

2015-02-20

Task scheduling for dual-arm industrial robots  
through constraint programming  
MinZinc modeling and solver comparison

Tommy Kvant  
Institute of Computer Science  
Lund University  
February 20, 2015

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

## MinZinc modeling and solver comparison

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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

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

## └ Outline

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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



Introduction - YuMi®

- Dual-armed robot
- Flexible
- Fine motor skills



Photo: ABB



# Introduction - Project goal

Task scheduling for dual-arm industrial robots through constraint programming

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

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# Introduction - MiniZinc

Task scheduling for dual-arm industrial robots through constraint programming

- └ Introduction
  - └ MiniZinc
    - └ Introduction - MiniZinc

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# Case Study



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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

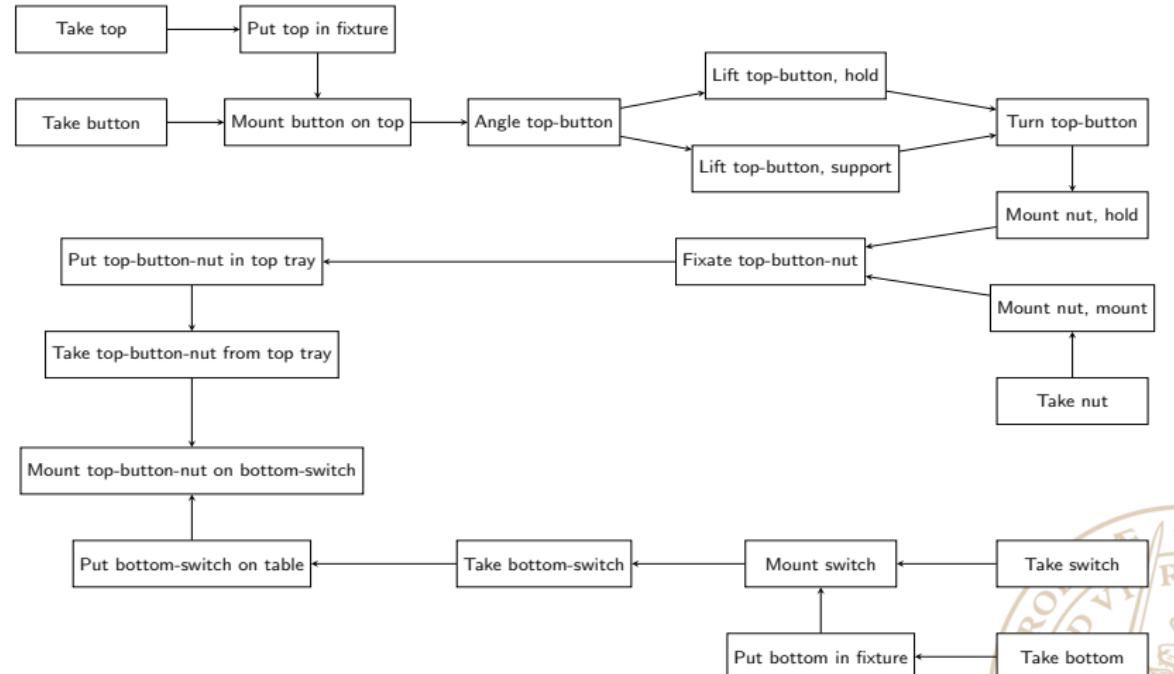
- └ Physical Entities

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



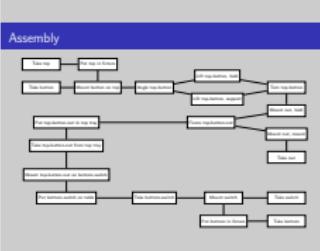
# Assembly

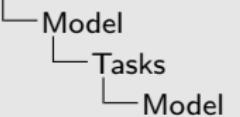


Task scheduling for dual-arm industrial robots through constraint programming  
└ Case Study

└ Assembly

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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

### Task1

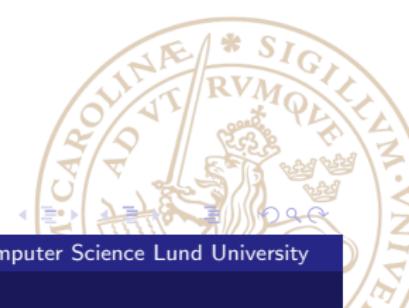
## Task2

### Task3

## Task 4

## Task

- 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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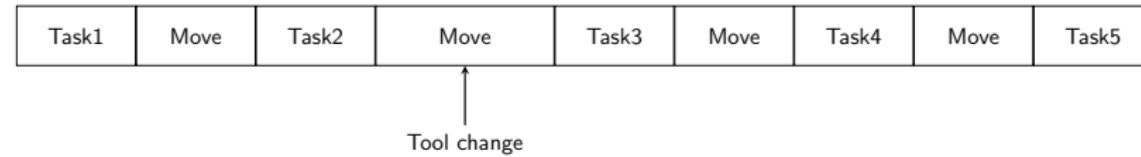


- Tasks behöver olika tools → måste utföra tool change
  - utförs mellan två tasks → tiden att röra sig mellan två tasks tar längre tid → bakar in tool change tiden i move
  - Det förekommer ett tool change om tiden för move tar längre tid än det egentligen skulle göra



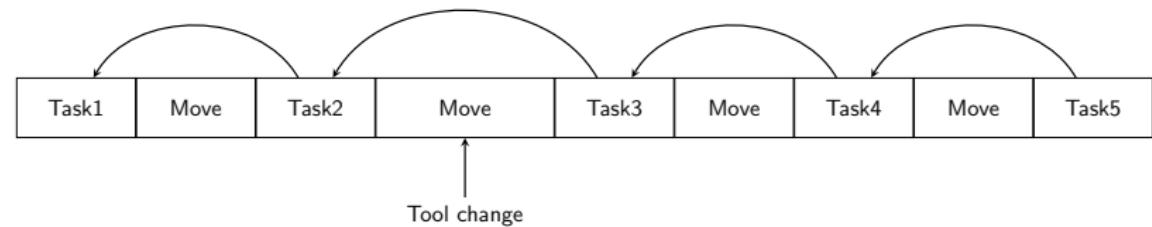
Model

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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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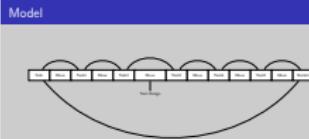


- Detta = Job Shop Problem with sequence-dependent setup times
  - För att se till att detta uppfylls kan constraintet circuit användas
  - Skapar en Hamiltonian circuit
  - Uppnår det genom att koppla ihop första och sista noden.
  - Constraint som säger att task måste komma efter sin predecessor →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



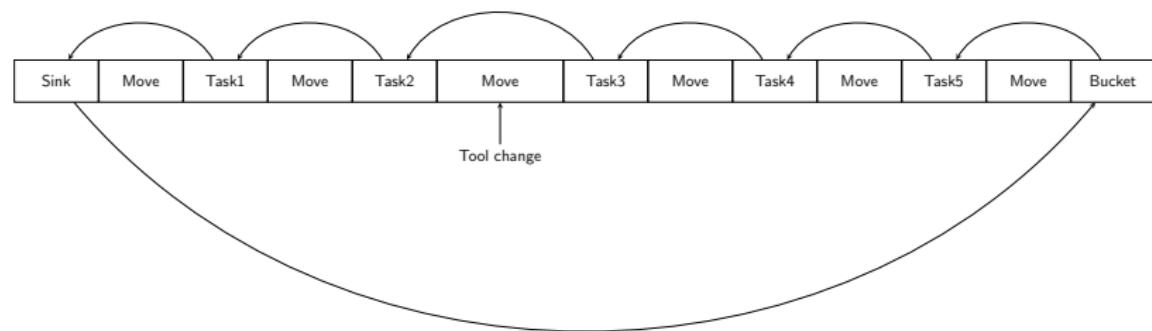
Model

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



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- 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



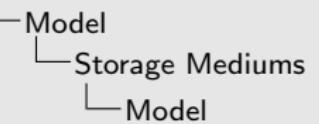
# Model

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## Components

- Primitive components
- Sub-assemblies





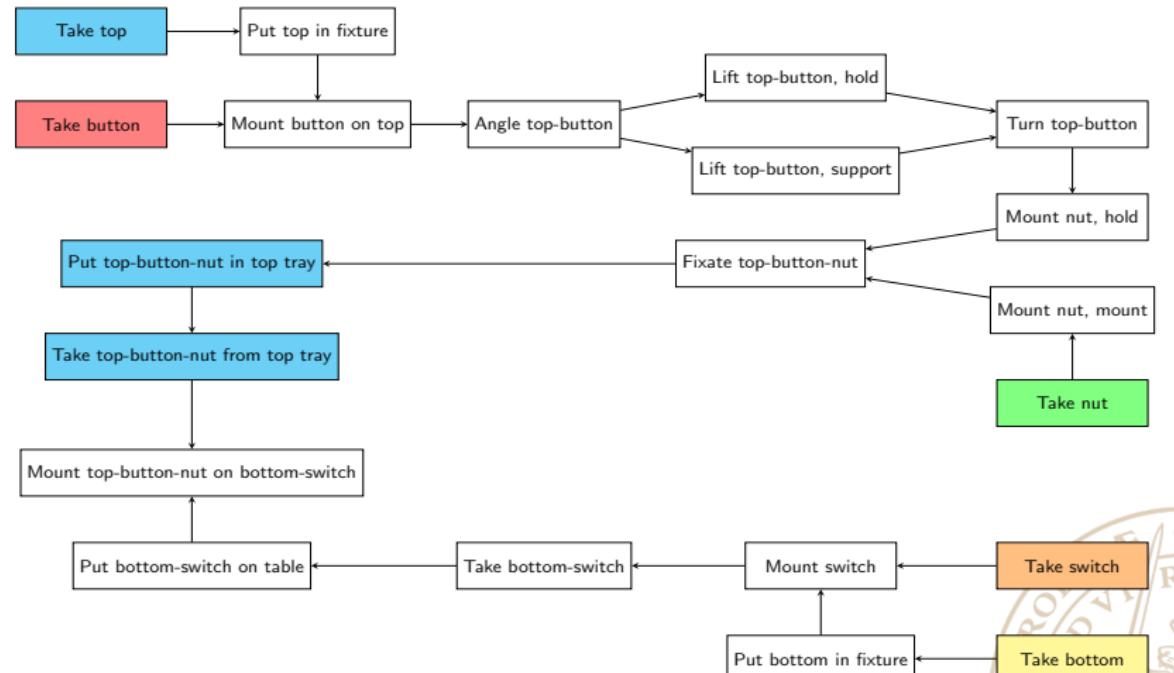
# Model

## Storage mediums

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

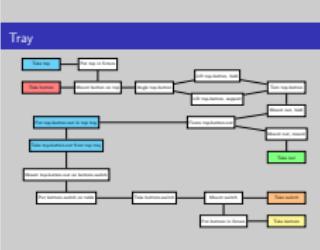


## Tray

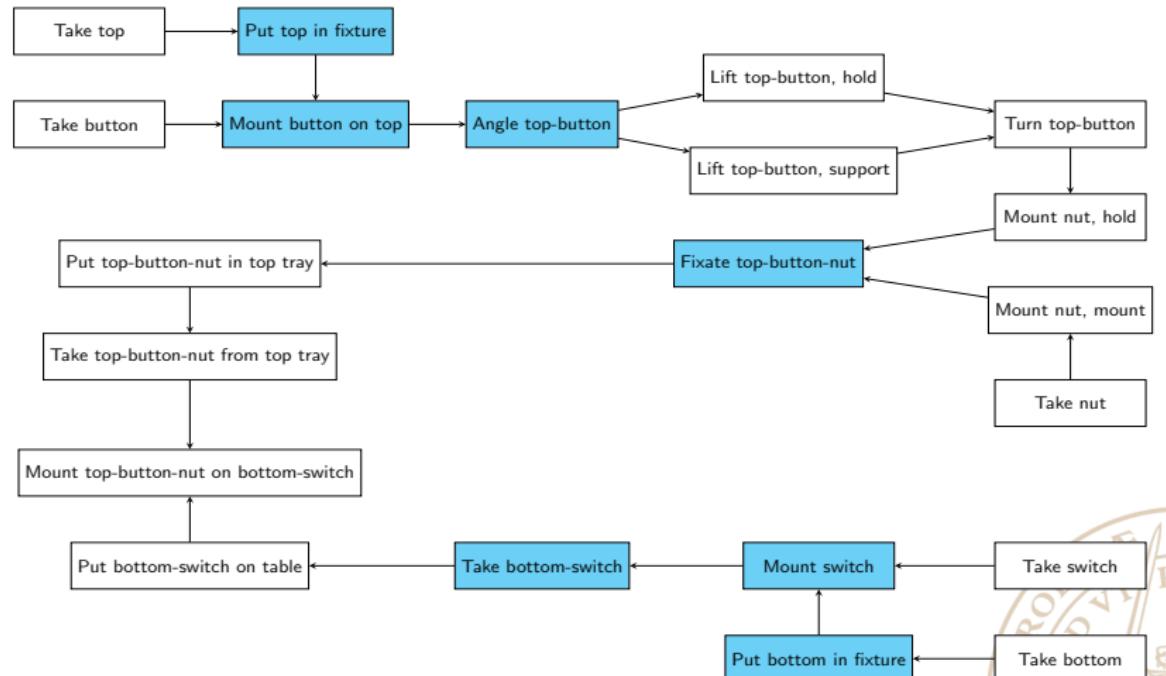


Task scheduling for dual-arm industrial robots through constraint programming  
└ Model  
  └ Storage Mediums  
    └ Tray

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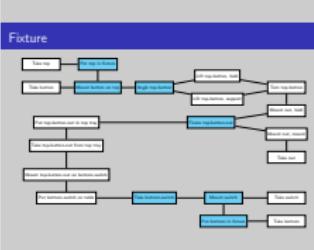
## Fixture



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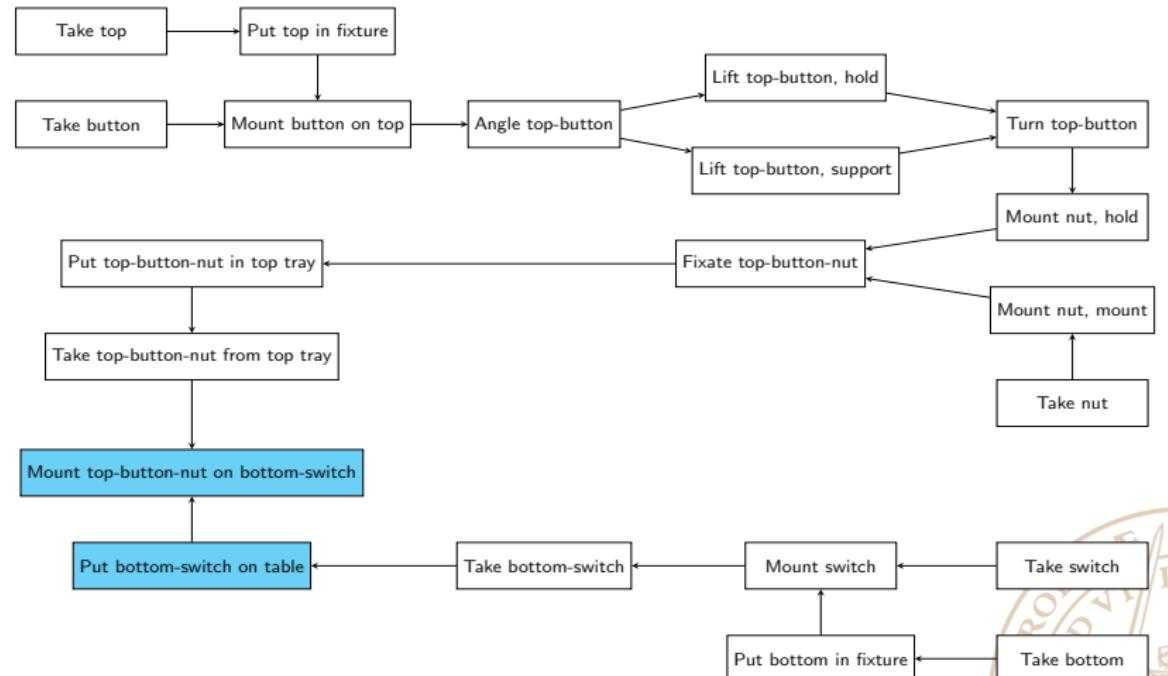
## Task scheduling for dual-arm industrial robots through constraint programming

- 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

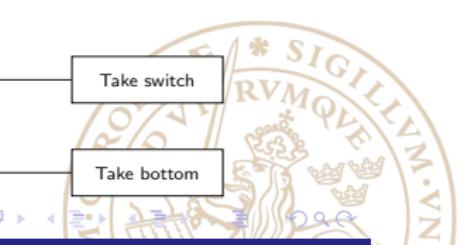
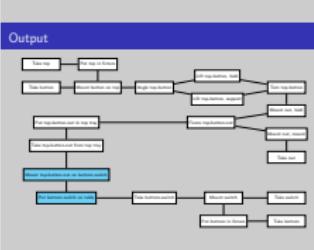
## Output



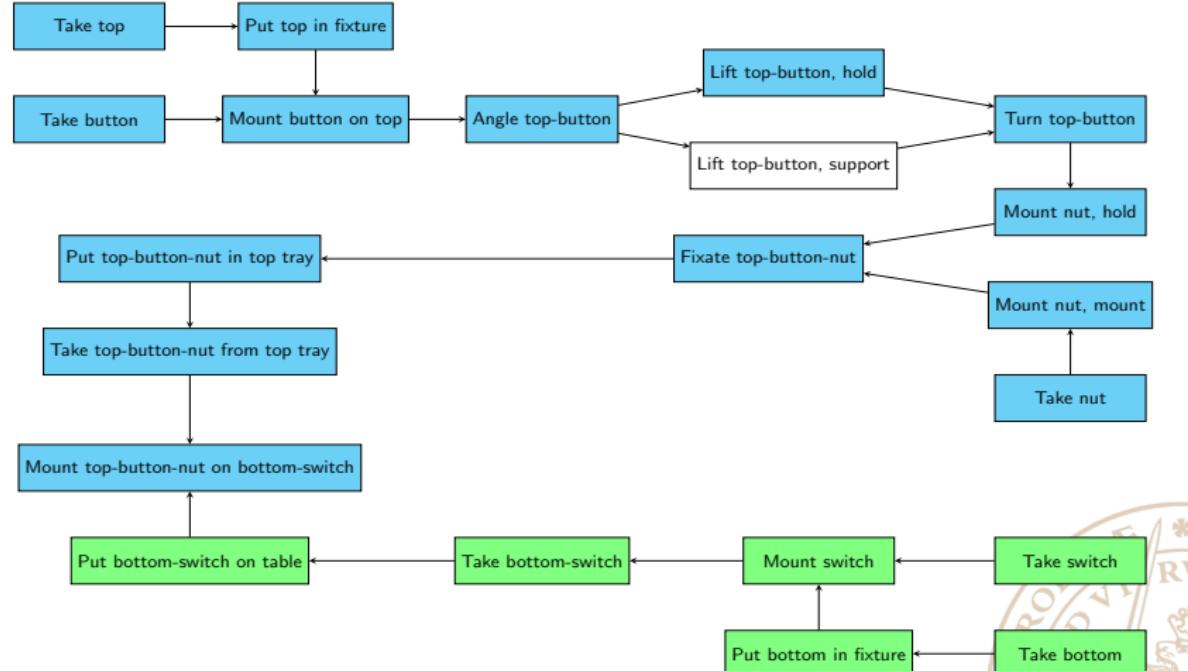
# Task scheduling for dual-arm industrial robots through constraint programming

```
└ Model
    └ Storage Mediums
        └ Output
```

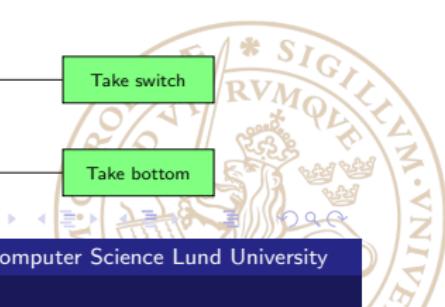
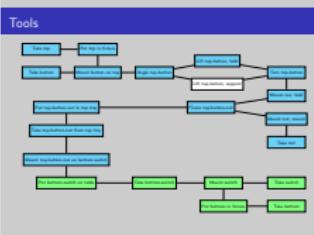
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## Tools



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



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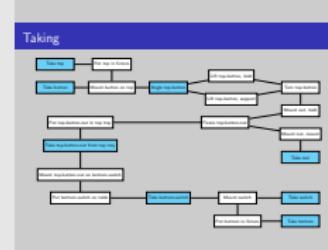
# Model

## Label tasks

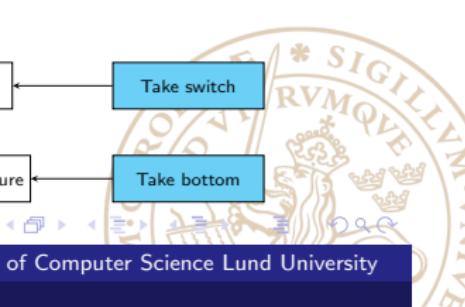
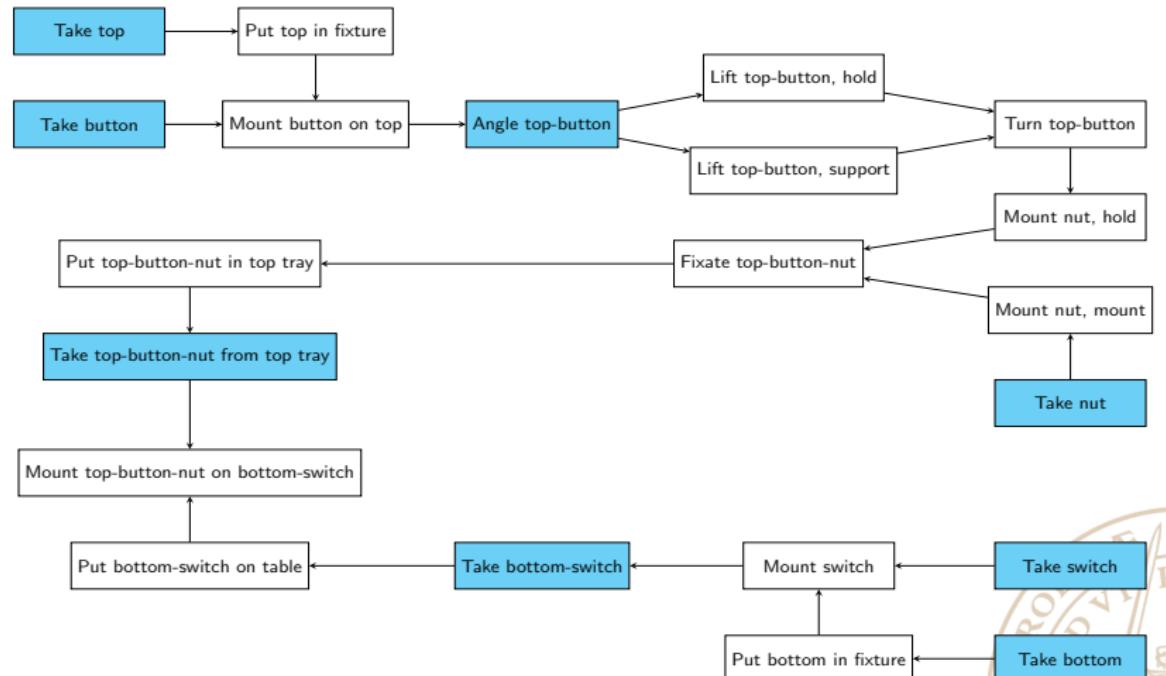
- Taking
- Mounting
- Putting
- Moving



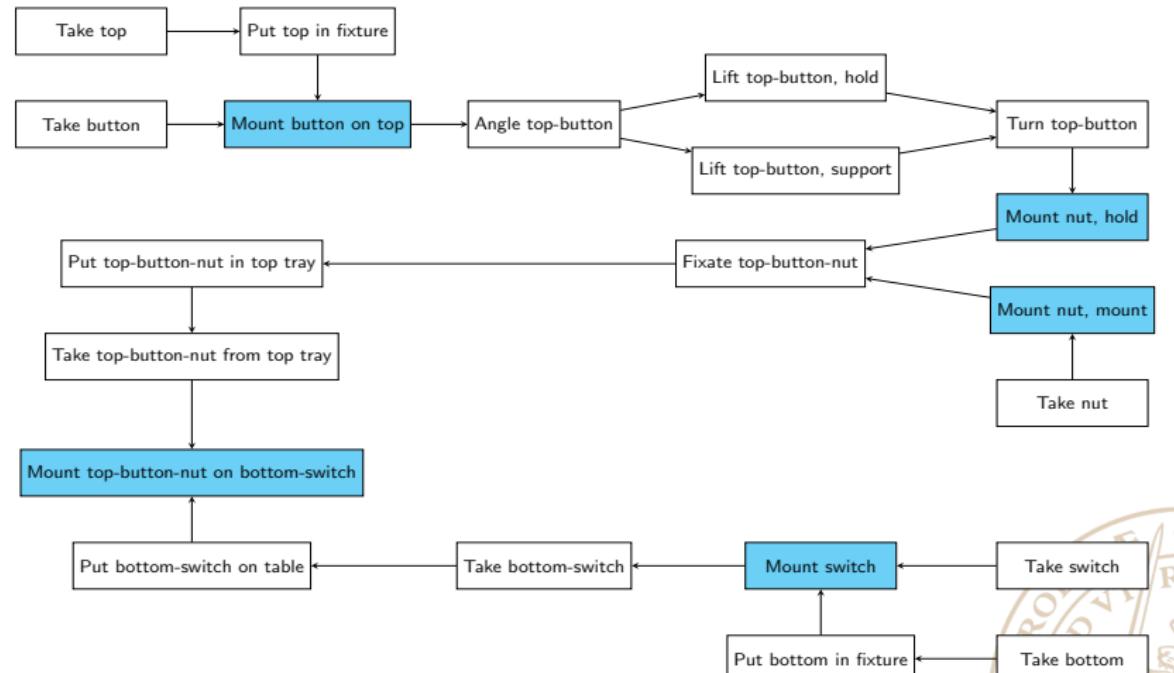
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Angle skulle kunna delas in i två tasks, en taking och en moving



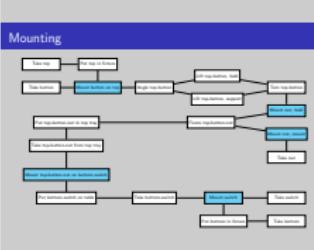
# Mounting



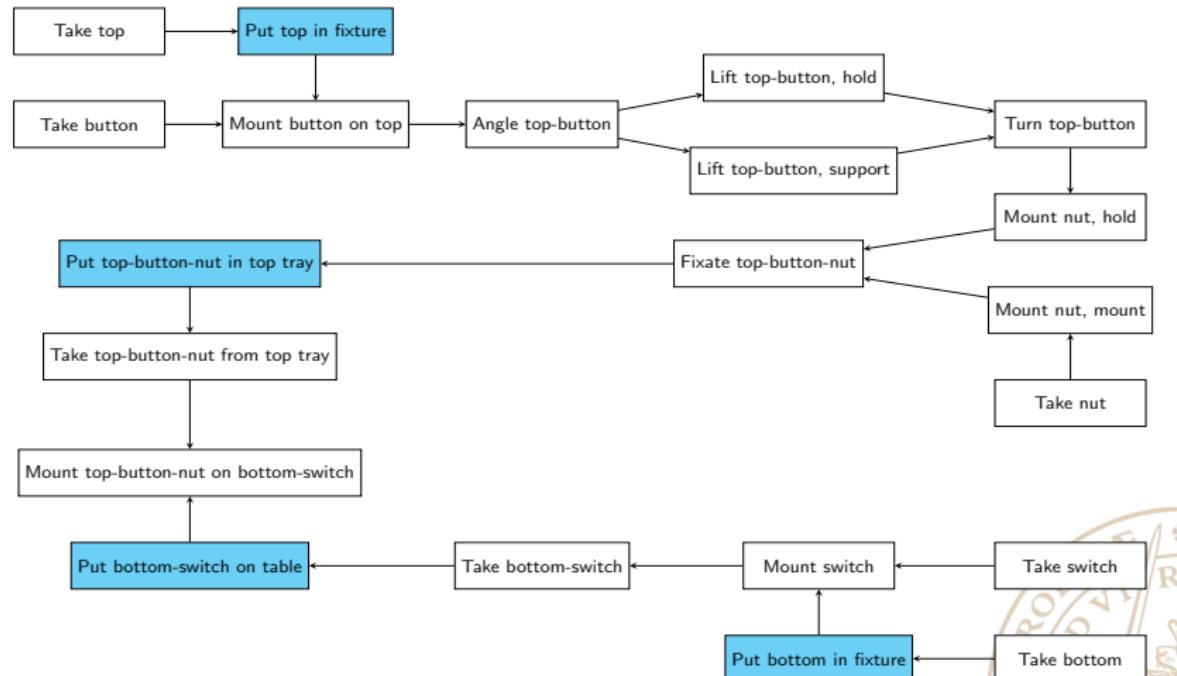
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Task scheduling for dual-arm industrial robots through constraint programming

- Model
- Labeling
- Mounting



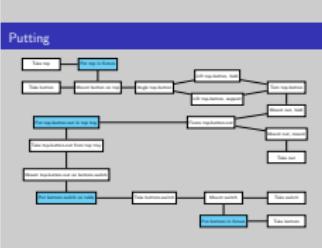
## Putting



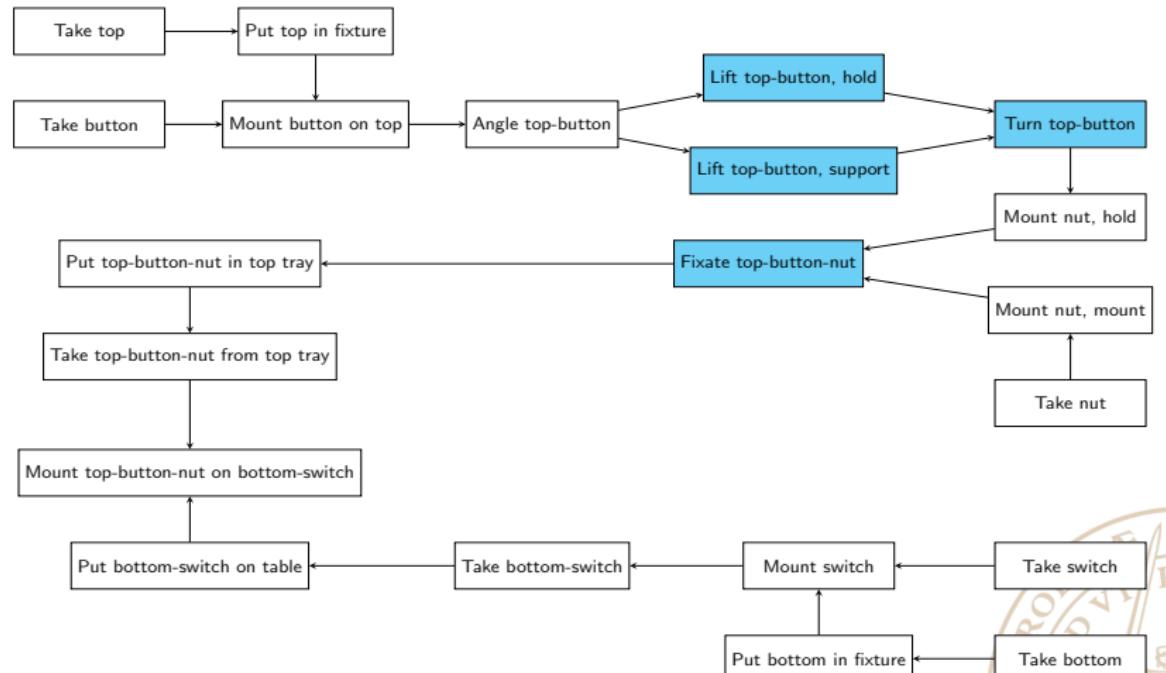
## Task scheduling for dual-arm industrial robots through constraint programming

Model  
└ Labeling  
└ Putting

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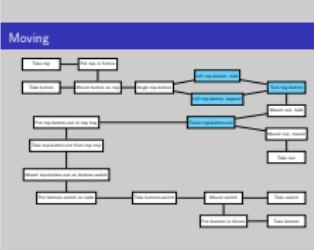
# Moving



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Task scheduling for dual-arm industrial robots through constraint programming

- Model
- Labeling
- Moving



Model

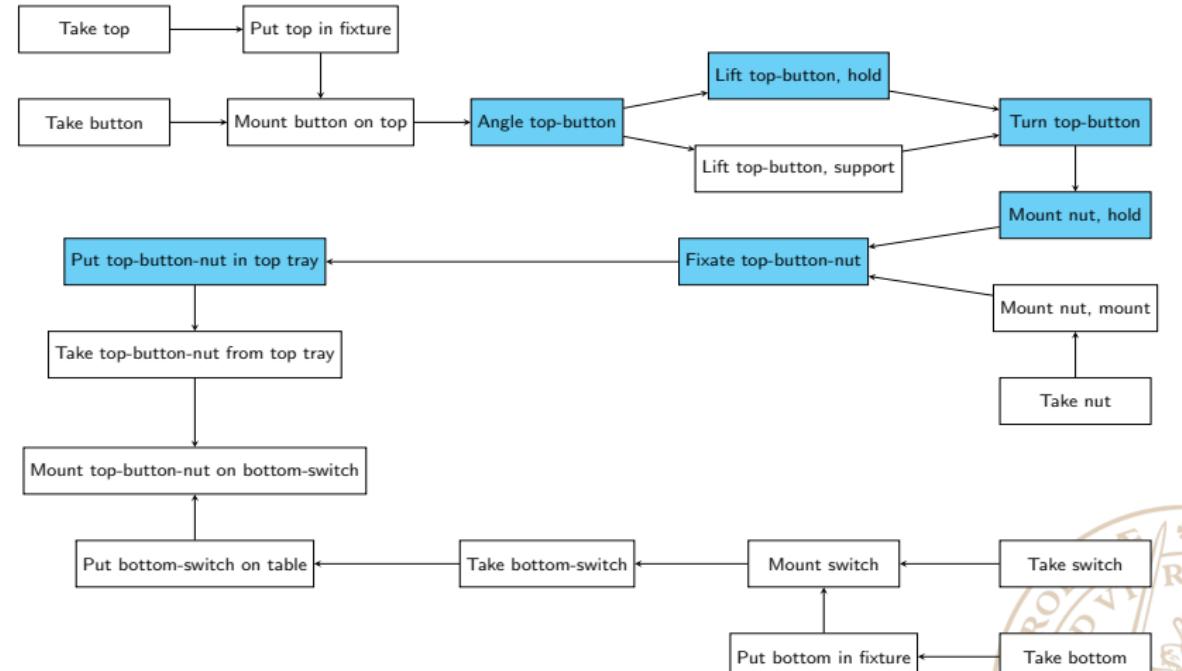
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## Group tasks

- Ordered group
  - Concurrent group



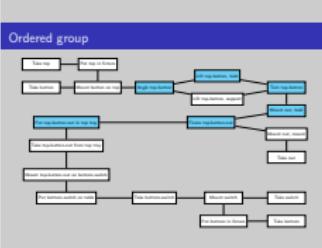
## Ordered group



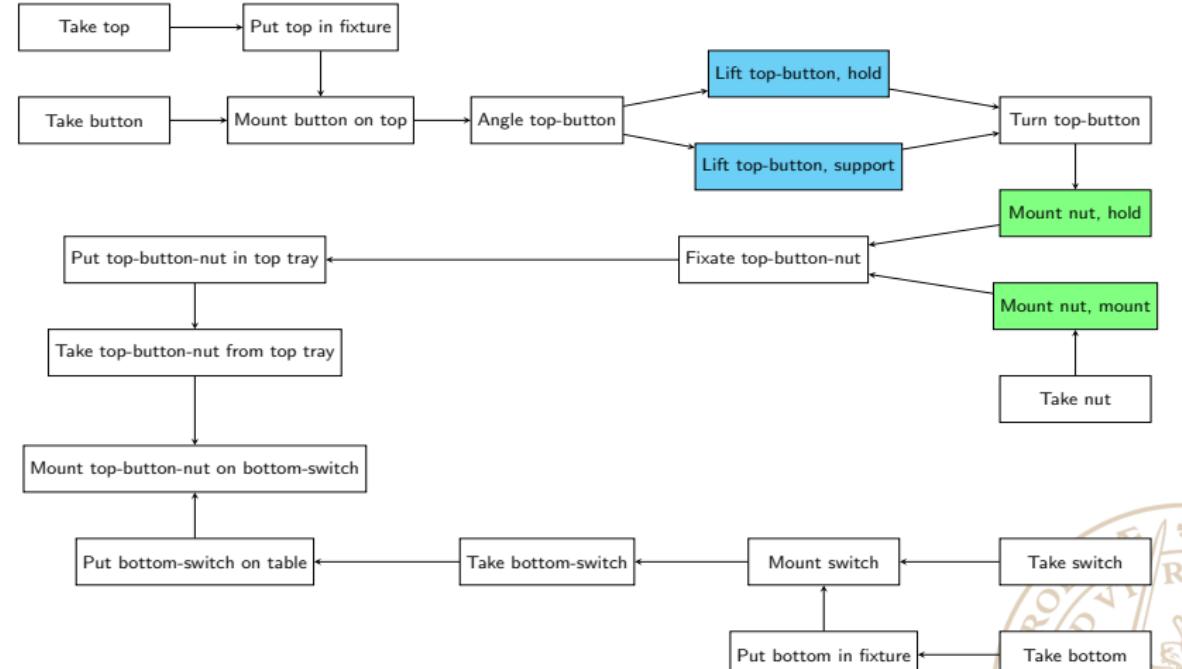
Task scheduling for dual-arm industrial robots through constraint programming

- └ Model
- └ Grouping
- └ Ordered group

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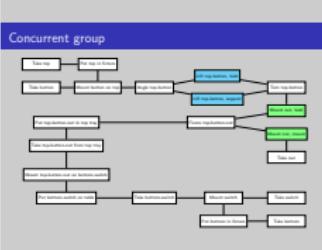


# Concurrent group



Task scheduling for dual-arm industrial robots through constraint programming  
└ Model  
  └ Grouping  
    └ Concurrent group

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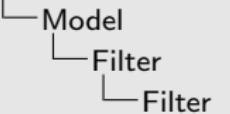


## Filter

- 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

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

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## Criteria

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

└ Evaluation  
  └ Solvers  
    └ Criteria

- FlatZinc parser
  - Free



## Solvers Tested

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



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

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



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



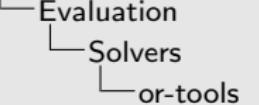
# Gecode

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

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



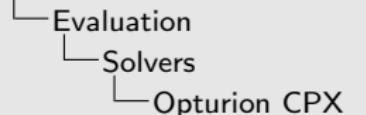
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1. Utilising multiple cores: Inte säker om parallel sökning, nämns i dokumentationen som "parallel solving", explicit utesluten ur dokumentationen



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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



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



# Assembly Times

Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation
- └ Results
- └ Assembly Times

Assembly Times

Manual Time  
516 t.u.

# Manual Time

## 516 t.u.



## Assembly Times

Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation
- └ Results
- └ Assembly Times

Assembly Times

Manual Time  
516 t.u.

Solver Time  
512 t.u.

Manual Time  
516 t.u.

Solver Time  
512 t.u.



# Solver Time

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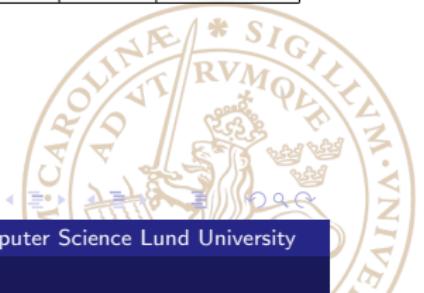
## Task scheduling for dual-arm industrial robots through constraint programming

└ Evaluation  
  └ Results  
    └ Solver Time

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

	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
G12/FD	-	-	-	-
JaCoP	658	-	1011156	-
Gecode	-	60	-	71761
or-tools	271	!	380	!
Opturion CPX	-	!	-	!
Choco3	-	-	-	-



# Solver Time

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

- └ Evaluation
- └ Results
- └ Solver Time

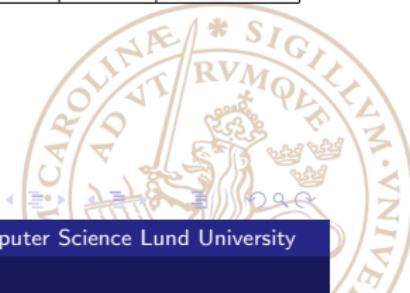
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Solver Time

	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 lösning, inte optimal

	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

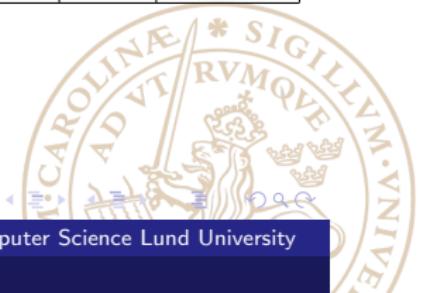
- └ Evaluation
- └ Results
- └ Solver Time

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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
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
G12/FD	-	-	-	-
JaCoP	658	-	1011156	-
Gecode	-	60	-	71761
or-tools	271	!	380	!
Opturion CPX	-	!	-	!
Choco3	-	-	-	-



# Solver Time

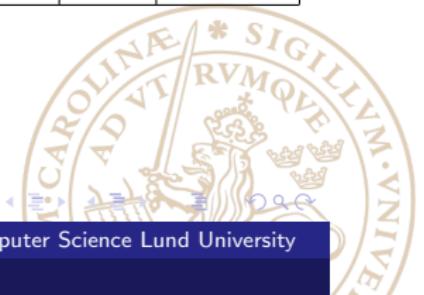
## Task scheduling for dual-arm industrial robots through constraint programming

- └ 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	-	-	-	-	-	-	-	-



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

# Solver Time

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

- └ Evaluation
- └ Results
- └ Solver Time

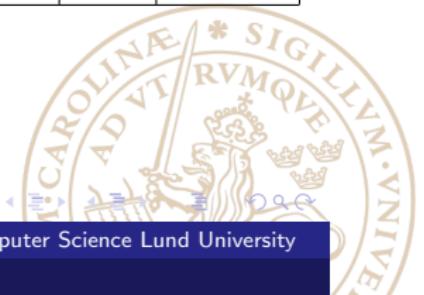
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Solver Time

	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 ungefärd 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

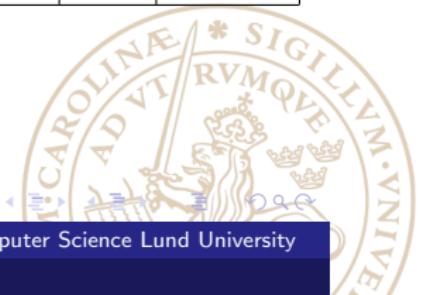
## Task scheduling for dual-arm industrial robots through constraint programming

- └ Evaluation
- └ Results
- └ Solver Time

2015-02-20

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	-	-	-	-