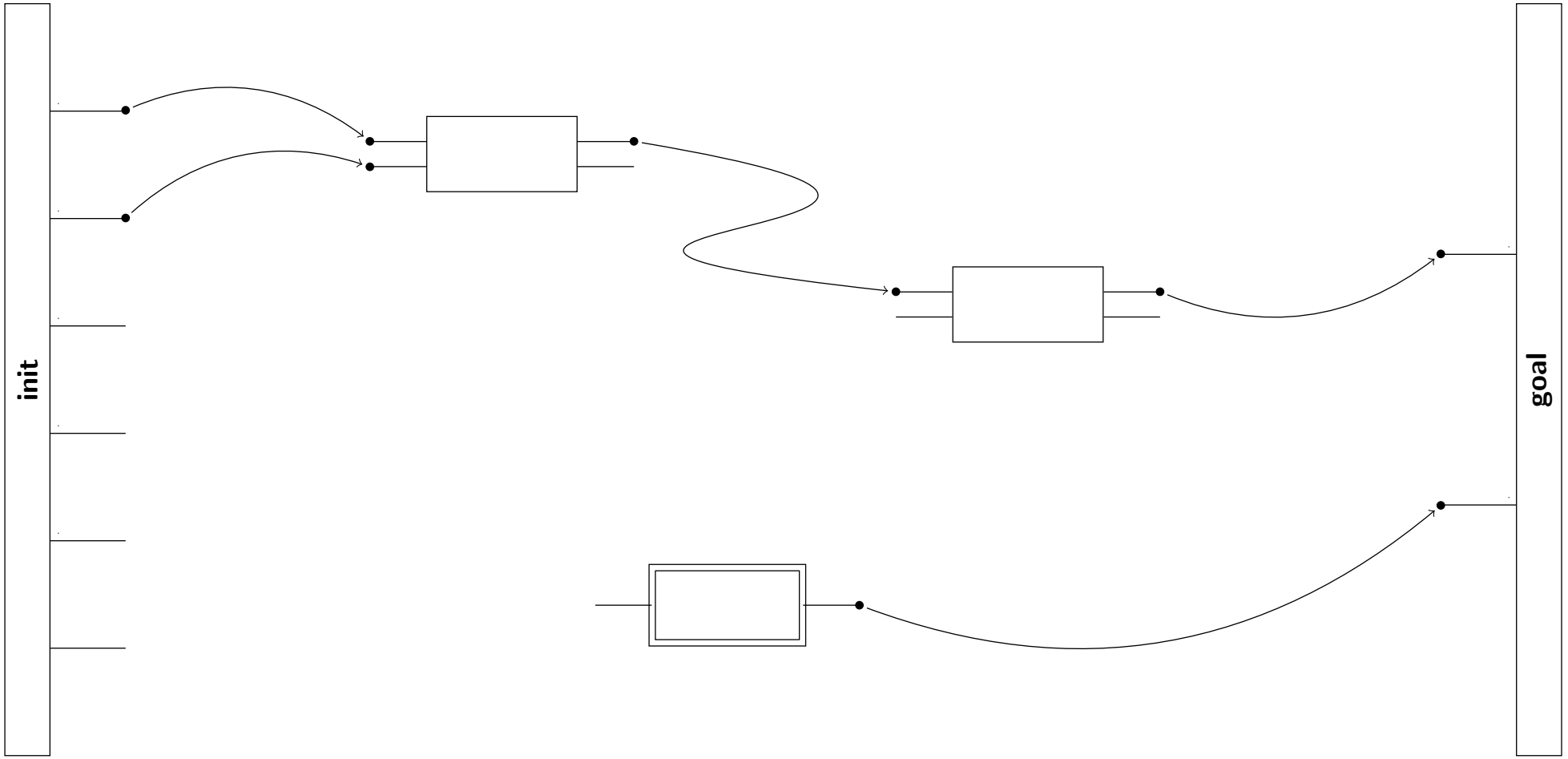

init
goal
abstract tasks

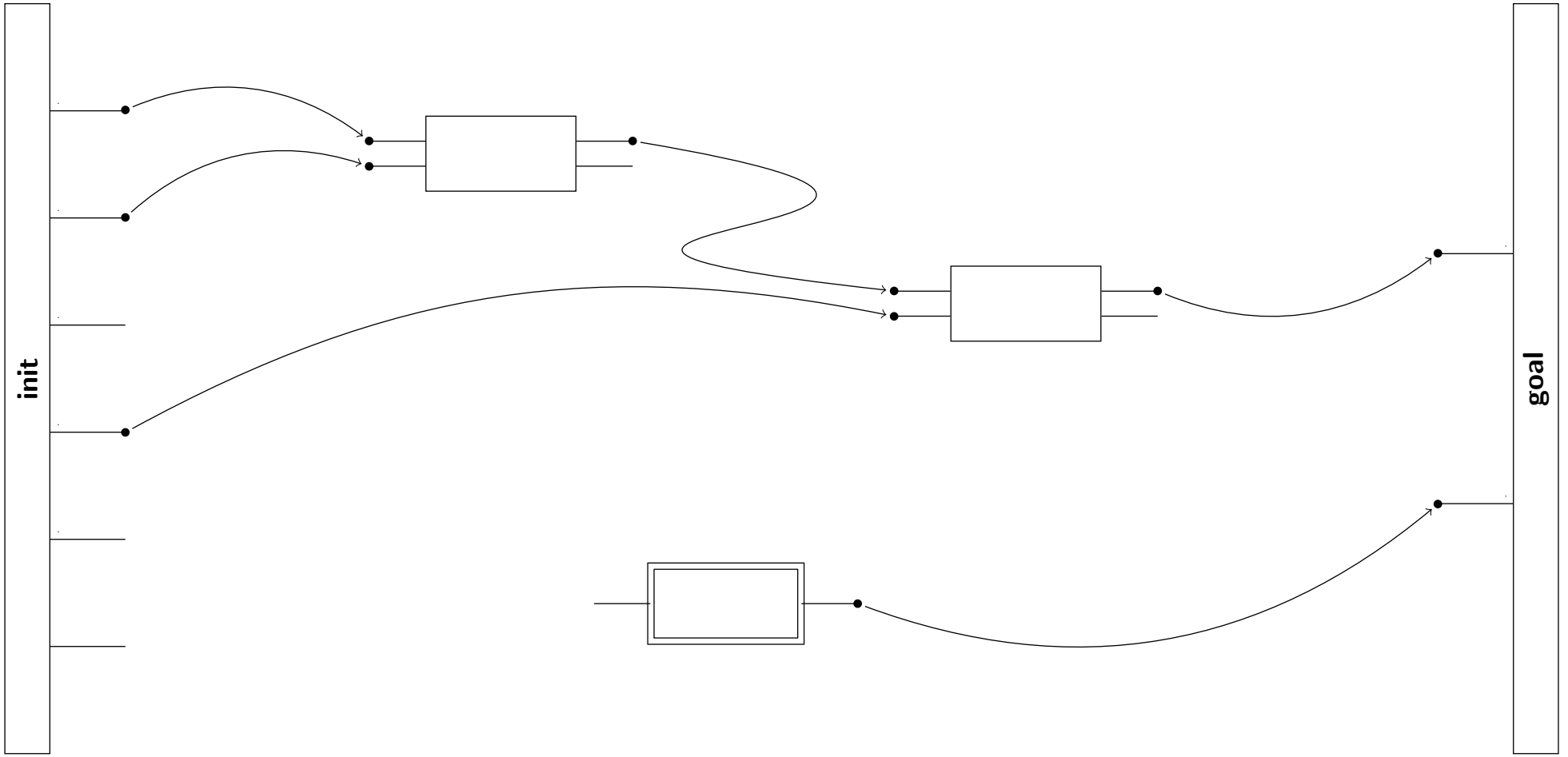

init
goal
causal links

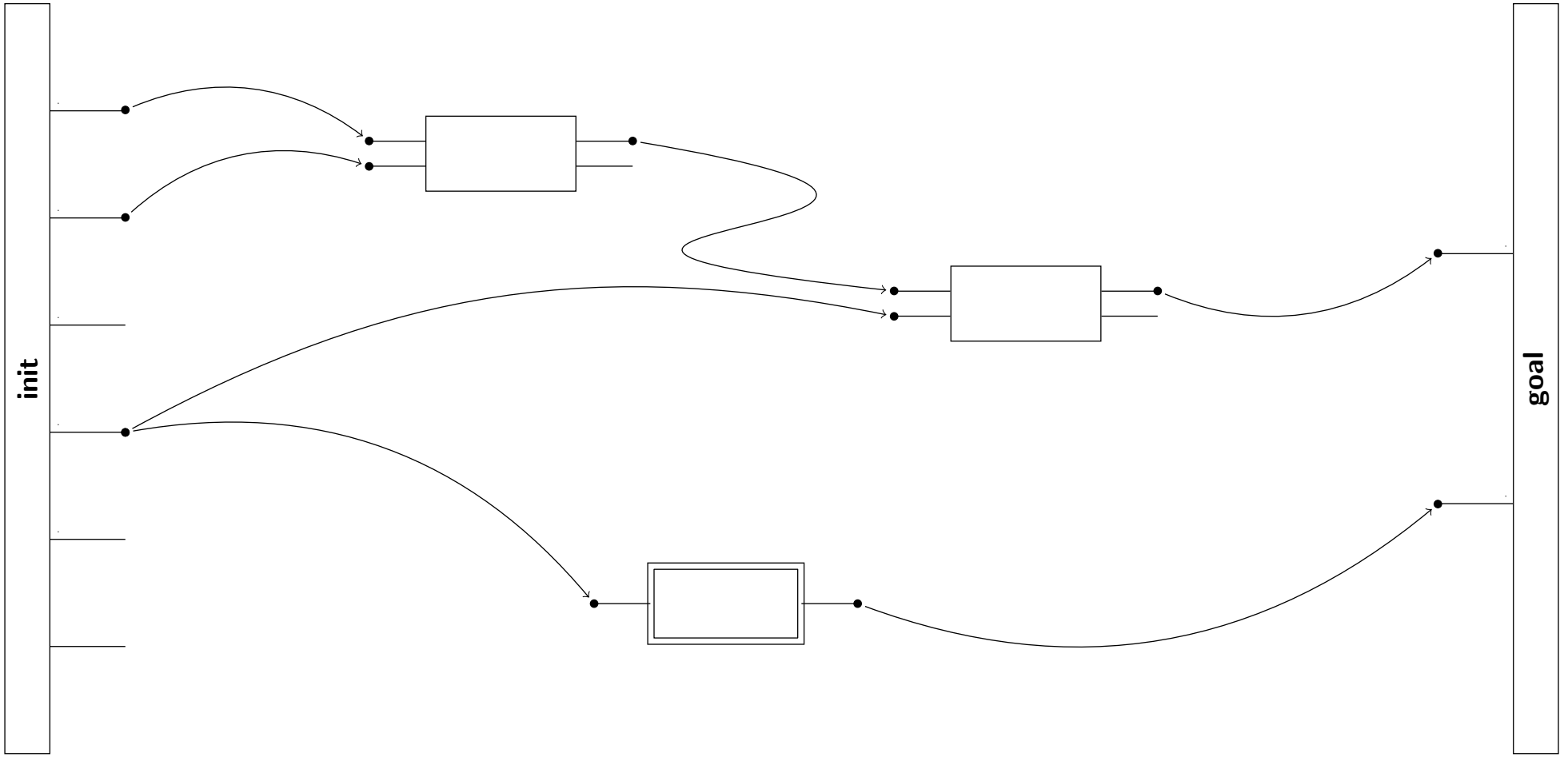

init
goal
methods

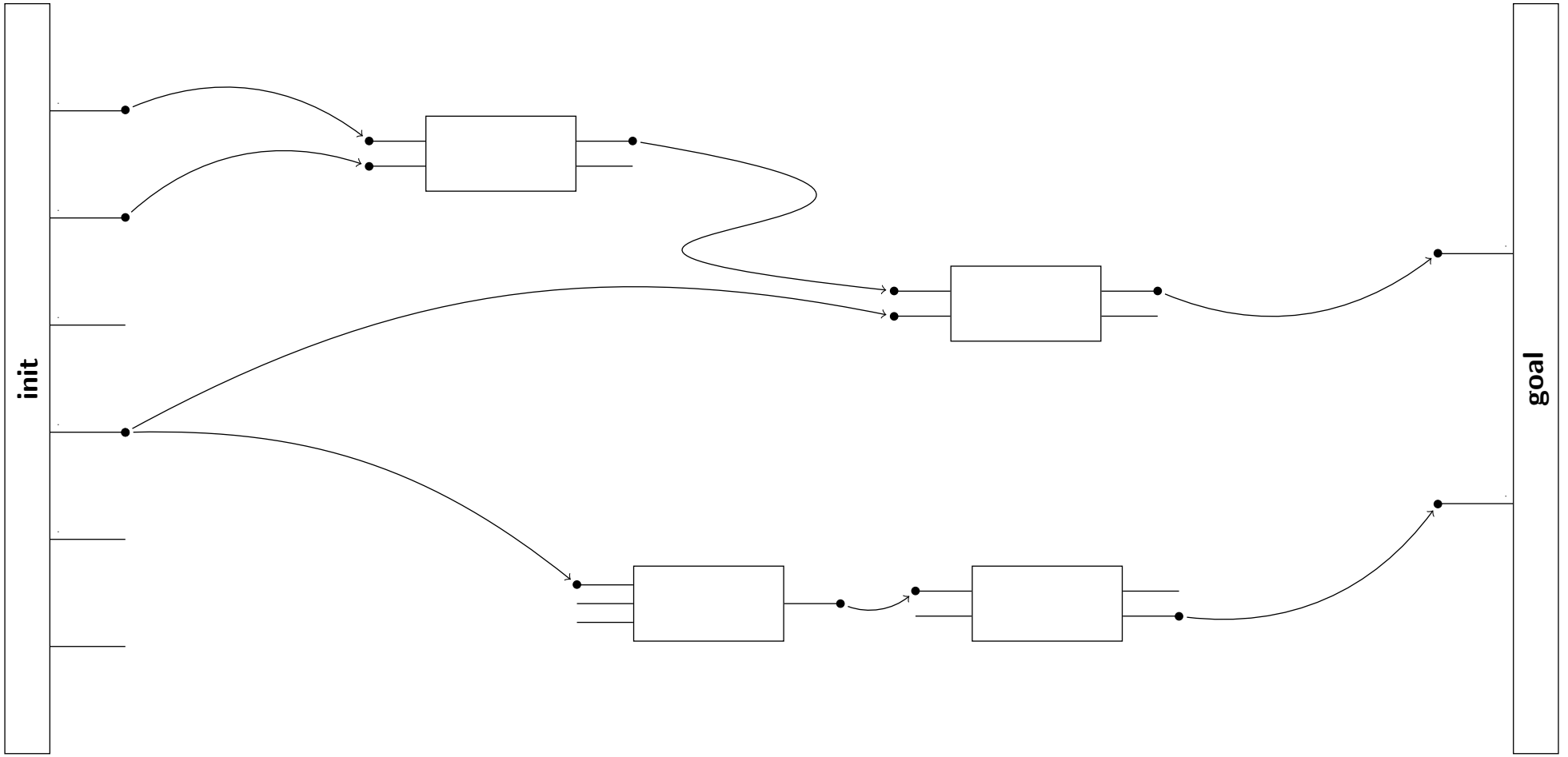

init
goal

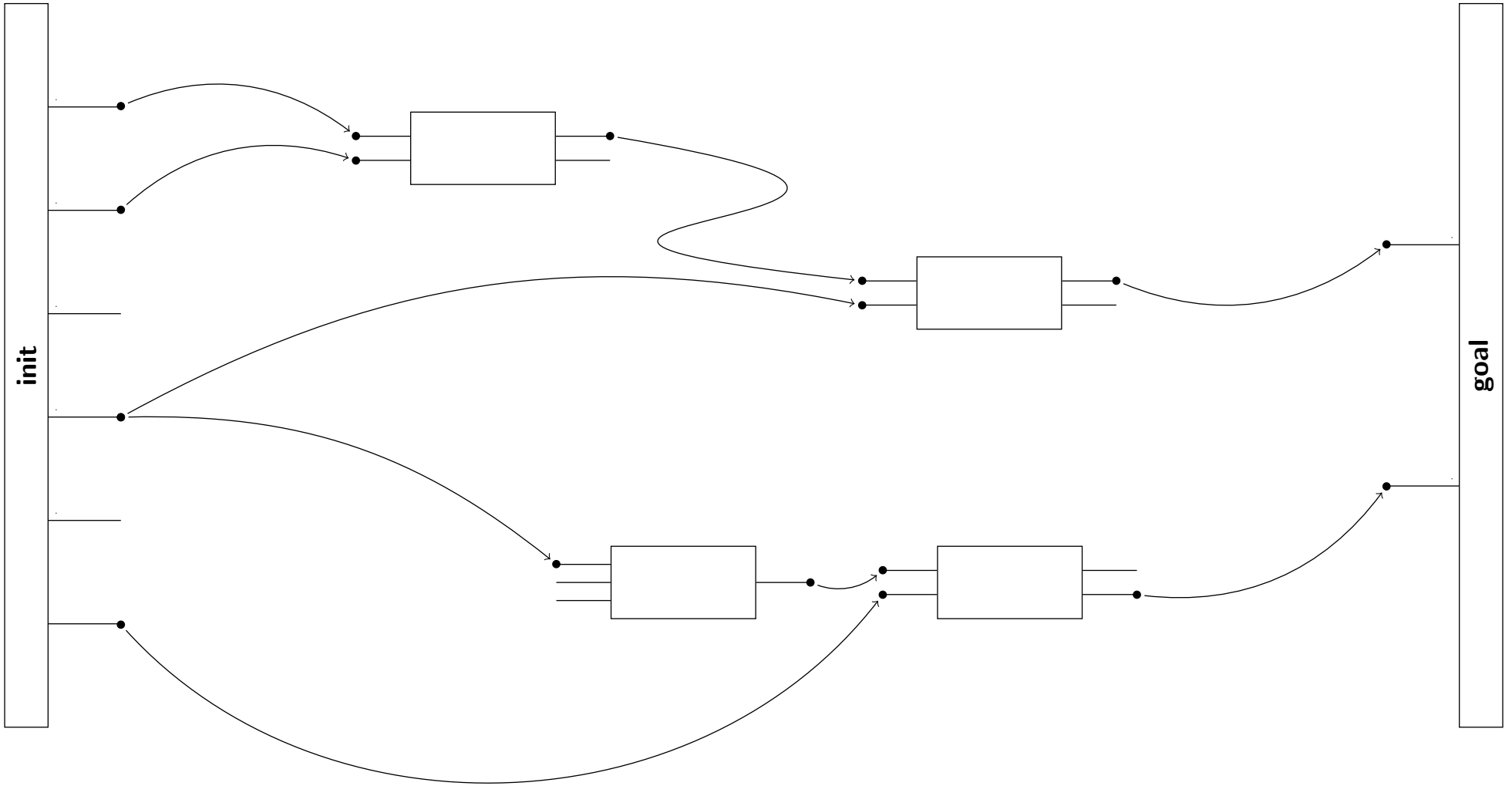

init
goal

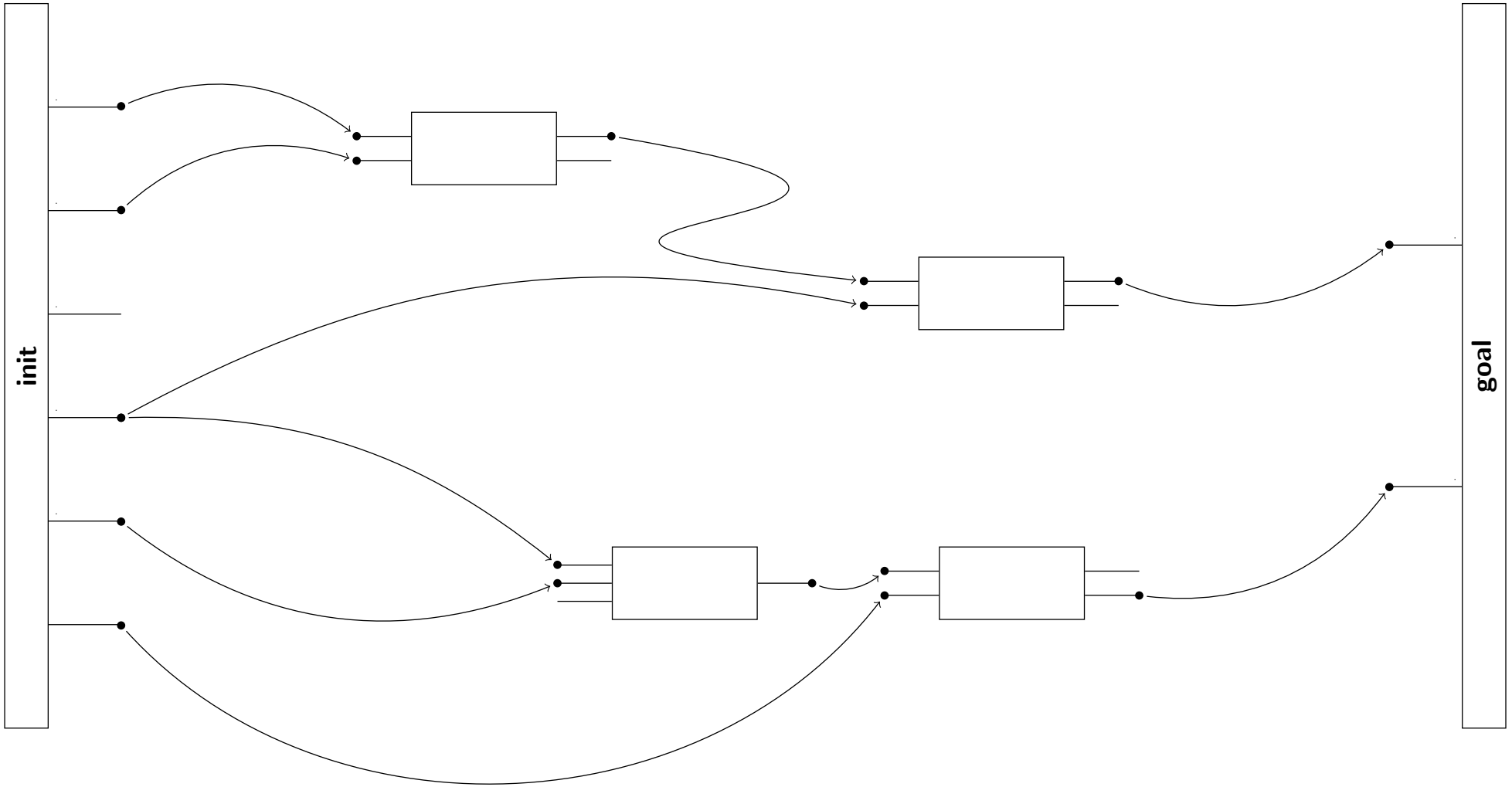

init
goal

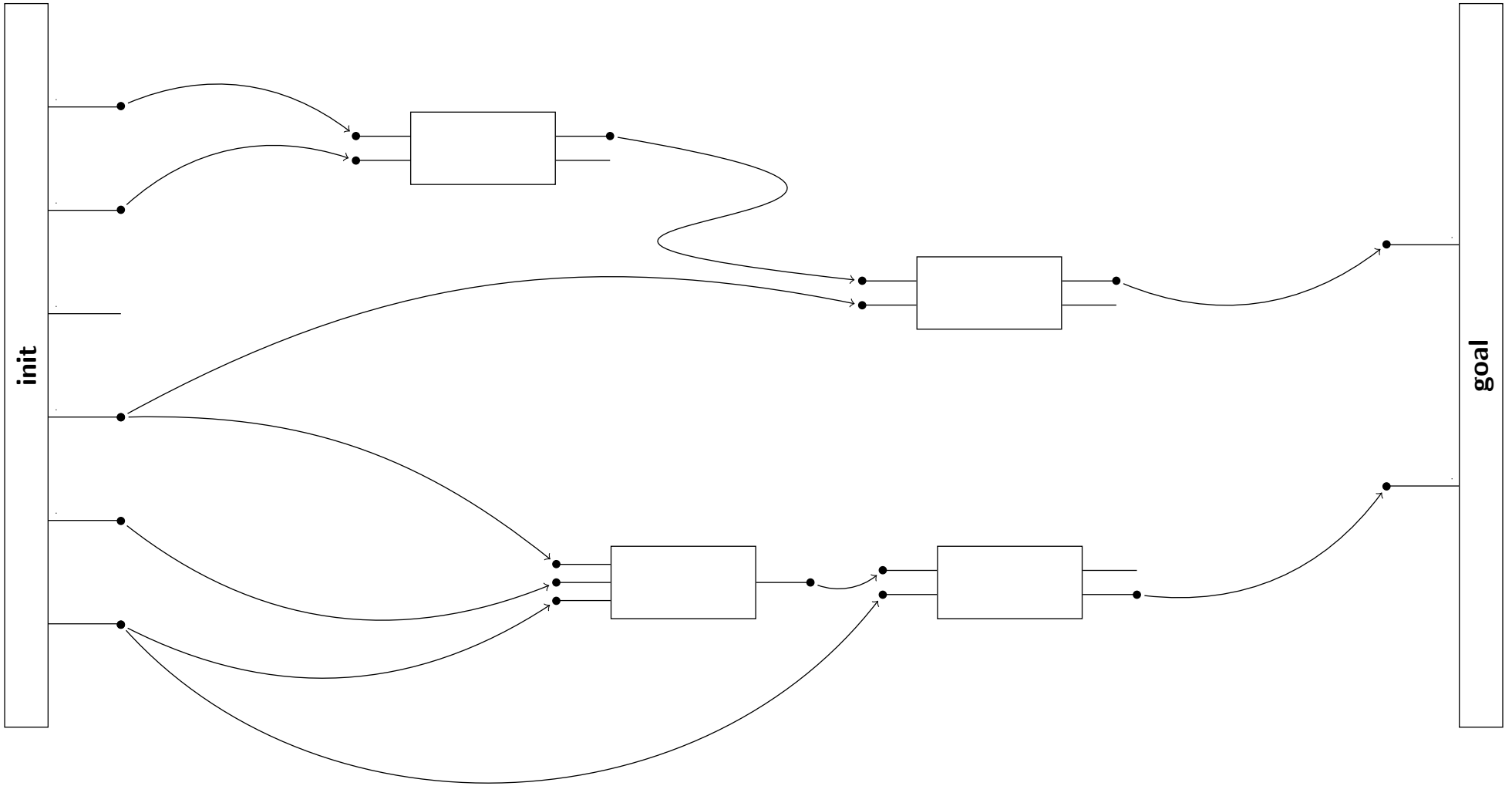

init
goal


init
goal


init
goal


init
goal


init
goal


init
goal

Algorithm 1: PANDA[1]

```
1 Fringe ← {P_init}
2 while Fringe ≠ ∅ do
3     P ← planSel (Fringe)
4     if Flaws(P) = ∅ then return P
5     f ← flawSel (Flaws(P))
6     Fringe ← (Fringe \ {P}) ∪ { modify(m, P) | m ∈ Mods(f, P) }
7 return fail
```

Two decision points:

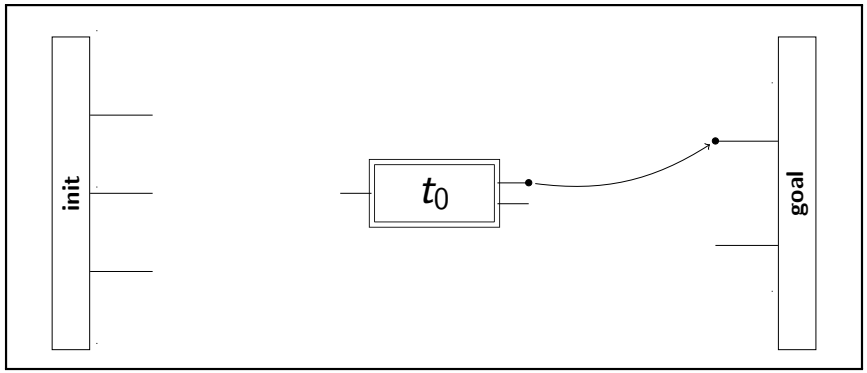
- Which plan to select? ($\rightarrow$ use heuristics)
- Which flaw to select? ($\rightarrow$ flaw selection strategies)

[1] Schattenberg: Hybrid Planning & Scheduling. Ph.D. Thesis. 2009

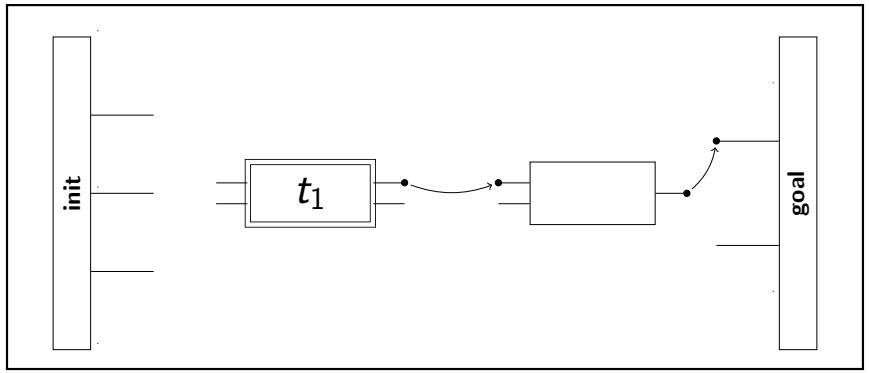
Heuristic should estimate the goal distance of partial plans:

- goal distance = number of modifications to turn a partial plan into a solution
- for instance, heuristic can incorporate:
  - yet unprotected preconditions
  - abstract tasks (and their sub tasks)

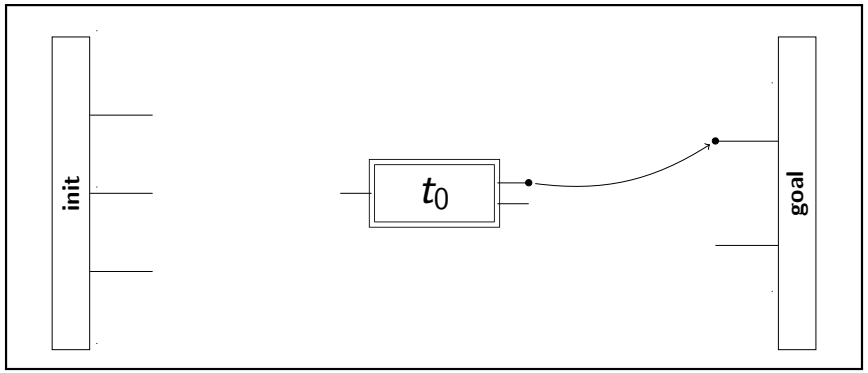
⇝ appendix: related work



1 abstr. task, 2 open preconditions
$\rightarrow$ at least 3 modifications



1 abstr. task, 4 open preconditions
$\rightarrow$ at least 5 modifications



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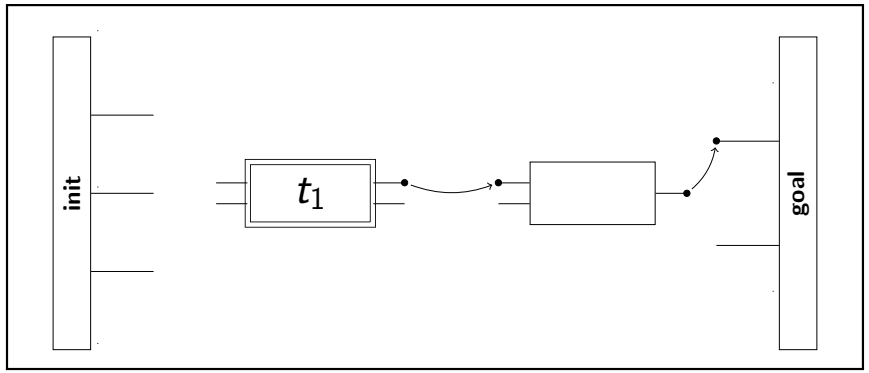
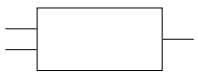
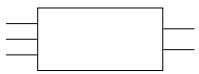


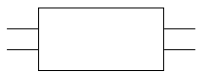
1 abstr. task, 4 open preconditions
$\rightarrow$ at least 5 modifications

... but inspecting the task hierarchy reveals
that t_0 and t_1 decompose into:


and


5 open preconditions

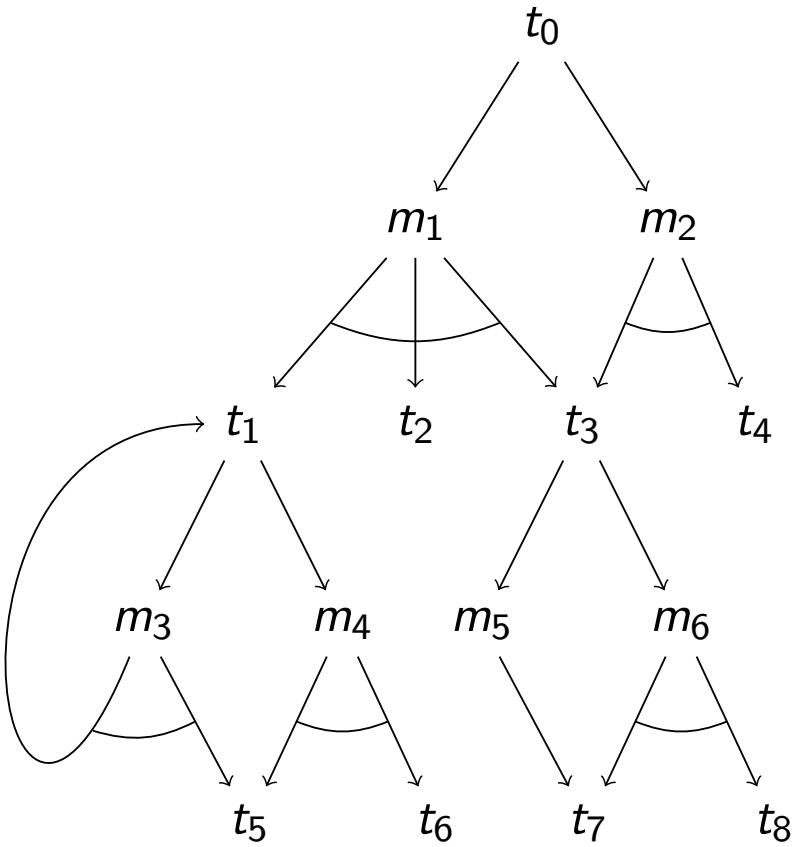
$\Rightarrow$ at least 8 modifications



2 open preconditions

$\Rightarrow$ at least 7 modifications

A TDG is a ground representation of the decomposition structure:



A TDG is a bipartite graph $\mathcal{G}$ $\langle V_T, V_M, E_{(T,M)}, E_{(M,T)} \rangle$ with

- V_T, the task vertices,
- V_M, the method vertices,
- $E_{(T,M)}$, the task edges,
- $E_{(M,T)}$, the method edges

Elkawkagy et al.: Landmarks in hierarchical planning. (ECAI '10)
Elkawkagy et al.: Improving hierarchical planning performance by the use of landmarks. (AAAI '12)

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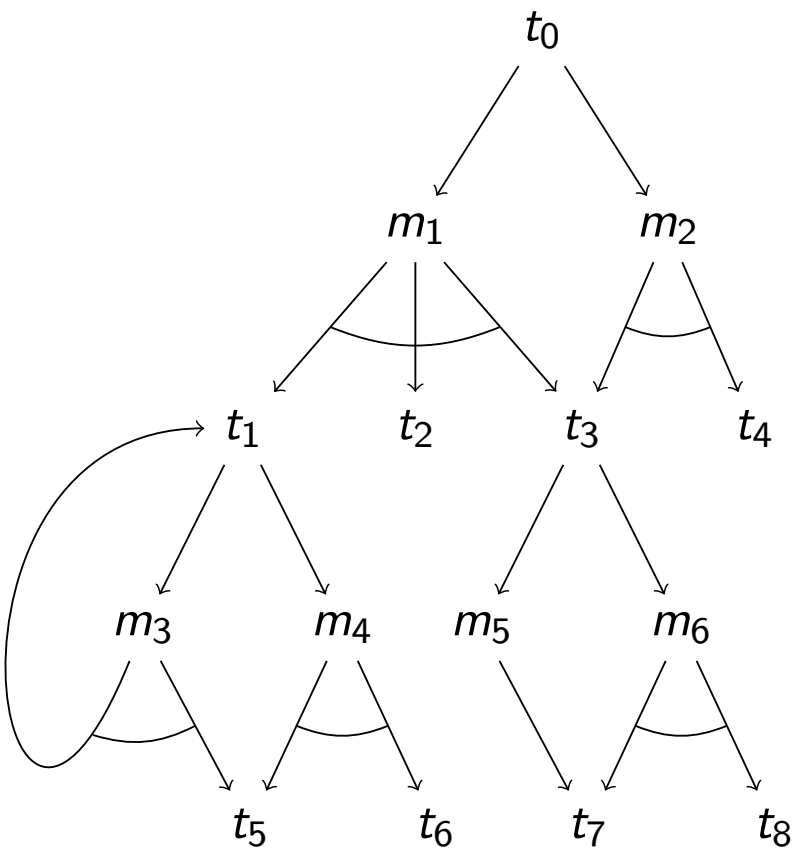

Subtasks:

$$S(t) := \{ \{t' \mid (m, t') \in E_{(M,T)}\} \mid (t, m) \in E_{(T,M)} \}$$

Mandatory tasks:

$$M(t) := \bigcap_{s \in S(t)} s$$

$$M^*(t) := M(t) \cup \bigcup_{t' \in M(t)} M^*(t')$$

In the example TDG:

$$S(t_0) = \{ \{t_1, t_2, t_3\}, \{t_3, t_4\} \}$$
$$M(t_0) = \{ t_3 \}$$
$$M^*(t_0) = \{ t_3, t_7 \}$$

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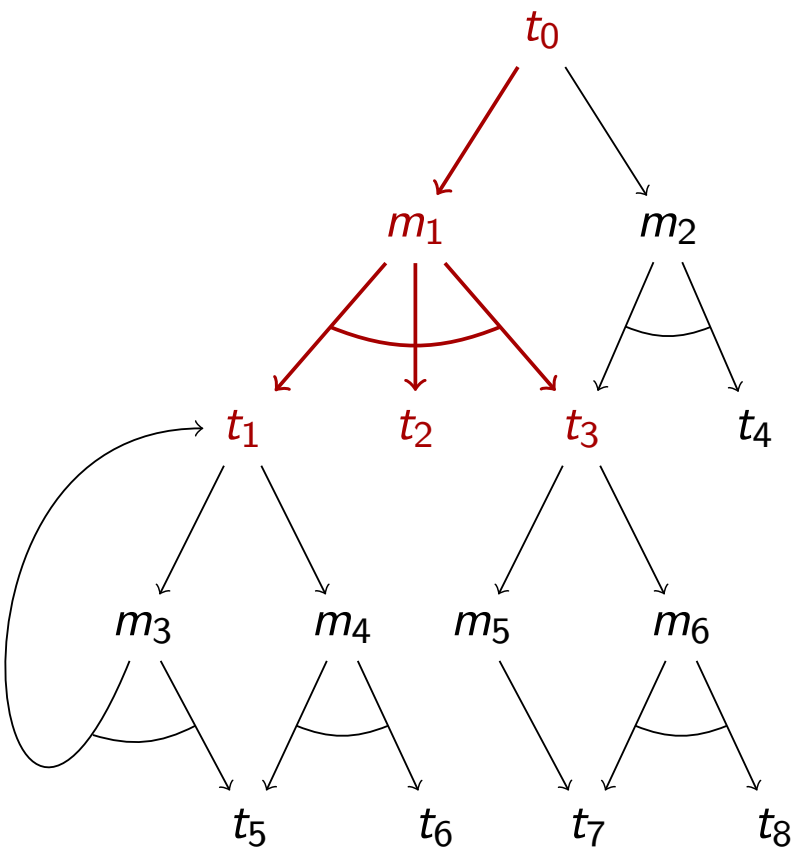

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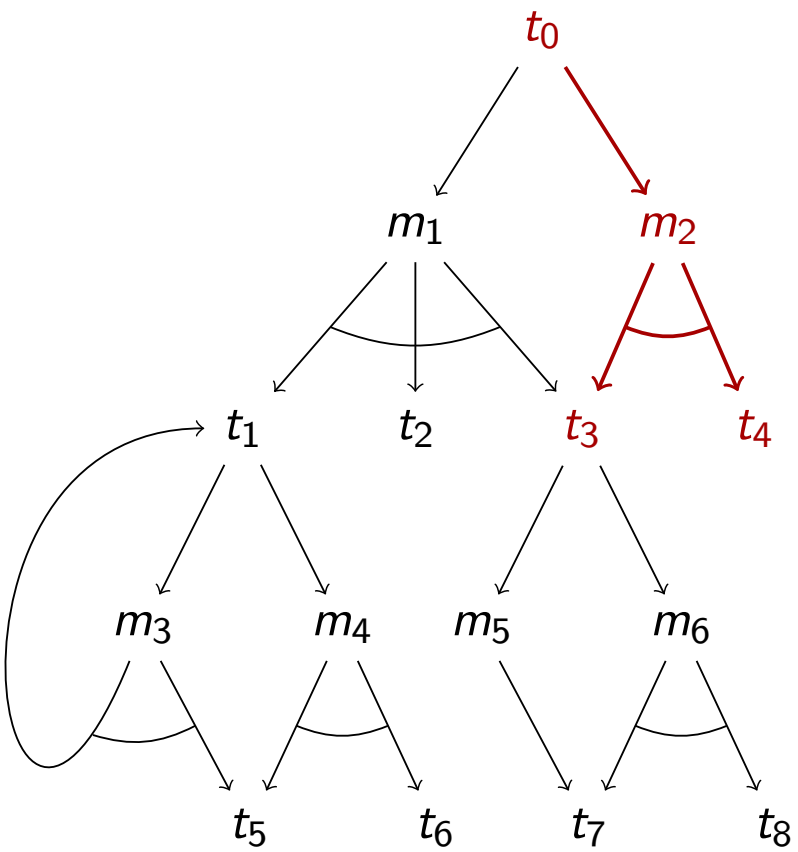

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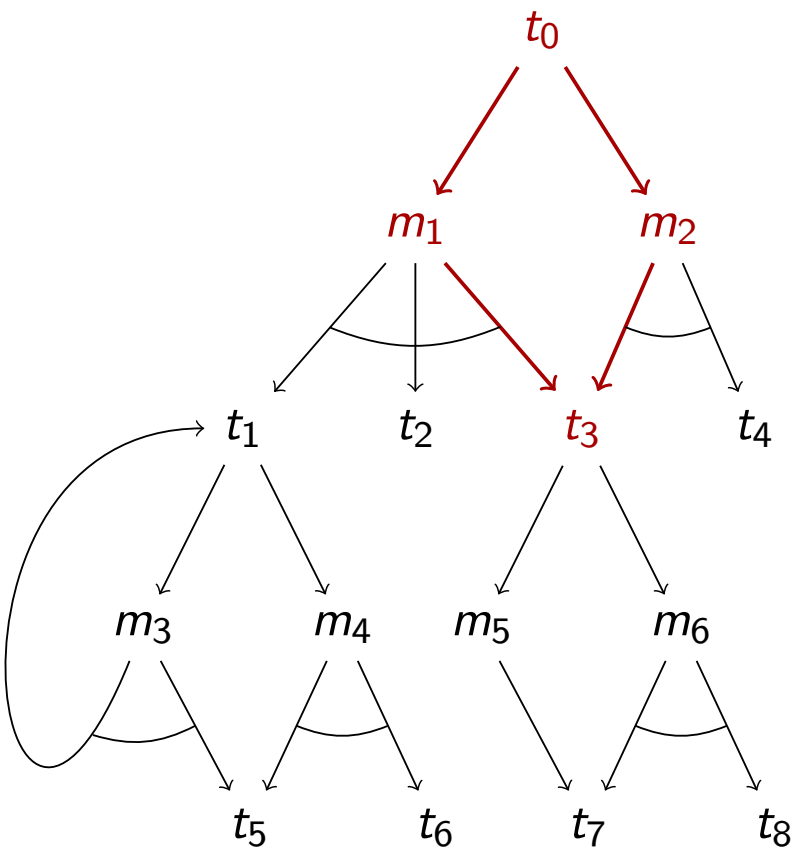

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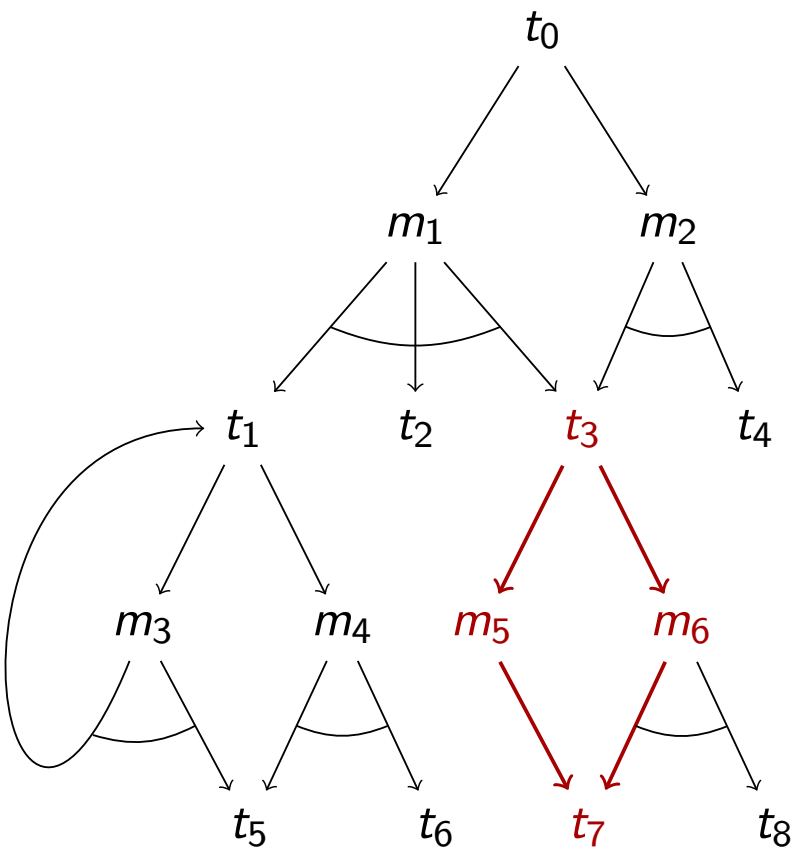

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$$M(t_0) = \{ t_3 \}$$

$$M^*(t_0) = \{ t_3, t_7 \}$$

Let $P = (T, CL, \prec)$ be a plan and T its tasks.

$$TC(t) := |M^*(t)| \qquad \text{(task cardinality)}$$

$$PC(t) := \sum_{t' \in M^*(t)} |prec(t')| \qquad \text{(precondition cardinality)}$$

$$h_{TC+PC}(P) := \sum_{t \in T} TC(t) + PC(t)$$

$\rightarrow$ heuristic focuses on the mandatory tasks

Let $P = (T, CL, \prec)$ be a plan and T its tasks.

$$h(t) := \begin{cases} |prec(t)| & \text{if t is primitive} \\ 1 + \min\limits_{\substack{\langle t, P'=(T', CL', \prec') \rangle \\ \in Methods}} \sum\limits_{t' \in T'} h(t') & \text{if t is abstract} \end{cases}$$

$$h_{MME}(P) := \sum_{t \in T \text{ is abstract}} h(t)$$

$\rightarrow$ heuristic traverses the complete TDG

$\rightsquigarrow$ appendix: more specific version

- UM-Translog (logistics domain, orig. developed 1995)
- Satellite (adopted from IPC benchmark)
- SmartPhone (modeled along an actual SmartPhone)
- Woodworking (adopted from IPC benchmark)

$\rightsquigarrow$ appendix: domain and solution properties

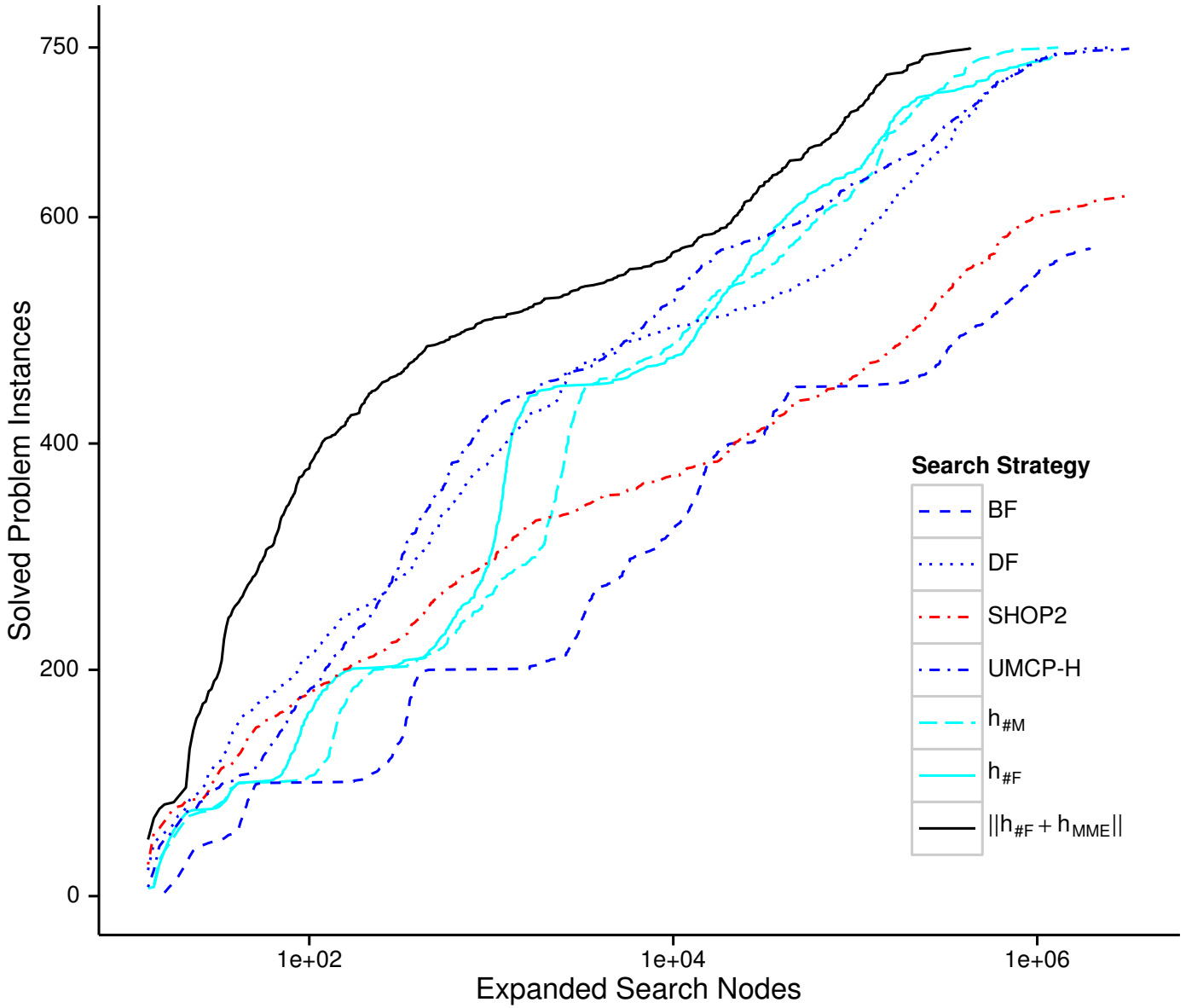
Baseline Configurations:

- BF / DF (Breadth and Depth First search)
- UMCP: BF, DF, heuristic version
- SHOP2

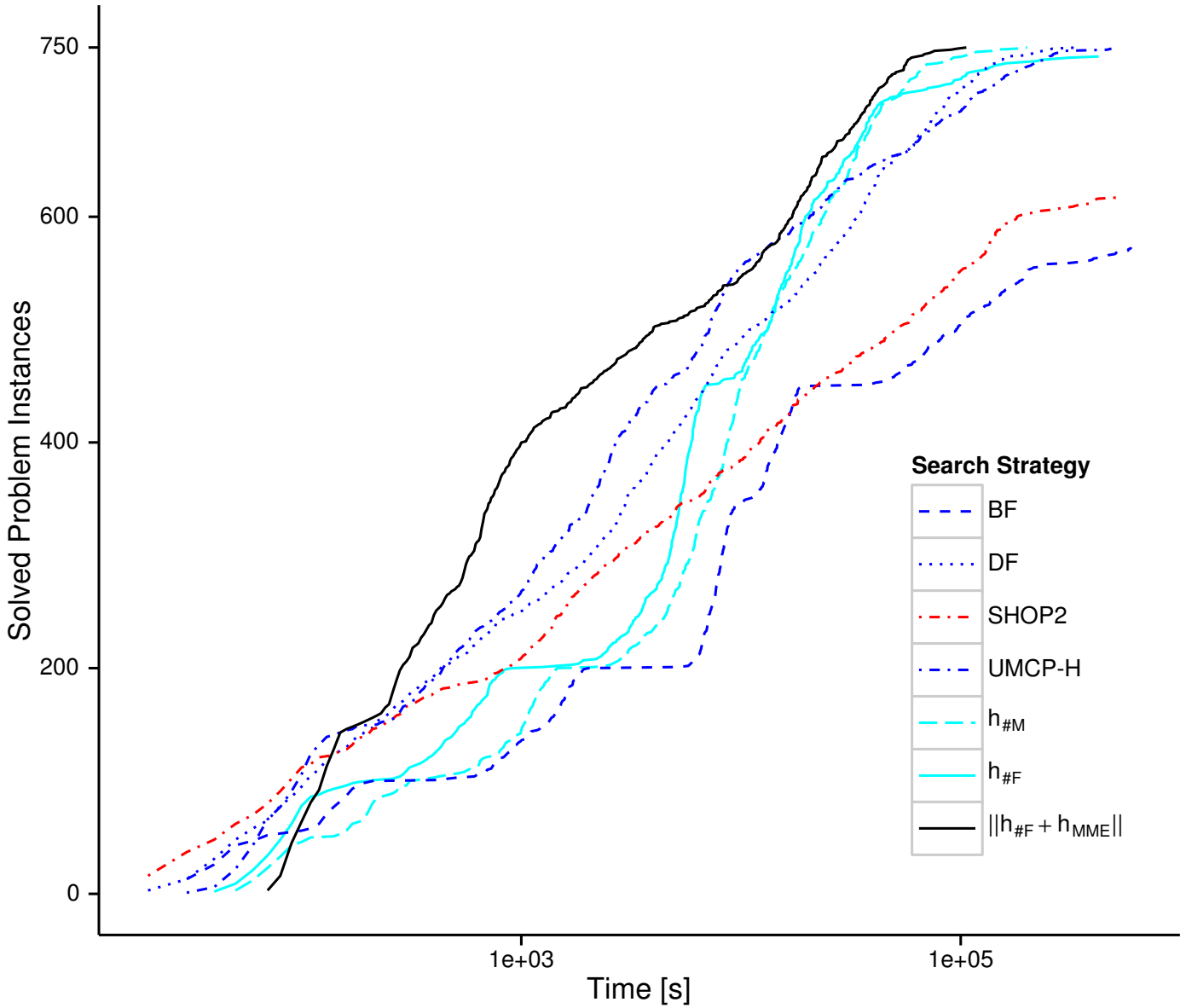
Greedy Search with Heuristics:

- $h_{\#M}$ (sum of modifications for all flaws)
- $h_{\#F}$ (number of flaws)
- $h_{\#F} + h_{TC+PC}$
- $h_{\#F} + h_{MME}$
- normalized versions thereof: $\|h(P)\| := \frac{h(P)}{|T|}$

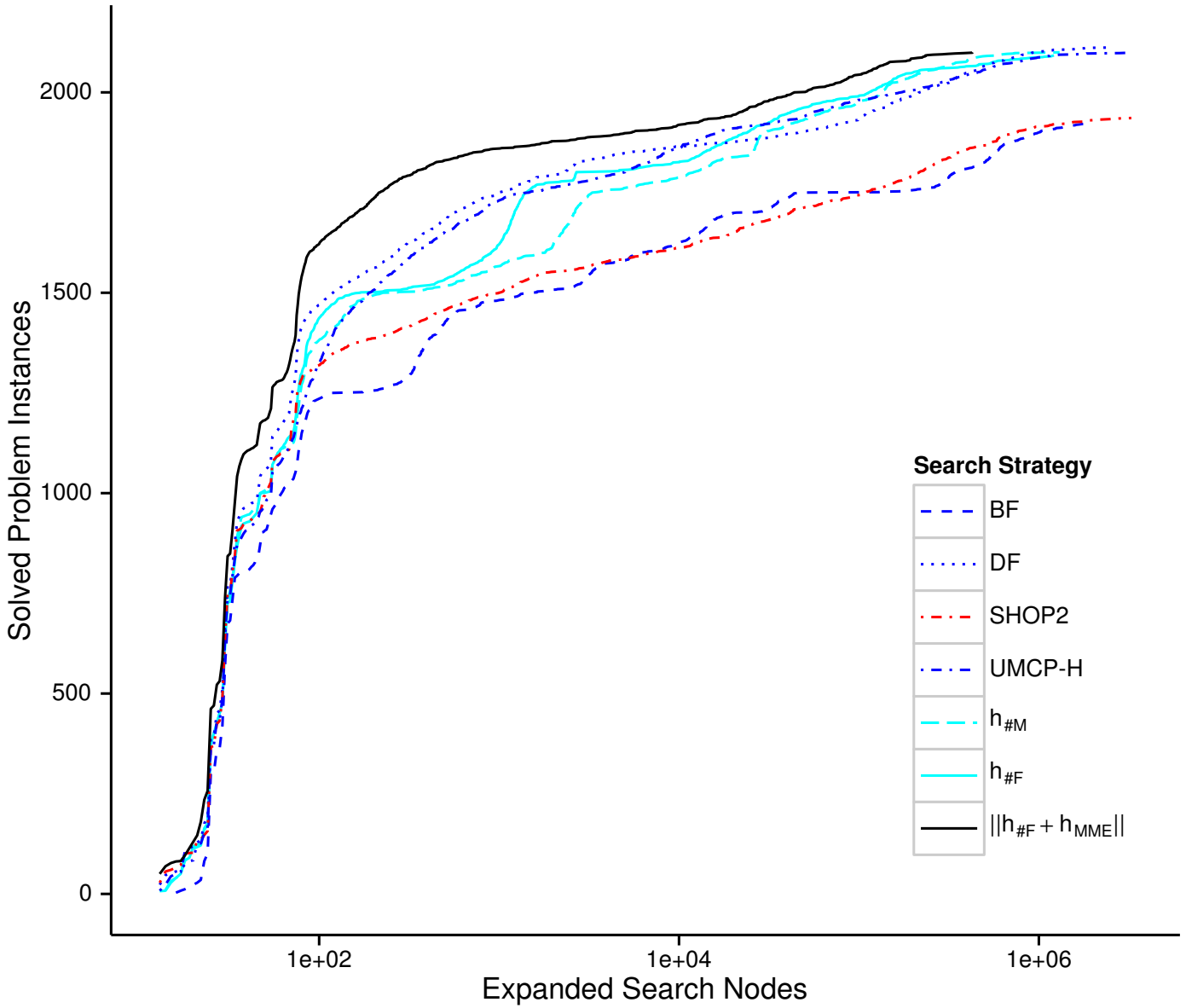
Solved instances in Satellite domain: (expanded nodes)



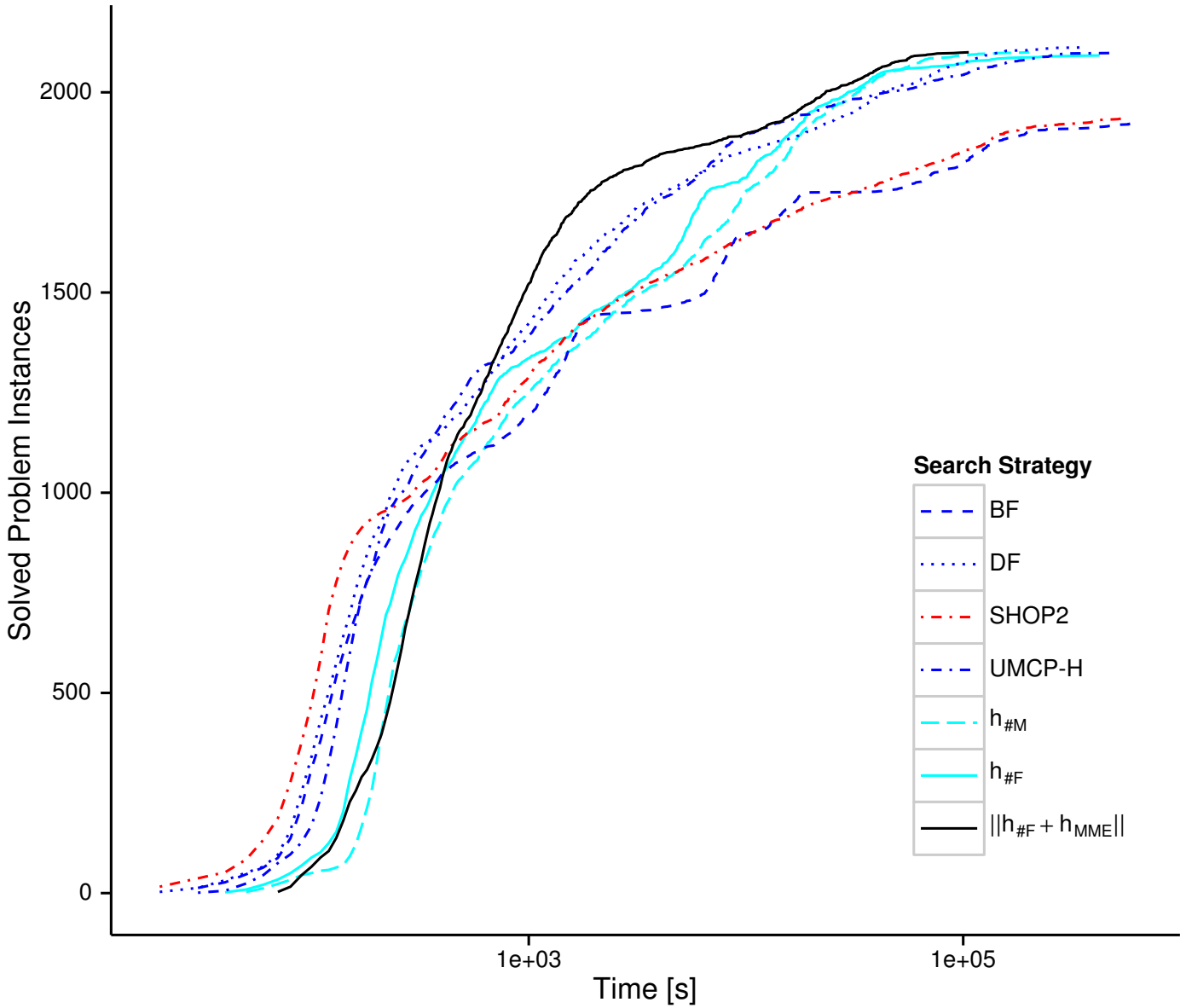
Solved instances in Satellite domain: (CPU time)



Solved instances in all domains: (expanded nodes)



Solved instances in all domains: (CPU time)



We proposed:

- a novel algorithm (PANDA) for hybrid planning
- two novel heuristics for hybrid planning:
  - h_{TC+PC}: focuses on the mandatory tasks
  - h_{MME}: traverses the complete TDG
- empirical results prove TDG-based heuristics to be more informed than others $\rightsquigarrow$ appendix: tables and additional plots

Heuristics for (non-hierarchical) POCL planning:

- #open preconditions[1]
- *relax* (FF) heuristic[1] and *add* heuristic[2]

Heuristics for hybrid planning:

- ignore task hierarchy and use POCL heuristics
- ratio of certain flaws and modifications[3]
- use TDG for modification ordering[4]

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1 Nguyen and Kambhampati: Reviving Partial Order Planning. (IJCAI '01)
2 Younes and Simmons: VHPOP: Versatile heuristic partial order planner. (JAIR '03)
3 Schattenberg: Hybrid Planning & Scheduling. Ph.D. Thesis. 2009
4 Elkawkagy et al.: Improving hierarchical planning performance by the use of landmarks. (AAAI '12)

Let V be an arbitrary set of tasks.

For a primitive task t, we set $h(t, V) := |prec(t)|$.
For an abstract task t, we set:

$$h(t, V) := \begin{cases} 1 + |prec(t)| & \text{if } t \in V \\ 1 + \min\limits_{s \in S(t)} \sum\limits_{t' \in s} h(t', \{t\} \cup V) & \text{else} \end{cases}$$

$$h_{MME}(P) := \sum_{t \in T \text{ is abstract}} h(t, \emptyset)$$

$\rightarrow$ heuristic traverses the complete TDG

UM-Translog

- domain properties
  - lifted primitive tasks: 48
  - lifted abstract tasks: 21
  - methods: 51
  - recursion? yes *(note revised version of paper)*
- TDG properties
  - ground primitive tasks: 7 to 22
  - ground abstract tasks: 12 to 30
  - avg. branching factor: 1 to 1.11
  - longest path: 11
  - cyclic? no
- solution properties
  - minimal number of modifications: 25 to 76

Satellite

- domain properties
  - lifted primitive tasks: 5
  - lifted abstract tasks: 3
  - methods: 8
  - recursion? no
- TDG properties
  - ground primitive tasks: 7 to 87
  - ground abstract tasks: 4 to 16
  - avg. branching factor: 2.75 to 15.1
  - longest path: 4
  - cyclic? no
- solution properties
  - minimal number of modifications: 13 to 41

SmartPhone

- domain properties
  - lifted primitive tasks: 87
  - lifted abstract tasks: 50
  - methods: 94
  - recursion? yes
- TDG properties
  - ground primitive tasks: 10 to 19
  - ground abstract tasks: 7 to 22
  - avg. branching factor: 1.42 to 1.95
  - longest path: 4 to 6
  - cyclic? yes and no
- solution properties
  - minimal number of modifications: 18 to 54

Woodworking

- domain properties
  - lifted primitive tasks: 13
  - lifted abstract tasks: 6
  - methods: 14
  - recursion? no
- TDG properties
  - ground primitive tasks: 10 to 64
  - ground abstract tasks: 15 to 492
  - avg. branching factor: 2.53 to 7.21
  - longest path: 2 to 4
  - cyclic? no
- solution properties
  - minimal number of modifications: 22 to 53

UM-Translog

Problem	#06			#09			#12			#13			#14		
Strategy	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t
BF	71	0.06	**0**	765	0.54	5	85	0.03	**1**	77	0.03	**1**	78	0.03	**1**
DF	62	0.14	**0**	**76**	0.02	*2*	*80*	0.05	**1**	*73*	0.04	**1**	*73*	0.05	**1**
SHOP2	21121	2.43	6	*80*	0.37	*2*	94	0.25	**1**	**71**	0.08	**1**	83	0.28	**1**
UMCP-BF	205	0.19	*1*	1548	0.08	8	174	0.14	3	266	0.13	6	168	0.16	3
UMCP-DF	119	0.57	*1*	542	0.74	4	133	0.33	*2*	168	0.47	4	126	0.32	*2*
UMCP-H	93	0.55	**0**	315	1.08	4	99	0.29	**1**	132	0.49	3	90	0.25	**1**
$h_{\#M}$	58	0.10	**0**	81	0.07	3	84	0.02	*2*	75	0.02	*2*	77	0.02	*2*
$\|h_{\#M}\|$	56	0.10	**0**	**76**	0.02	3	84	0.03	*2*	76	0.02	*2*	77	0.03	*2*
$h_{\#F}$	58	0.08	**0**	96	0.17	3	84	0.02	**1**	76	0.03	*2*	77	0.02	*2*
$\|h_{\#F}\|$	58	0.08	**0**	**76**	0.02	*2*	83	0.03	**1**	75	0.02	*2*	77	0.03	*2*
$h_{\#F} + h_{TC+PC}$	**54**	0.05	**0**	**76**	0.02	**1**	**78**	0.03	**1**	75	0.03	*2*	**71**	0.03	**1**
$\|h_{\#F} + h_{TC+PC}\|$	57	0.11	**0**	**76**	0.03	**1**	*80*	0.04	**1**	75	0.03	*2*	*73*	0.04	**1**
$h_{\#F} + h_{MME}$	*55*	0.07	**0**	**76**	0.02	**1**	**78**	0.04	**1**	75	0.03	*2*	**71**	0.04	**1**
$\|h_{\#F} + h_{MME}\|$	64	0.12	*1*	**76**	0.03	**1**	81	0.04	**1**	76	0.03	*2*	74	0.04	**1**

Satellite

X–Y–Z: X observations, Y satellites, Z modes

Problem	3–1–3			3–2–2			3–2–3			3–3–2			3–3–3		
Strategy	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t
BF	—	—	—	710661	0.34	140	—	—	—	322284	0.32	69	(16) 1122746	0.25	338
DF	668416	0.77	109	106748	1.22	28	318515	0.96	61	43456	1.18	16	239418	0.89	48
SHOP2	472177	0.88	99	(37) 294693	1.37	77	(11) 532783	1.29	133	(29) 339167	1.22	83	(13) 461074	1.66	101
UMCP-BF	605241	0.10	122	—	—	—	—	—	—	—	—	—	—	—	—
UMCP-DF	*129381*	0.89	**32**	(48) 287016	1.52	63	762774	1.13	151	(49) 350331	1.51	72	581613	0.68	133
UMCP-H	**125524**	0.77	*33*	19992	1.03	*11*	(49) 636852	1.03	133	24799	0.99	12	513303	0.58	122
$h_{\#M}$	219016	0.64	42	36058	0.97	19	205674	0.63	46	25465	0.97	15	247083	1.07	52
$\|h_{\#M}\|$	354407	0.91	72	88179	0.96	29	308752	0.95	66	*5996*	0.99	*10*	184650	2.34	41
$h_{\#F}$	(42) 468944	0.73	101	19827	0.48	17	122587	0.96	34	30125	0.57	18	163326	0.93	37
$\|h_{\#F}\|$	245524	0.75	46	112265	1.12	31	126640	1.12	31	20535	2.22	13	64105	2.30	**19**
$h_{\#F} + h_{TC+PC}$	599905	0.47	106	**5174**	1.54	**10**	*84298*	1.88	**26**	**3972**	0.86	11	*50111*	1.93	**19**
$\|h_{\#F} + h_{TC+PC}\|$	132639	0.81	44	14283	1.63	12	113607	1.37	36	9438	1.68	*10*	**47144**	1.40	*20*
$h_{\#F} + h_{MME}$	807016	0.46	142	*11600*	1.42	*11*	179804	1.22	44	7477	2.02	**8**	85274	1.45	26
$\|h_{\#F} + h_{MME}\|$	145929	0.64	46	14862	2.46	*11*	**59059**	1.10	*27*	14435	2.03	*10*	51977	1.28	22

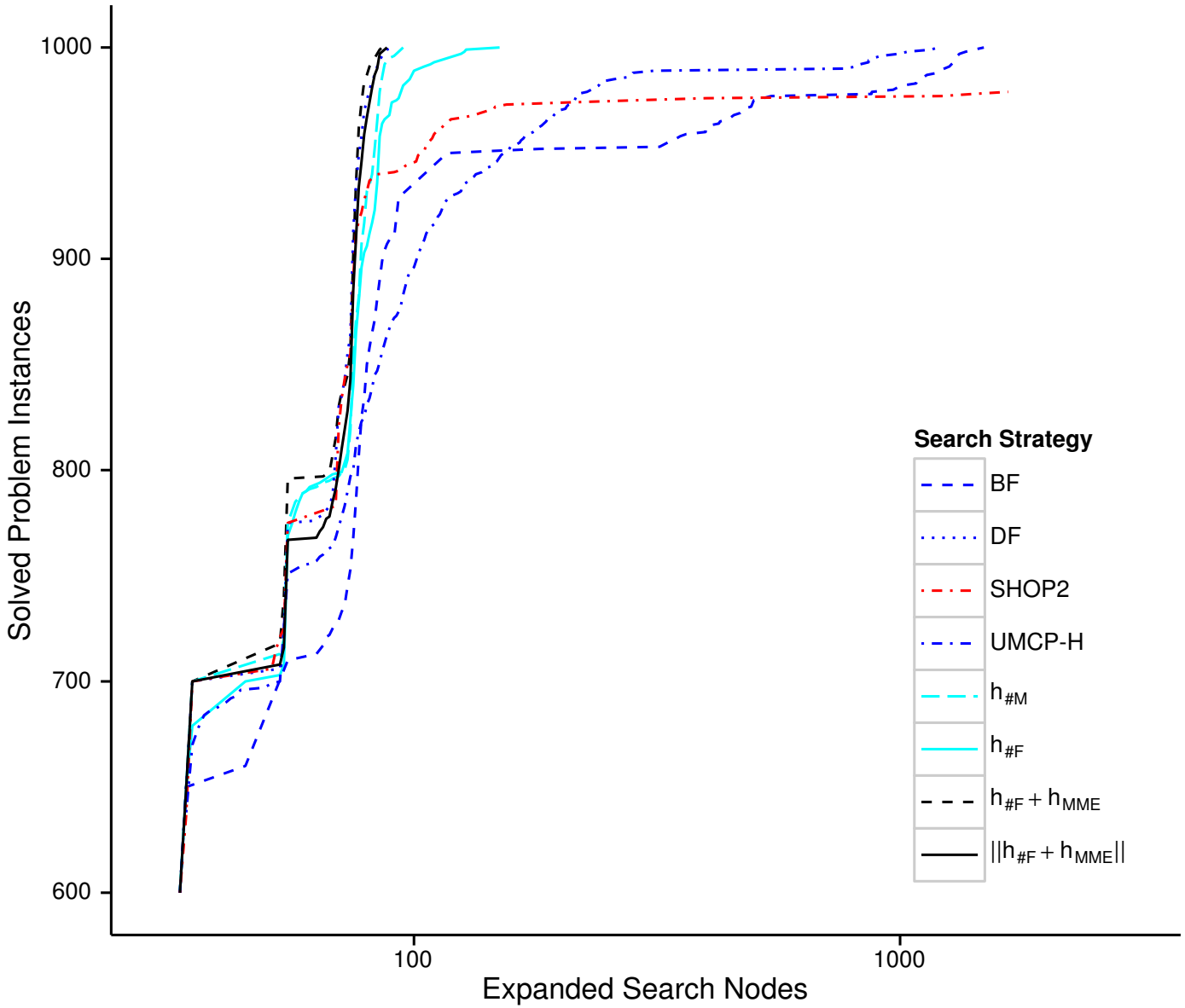
SmartPhone

Problem / Strategy	#1 μ_s	#1 σ_s/μ_s	#1 μ_t	#2 μ_s	#2 σ_s/μ_s	#2 μ_t	#3 μ_s	#3 σ_s/μ_s	#3 μ_t
BF	30	0.14	**0**	486980	0.24	103	—	—	—
DF	20	0.06	**0**	(12) 166	1.57	*1*	164	1.04	**1**
SHOP2	20	0.08	**0**	(8) **82**	0.24	**0**	60486	2.30	22
UMCP-BF	58	0.24	**0**	—	—	—	375530	0.04	55
UMCP-DF	*19*	0.08	**0**	(5) 2033	1.27	2	15863	1.45	6
UMCP-H	**18**	0.00	**0**	—	—	—	15964	1.21	7
$h_{\#M}$	**18**	0.00	**0**	—	—	—	27114	0.04	17
$\|h_{\#M}\|$	**18**	0.00	**0**	—	—	—	27111	0.04	17
$h_{\#F}$	*19*	0.05	**0**	—	—	—	1608	0.61	9
$\|h_{\#F}\|$	20	0.00	**0**	—	—	—	826	0.78	7
$h_{\#F} + h_{TC+PC}$	22	0.08	**0**	—	—	—	*112*	0.40	*2*
$\|h_{\#F} + h_{TC+PC}\|$	21	0.02	**0**	(4) *120*	0.11	*1*	**67**	0.15	**1**
$h_{\#F} + h_{MME}$	**18**	0.00	**0**	(2) 139	0.13	*1*	164	0.30	*2*
$\|h_{\#F} + h_{MME}\|$	20	0.07	**0**	—	—	—	230	0.89	*2*

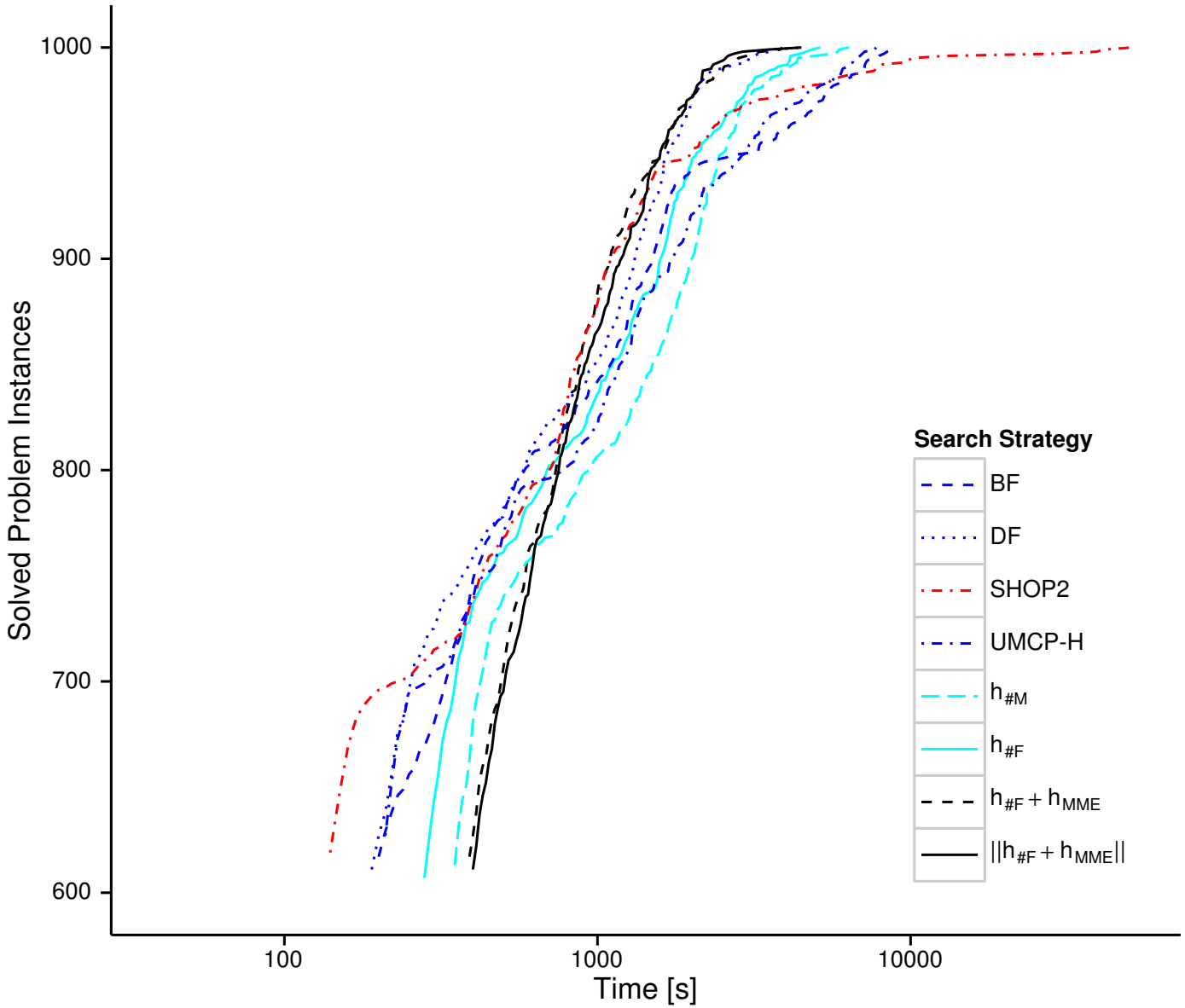
Woodworking

Problem	#1			#2			#3			#4			#5		
Strategy	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t	μ_s	σ_s/μ_s	μ_t
BF	**23**	0.02	**0**	*48*	0.01	**0**	60	0.05	**0**	565	0.25	**1**	474	0.27	*1*
DF	**23**	0.02	**0**	**47**	0.01	**0**	46	0.18	**0**	210	0.41	**1**	168	0.43	*1*
SHOP2	30	0.59	**0**	96	1.90	*1*	332	1.56	*2*	(29) 198536	1.78	86	(30) 152786	1.93	59
UMCP-BF	26	0.18	**0**	54	0.19	**0**	74	0.15	**0**	1642	0.31	*2*	1612	0.18	2
UMCP-DF	*24*	0.11	**0**	*48*	0.07	**0**	51	0.25	**0**	164	0.32	**1**	167	0.34	*1*
UMCP-H	25	0.11	**0**	49	0.10	**0**	50	0.25	**0**	115	0.34	**1**	106	0.39	**0**
$h_{\#M}$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.07	**0**	99	0.17	**1**	74	0.19	*1*
$\|h_{\#M}\|$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.07	**0**	103	0.24	**1**	71	0.23	*1*
$h_{\#F}$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.02	**0**	*89*	0.20	**1**	*67*	0.12	*1*
$\|h_{\#F}\|$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.02	**0**	90	0.27	**1**	**62**	0.10	*1*
$h_{\#F} + h_{TC+PC}$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.03	**0**	92	0.24	**1**	71	0.18	*1*
$\|h_{\#F} + h_{TC+PC}\|$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.03	**0**	101	0.51	**1**	72	0.27	*1*
$h_{\#F} + h_{MME}$	**23**	0.02	**0**	**47**	0.01	**0**	**36**	0.02	**0**	**82**	0.47	**1**	84	0.43	*1*
$\|h_{\#F} + h_{MME}\|$	**23**	0.02	**0**	**47**	0.01	**0**	*37*	0.07	**0**	171	0.47	**1**	175	0.37	*1*

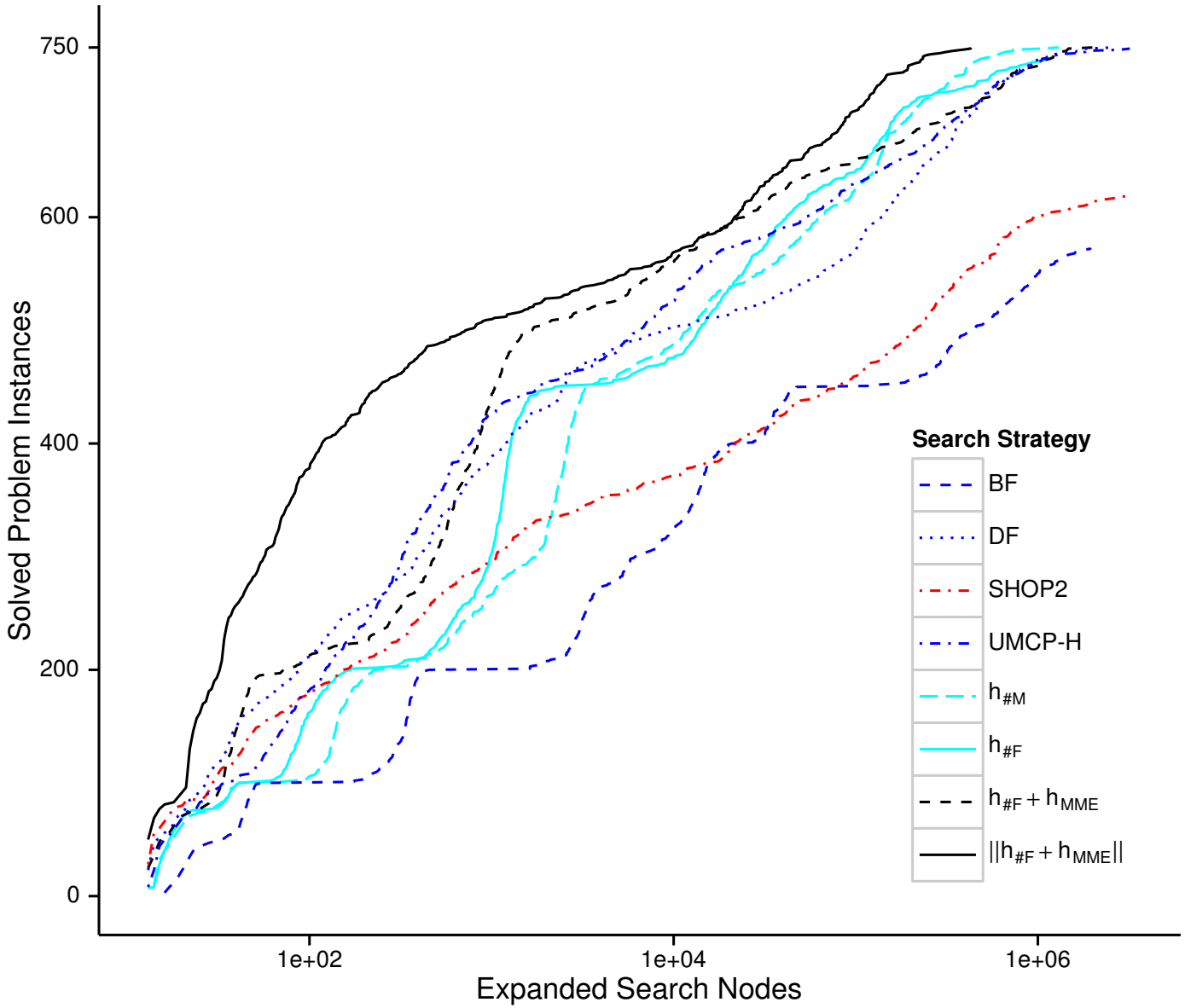
Solved instances in UM-Translog domain: (expanded nodes)



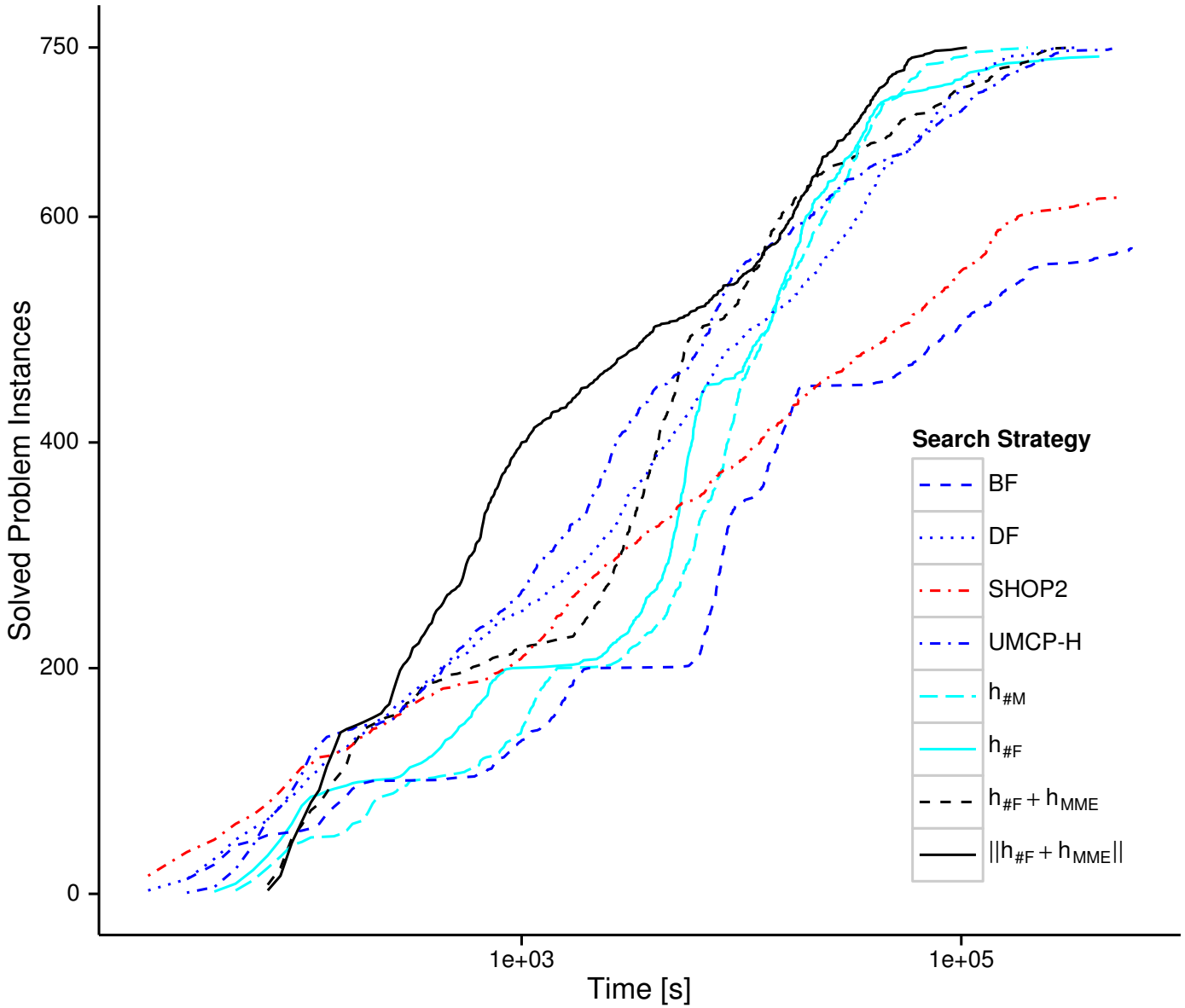
Solved instances in UM-Translog domain: (CPU time)



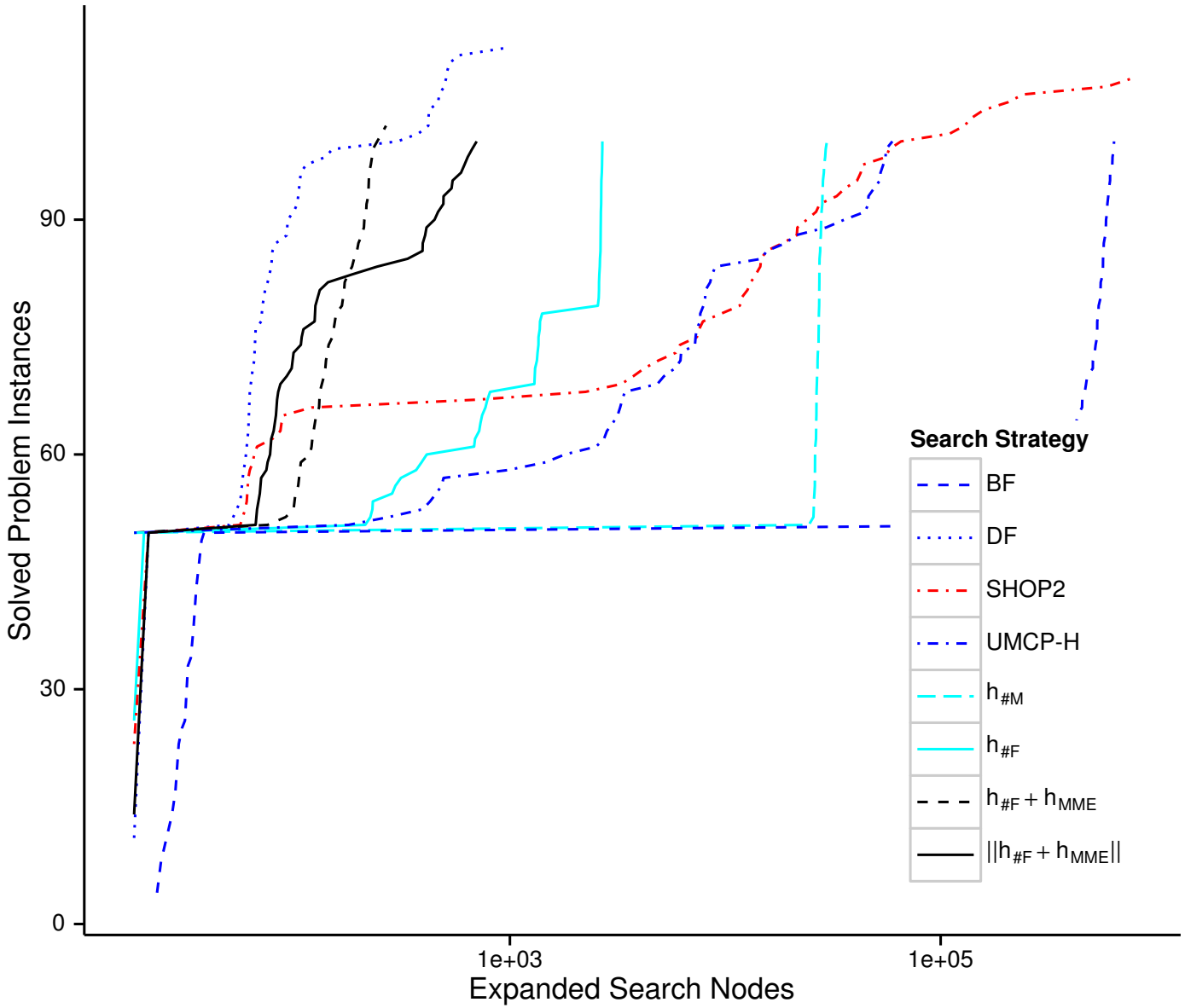
Solved instances in Satellite domain: (expanded nodes)



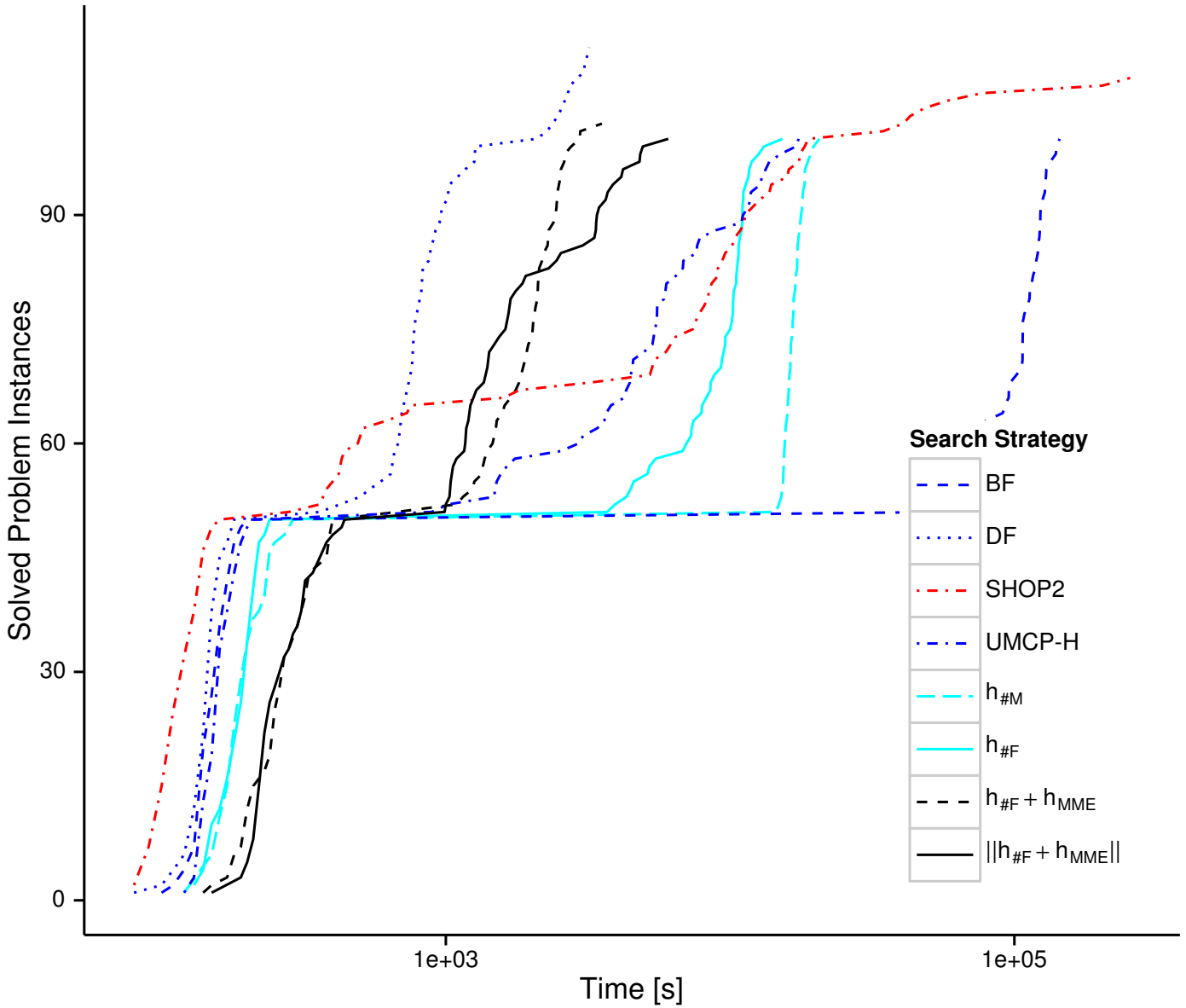
Solved instances in Satellite domain: (CPU time)



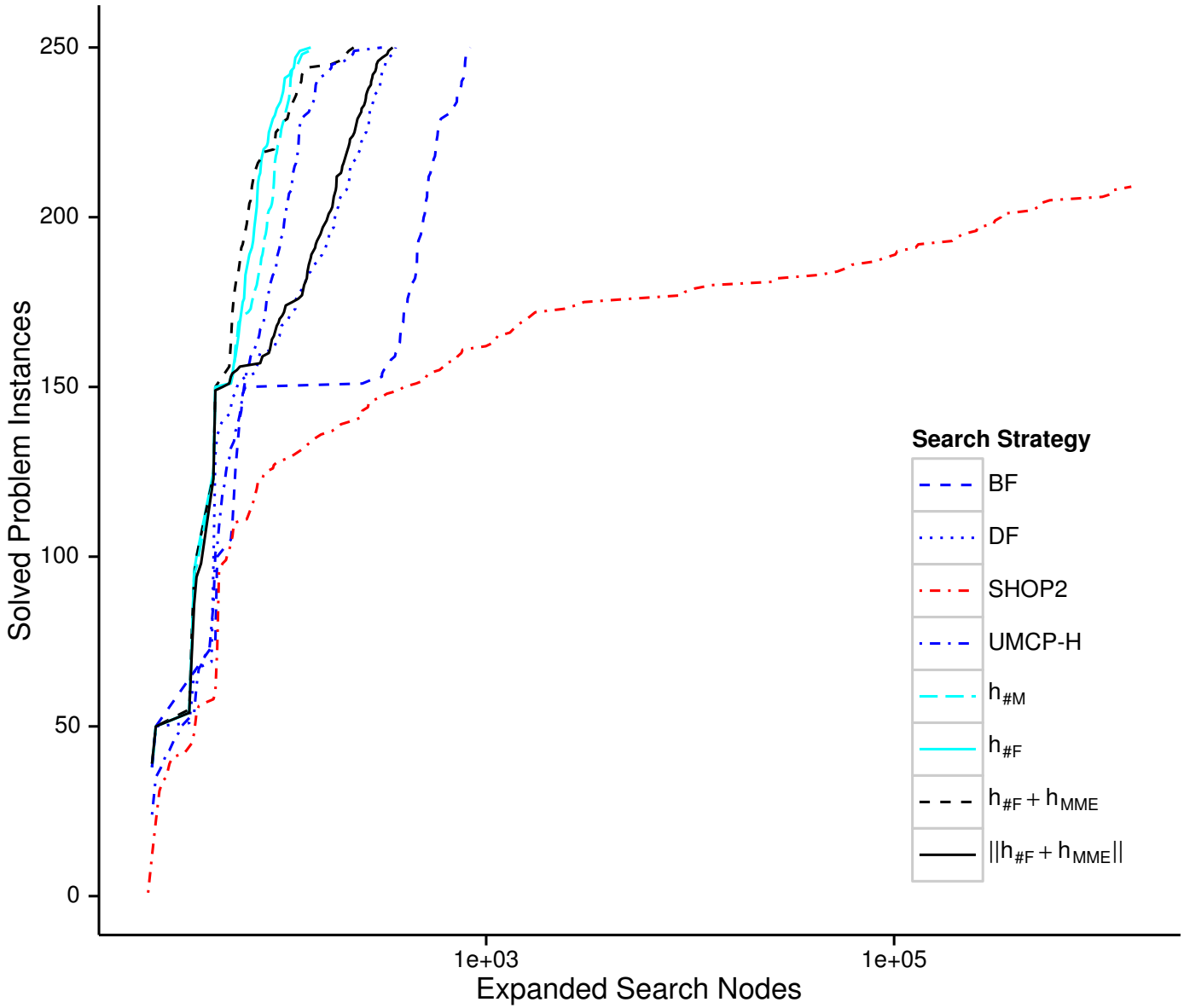
Solved instances in SmartPhone domain: (expanded nodes)



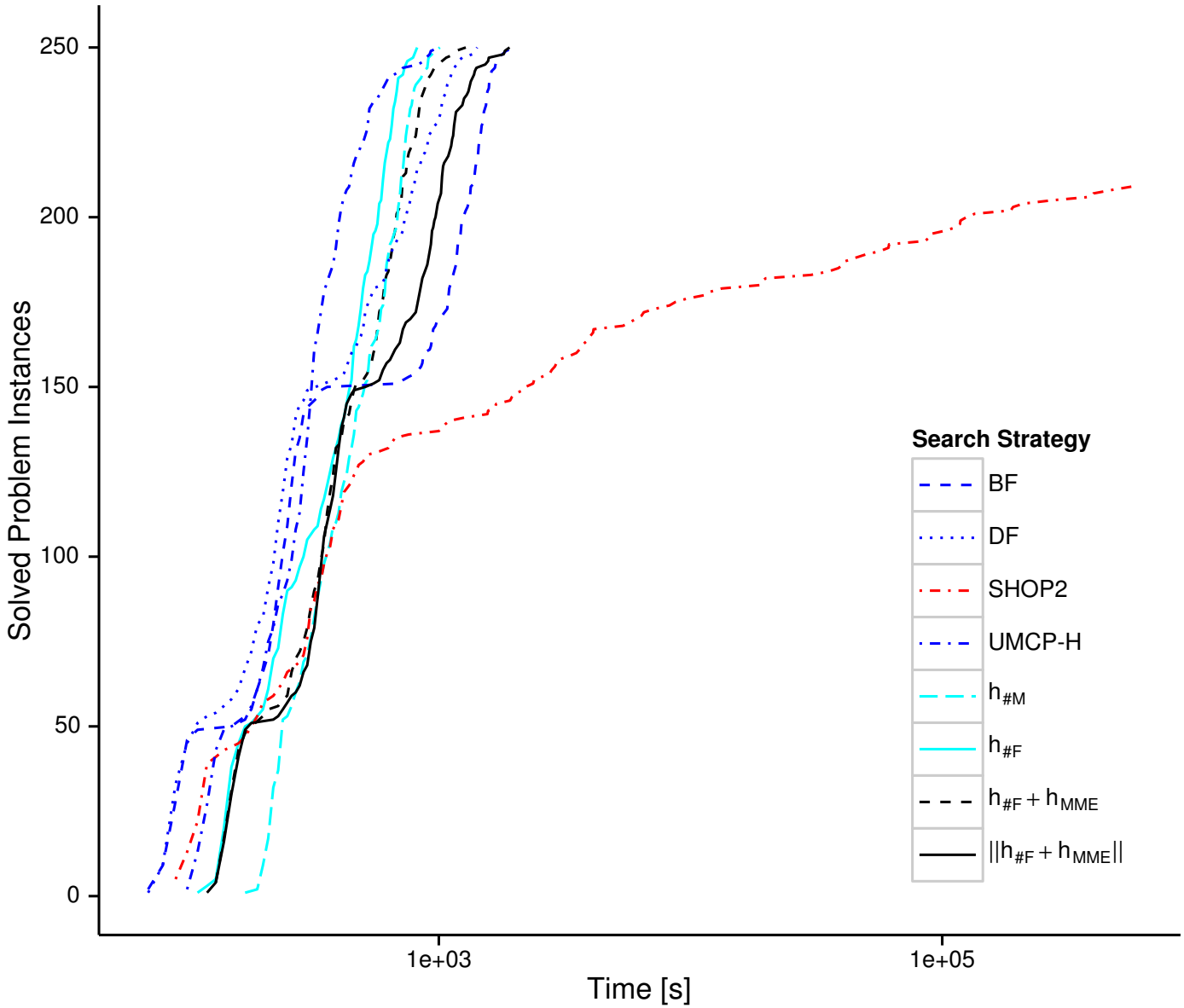
Solved instances in SmartPhone domain: (CPU time)



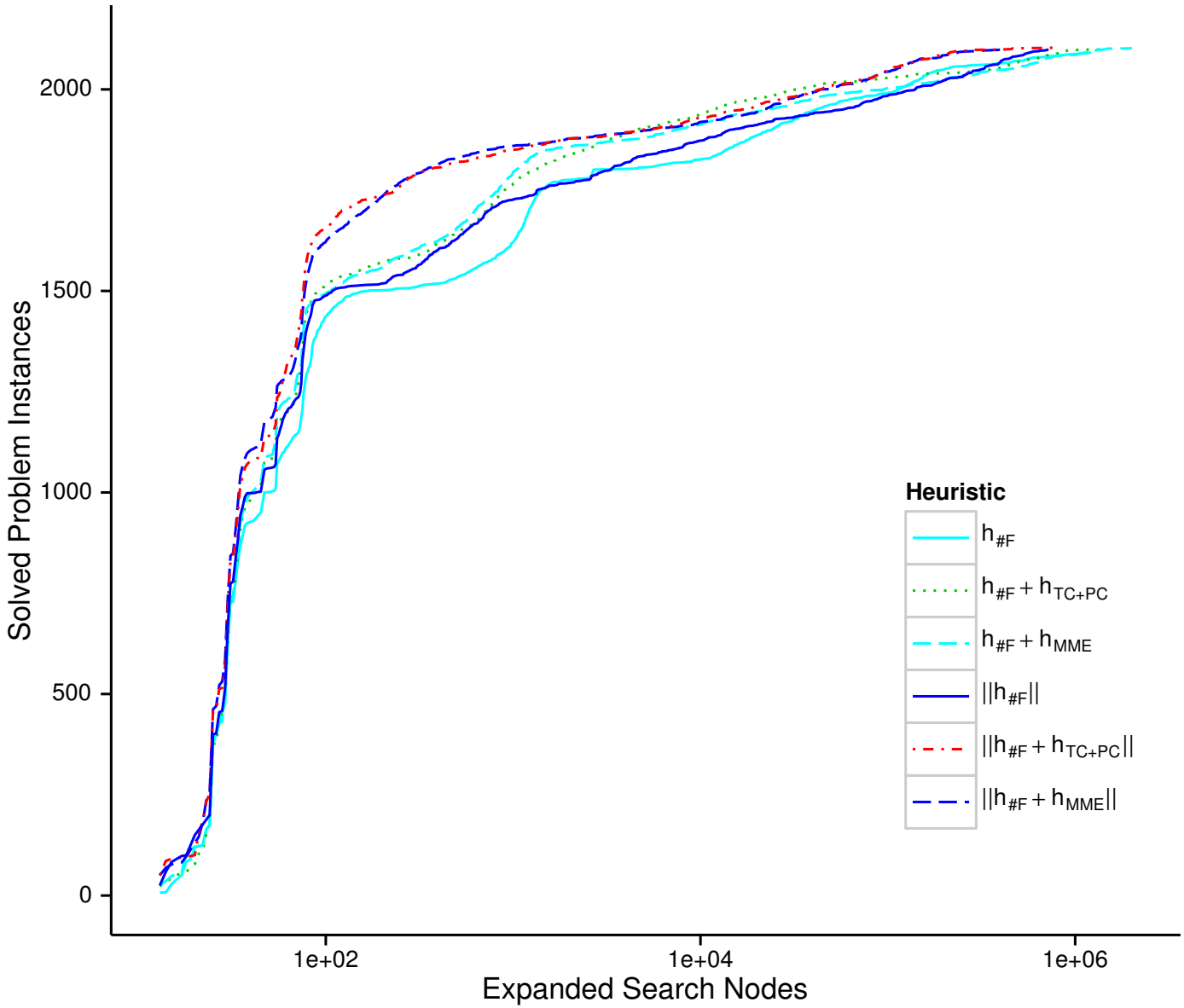
Solved instances in Woodworking domain: (expanded nodes)



Solved instances in Woodworking domain: (CPU time)



Solved instances in all domains: (expanded nodes)



Solved instances in all domains: (CPU time)