Partial-Order Causal-Link Planning with Preferences

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Motivation

Solving problem “travel from Ulm to Munich”:

- Example for P1: 1 Task, Costs 100€, Time 3h, 0 Transfers
  [Diagram: Ulm → Car → Munich]

- Example for P2: 2 Tasks, Costs 130€, Time 2.5h, 1 Transfer
  [Diagram: Ulm → Taxi → Station → Train → Munich]

How to measure the quality of those plans?

- Typical quality measurements of a plan are costs like money, time or number of tasks.
We can clearly measure which plan is cheaper, faster or has more tasks, but what about other properties?

- P1: Car is at Munich in the final state
  
  ![Diagram](Ulm → Car → Munich)

- P2: Car is at home in the final state
  
  ![Diagram](Ulm → Taxi → Station → Train → Munich)

→ Preferences can be used to describe properties of plans to support each user individually
→ Preferences are state features, called Soft-Goals, that are optional
Motivation

Features provided by preferences:

• Quality of plans can be measured by taking Soft-Goals into account

• Soft-Goals are optional whereas “normal” goals must be fulfilled in order to find a solution (which might be too restrictive, since humans tend to define more goals than possibly satisfiable)
Task of the master thesis

- **Extend PANDA$_2$**
  - Integrate and handle Soft-Goals, which correspond to “at-end” preferences in PDDL3.0
  - Develop different strategies to handle Soft-Goals
  - Implement planning graph

- Evaluation of the implementation
Planning problem with preferences

Definition of a planning problem: \( \pi = \langle V, A, s_{init}, s_{goal}, Prefs \rangle \)

- \( V \) is a finite set of state variables
- \( A \) is a finite set of actions where:
  - \( a = \langle \text{pre}, \text{add}, \text{del} \rangle \in A \) where \( \text{pre}, \text{add}, \text{del} \subseteq V \)
  - \( a \) is applicable in a state \( s \in 2^V \) iff \( \text{pre} \subseteq s \)
  - If \( a \) is applied in \( s \), it leads to \((s \setminus \text{del}) \cup \text{add}\)
- \( s_{init} \in 2^V \) and \( s_{goal} \subseteq V \)

Preferences: Can be arbitrary formulæ over literals which can be transformed into “Disjunctive Normal Form” (DNF)

- \( Prefs \) is a finite set of preferences
- \( \{\text{disjunct}_1, \ldots, \text{disjunct}_n\} \in Prefs \) represents a formula in DNF, where \( \text{disjunct}_j \subseteq V, j = 1, \ldots, n \)
Planning problem with preferences

Action sequence \( \overline{a} \) is a solution iff \( \overline{a}(s_{\text{init}}) \) fulfills \( s_{\text{goal}} \)

Possible quality measurement called “Benefit”:

- \( \text{Ben}(\overline{a}) = \sum_{p \in \text{Prefs}} \text{benefit}(p) \)

\( \overline{a}(s_{\text{init}}) \) fulfills \( p \)

Used quality measurement called “NetBenefit”:

- \( \text{NetBen}(\overline{a}) = \sum_{p \in \text{Prefs}} \text{benefit}(p) - \sum_{a \in \overline{a}} \text{costs}(a) \)

\( \overline{a}(s_{\text{init}}) \) fulfills \( p \)
Solving planning problems with preferences

- Based on a fringe which contains a set of partial plans
- Planselection selects a partial plan out of the fringe
- Partial plan has flaws, which need to be addressed in order to get a plan
- Flawselection decides which flaw of the partial plan is addressed
  → Results in new partial plans that are branched into the fringe

Illustration of the search space:
Approaches to resolve preferences

- Developed and implemented two different strategies:
  - “Split strategy”
  - “No-split strategy”
- Basis for both strategies are preferences in DNF
  → Presentation of strategies on next slides
Approaches to resolve preferences — "Split strategy"

→ Basic idea: Split DNF into its disjuncts

First selection of the preference $p$ (example):

$$ p = \psi_{11} \lor (\psi_{21} \land \psi_{22}) $$

$p_1 = \psi_{11}$

$p_2 = \psi_{21} \land \psi_{22}$

Each subsequent selection of the preference:

$p_1 = \psi_{11}$

$p_2 = \psi_{21} \land \psi_{22}$

Supporters

Supporters

2

1

3
Approaches to resolve preferences — “No-split strategy”

→ Basic idea: Stay flexible and work on different disjuncts

\[ p = \psi_1 \lor (\psi_2 \land \psi_2) \]

2 1 3

Supporters

- Literals are protected according to the used flaw selection strategy which will be explained on the next slides
Selection methods for preferences

How do we decide which literal of which preference we protect next?

→ Basic idea: LCFR (Least Cost Flaw Repair)

\[
LCFR_{DNF} \circ (P) = \min_i \left[ \min_{\varphi_j} \left( \circ \ |supporter(P, f_i(\psi_{jk}))| \right) \right]
\]

with \( i = 1, \ldots, |Prefs(P)| \) and \( \circ \in \{\prod, \sum, \min\} \)

\( p_i \in Prefs, p_i = \varphi_1 \lor \ldots \lor \varphi_n, \varphi_j = \psi_{j_1} \land \ldots \land \psi_{j_k}, j = 1, \ldots, n \)

→ 3 Strategies:

- \( LCFR_{DNF} - \prod \)
- \( LCFR_{DNF} - \sum \)
- \( LCFR_{DNF} - \min \)
Selection methods for preferences — $LCFR_{DNF-\prod}$

$$LCFR_{DNF-\prod}(P) = \min_i \left[ \min_{\varphi_j} \left( \prod_{\psi_{jk}} |\text{supporter}(P, f_i(\psi_{jk}))| \right) \right]$$

Example: Plan P has a preference $p$

$$p = \psi_{11} \lor (\psi_{21} \land \psi_{22})$$

Calculated values: $2 \quad 1 \times 3 = 3$

$\rightarrow LCFR_{DNF-\prod} = 2 \rightarrow \varphi_1$ is selected
$\rightarrow$ Literal with fewest supporters of $\varphi_1$ is $\psi_{11}$
Selection methods for preferences — $LCFR_{DNF} - \sum$

$$LCFR_{DNF} - \sum (P) = \min_i \left[ \min_{\varphi_j} \left( \sum_{\psi_{jk}} |\text{supporter}(P, f_i(\psi_{jk}))| \right) \right]$$

Example: Plan P has a preference $p$

$$p = \psi_{11} \lor (\psi_{21} \land \psi_{22})$$

Calculated values: $2$, $1 + 3 = 4$

$\rightarrow LCFR_{DNF} - \sum = 2 \rightarrow \varphi_1$ is selected

$\rightarrow$ Literal with fewest supporters of $\varphi_1$ is $\psi_{11}$
Selection methods for preferences — $LCFR_{DNF}$-\(\text{min}\)

\[
LCFR_{DNF}\text{-min}(P) = \min_i \left[ \min_{\varphi_j} \left( \min_{\psi_{jk}} |\text{supporter}(P, f_i(\psi_{jk}))| \right) \right]
\]

Example: Plan P has a preference \(p\)

\[
p = \psi_{11} \lor (\psi_{21} \land \psi_{22})
\]

Calculated values: 2 1 3

\[\rightarrow LCFR_{DNF}\text{-min} = 1 \rightarrow \psi_{21}\text{ is selected.}\]
Evaluation

Evaluation compares:

- Solve “normal” goals first vs. solve Soft-Goals first
- “Split strategy” vs. “No-split strategy”
- $LCFR_{DNF}-\min$ vs. $LCFR_{DNF}-\prod$ vs. $LCFR_{DNF}-\sum$
- “A* NetBenefit” vs. “Uniform NetBenefit”
  \[ \rightarrow \text{24 resulting configurations} \]

Used planning domains and problems:

- 200 randomly generated planning problems
  \[ \rightarrow 24 \times 200 = 4800 \text{ test cases} \]
- 6 user assistance planning problems modeled by Claudia Bolch
  \[ \rightarrow 24 \times 6 = 144 \text{ test cases} \]
Solve Soft-Goals first

Random-Problems:
• 2400 tests done
• 6 solutions found
→ Only 0.25% solved

User-Assistance-Problems:
• 72 tests done
• 49 solutions found
→ It’s more important to find a solution than solving preferences
→ Therefor “normal” goals must be solved first

Solve “normal” goals first

Random-Problems:
• 2400 tests done
• 2400 solutions found
→ 100% solved

User-Assistance-Problems:
• 72 tests done
• 63 solutions found
Evaluation — Approaches to resolve preferences

“Split strategy”

“No-split strategy”

→ “No-split strategy” dominates “Split strategy”
→ But: “Split strategy” has room for improvement
Evaluation — Selection methods for preferences

\[ LCFR_{DNF}\text{- min} \]

\[ LCFR_{DNF}\text{- \( \prod \)} \]

\[ LCFR_{DNF}\text{- \( \sum \)} \]

As expected: \( LCFR_{DNF}\text{- min} \) is dominated by other strategies
Reason: \( LCFR_{DNF}\text{- min} \) is not aware of DNF
Summary

- Planning algorithm was extended to enable the use of preferences
  - Developed and implemented different methods to resolve preferences
  - Developed and implemented different methods for soft-flaw selection
  - Evaluated combinations of different strategies
- Implemented the planning graph (used for heuristic estimation)
Algorithm 1: Preference-based POCL planning algorithm.

Input : The fringe Fringe = \{P_{init}\}.

Output : A plan or fail.

1. best-nB := −\infty
2. best-P := fail
3. while Fringe ≠ ∅ and "no timeout" do
4. \hspace{1em} P = planSel(Fringe)
5. \hspace{1em} Fringe = Fringe \{P\}
6. \hspace{1em} if flaws_h(P) = ∅ and netBen(P) > best-nB then
7. \hspace{2em} best-nB := netBen(P)
8. \hspace{2em} best-P := P
9. \hspace{1em} f = flawSel(flaws_h(P) \cup flaws_s(P))
10. Fringe = Fringe \cup resolveFlaw(P, f)
11. return best-P
Appendix — Example: Planning Graph

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Appendix — Semantics of preferences in PDDL3.0

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{at end } \phi) \quad \text{iff} \quad S_n \models \phi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models \phi \quad \text{iff} \quad S_n \models \phi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{always } \phi) \quad \text{iff} \quad \forall i : 0 \leq i \leq n \cdot S_i \models \phi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{sometime } \phi) \quad \text{iff} \quad \exists i : 0 \leq i \leq n \cdot S_i \models \phi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{within } t \phi) \quad \text{iff} \quad \exists i : 0 \leq i \leq n \cdot S_i \models \phi \quad \text{and } t_i \leq t\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{at-most-once } \phi) \quad \text{iff} \quad \forall i : 0 \leq i \leq n \cdot \text{if } S_i \models \phi \text{ then } \exists j : j \geq i \cdot \forall k : i \leq k \leq j \cdot S_k \models \phi \quad \text{and } \forall k : k > j \cdot S_k \models \neg \phi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{sometime-after } \phi \psi) \quad \text{iff} \quad \forall i \cdot \text{if } S_i \models \phi \text{ then } \exists j : i \leq j \leq n \cdot S_j \models \psi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{sometime-before } \phi \psi) \quad \text{iff} \quad \forall i \cdot \text{if } S_i \models \phi \text{ then } \exists j : 0 \leq j < i \cdot S_j \models \psi\]

\[\langle (S_0, 0), (S_1, t_1), \ldots, (S_n, t_n) \rangle \models (\text{always-within } t \phi \psi) \quad \text{iff} \quad \forall i \cdot \text{if } S_i \models \phi \text{ then } \exists j : i \leq j \leq n \cdot S_j \models \psi \quad \text{and } t_j - t_i \leq t\]
Appendix — More details: “Split strategy”

First selection of the preference $p_i$ in plan $P$:

\[ P : p_i = \varphi_1 \lor \cdots \lor \varphi_n \]

\[ P_1 : p'_i = \varphi_1 \quad \cdots \quad P_n : p'_i = \varphi_n \quad P_{n+1} : f_i \notin \text{flaws}(P) \]

Each following selection of the simplified preference $p'$:

\[ P : p' = \varphi_j \]

\[ P_1 : \psi_{jk} \text{ protected} \quad \cdots \quad P_n : \psi_{jk} \text{ protected} \]
Appendix — Room for improvement of “Split strategy”

- Fringe contains partial plans
- “Split strategy” splits preference and branches the resulting partial plans into the fringe

\[ P : \ p_i = \varphi_1 \lor \cdots \lor \varphi_n \]

\[ P_1 : \ p'_i = \varphi_1 \]
\[ \cdots \]
\[ P_n : \ p'_i = \varphi_n \]

- Currently PANDA2 is not able to differentiate between the partial plans \( P_1, \ldots, P_n \)
  \( \rightarrow \) Random selection of a partial plan among \( P_1, \ldots, P_n \)
  \( \rightarrow \) But: Preference was selected because of a specific disjunct \( \varphi_j \) thus the partial plan \( P_j \) with \( 1 \leq j \leq n \) should be preferred
Appendix — More details: “No-split strategy”

Branching of generated partial plans if preference \( p \) in partial plan \( P \) is selected:

\[
P : p = \varphi_1 \lor \cdots \lor \varphi_j
\]

\[
P_1 : \psi_{j_k} \text{ protected} \quad \cdots \quad P_n : \psi_{j_k} \text{ protected} \quad P_{n+1} : f_i \notin \text{flaws}(P_{n+1}) \quad P_{n+2} : p_i' = p_i \setminus \varphi_j
\]