

2015-02-21

Task scheduling for dual-arm industrial robots through constraint programming

MinZinc modeling and solver comparison

Tommy Kvant

Institute of Computer Science
Lund University

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Outline

1 Introduction

- YuMi®
- Project goal
- MiniZinc

2 Case Study

3 Model

- Tasks
- Components

■ Storage Mediums

- Tools
- Labeling
- Grouping
- Filter

4 Evaluation

- Solvers
- Results

Task scheduling for dual-arm industrial robots through constraint programming

└ Outline

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Introduction - YuMi®

- Dual-armed robot
 - Flexible
 - Fine motor skills

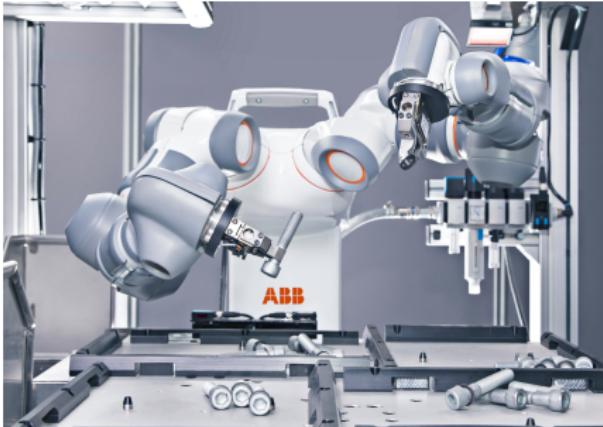


Photo: ABB



Introduction - Project goal

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Task scheduling for dual-arm industrial robots through constraint programming

- └ Introduction
- └ Project goal
- └ Introduction - Project goal



Introduction - MiniZinc

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Task scheduling for dual-arm industrial robots through constraint programming

—Introduction

└─ MiniZinc

└─ Introduction - MiniZinc



Case Study



Task scheduling for dual-arm industrial robots through
constraint programming

└ Case Study

└ Case Study

Skruvarna inte med

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Case Study

Task scheduling for dual-arm industrial robots through constraint programming

└ Case Study

└ Case Study

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Physical Entities

- Machines
- Tools
- Components
- Tray
- Fixture
- Output

Task scheduling for dual-arm industrial robots through constraint programming

- └ Case Study

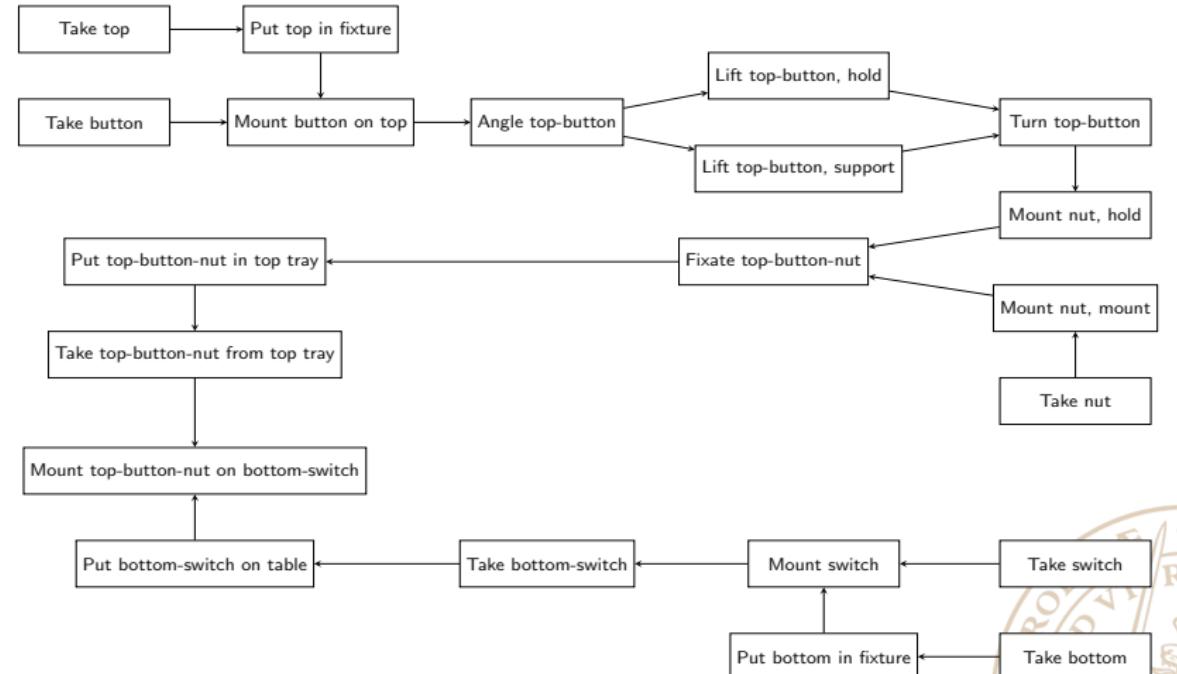
- └ Physical Entities

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- Machines
- Tools
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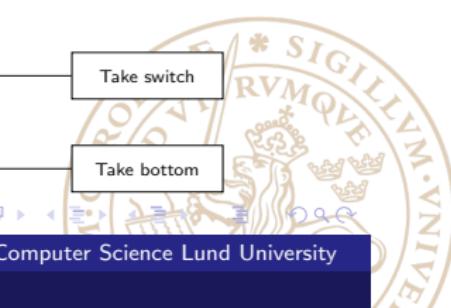
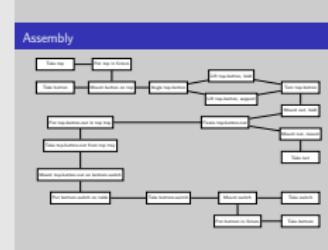
Assembly



Task scheduling for dual-arm industrial robots through constraint programming
└ Case Study

└ Case Study

└─ Assembly

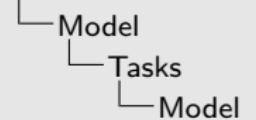


Model

Job Shop Problem

- n jobs, varying size
 - m identical machines
 - NP-complete for $m \geq 2$ and $n \geq 3$

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Model

- Job Shop Problem
 - n jobs, varying size
 - m identical machines
 - NP-complete for $m \geq 2$ and $n \geq 3$

- Vill schemalägg tasks som ett job shop problem
 - I literatur jobs innehåller operations, här tittar vi på 1 job och operations kallas vi tasks
 - Varje jobb kan hanteras av vilken maskin som helst → Flexible Job Shop Scheduling



Model

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- En task kommer efter den andra
 - Men tasks:en sker på olika ställen i rummet → det tar tid att flytta sig mellan dem → måste räkna med det



Model

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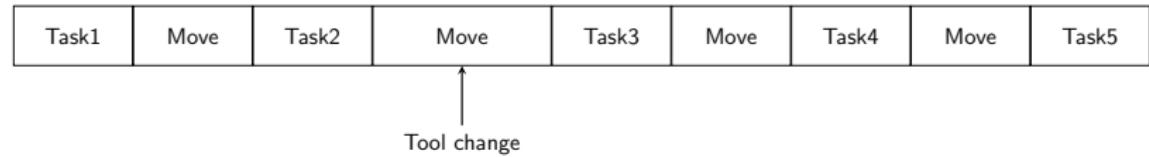


- Tasks behöver olika tools → måste utföra tool change
 - utförs mellan två tasks → tiden att röra sig mellan två tasks tar längre tid → bakar in tool change tiden i move
 - Det förekommer ett tool change om tiden för move tar längre tid än det egentligen skulle göra

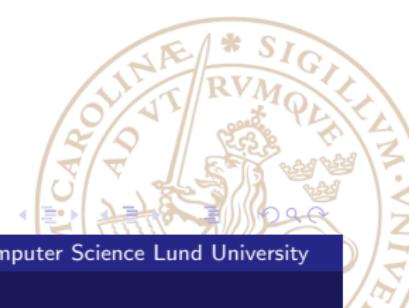


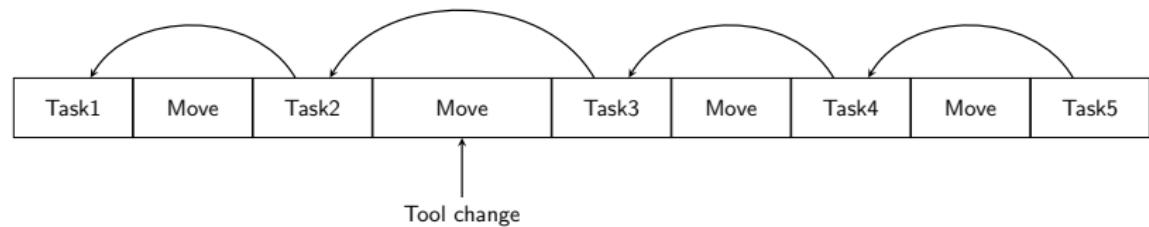
Model

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- Hur lång tid det tar beror på vilken task som kommer innan → vi måste veta vilken task som kommer innan, *predecessor*





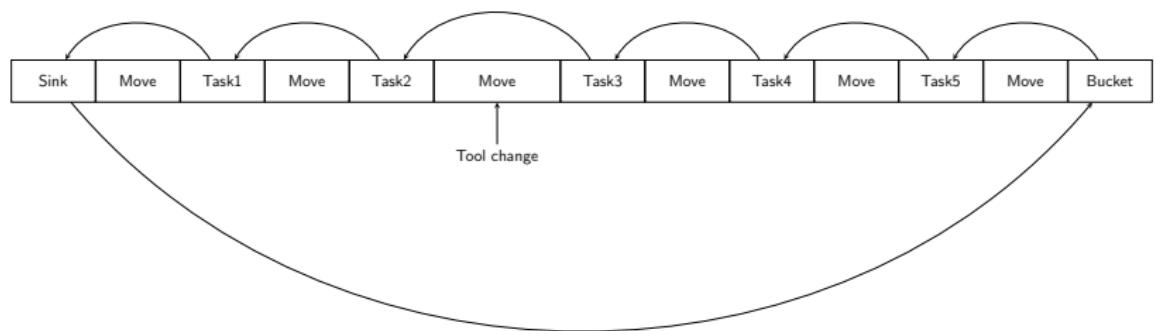
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- Detta = Job Shop Problem with sequence-dependent setup times
 - För att se till att detta uppfylls kan constraintet circuit användas
 - Skapar en Hamiltonian circuit
 - Uppnår det genom att koppla ihop första och sista noden.
 - Constraint som säger att task måste komma efter sin predecessor → Första och sista task:en kan inte kopplas ihop



Model



- Introducerar sink node/startTask & bucket node/goalTask
 - Hintintills 3 saker att schemalägga: tasks, moves, predecessors
 - Men detta måste göras för varje mackin, tasks måste fördelas



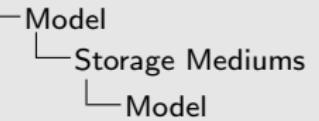
Model

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Model

Task scheduling for dual-arm industrial robots through constraint programming



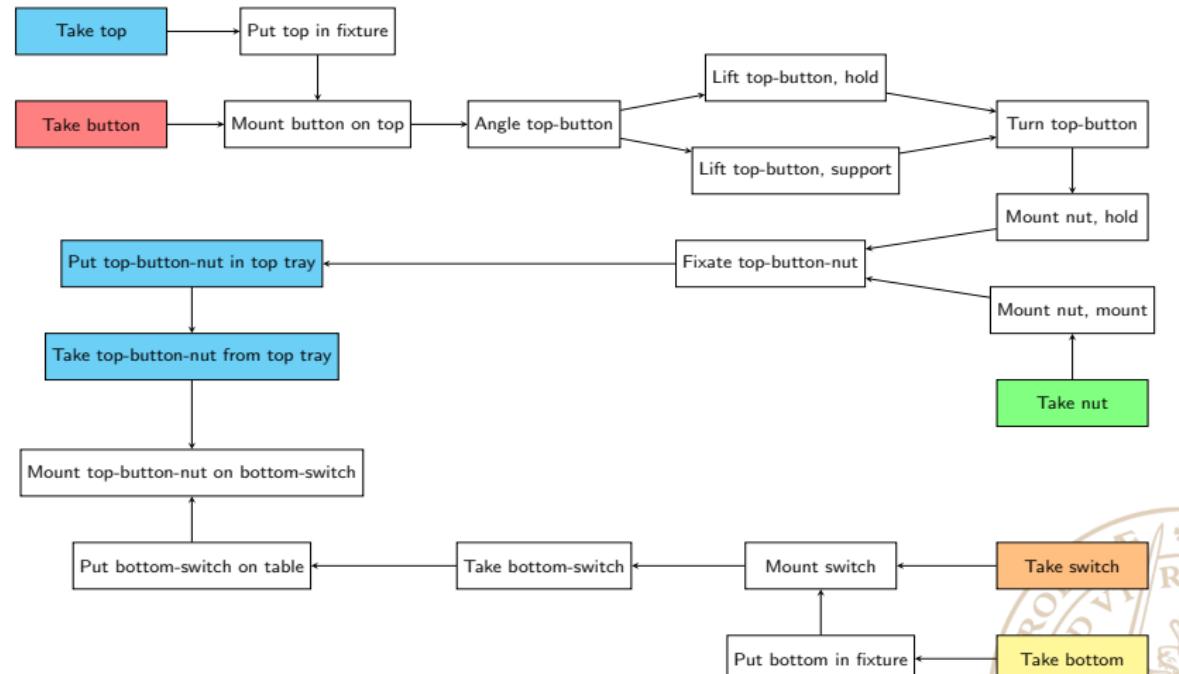
Storage mediums
■ Tray - Top tray, Button tray, etc.
■ Fixture
■ Output

Storage mediums

- Tray - Top tray, Button tray, etc.
- Fixture
- Output



Tray

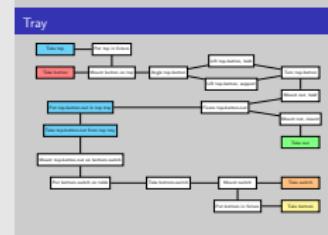


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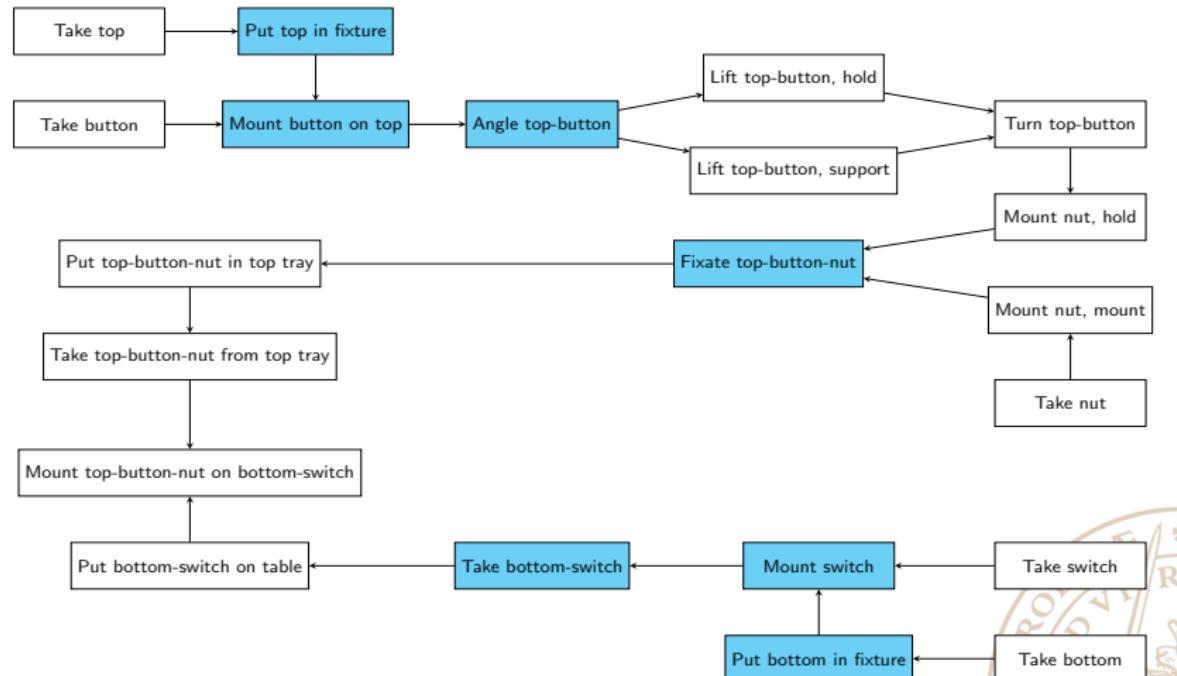
Task scheduling for dual-arm industrial robots through constraint programming

Model

- Storage Mediums
- Tray



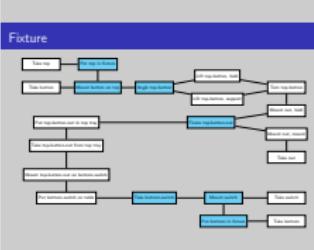
Fixture



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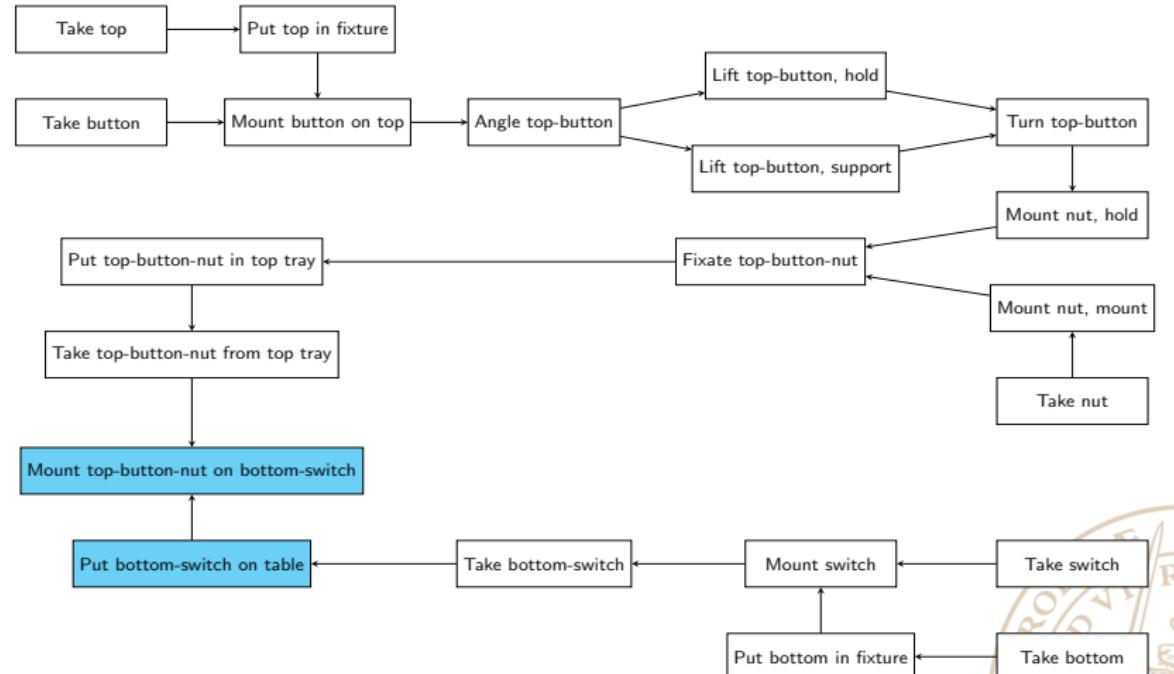
Task scheduling for dual-arm industrial robots through constraint programming

- └ Model
 - └ Storage Mediums
 - └ Fixture



- Individuella tasks får inte överlappa på fixtures
- Tiden då fixtures är upptagna får inte överlappa, identifiera put och take för en komponent och komponent som har put komponenten som en del i dess sub-assembly

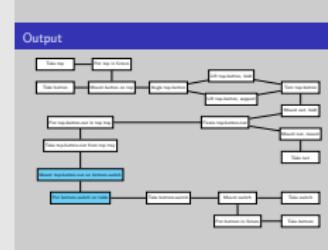
Output



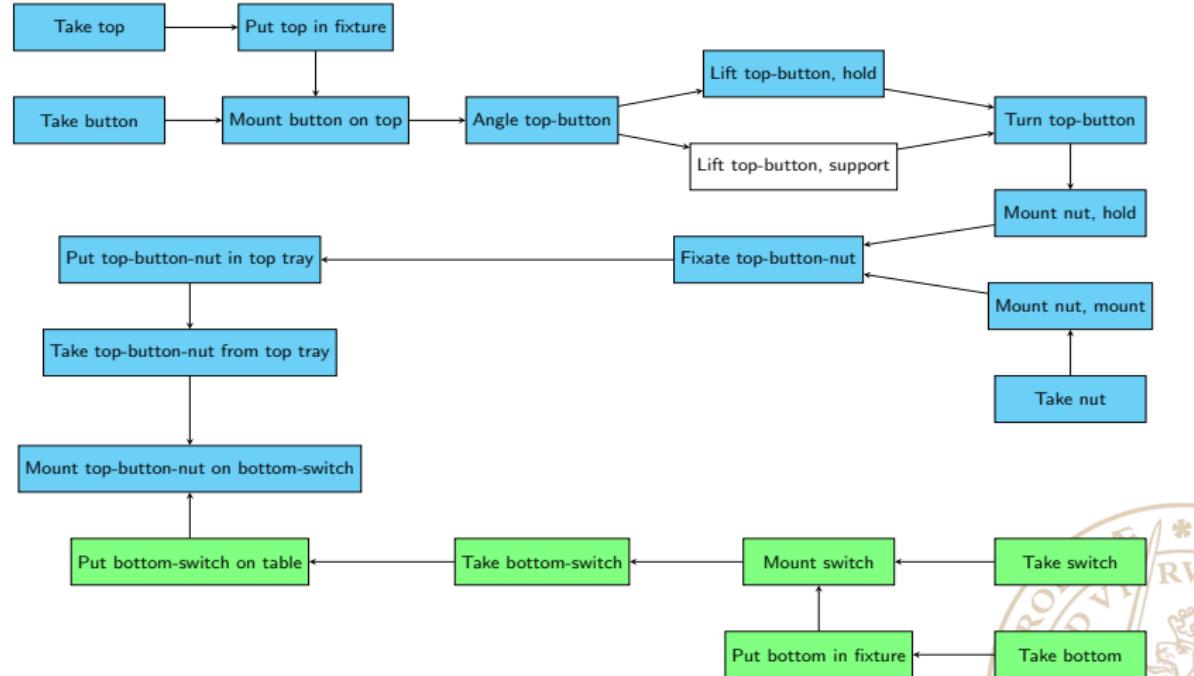
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Task scheduling for dual-arm industrial robots through constraint programming

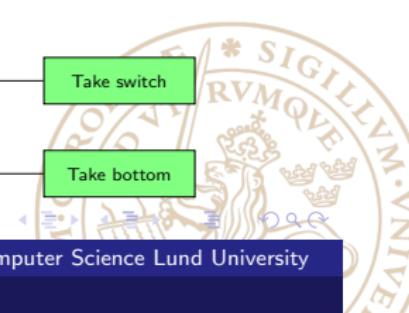
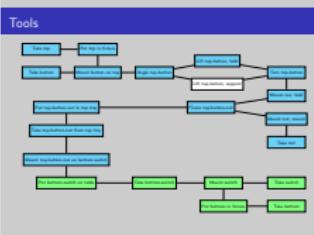
- Model
- Storage Mediums
- Output



Tools



Notera att "Lift top-button" inte har tool specificerad

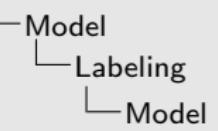


Model

Label tasks

- Taking
- Mounting
- Putting
- Moving

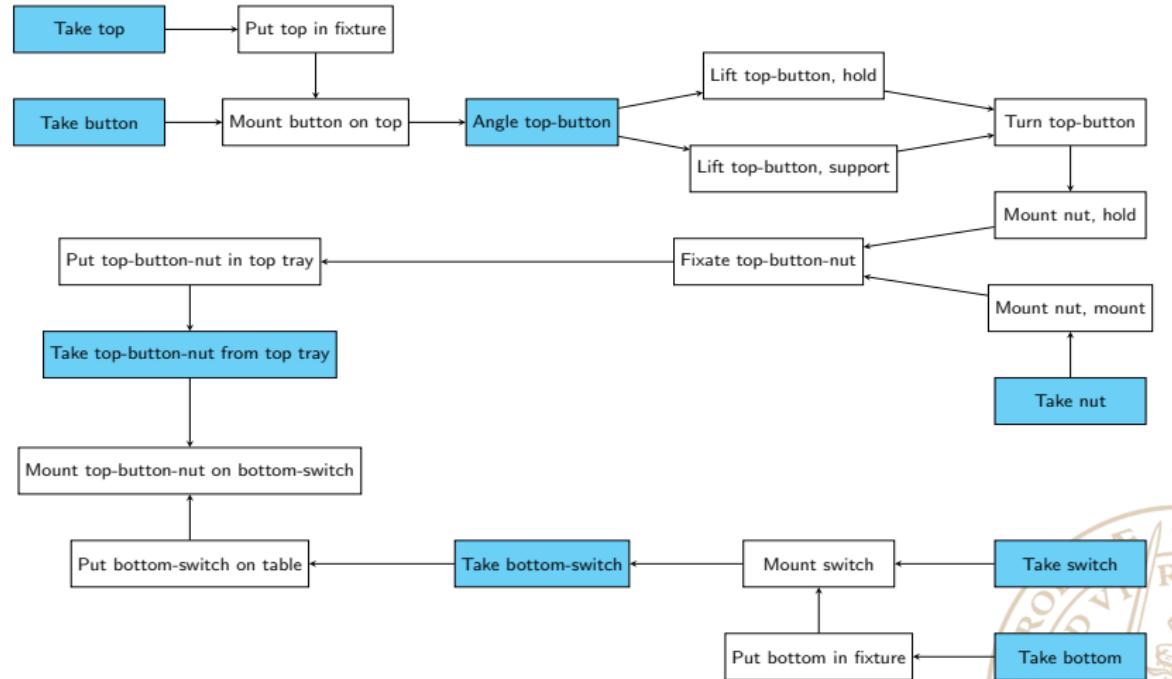
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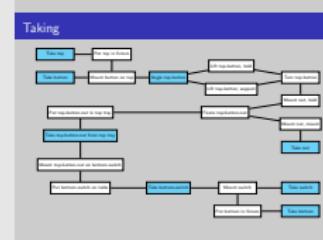
Model

Label tasks
■ Taking
■ Mounting
■ Putting
■ Moving

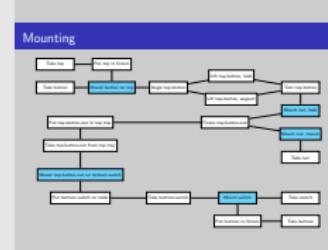
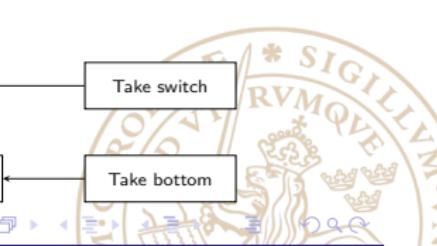
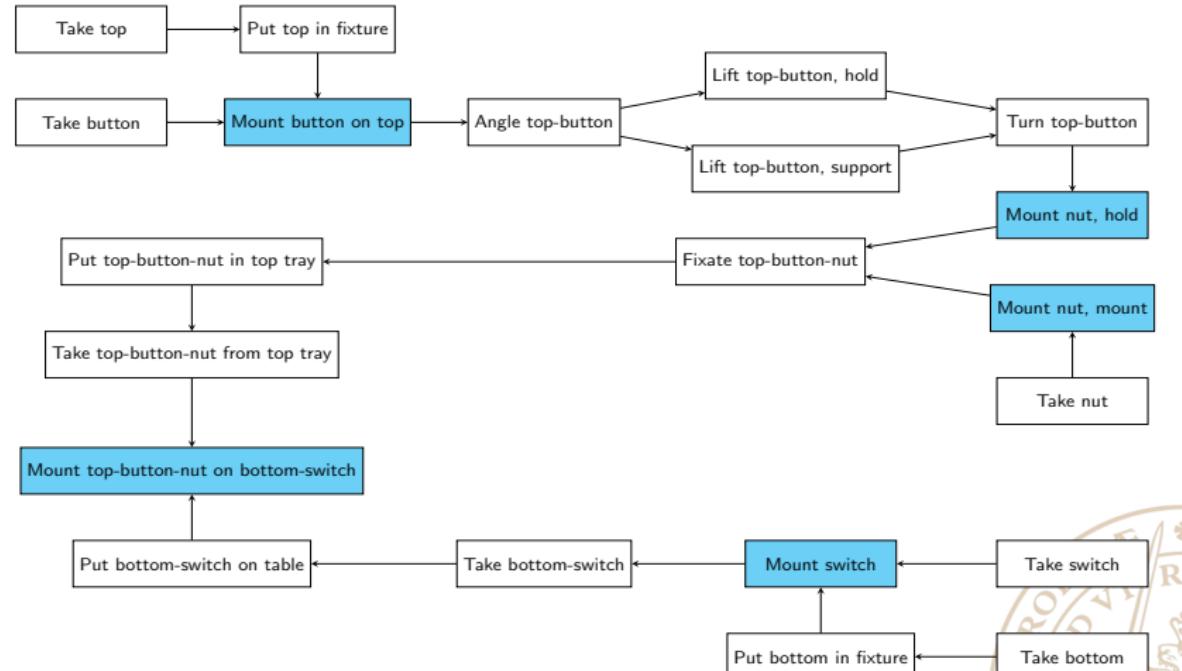




Angle skulle kunna delas in i två tasks, en taking och en moving

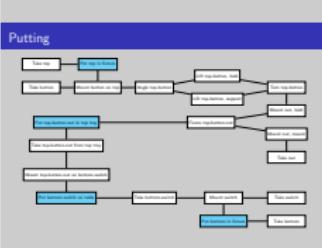
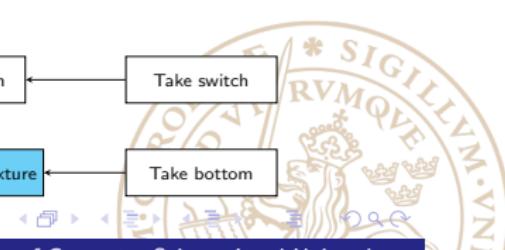
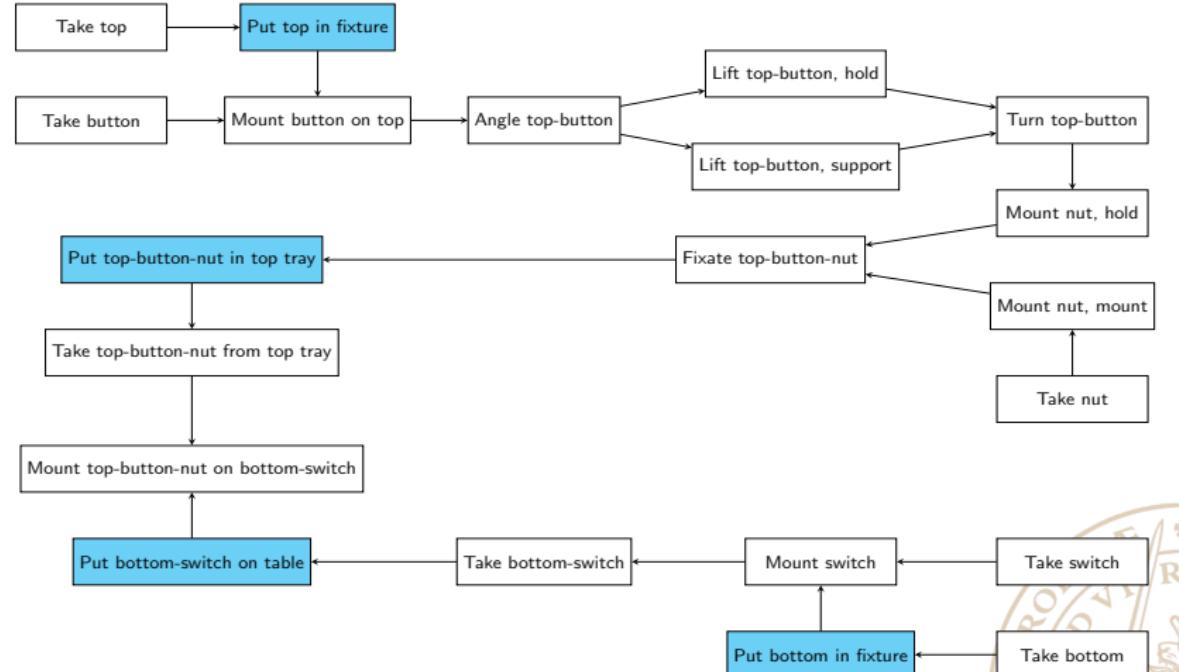


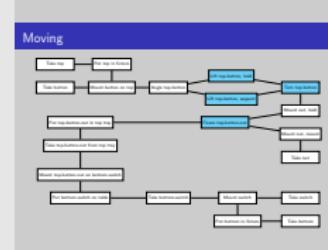
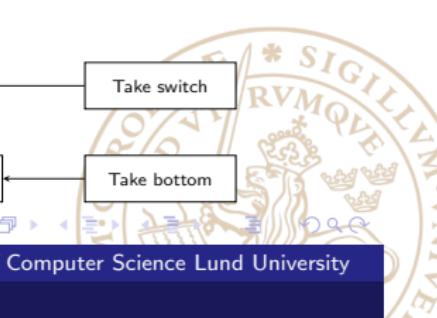
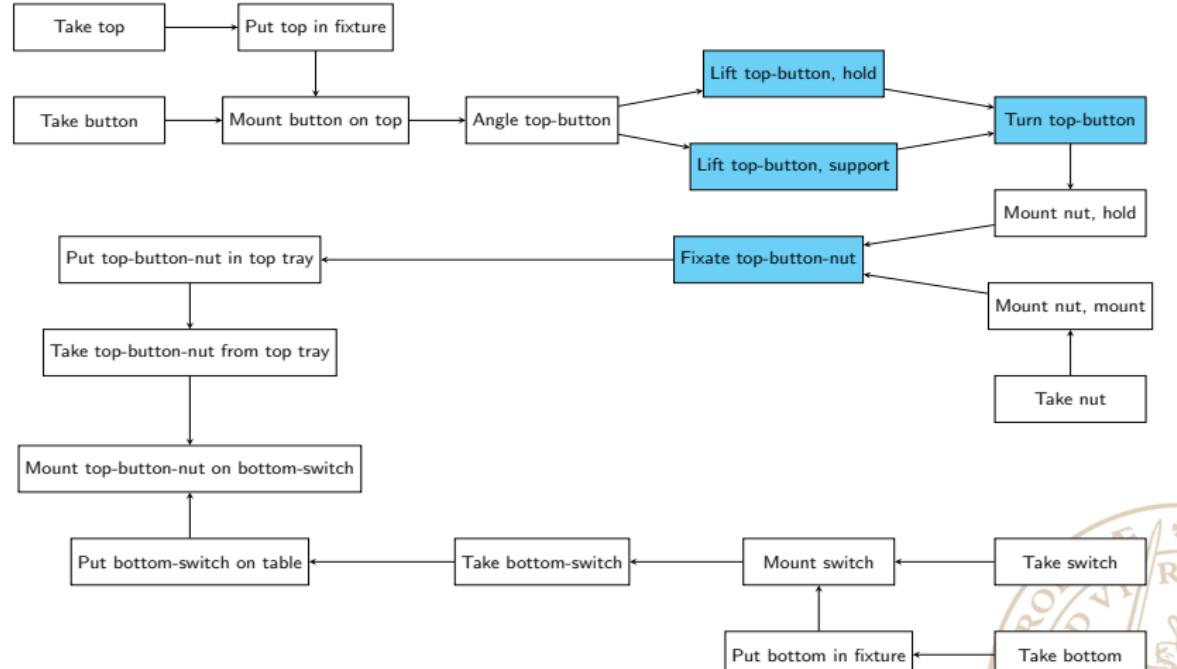
Mounting



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Putting





Model

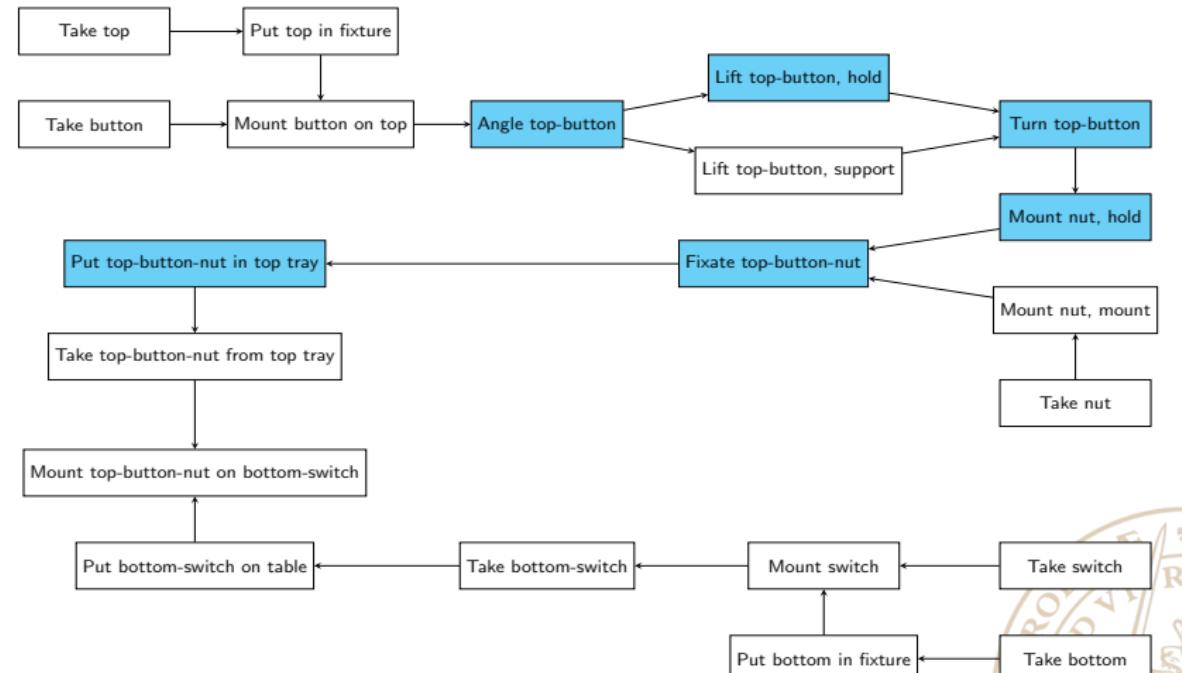
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Group tasks

- Ordered group
- Concurrent group



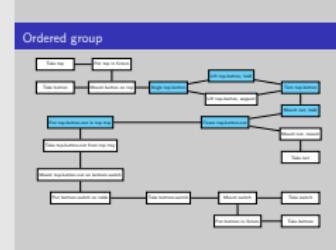
Ordered group



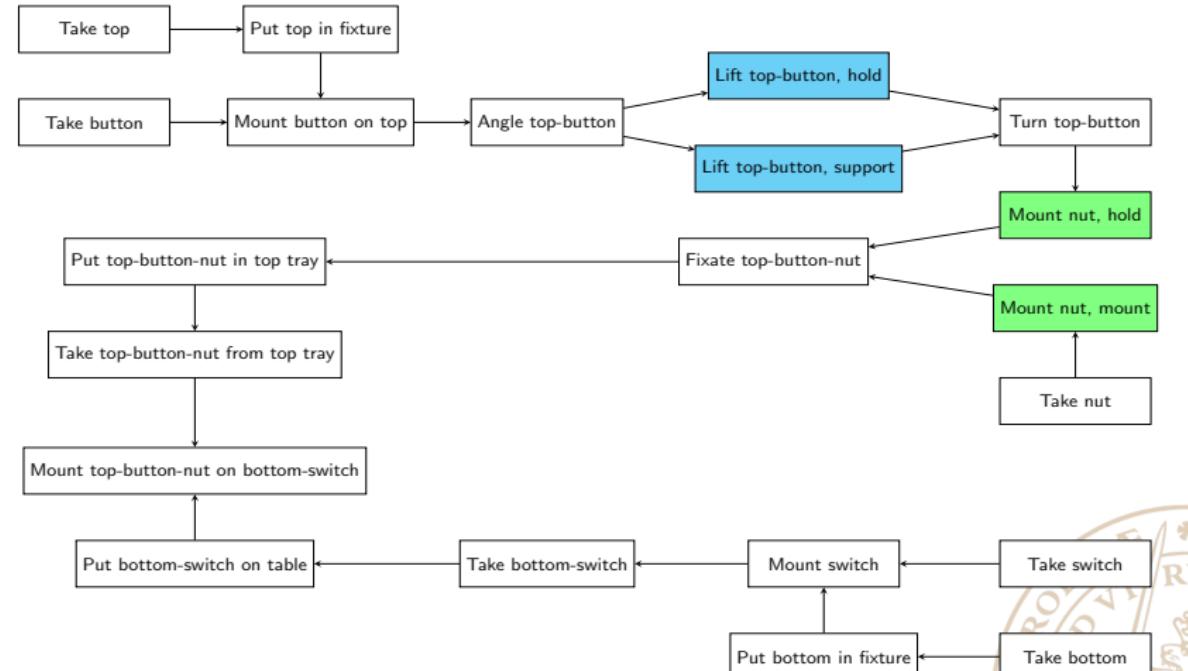
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Task scheduling for dual-arm industrial robots through constraint programming

- Model
- Grouping
- Ordered group



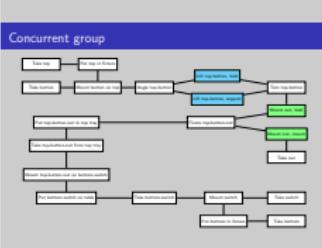
Concurrent group



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Task scheduling for dual-arm industrial robots through constraint programming

- Model
- Grouping
- Concurrent group



Filter

- Temporal filter
- Predecessor filter

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Task scheduling for dual-arm industrial robots through constraint programming



Temporal filter
Predecessor filter

Temporal filter:

- Tider för move mellan tasks vet vi genom att en tidsmatris tillhandahålls av den som vill schemalägga
- Den tillsammans med tiderna för att byta mellan tools = ny matris med alla möjliga moves inkl. tool change
- → vi kan räkna ut värsta och bästa fallet för hela assemblyn
- mha. detta kan vi begränsa startTime för tasks

Predecessor filter:

- Vi vet att put och mount tasks inte kan komma först, då komponenten måste plockas upp först → $\text{pred}(\text{putTask}/\text{mountTask}) \neq \text{startTask}$
- Då allting måste sitta i outputs i slutet av assemblyn → $\text{pred}(\text{goalTask}) \neq \text{takeTask}$
- Tasks som använder components som är sub-components i en annan task måste ske innan den tasken → inte ha den som predecessor



Evaluation

- Test with 6 solvers
- MiniZinc 1.6 & 2.0.1
- Combination of filters

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Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation

- └ Evaluation

- Test with 6 solvers
- MiniZinc 1.6 & 2.0.1
- Combination of filters



Criteria

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```
└─ Evaluation
    └─ Solvers
        └─ Criteria
```

- FlatZinc parser
 - Free



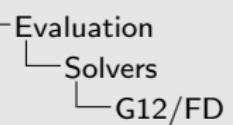
Solvers Tested

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- G12/FD
 - JaCoP
 - Gecode
 - or-tools
 - Opturion CPX
 - Choco3



Task scheduling for dual-arm industrial robots through constraint programming

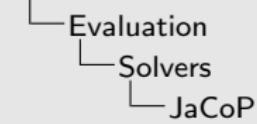


- NICTA: National ICT Australia, Australia's Information Communications Technology (ICT) Research Centre, störst

- G12 Team, NICTA
 - Mercury
 - Default solver for MiniZinc



Task scheduling for dual-arm industrial robots through constraint programming



- Java Constraint Programming solver
 - Open Source
 - Developed since 2001 - Krzysztof Kuchcinski & Radoslaw Szymanek
 - Silver medal



Gecode

- C++
 - Open Source
 - Christian Schulte
 - Parallel searches - utilising multiple cores
 - All gold medals 2008-2012

Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation
 - └ Solvers
 - └ Gecode

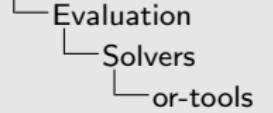
1. Christian Schulte: lett utvecklingen, många andra som bidragit
 2. All gold medals 2008-2012: i alla kategorier



- C++
- Google - Operational Research
- Open Source
- Utilising multiple cores
- Gold medals 2013-2014

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Task scheduling for dual-arm industrial robots through constraint programming



- C++
- Google - Operational Research
- Open Source
- Utilising multiple cores
- Gold medals 2013-2014

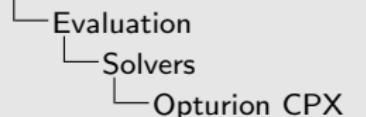
1. Utilising multiple cores: Inte säker om parallel sökning, nämns i dokumentationen som "parallel solving", explicit utesluten ur dokumentationen



Opturion CPX

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1. Opturion Pty Ltd: Härstammar från G12
 2. Commercial: kostar, akademisk licens
 3. SAT combo: FD + SAT, SAT = satslogik, väldigt effektiv på att lösa stora problem, sägs att satslogik → sökning inte slöas ner av stora domäner

- Opturion Pty Ltd
 - Commercial
 - SAT combo
 - Gold medals 2013, all silver medals 2014



Choco3

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Task scheduling for dual-arm industrial robots through constraint programming

- ```
- Evaluation
 └── Solvers
 └── Choco3
```

- Java
  - Open Source
  - Developed since early 2000 - Jean-Guillaume Fages & Charles Prud'homme
  - Not same as predecessor Choco2

- Java
  - Open Source
  - Developed since early 2000 - Jean-Guillaume Fages & Charles Prud'homme
  - Not same as predecessor Choco2



Assembly Times

# Manual Time

## 516 t.u.



## Assembly Times

Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation
- └ Results
- └ Assembly Times

Manual Time      Solver Time  
516 t.u.          512 t.u.

Manual Time  
516 t.u.

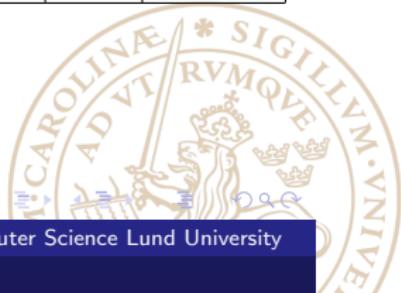
Solver Time  
512 t.u.

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## Solver Time

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- 1011156 - 0:16:51
  - 71761 - 0:01:11
  - 71186 - 0:01:11

Vi kan se att i nästan alla fall hjälper filtrena i någon grad  
Vilket filter bäst är svårt att säga, temp verkar bäst i flesta fall

## Solver Time

## Task scheduling for dual-arm industrial robots through constraint programming

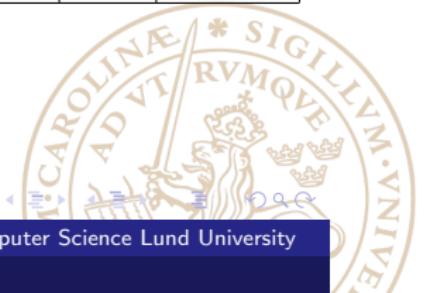
- └ Evaluation
- └ Results
- └ Solver Time

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Hittar lösning, inte optimal

|              | Pred & Temp | Pred  | Temp    | None  |
|--------------|-------------|-------|---------|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 |
| G12/FD       | -           | -     | -       | -     |
| JaCoP        | 658         | -     | 1011156 | -     |
| Gecode       | -           | 60    | -       | 71761 |
| or-tools     | 271         | !     | 380     | !     |
| Opturion CPX | -           | !     | -       | !     |
| Choco3       | -           | -     | -       | -     |

|              | Pred & Temp | Pred  |         | Temp  |     | None  |     |       |
|--------------|-------------|-------|---------|-------|-----|-------|-----|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 | 1.6 | 2.0.1 | 1.6 | 2.0.1 |
| G12/FD       | -           | -     | -       | -     | -   | -     | -   | -     |
| JaCoP        | 658         | -     | 1011156 | -     | -   | -     | -   | -     |
| Gecode       | -           | 60    | -       | 71761 | -   | 99    | -   | 71186 |
| or-tools     | 271         | !     | 380     | !     | 302 | !     | 457 | !     |
| Opturion CPX | -           | !     | -       | !     | -   | !     | -   | !     |
| Choco3       | -           | -     | -       | -     | -   | -     | -   | -     |



## Solver Time

## Task scheduling for dual-arm industrial robots through constraint programming

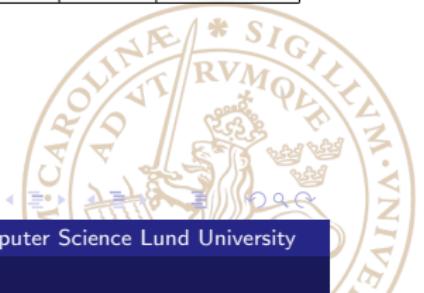
- └ Evaluation
- └ Results
- └ Solver Time

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Hittar hittar alla lösningar, inklusive optima

|              | Pred & Temp | Pred  | Temp    | None  |     |       |     |       |
|--------------|-------------|-------|---------|-------|-----|-------|-----|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 | 1.6 | 2.0.1 | 1.6 | 2.0.1 |
| G12/FD       | -           | -     | -       | -     | -   | -     | -   | -     |
| JaCoP        | 658         | -     | 1011156 | -     | -   | -     | -   | -     |
| Gecode       | -           | 60    | -       | 71761 | -   | 99    | -   | 71186 |
| or-tools     | 271         | !     | 380     | !     | 302 | !     | 457 | !     |
| Opturion CPX | -           | !     | -       | !     | -   | !     | -   | !     |
| Choco3       | -           | -     | -       | -     | -   | -     | -   | -     |

|              | Pred & Temp | Pred  |         | Temp  |     | None  |     |       |
|--------------|-------------|-------|---------|-------|-----|-------|-----|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 | 1.6 | 2.0.1 | 1.6 | 2.0.1 |
| G12/FD       | -           | -     | -       | -     | -   | -     | -   | -     |
| JaCoP        | 658         | -     | 1011156 | -     | -   | -     | -   | -     |
| Gecode       | -           | 60    | -       | 71761 | -   | 99    | -   | 71186 |
| or-tools     | 271         | !     | 380     | !     | 302 | !     | 457 | !     |
| Opturion CPX | -           | !     | -       | !     | -   | !     | -   | !     |
| Choco3       | -           | -     | -       | -     | -   | -     | -   | -     |



# Solver Time

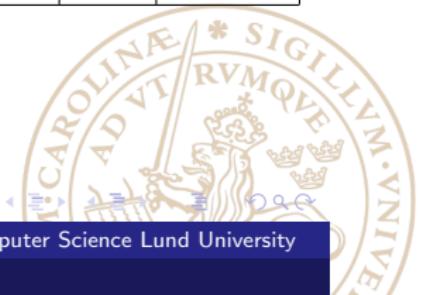
## Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation
- └ Results
- └ Solver Time

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Hittar 3 lösningar, inklusive optimala

|              | Pred & Temp |       | Pred    |       | Temp |       | None |       |
|--------------|-------------|-------|---------|-------|------|-------|------|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 | 1.6  | 2.0.1 | 1.6  | 2.0.1 |
| G12/FD       | -           | -     | -       | -     | -    | -     | -    | -     |
| JaCoP        | 658         | -     | 1011156 | -     | -    | -     | -    | -     |
| Gecode       | -           | 60    | -       | 71761 | -    | 99    | -    | 71186 |
| or-tools     | 271         | !     | 380     | !     | 302  | !     | 457  | !     |
| Opturion CPX | -           | !     | -       | !     | -    | !     | -    | !     |
| Choco3       | -           | -     | -       | -     | -    | -     | -    | -     |



# Solver Time

2015-02-21

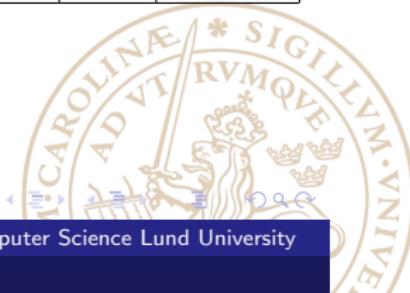
## Task scheduling for dual-arm industrial robots through constraint programming

- ─ Evaluation
- ─ Results
- ─ Solver Time

|              | Pred & Temp | Pred  | Temp    | None  |
|--------------|-------------|-------|---------|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 |
| G12/FD       | -           | -     | -       | -     |
| JaCoP        | 658         | -     | 1011156 | -     |
| Gecode       | -           | 60    | -       | 71761 |
| or-tools     | 271         | !     | 380     | !     |
| Opturion CPX | -           | !     | -       | !     |
| Choco3       | -           | -     | -       | -     |

Hittar 1 lösning, den optima, på ungefär samma tid som den tidigare

|              | Pred & Temp |       | Pred    |       | Temp |       | None |       |
|--------------|-------------|-------|---------|-------|------|-------|------|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 | 1.6  | 2.0.1 | 1.6  | 2.0.1 |
| G12/FD       | -           | -     | -       | -     | -    | -     | -    | -     |
| JaCoP        | 658         | -     | 1011156 | -     | -    | -     | -    | -     |
| Gecode       | -           | 60    | -       | 71761 | -    | 99    | -    | 71186 |
| or-tools     | 271         | !     | 380     | !     | 302  | !     | 457  | !     |
| Opturion CPX | -           | !     | -       | !     | -    | !     | -    | !     |
| Choco3       | -           | -     | -       | -     | -    | -     | -    | -     |



# Solver Time

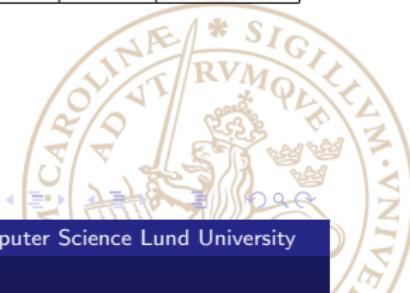
2015-02-21

Task scheduling for dual-arm industrial robots through constraint programming

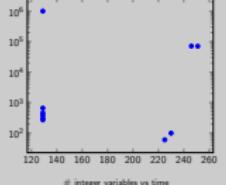
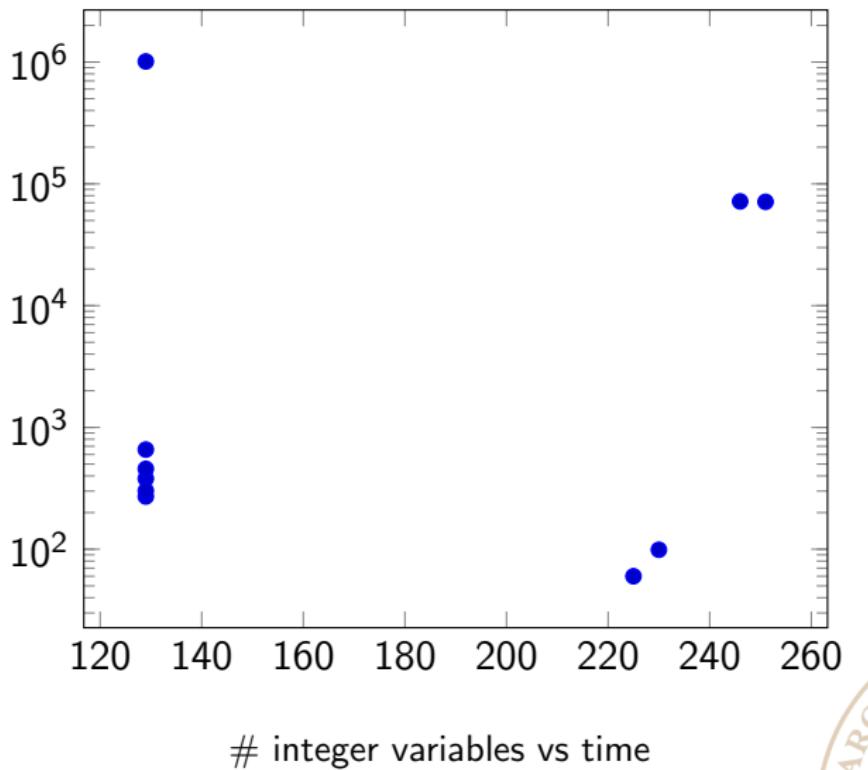
- ↳ Evaluation
- ↳ Results
- ↳ Solver Time

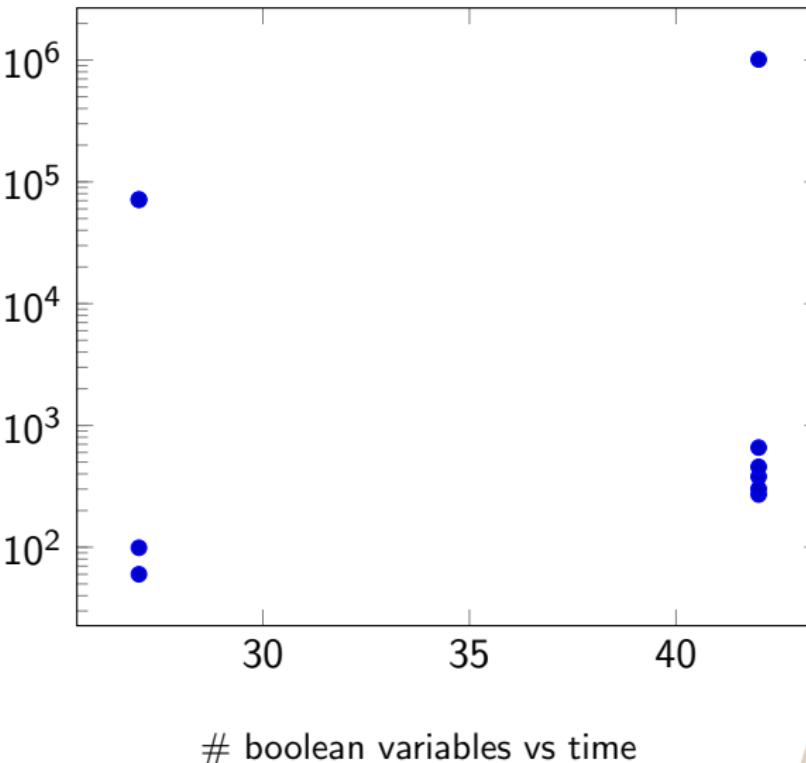
Hittar 2 lösningar direkt

|              | Pred & Temp |       | Pred    |       | Temp |       | None |       |
|--------------|-------------|-------|---------|-------|------|-------|------|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 | 1.6  | 2.0.1 | 1.6  | 2.0.1 |
| G12/FD       | -           | -     | -       | -     | -    | -     | -    | -     |
| JaCoP        | 658         | -     | 1011156 | -     | -    | -     | -    | -     |
| Gecode       | -           | 60    | -       | 71761 | -    | 99    | -    | 71186 |
| or-tools     | 271         | !     | 380     | !     | 302  | !     | 457  | !     |
| Opturion CPX | -           | !     | -       | !     | -    | !     | -    | !     |
| Choco3       | -           | -     | -       | -     | -    | -     | -    | -     |

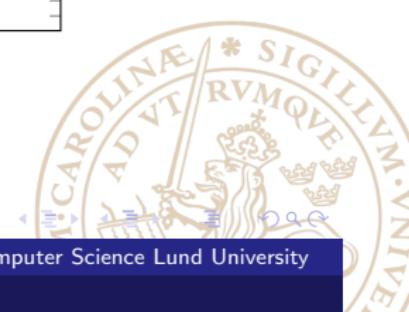
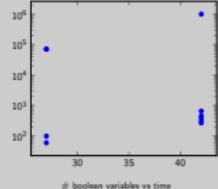


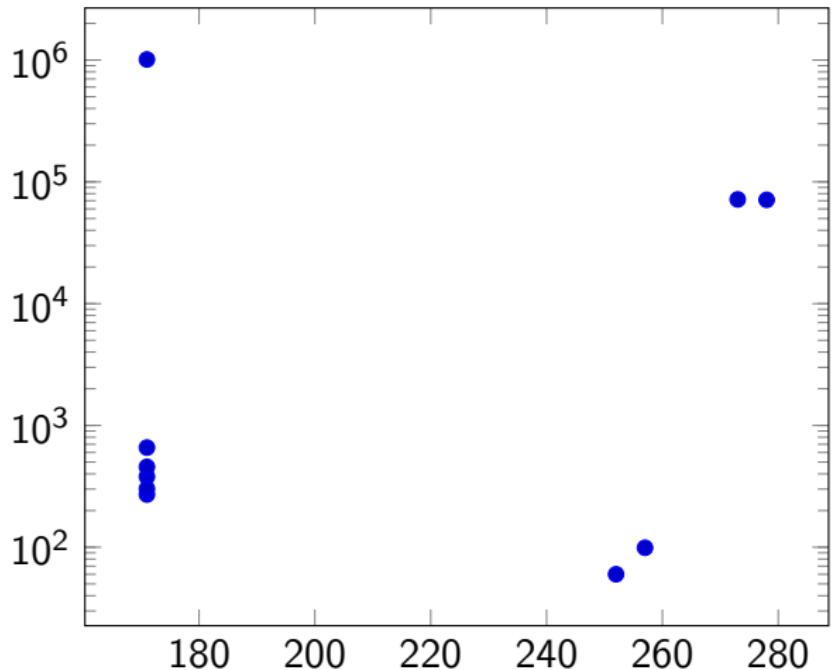
|              | Pred & Temp | Pred  | Temp    | None  |
|--------------|-------------|-------|---------|-------|
|              | 1.6         | 2.0.1 | 1.6     | 2.0.1 |
| G12/FD       | 1.6         | 2.0.1 | -       | -     |
| JaCoP        | 658         | -     | 1011156 | -     |
| Gecode       | -           | 60    | -       | 71761 |
| or-tools     | 271         | !     | 380     | !     |
| Opturion CPX | -           | !     | -       | !     |
| Choco3       | -           | -     | -       | -     |



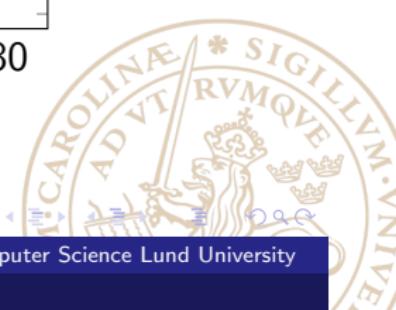


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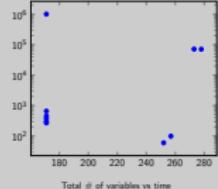




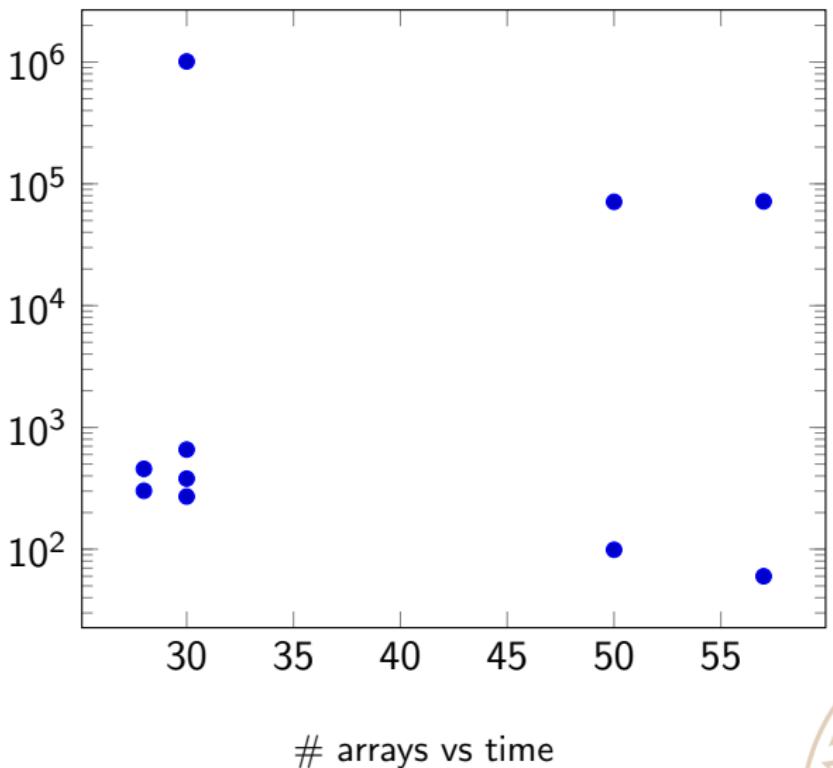
Total # of variables vs time



2015-02-21



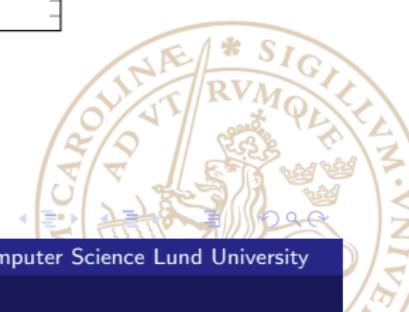
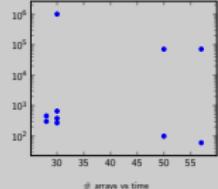
Total # of variables vs time

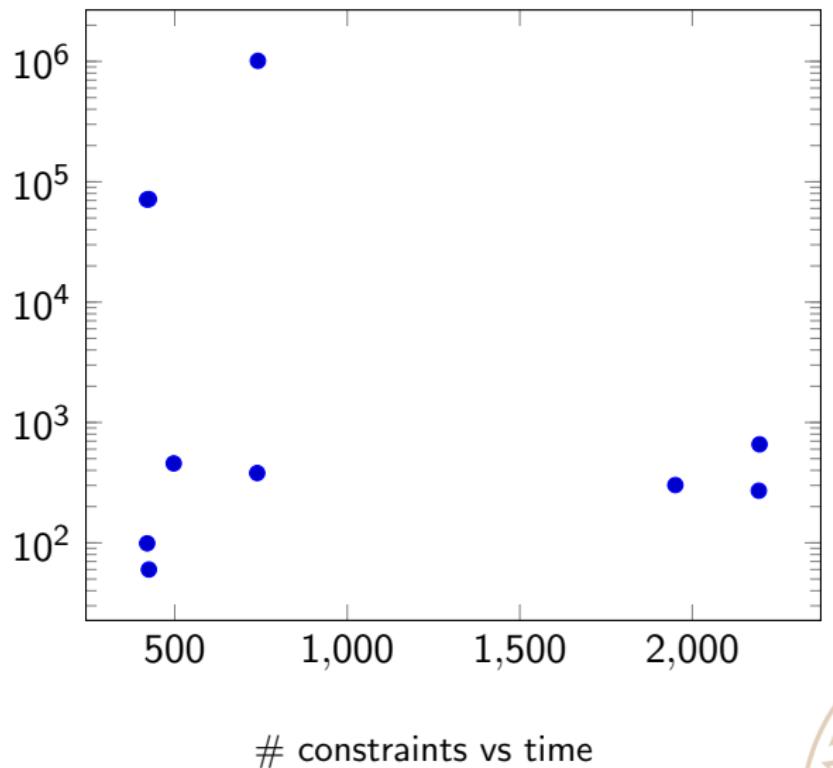


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## Task scheduling for dual-arm industrial robots through constraint programming

- ─ Evaluation
- ─ Results

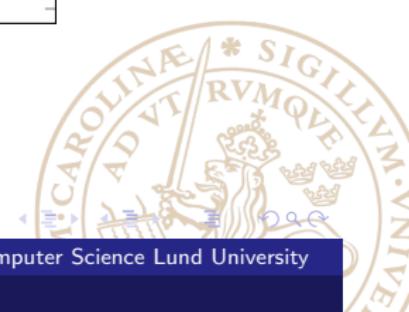
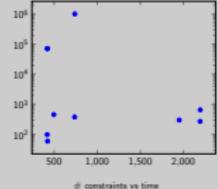


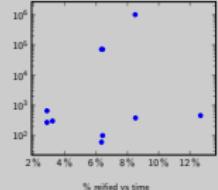
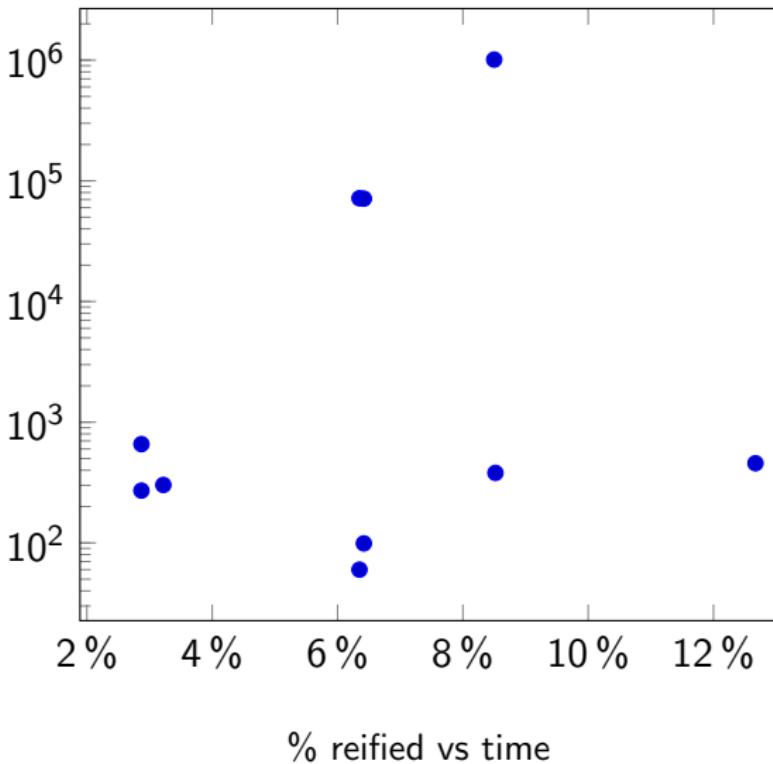


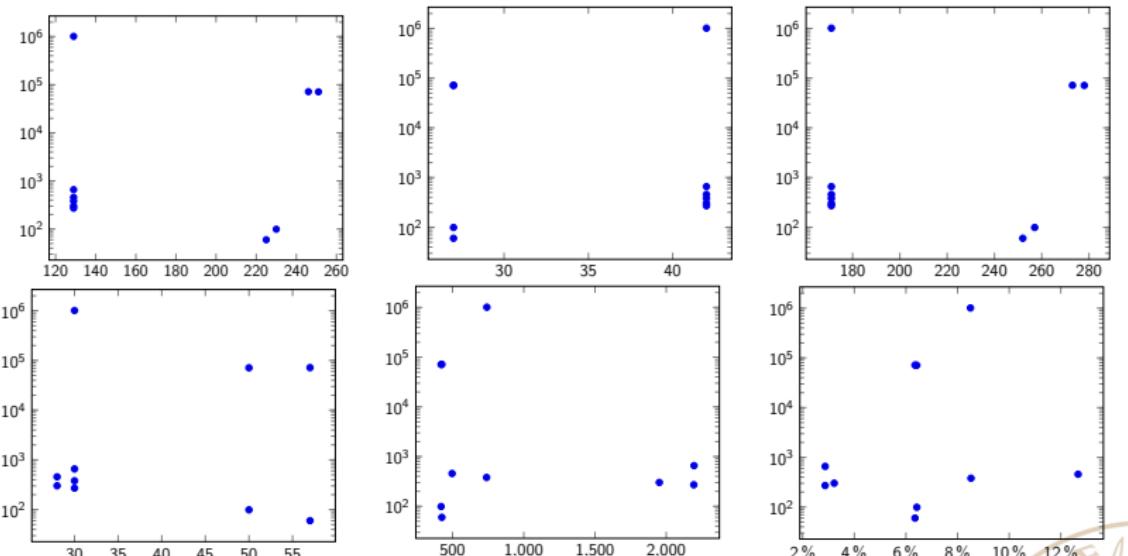
2015-02-21

## Task scheduling for dual-arm industrial robots through constraint programming

- ─ Evaluation
- ─ Results







2015-02-21

## Task scheduling for dual-arm industrial robots through constraint programming

- ─ Evaluation
- └ Results

