Task scheduling for dual-arm industrial robots through constraint programming

MiniZinc modeling and solver comparison

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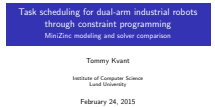

Outline

Introduction - Project goal

- Constraint Programming model for dual-armed robots such as YuMi®
  - Change tools
  - Carry only one component at the time
  - Same duration for tool changes, regardless of direction
  - Use trays, fixtures and outputs
- Implement the model in MiniZinc
- Test the model with 6 solvers and compare the results

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Introduction - MiniZinc

- Declarative language
- Medium level
- Translates to FlatZinc
- Aims to be standard
- Many solvers can read FlatZinc

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- Declarative language + declarative paradigm = good fit
- Many CP languages available, based on imperative languages = messy syntax
- Medium level: Högt nog för att formulera komplicerade uttryck, tex. for-loopar, lågt nog för att lätt kunna översättas till FlatZink
- FlatZink låg nivå → läses lätt in av solvers
- Siktar på att bli standard, lätt att läsa in FlatZinc → relativt många solvers kan läsa in modeller

Introduction - YuMi®

- Dual-armed robot
- Flexible - multiple tools
- Fine motor skills

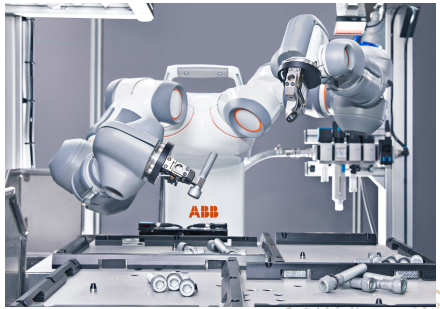
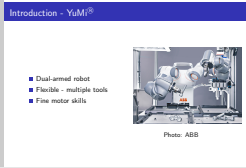


Photo: ABB



Mycket av produktion i dagens samhälle automatiseras & många produkter serier har kort livsspann → produktionen av nya serier behöver anpassas relativt snabbt → YuMi

1. Montera endast mellan maskiner utan tray

Case Study

Case Study

Skruvarna inte med

Case Study

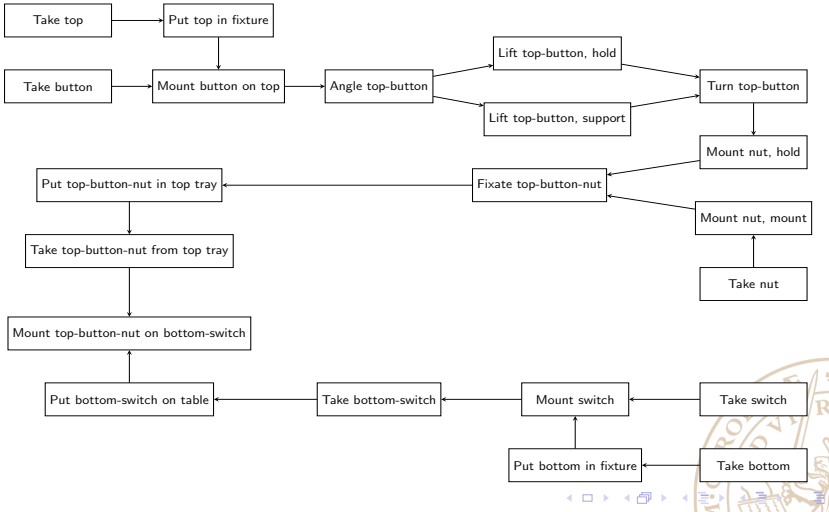
Case Study

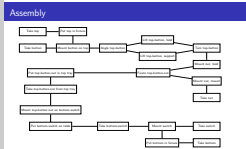
Physical Entities

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

Physical Entities
Machines
Tools
Components
Tray
Fixture
Output

Assembly

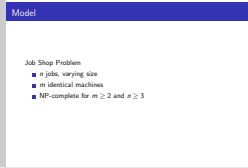

Take top
Put top in fixture
Take button
Mount button on top
Angle top-button
Lift top-button, hold
Lift top-button, support
Turn top-button
Mount nut, hold
Mount nut, mount
Take nut
Fixate top-button-nut
Put top-button-nut in top tray
Take top-button-nut from top tray
Mount top-button-nut on bottom-switch
Put bottom-switch on table
Take bottom-switch
Mount switch
Take switch
Put bottom in fixture
Take bottom


Assembly

Model

Job Shop Problem

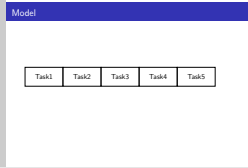
- n jobs, varying size
- m identical machines
- NP-complete for $m \geq 2$ and $n \geq 3$



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

Model

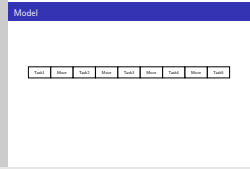
Task1	Task2	Task3	Task4	Task5



- En task kommer efter den andra
- Längden på en task, *duration*, tillhandahålls av den som skapar assemblyn

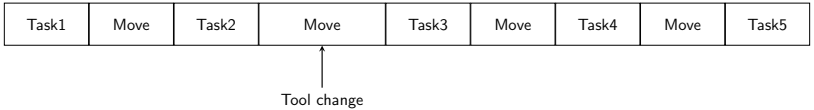
Model

Task1	Move	Task2	Move	Task3	Move	Task4	Move	Task5



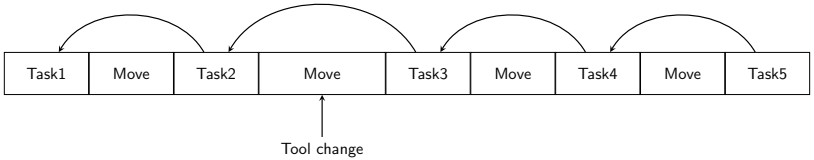
- Men tasks:en sker på olika ställen i rummet → det tar tid att flytta sig mellan dem → måste räkna med det
- Tider för move mellan tasks tillhandahålls genom en tidsmatris av den som vill schemalägga

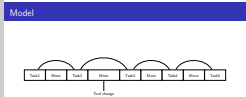
Model



- 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
- Tidsmatrisen tillsammans med tiderna för att byta mellan tools = ny matris med alla möjliga moves inkl. tool change

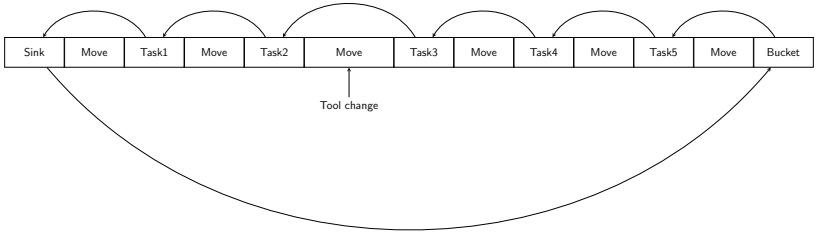
Model

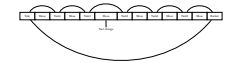




- Hur lång tid det tar beror på vilken task som kommer innan → vi måste veta vilken task som kommer innan, *predecessor*
- Detta = Job Shop Problem with sequence-dependent setup times
- För att se till att detta uppfylls kan constraintet `circuit` användas
- Skapar en Hamiltonian circuit
- Uppnår det 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

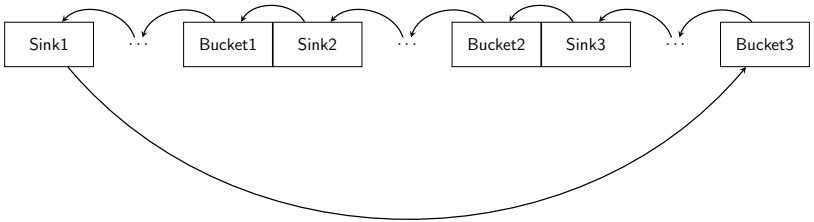
Model

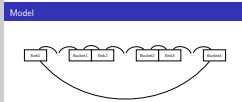




- Introducerar sink node/startTask & bucket node/goalTask
- Men detta måste göras för varje maskin, tasks måste fördelas $\rightarrow$ *usingMachine*$(t) \rightarrow$ task och predecessor måste vara på samma maskin

Model





- För att göra det för flear maskiner: Istället för lika många circuits som maskiner, kopplar ihop alla curcuits till en lång circuit
- Vi har alltså 4 variabler att schemalägga: start time för tasks, start time för moves, predecessors & usingMachine

Defining Tasks

- Components
- Tray, Fixture, Output
- Tool
- Action - Taking, Putting, Mounting, Moving

Defining Tasks
Components
Tray, Fixture, Output
Tool
Action - Taking, Putting, Mounting, Moving

- Tray, Fixture, Output - Får inte överlappa
- Tool - Om det behövs ett visst tool
- Moving - För att skapa mer komplexa moves och använda två maskiner för ett move, t.ex. som i vårt case
- Taking, Putting, Mounting - Kan sätta upp constraints mellan. Kan inte göra det med Moving, löser bland annat det genom: ↓

Model

Group tasks

- Ordered group
- Concurrent group

Model
Group tasks
Ordered group
Concurrent group

- Task som ska hända efter varandra i en viss ordning på samma maskin
-
- Representera en task med flera maskiner

Filter

- Temporal filter
- Predecessor filter

Filter
Temporal filter
Predecessor filter

Filtrera domäner
Temporal filter:

- Matris med alla möjliga moves → 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
  - Assembly times
  - Solver time
  - FlatZinc file
- MiniZinc 1.6 & 2.0.1
- Combination of filters

Evaluation
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FlatZinc file:

- Antal variabler
- Antal constraints
- Andel av constraints som är reified constraints

Reified:

- Kopplar ihop ett constraint med en variable("sanningsvärde") $\rightarrow$ är variabeln sann måste constraint:et gälla, är varibeln falsk kan inte constraint:et gälla, och vise versa
- Används ofta för implikationer och ekvivalenser
- Kan göra söktiden längre
- Aktivt unvikit direkta användningar

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
or-tools
Opturion CPX
Choco3

Assembly Times

Manual Time
516 t.u.

Assembly Times
Manual Time
516 t.u.

- Uppskattat från video
- 1 t.u. $\neq$ 1 s. 1 t.u. $\approx$ 4 s
- I stort sätt samma tid
- Assemblyn från solver samma som handgjord
- Skillnad beror på när moves påbörjas i relation till andra tasks

Assembly Times

Manual Time
516 t.u.

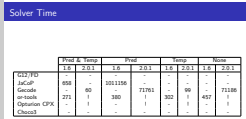
Solver Time
512 t.u.

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

- Uppskattat från video
- 1 t.u. $\neq$ 1 s. 1 t.u. $\approx$ 4 s
- I stort sätt samma tid
- Assemblyn från solver samma som handgjord
- Skillnad beror på när moves påbörjas i relation till andra tasks

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	-	-	-	-	-	-	-	-

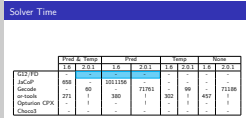


- Tid - Solvern hittade den optimala lösningen och avslutade sökninigen → konstaterade att det var den optimala, inom 4h
- ! - Fel i inläsning av FlatZinc
- - - Solvern avslutade inte sökningen inom 4h, men kan ha hittat lösningar(inklusive optimal)
- Notera Gecode och 2.0.1 vs 1.6
- 1011156 - 0:16:51
- 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

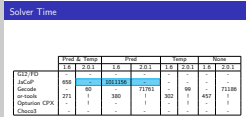
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-



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	-	-	-	-	-	-	-	-

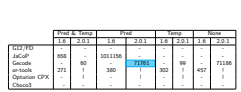


Hittar hittar alla lösningar, inklusive optimala

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	-	-	-	-	-	-	-	-

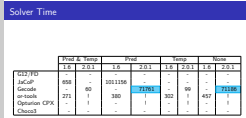
Solver Time



Hittar 3 lösningar, inklusive optimala

Solver Time

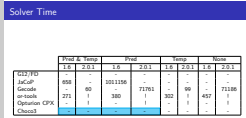
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-



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

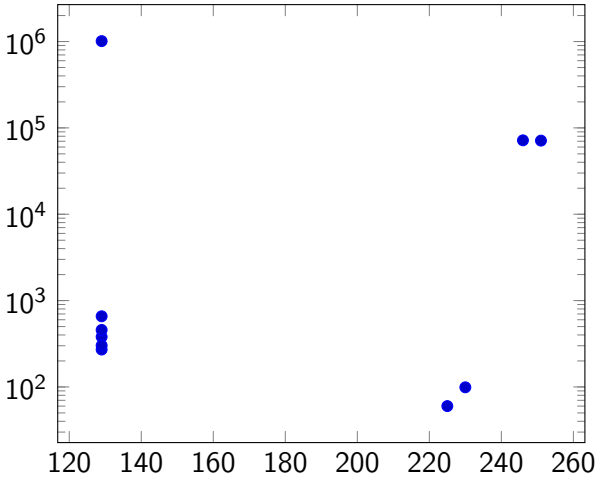
Solver Time

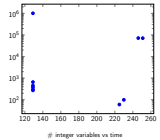
	Pred & Temp		Pred		Temp		None	
	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1	1.6	2.0.1
G12/FD	-	-	-	-	-	-	-	-
JaCoP	658	-	1011156	-	-	-	-	-
Gecode	-	60	-	71761	-	99	-	71186
or-tools	271	!	380	!	302	!	457	!
Opturion CPX	-	!	-	!	-	!	-	!
Choco3	-	-	-	-	-	-	-	-

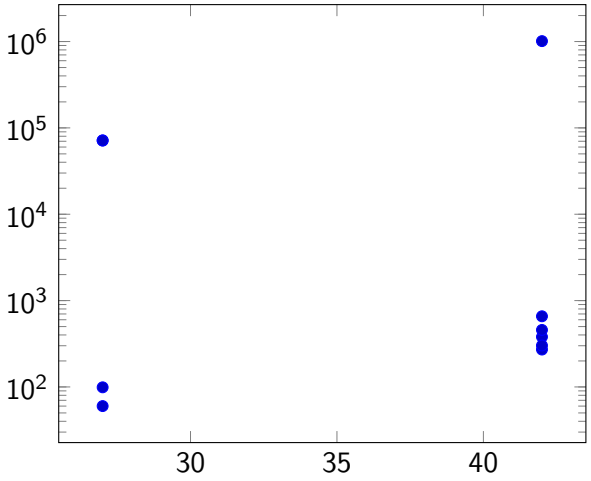


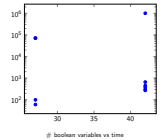
Hittar 2 lösningar direkt

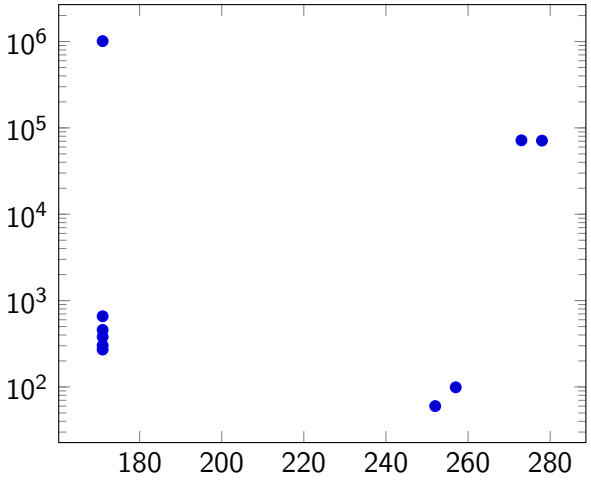
- np-komplett → kan inte garatera någon lösning
- Vi vet endast att de som avslutade sökningen i detta fallet kan avsluat sökninigen inom tid → vet inget om andra fall
- Även de solvers som inte avlsutade sökningen kan vara av värde i andra situationer


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

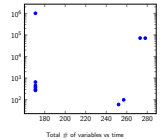


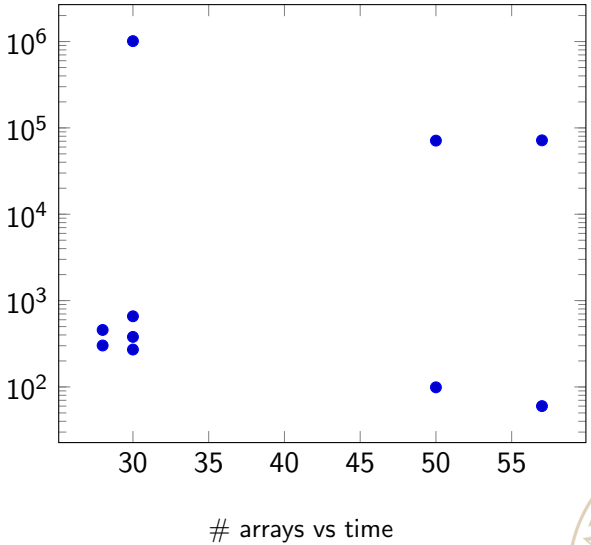

10^6
10^5
10^4
10^3
10^2
30
35
40
boolean variables vs time

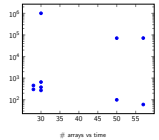


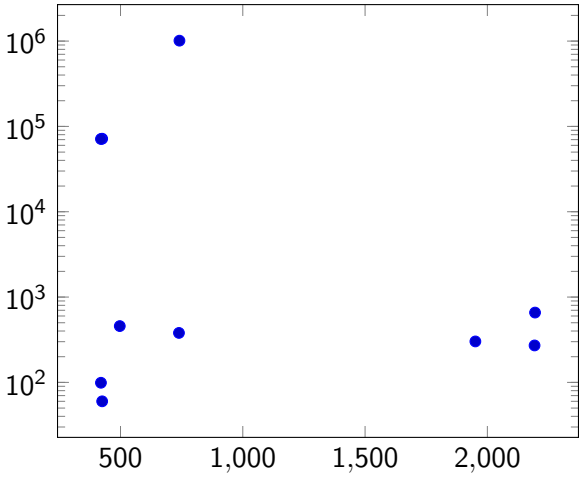


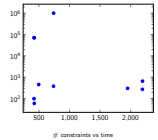
Total # of variables vs time

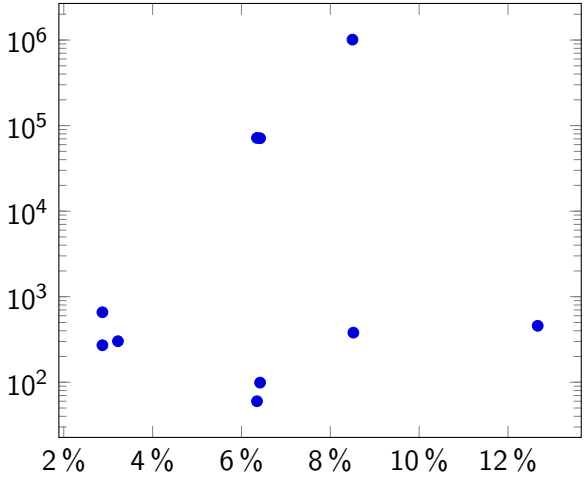


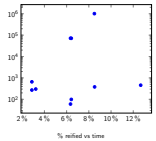

10^6
10^5
10^4
10^3
10^2
30
35
40
45
50
55
arrays vs time

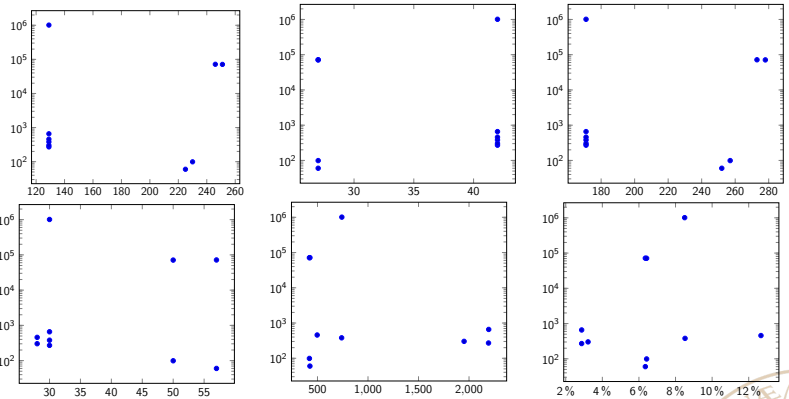


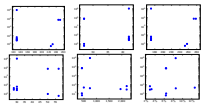

10^6
10^5
10^4
10^3
10^2
500
1,000
1,500
2,000
constraints vs time




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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Further work

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1. Kanske dyker upp problem missade. T.ex. kollisioner
2. Endast testat filter i grupp, alla filter kanske inte behövs, bygga vidare på dem som fungerade bäst
3. Vi antar att det finns en uppsättning tools till varje maskin, så kanske inte är fallet, finns kanske bara ett visst antal tools tillgängliga
4. Vi har bara resultat för denna assemblyn, resultat kanske varierar beroende på assembly