Reasoning Agents Exam
Artificial Intellingence and Robotics
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# LTLf based trace alignment Project

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# Table of Contents



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# Business Process

- BP defines the temporal (partial) ordering of some activities
- Activities execution are stored in logs → set of traces
- Sometimes the log traces can be *inconsistent* with the expected process behavior → need to repair the traces
- Process Mining is the analysis of (business) process starting from event logs

# Trace Alingment for Business Process

**Trace alignment** is the problem of:

- Checking whether an actual trace conforms to the expected process behavior (process model) and, if not...
- Finding a “minimal set” of changes that “align” the trace to the process
  - Changes consist in adding / removing activities from traces
- Focus on trace alignment against *declarative* specifications (descriptive) → constraints expressed in DECLARE language or LTL*f*

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# Trace Alingment in Declarative BP

Given:

- A trace $\rho$ over a finite event (possible activity) alphabet $\Sigma = \{\sigma 1, \ldots, \sigma n\}$
- A constraint $\varphi$
- A *cost* function associating «positive» cost to additions / deletions of events

Find a trace $\rho'$ such that:

- $\rho'$ satisfies $\varphi$, i.e. $\rho' \models \varphi$
- cost($\rho$, $\rho'$) is minimal (turning from the original trace to the other)

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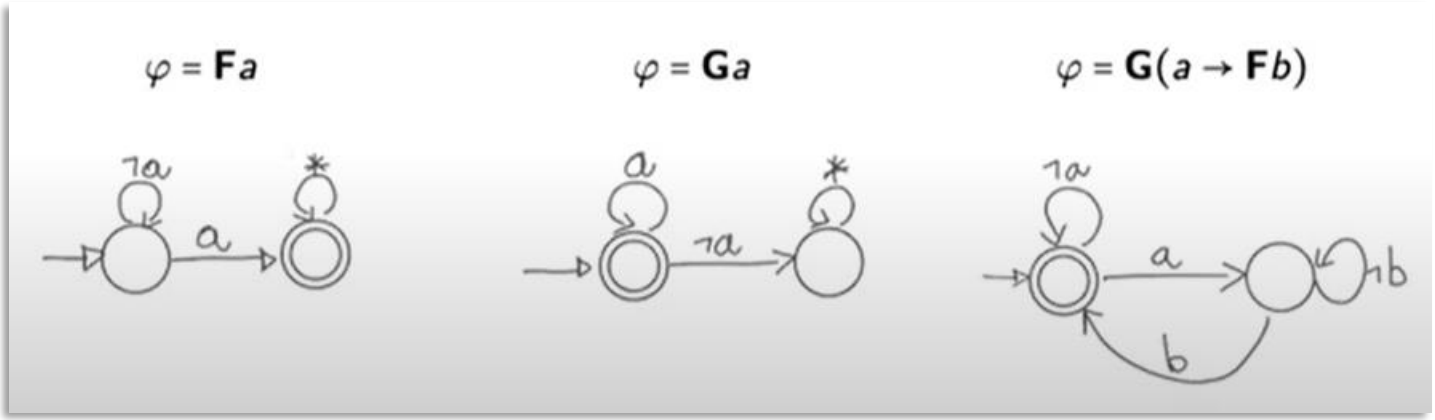
# Trace Alingment in Declarative BP – LTL*f*

Constraints specification can be done through DECLARE language template that can be translated in LTL*f* translation

| DECLARE template | LTL*f* translation |
|---|---|
| *Existence(a)* | **F***a* |
| *Response(a, b)* | **G**(*a* → **F**b) |
| *Choice(a, b)* | **F***a* ∨ **F***b* |
| *ChainResponse(a, b)* | **G**(*a* → **X***b*) |

# LTL*f* Formulas as NFAs (property)

- Every LTLf formula has a corresponding (exponential) NFA $A_\varphi$ s.t
  - For every trace $\rho$ : $\rho \models \varphi \leftrightarrow A_\varphi$ *accepts* $\rho$



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# Automata-based Solution for Trace Alignment

Given:

- trace $\rho$
- constraint $\varphi$

Define two automatons:

- *Augmented trace automaton* $T^+$ : accepts all modifications of $\rho$ (where the changes are marked)
- *Augmented constraint automaton* $A^+$ : accepts all traces that satisfy $\varphi$ && all modifications of $\rho$ that satisfy $\varphi$

Find minimal-cost $\rho'$ s.t. is accepted by $T^+$ && $A^+$ (satisfies both)

- Corresponds to find minimal-cost accepting path $\rho'$ on product automaton $T^+$ x $A^+$

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# Trace Alingment as Planning Problem

Use Planning to search for minimal-cost $\rho'$

- Domain
  - Models product automaton $T^+ \times A^+$
  - *add* and *del* actions with positive cost (changes of input trace)
  - *sync* actions with null cost model events
- Problem
  - Initial State: all automata in their starting state
  - Goal: all automata in a final state
- Solution
  - Minimal-cost goal-reaching sequence of actions

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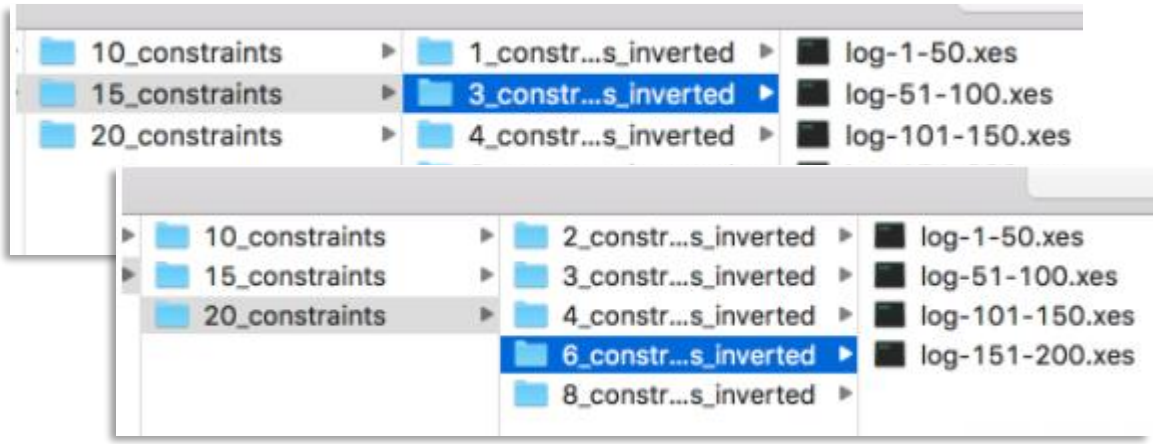
# Implementation – Dataset

Synthetic Logs:

- Traces having the same alphabet of activities, containing 10 / 15 / 20 constraints
- Each log contains different amount of noise (i.e. N constraints are inverted over the total of 10 / 15 / 20 constraints on which the traces are modeled)
- Different lengths:
  - 1-50
  - 51-100
  - 101-150
  - 151-200
  - 201-250



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# Implementation – from Traces/Constraints to Automata

Given a trace $t = e_1 \ldots e_m$, build a Trace **Automaton $T^+$** (DFA)

- $T = ( \Sigma_t , Q_t , q^t_0 , \rho_t , F_t )$
- $\Sigma_t$ = set of all the events occurring in t
- $Q_t$ = set of states
- $q^t_0$ = initial state
- $\rho_t$ = transition function
- $F_t$ = final state (for Trace Automaton is always one)

Build a **Constraint Automaton $A^+$** (NFA)

- $A = ( \Sigma_a , Q_a , q^a_0 , \rho_a , F_a )$
- $\Sigma_a$ = alphabet
- $Q_a$ = set of states
- $q^a_0$ = initial state
- $\rho_a$ = transition function
- $F_a$ = set of final state

***** Each propositional interpretation in a trace corrensponds to one proposition (a singleton) – in process mining only one event True at each time, in LTLf can be more than one event True at each time

# LTLf2DFA and MONA representation

**G**(activity14_complete ->**X**(activity15_complete))

**Transitions:**

State 0**: XX** -> state 1
State 1: 0**X** -> state 1
State 1: 1**X** -> state 2
State 2: 00 -> state 3
State 2: 01 -> state 1
State 2: 10 -> state 3
State 2: 11 -> state 2
State 3: **XX** -> state 3

Expanded state transitions…

State 0: 00 -> state 1
State 0: 01 -> state 1
State 0: 10 -> state 1
State 0: 11 -> state 1
State 1: 00 -> state 1
State 1: 01 -> state 1
**State 1: 10 -> state 2**
State 1: 11 -> state 2
State 2: 00 -> state 3
**State 2: 01 -> state 1**
**State 2: 10 -> state 3**
State 2: 11 -> state 2
State 3: 00 -> state 3
State 3: 01 -> state 3
State 3: 10 -> state 3
State 3: 11 -> state 3

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# LTLf2DFA and MONA representation

Sum of the labels to have always a singleton :

- If sum > 1 discard the transition
- If sum = 1 take into account the transition with the event True
- If sum = 0 save the negated transition to add in the pddl problem the complemented events present both in the constraints and in the trace
    - We have State 1: 0 -> state 2 , in constraints the event A and in the trace the events A, B, C. We add into the pddl the transitions “s1 B s2” and “s1 C s2”

**Transitions:**

State 0: 00 -> state 1
State 0: 01 -> state 1
State 0: 10 -> state 1
State 0: 11 -> state 1
State 1: 00 -> state 1
State 1: 01 -> state 1
**State 1: 10 -> state 2**
State 1: 11 -> state 2
State 2: 00 -> state 3
**State 2: 01 -> state 1**
**State 2: 10 -> state 3**
State 2: 11 -> state 2
State 3: 00 -> state 3
State 3: 01 -> state 3
State 3: 10 -> state 3
State 3: 11 -> state 3

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# Implementation – PDDL

## Domain

Actions

- add, del, sync (as defined in the original paper)

```
(:action add
 :parameters (?e - activity)
 :effect (and (increase (total-cost) 1)
          (forall (?s1 ?s2 - automaton_state)
            (when (and (cur_state ?s1)
                       (automaton ?s1 ?e ?s2))
                  (and (not (cur_state ?s1))
                       (cur_state ?s2))))))
```

```
(:action del
 :parameters (?t1 - trace_state ?e - activity
              ?t2 - trace_state)
 :precondition (and (cur_state ?t1) (trace ?t1 ?e ?t2))
 :effect(and (increase (total-cost) 1)
             (not (cur_state ?t1)) (cur_state ?t2)))
```

## Problem

**OBJECTS**
State and Activity instances involved in the trace automaton and in any constraint automaton

**INIT**
Transitions that connect two different states
Curr state + Final state of all automaton

**GOAL**
conjunction of the accepting states of the trace automaton and of the constraint automata

**METRIC**
( :metric **minimize** (total-cost) )

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# Results – 10 constraints

| Trace length | 3 inverted index | | 4 inverted index | | 6 inverted index | |
|---|---|---|---|---|---|---|
| | Alignment Cost | Total time | Alignment Cost | Total time | Alignment Cost | Total time |
| **1-50** | 1.77 | 0.05 | 2.74 | 0.11 | 4.23 | 0.17 |
| **51-100** | 2.11 | 0.19 | 5.86 | 0.72 | 9.74 | 1.21 |
| **101-150** | 3.03 | 0.65 | 9.68 | 2.21 | 16.23 | 3.18 |
| **151-200** | 3.79 | 1.26 | 13.4 | 4.11 | 21.63 | 5.65 |

- **Fast-downward planner – $h_{max}$ heuristic**
- **Alignment Cost – number of add/del to repair the trace (avg on 100 traces)**
- **Total Time in seconds (avg on 100 traces)**

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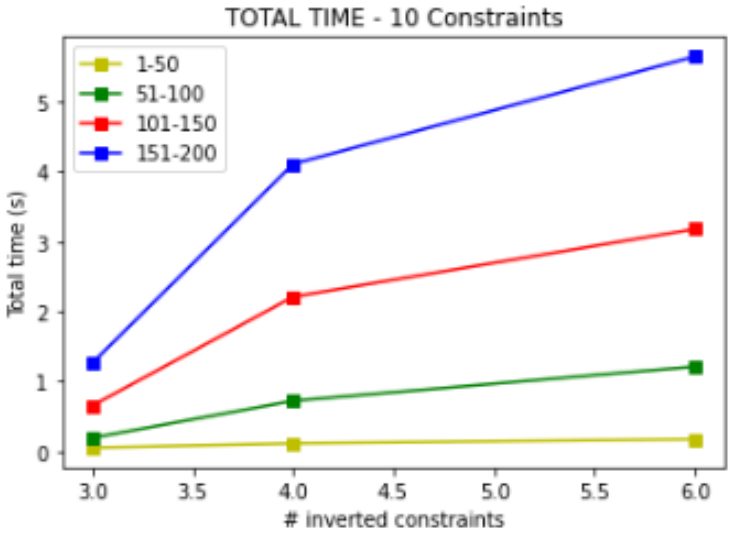
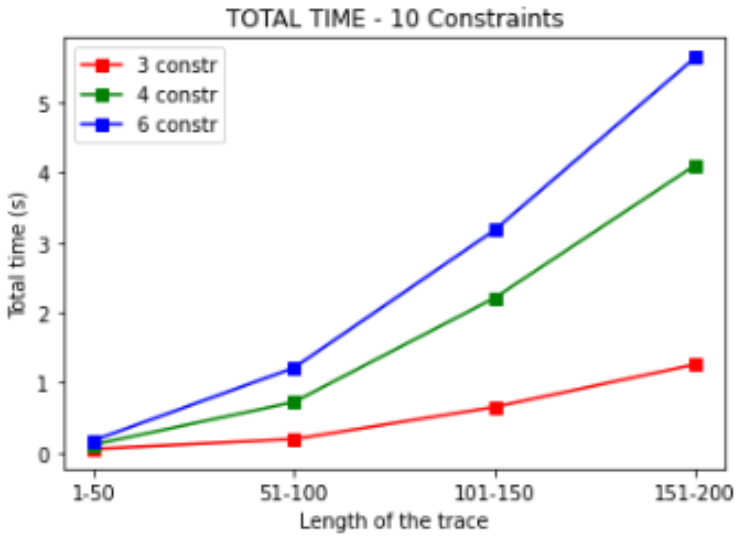
# Results – 10 constraints

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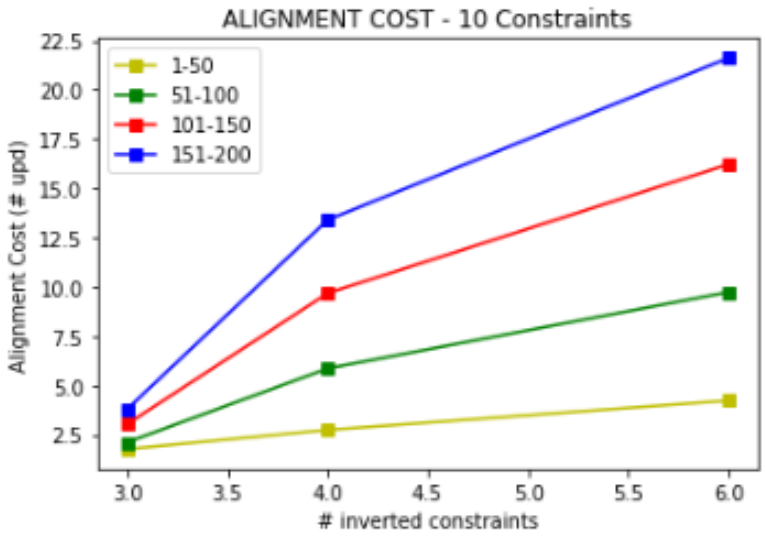


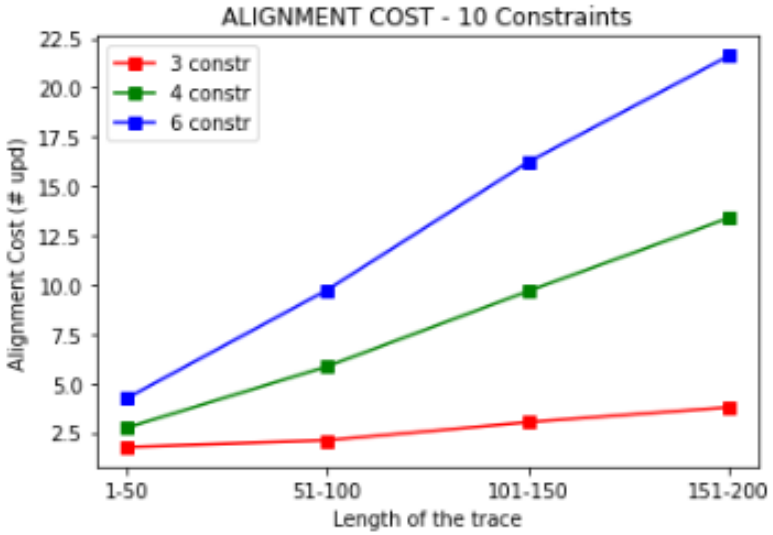


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# Results – 15 constraints

| Trace length | 4 inverted index | | 6 inverted index | | 8 inverted index | |
|---|---|---|---|---|---|---|
| | Alignment Cost | Total time | Alignment Cost | Total time | Alignment Cost | Total time |
| **1-50** | 3.8 | 1.3 | 6.24 | 3.26 | 7.64 | 4.79 |
| **51-100** | 5.94 | 5.78 | 9.52 | 10.59 | 13.09 | 15.39 |
| **101-150** | 9.49 | 17.66 | 14.47 | 25.5 | 19.49 | 35.17 |

- **Fast-downward planner – $h_{max}$ heuristic**
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- **Total Time in seconds (avg on 100 traces)**

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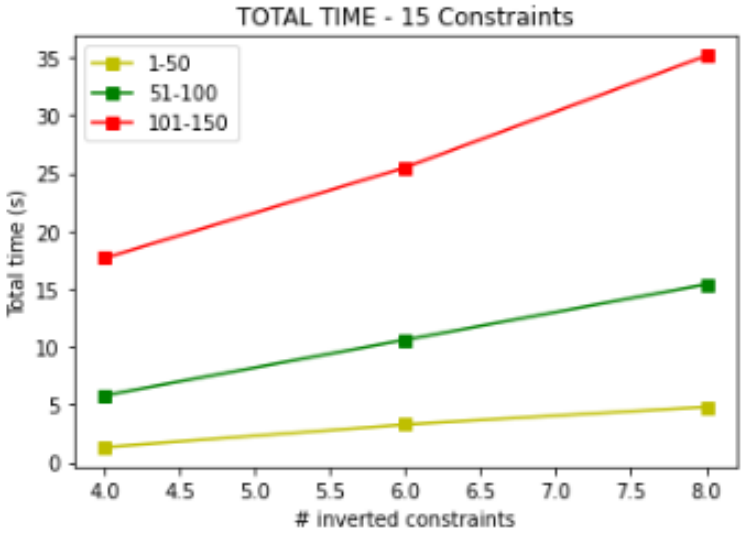
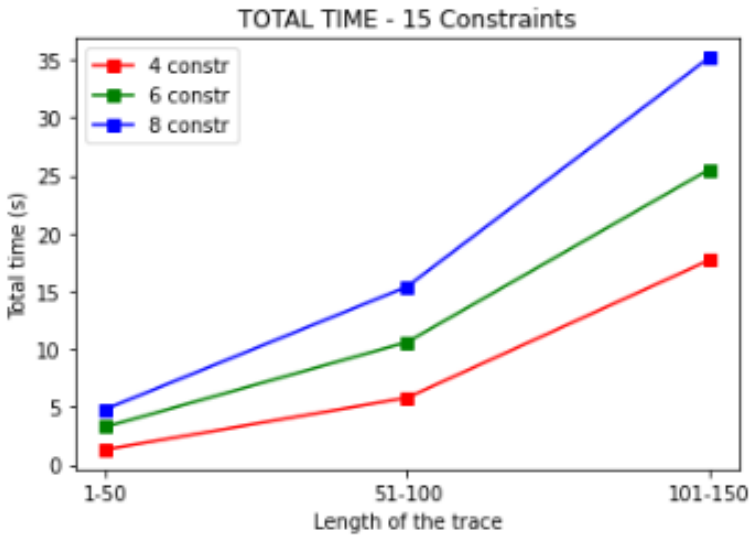
# Results – 15 constraints

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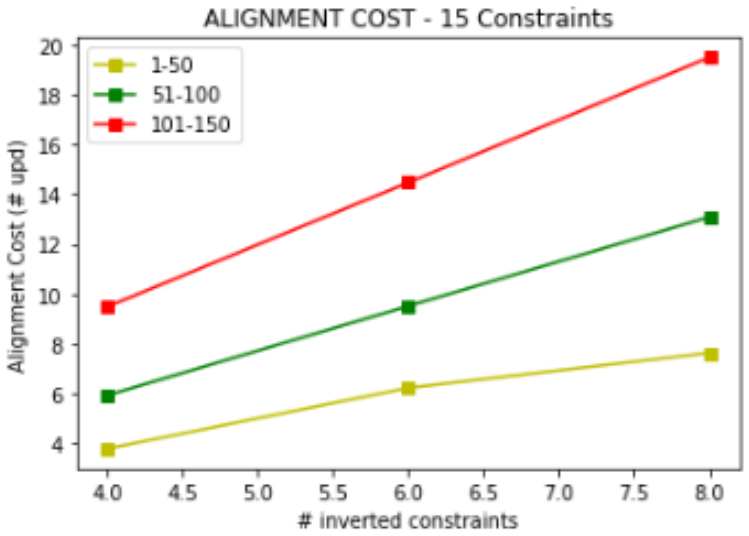
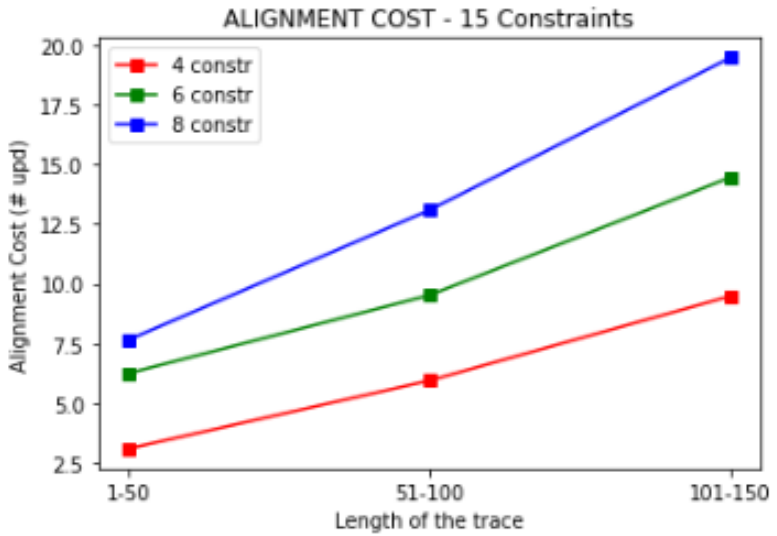
# Results – 15 constraints

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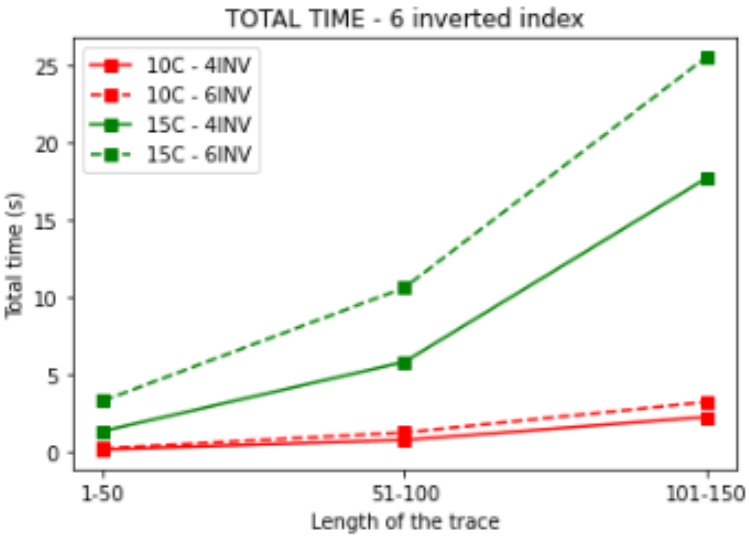
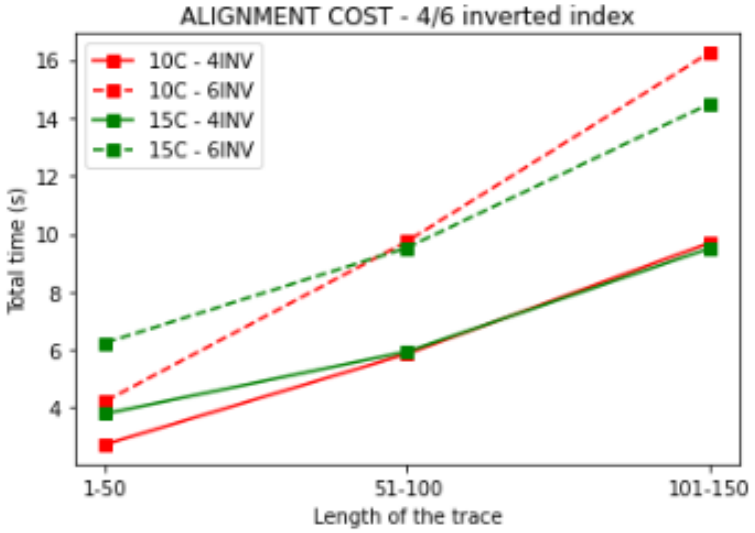
# Results – 10 vs 15 constraints on 4/6 inverted




- **Fast-downward planner – $h_{max}$ heuristic**
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- **Total Time in seconds (avg on 100 traces)**

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# References

On the Disruptive Effectiveness of Automated Planning for LTLf-Based Trace Alignment *Giuseppe De Giacomo, Fabrizio Maria Maggi, Andrea Marrella, Fabio Patrizi*

LTLf2DFA Tool

MONA Tool

Fast Downward Planner

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# THANKS

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