Task scheduling for dual-arm industrial robots through constraint programming

MiniZinc modeling and solver comparison

Tommy Kvant

Institute of Computer Science
Lund University

February 21, 2015

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Outline

Introduction - YuMi®

- Dual-armed robot
- Flexible
- Fine motor skills

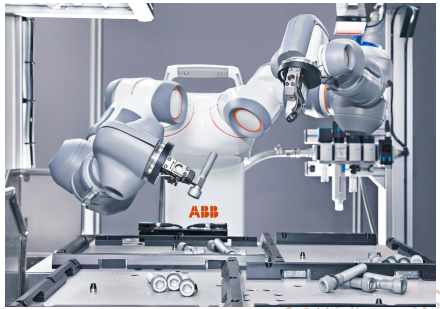
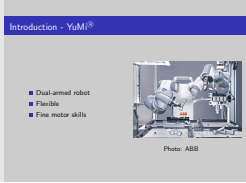


Photo: ABB

1. Montera endast mellan maskiner utan tray



Introduction - Project goal

Introduction - MiniZinc

Case Study

Case Study

Skruvarna inte med

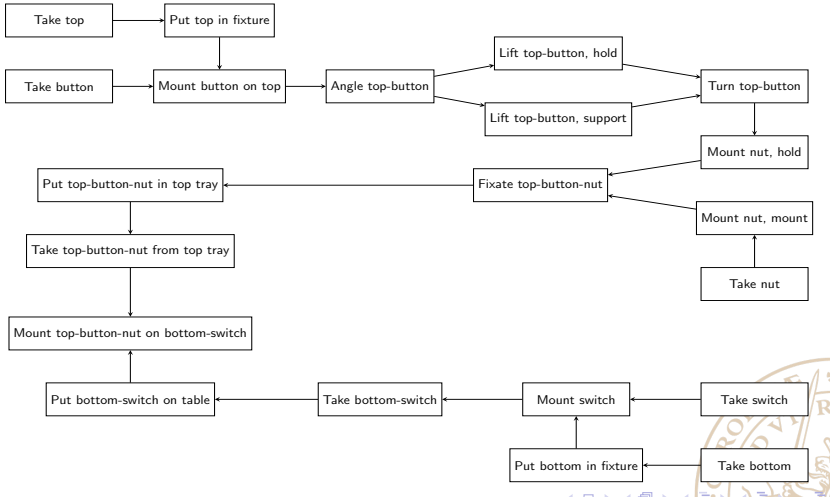
Case Study

Physical Entities

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

Physical Entities
Machines
Tools
Components
Tray
Fixture
Output

Assembly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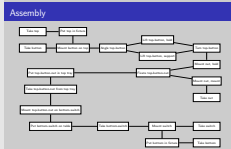

Assembly

Model

Job Shop Problem

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

Model
Job Shop Problem
n jobs, varying size
m identical machines
NP-complete for m ≥ 2 and n ≥ 3

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

Model

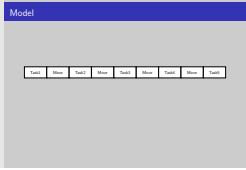
Task1	Task2	Task3	Task4	Task5

Model
Task1 Task2 Task3 Task4 Task5

- 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

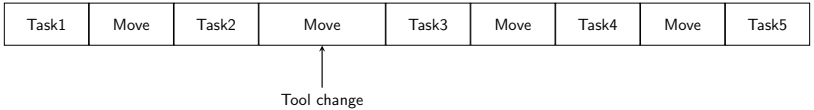
Model

Task1	Move	Task2	Move	Task3	Move	Task4	Move	Task5

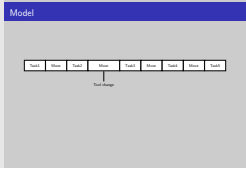


- Tasks behöver olika tools → måste utföra tool change
- utförs mellan två tasks → tiden att röra sig mellan två tasks tar längre tid → bakar in tool change tiden i move
- Det förekommer ett tool change om tiden för move tar längre tid än det egentligen skulle göra

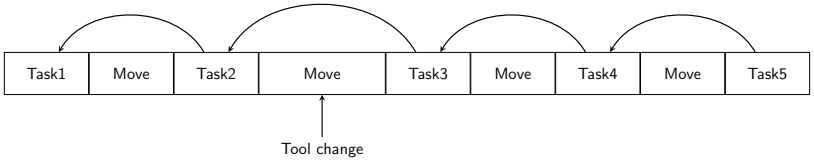
Model



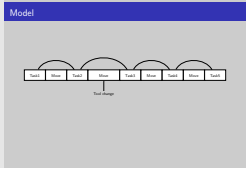
- Hur lång tid det tar beror på vilken task som kommer innan → vi måste veta vilken task som kommer innan, *predecessor*



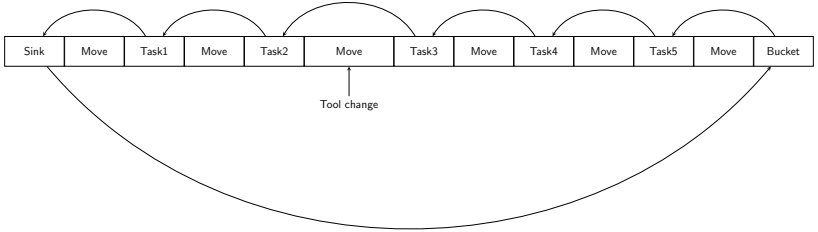
Model



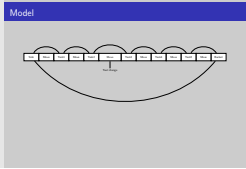
- Detta = Job Shop Problem with sequence-dependent setup times
- För att se till att detta uppfylls kan constraintet `circuit` användas
- Skapar en Hamiltonian circuit
- Uppnår det genom att koppla ihop första och sista noden.
- Constraint som säger att task måste komma efter sin predecessor → Första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

Components

- Primitive components
- Sub-assemblies

Model
Components
Primitive components
Sub-assemblies

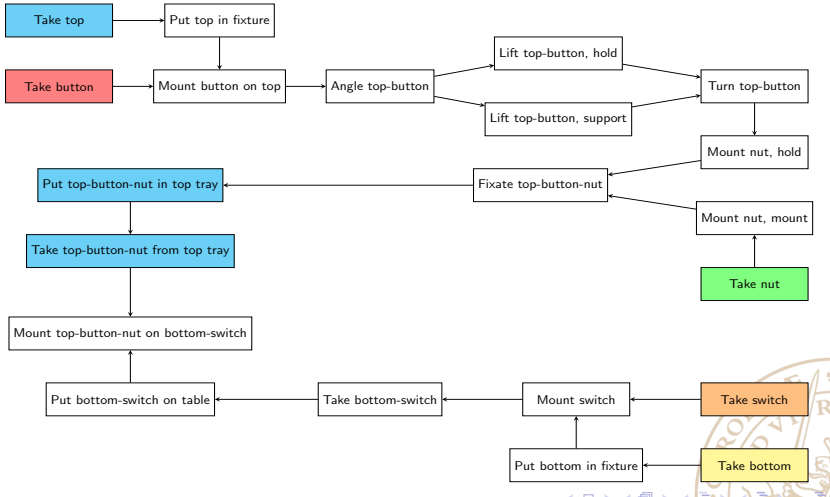
Model

Storage mediums

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

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

Tray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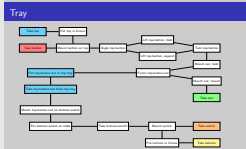
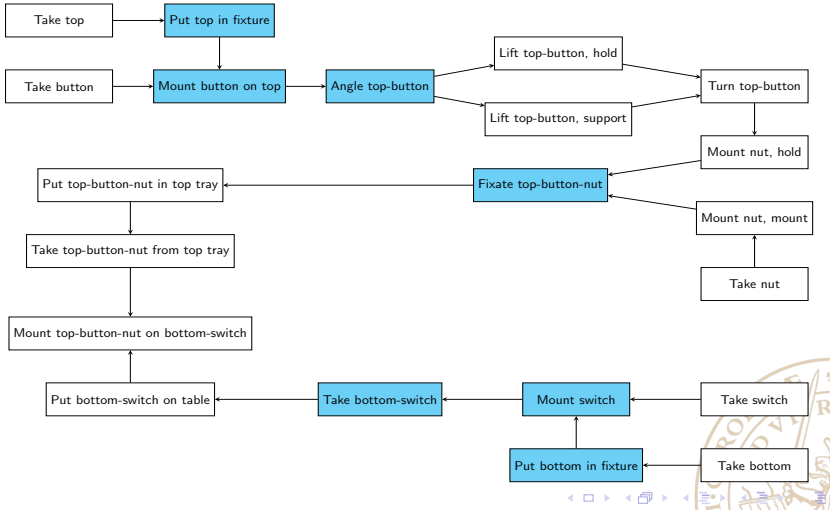
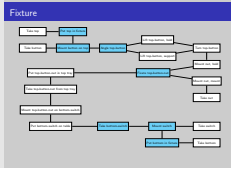

Tray

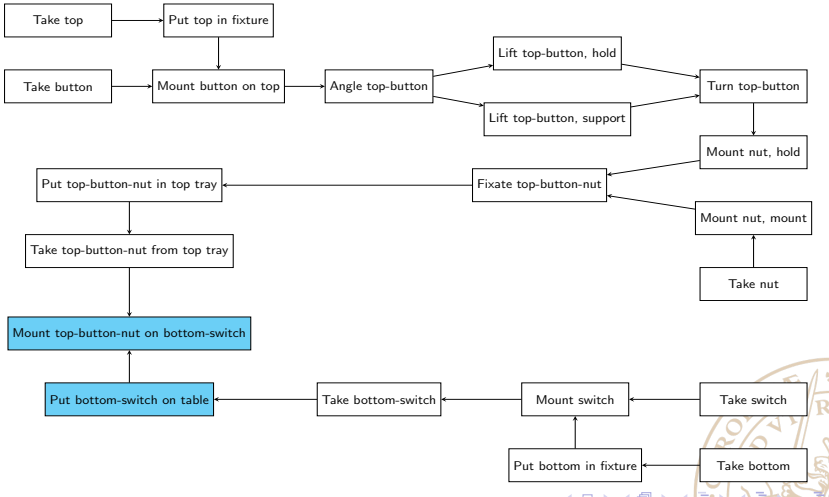
Fixture





- 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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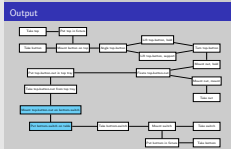
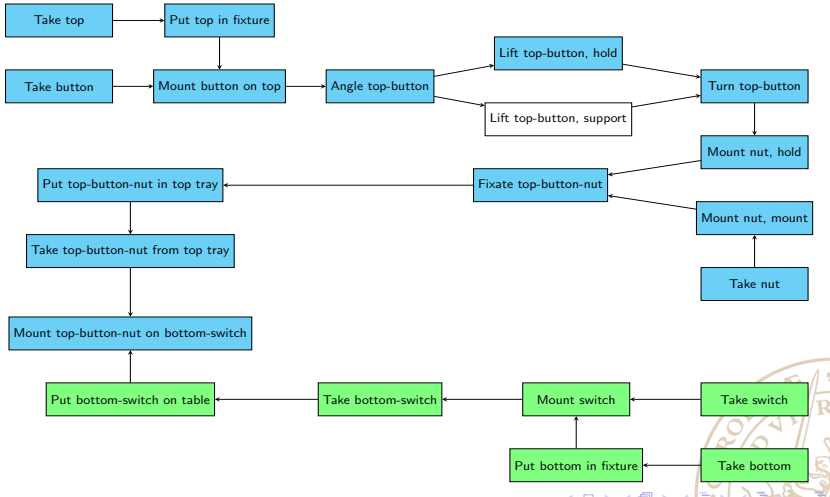
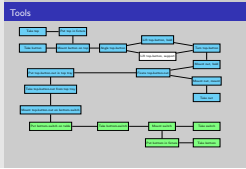

Output

Tools





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

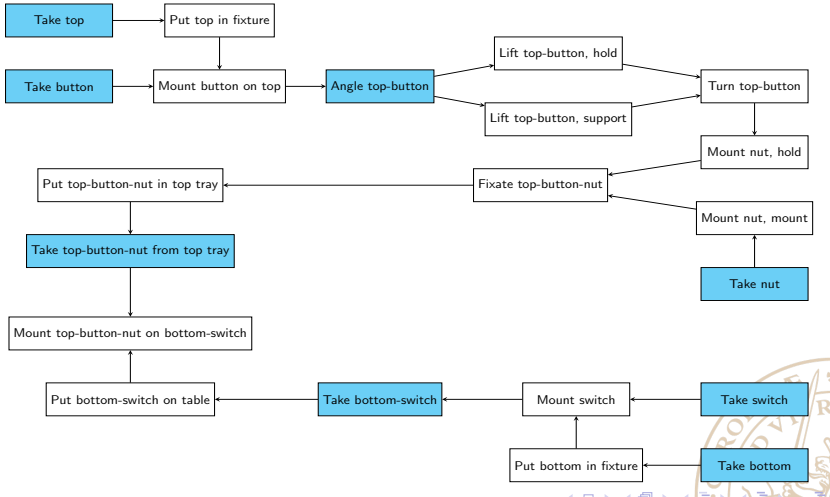
Model

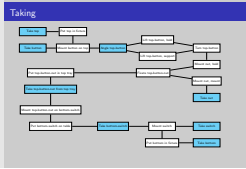
Label tasks

- Taking
- Mounting
- Putting
- Moving

Model
Label tasks
Taking
Mounting
Putting
Moving

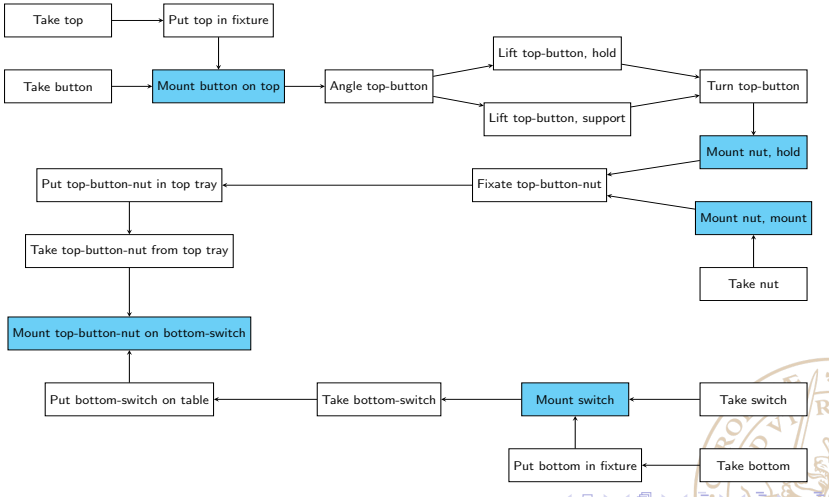
Taking





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

Mounting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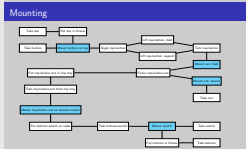
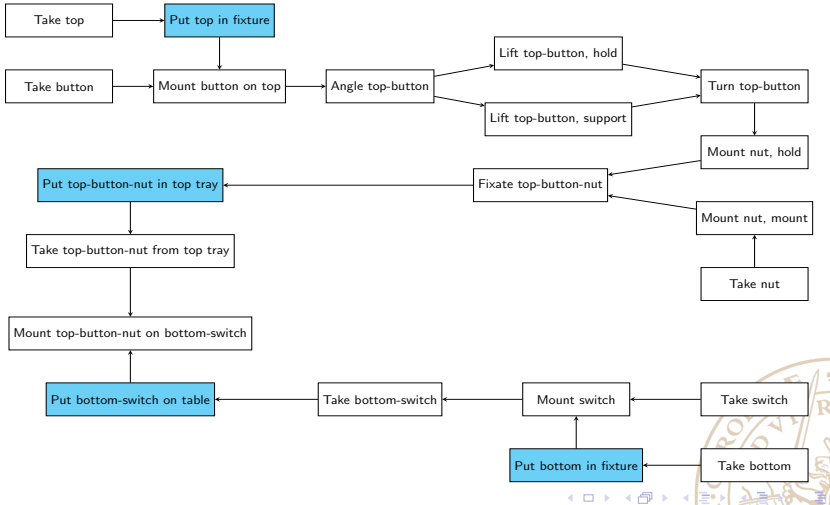

Mounting

Putting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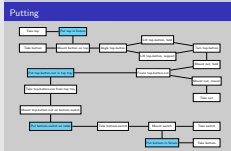
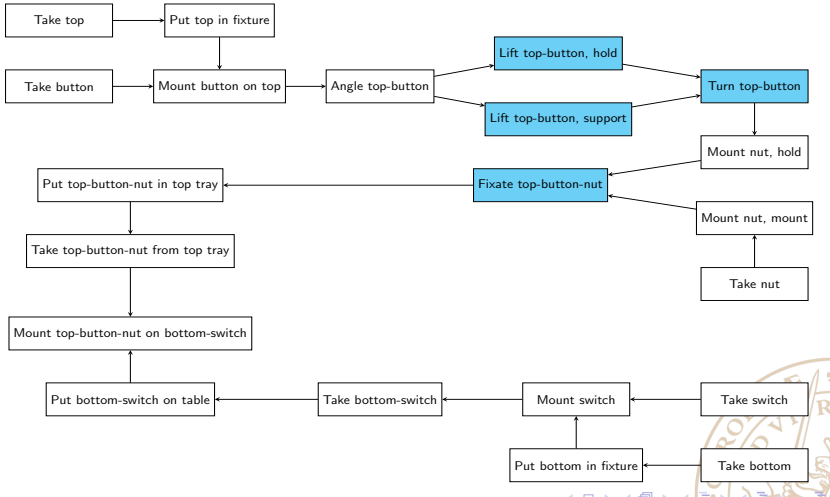

Putting

Moving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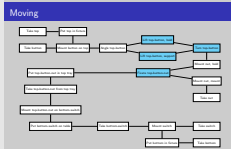

Moving

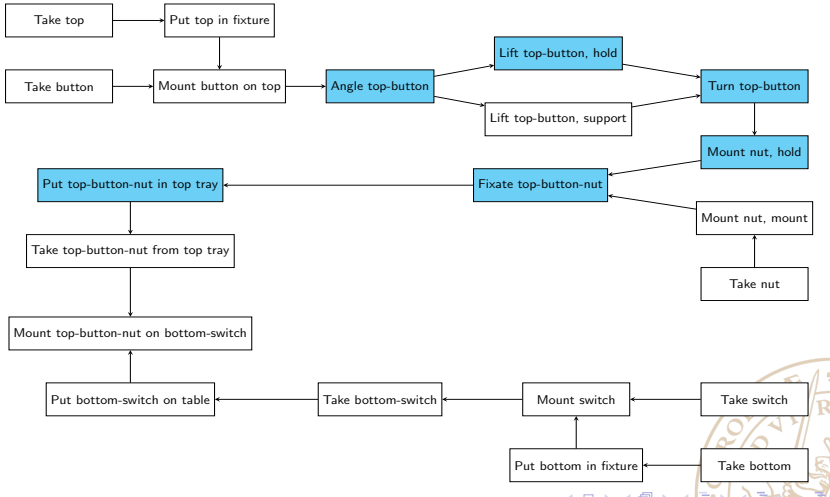
Model

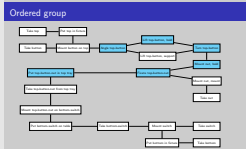
Group tasks

- Ordered group
- Concurrent group

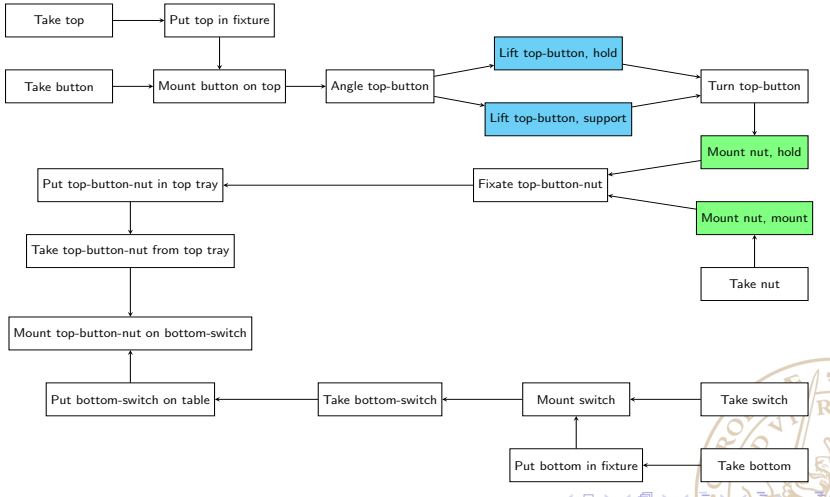
Model
Group tasks
Ordered group
Concurrent group

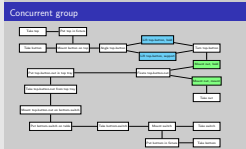
Ordered group





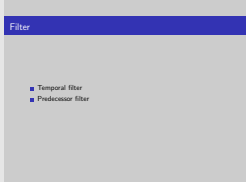
Concurrent group





Filter

- 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 → $pred(putTask/mountTask) \neq startTask$
- Då allting måste sitta i outputs i slutet av assemblyn → $pred(goalTask) \neq takeTask$
- 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

Criteria

- FlatZinc parser
- Free

Criteria
FlatZinc parser
Free

Solvers Tested

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

Solvers Tested
G12/FD
JaCoP
Gecode
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Opturion CPX
Choco3

G12/FD

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

G12/FD
G12 Team, NICTA
Mercury
Default solver for MiniZinc

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

JaCoP

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

JaCoP
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Gecode

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

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

or-tools

- C++
- Google - Operational Research
- Open Source
- Utilising multiple cores
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or-tools
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- Google - Operational Research
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1. Utilising multiple cores: Inte säker om parallell sökning, nämns i dokumentationen som "parrallel sovling", explicit utesluten ur dokumentationen

Opturion CPX

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

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

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 $\rightarrow$ sökning inte slöas ner av stora domäner

Choco3

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

Choco3
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
Manual Time
516 t.u.

Assembly Times

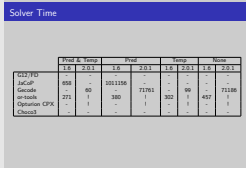
Manual Time
516 t.u.

Solver Time
512 t.u.

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

Solver Time

	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	-	-	-	-	-	-	-	-



- 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

	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
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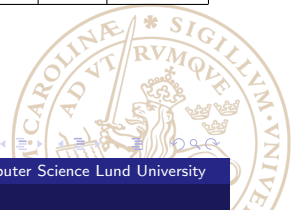
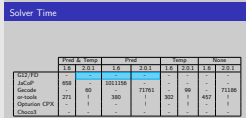
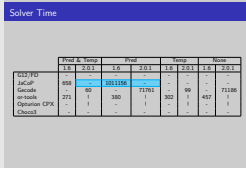




Hittar lösning, inte optimal

Solver Time

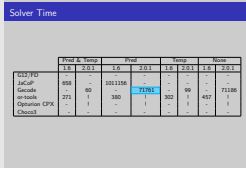
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-



Hittar hittar alla lösningar, inklusive optimala

Solver Time

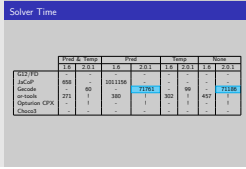
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-



Hittar 3 lösningar, inklusive optimala

Solver Time

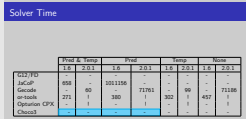
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-



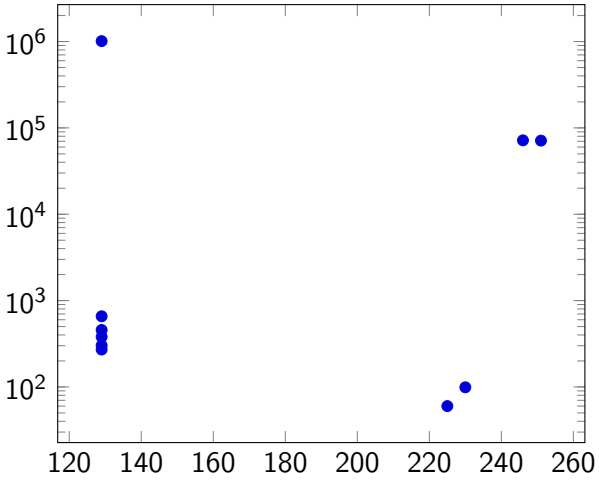
Hittar 1 lösning, den optimala, på ungefär samma tid som den tidigare

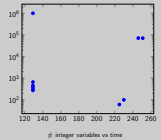
Solver Time

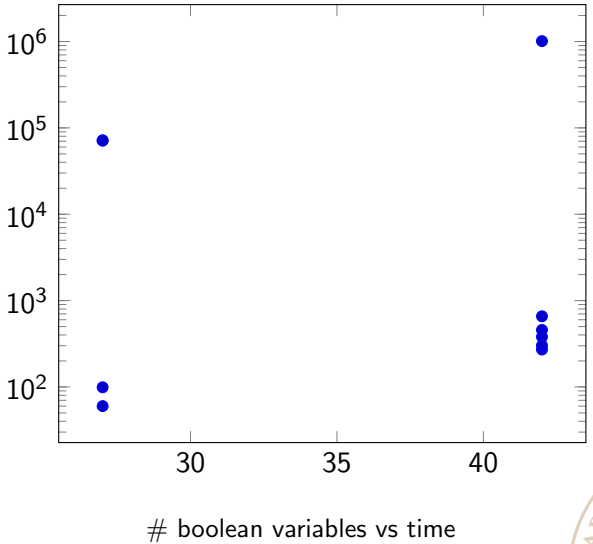
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-

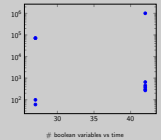


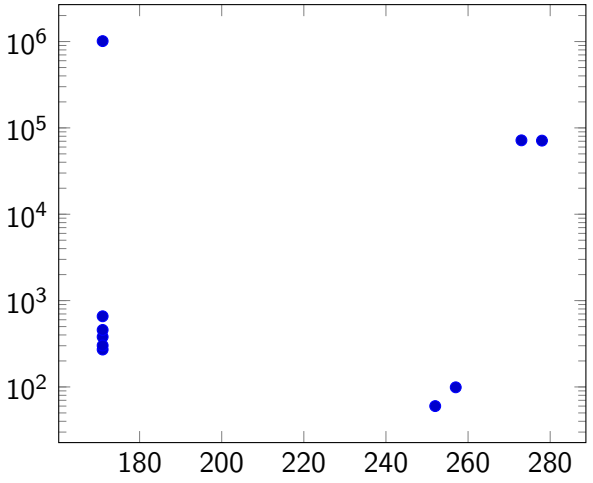
Hittar 2 lösningar direkt


10^6
10^5
10^4
10^3
10^2
120 140 160 180 200 220 240 260
integer variables vs time

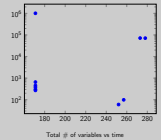


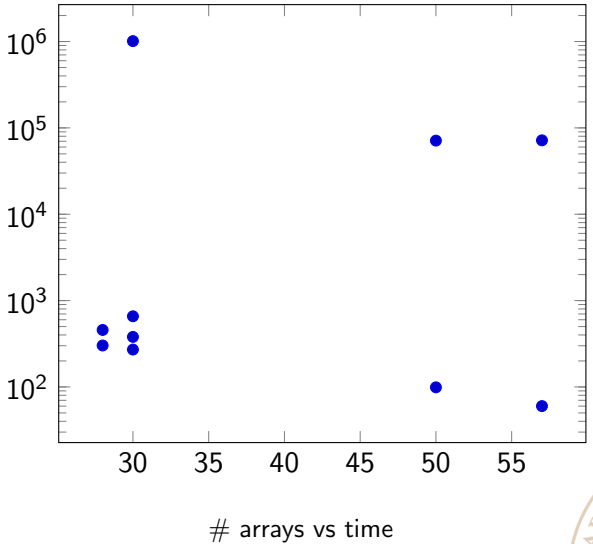

10^6
10^5
10^4
10^3
10^2
30
35
40
boolean variables vs time

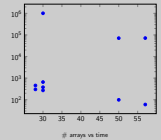


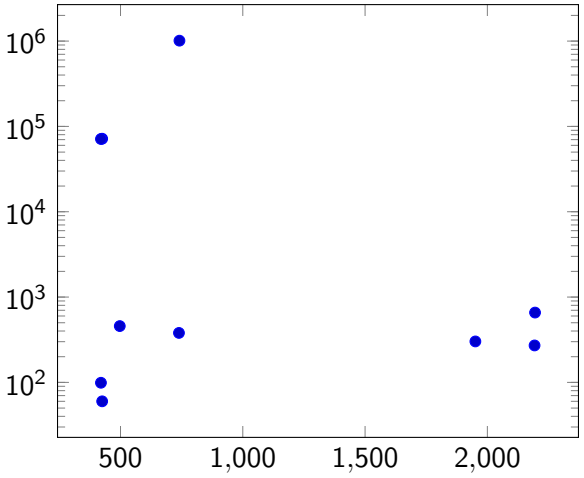


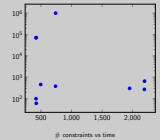
Total # of variables vs time

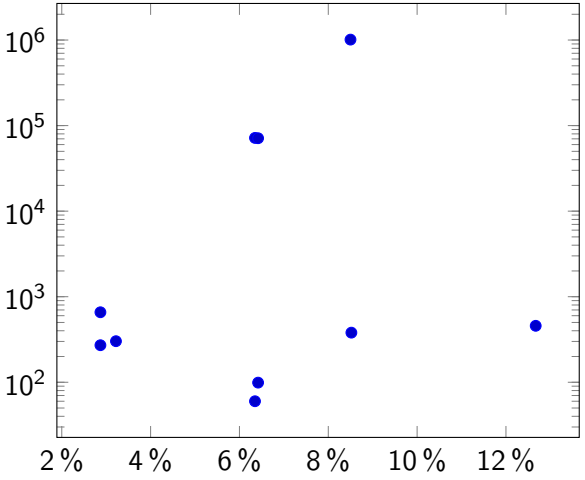


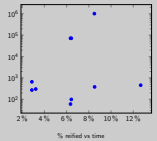

10^6
10^5
10^4
10^3
10^2
30
35
40
45
50
55
arrays vs time

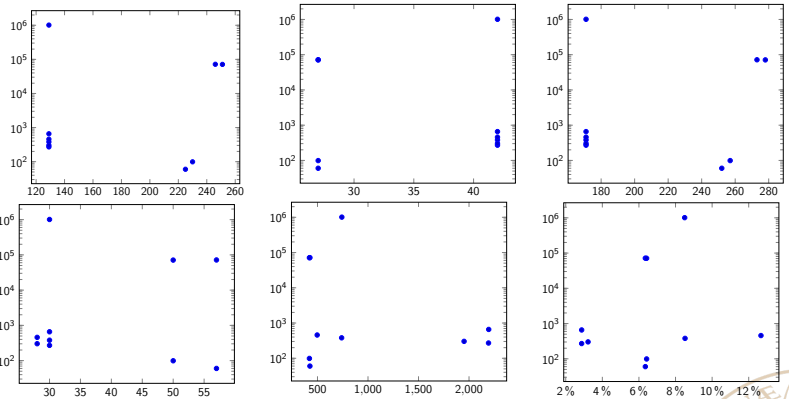


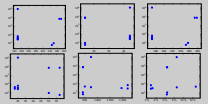

10^6
10^5
10^4
10^3
10^2
500
1,000
1,500
2,000
constraints vs time




10^6
10^5
10^4
10^3
10^2
2 %
4 %
6 %
8 %
10 %
12 %
% reified vs time




10^6
10^5
10^4
10^3
10^2
120 140 160 180 200 220 240 260
30 35 40
180 200 220 240 260 280
30 35 40 45 50 55
500 1,000 1,500 2,000
2% 4% 6% 8% 10% 12%



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