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

## MiniZinc modeling and solver comparison

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February 23, 2015





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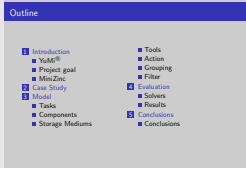
# Outline









# Introduction - YuMi®

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

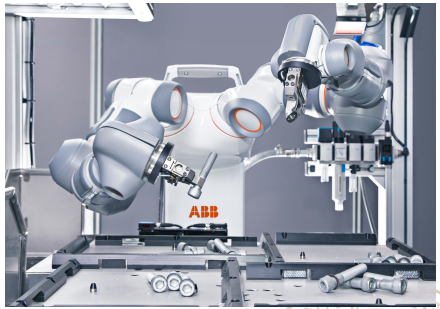
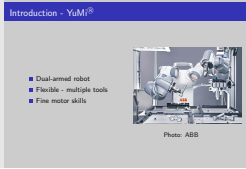



Photo: ABB





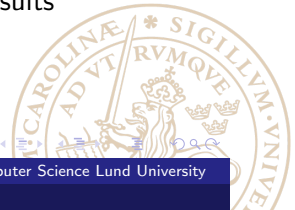



Mycket av produktion i dagens samhälle automatiseras & många produkter serier har kort livsspann → produktionen av nya serier behöver anpassas relativt snabbt → YuMi

1. Montera endast mellan maskiner utan tray

# 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







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

# Introduction - MiniZinc

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





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

- 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 läät 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

# Case Study





Case Study

Skruvarna inte med

# Case Study

# Physical Entities

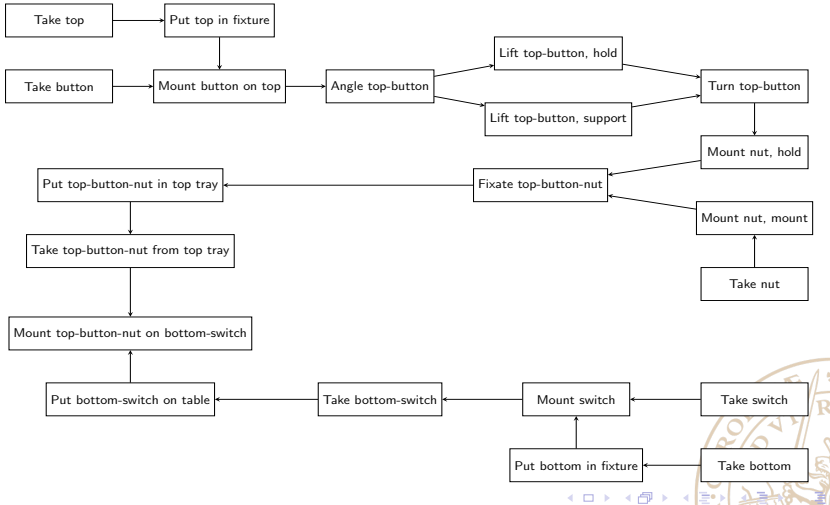
- Machines
- Tools
- Components
- Tray
- Fixture
- Output





Physical Entities
Machines
Tools
Components
Tray
Fixture
Output

# Assembly


Take top
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Take nut
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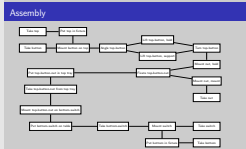
Put bottom-switch on table
Take bottom-switch
Mount switch
Take switch
Put bottom in fixture
Take bottom






Assembly

# Model

Job Shop Problem

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



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

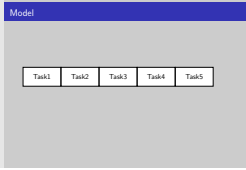
# Model

| Task1 | Task2 | Task3 | Task4 | Task5 |
|---|---|---|---|---|

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







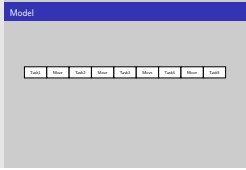
# Model

| 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







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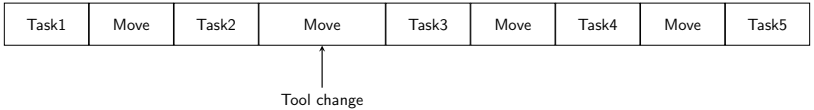
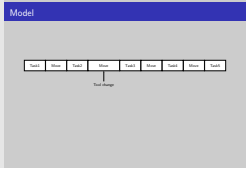



- Tasks behöver olika tools → måste utföra tool change
- utförs mellan två tasks → tiden att röra sig mellan två tasks tar längre tid → bakar in tool change tiden i move
- Det förekommer ett tool change om tiden för move tar längre tid än det egentligen skulle göra







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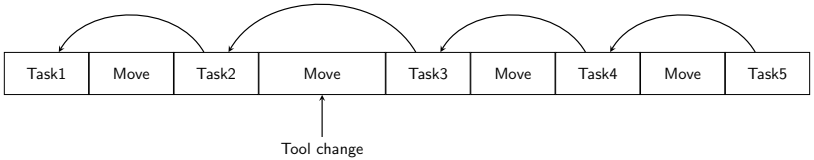
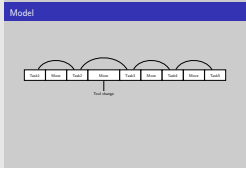



- Hur lång tid det tar beror på vilken task som kommer innan → vi måste veta vilken task som kommer innan, *predecessor*
- Tidsmatrisen tillsammans med tiderna för att byta mellan tools = ny matris med alla möjliga moves inkl. tool change
- Detta = Job Shop Problem with sequence-dependent setup times
- 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





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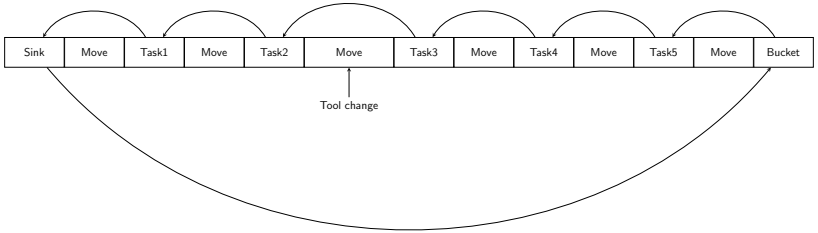
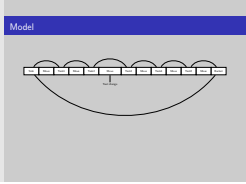



- Introducerar sink node/startTask & bucket node/goalTask
- Men detta måste göras för varje maskin, tasks måste fördelas $\rightarrow$ *usingMachine*$(t) \rightarrow$ task och predecessor måste vara på samma maskin







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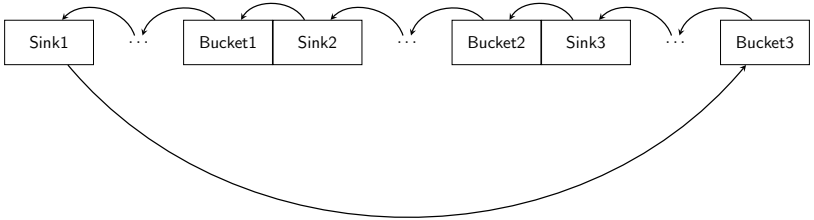
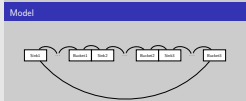



- För att göra det för flear maskiner: Istället för lika många circuits som maskiner, kopplar ihop alla curcuits till en lång circuit
- Vi har alltså 4 variabler att schemalägga: tasks, moves, predecessors & usingMachine







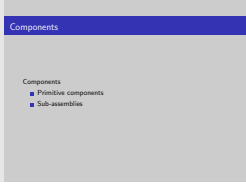
# Components

Components

- Primitive components
- Sub-assemblies








Hur definierar vi en task?

- Primitive components: komponenter som ges till assemblyn utifrån
- Sub-assemblies: består av primitive components och andra sub-assemblies
- I modellen ses båda som components → underkategorier
- man markerar den task en sub-assembly blir skapad

# Storage Mediums

Storage mediums

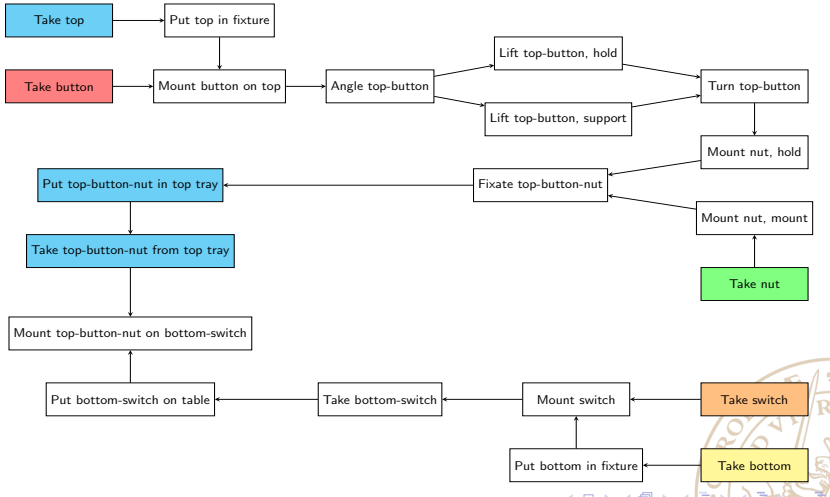
- Tray - Top tray, Button tray, etc.
- Fixture
- Output





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

# Tray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Take nut
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Put bottom-switch on table
Take bottom-switch
Mount switch
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Put bottom in fixture
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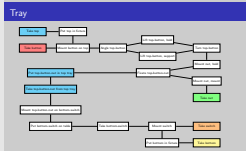
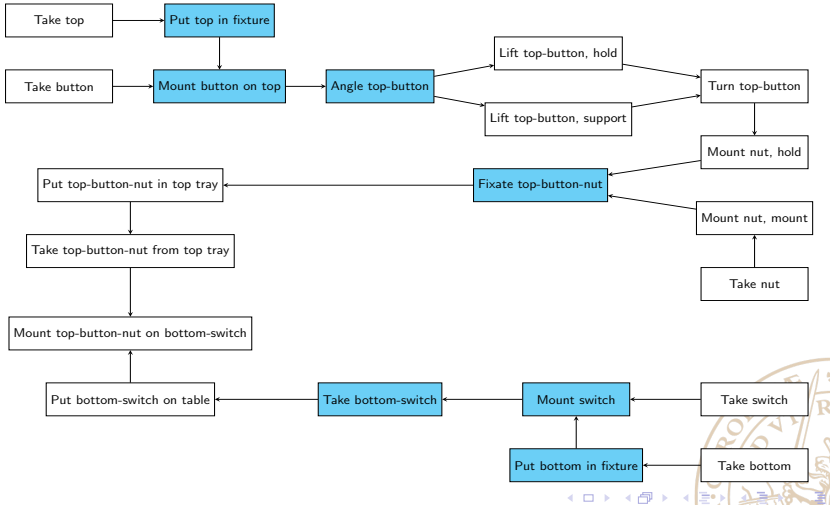
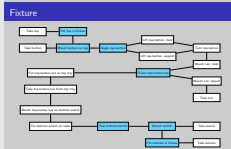

Tray

# Fixture





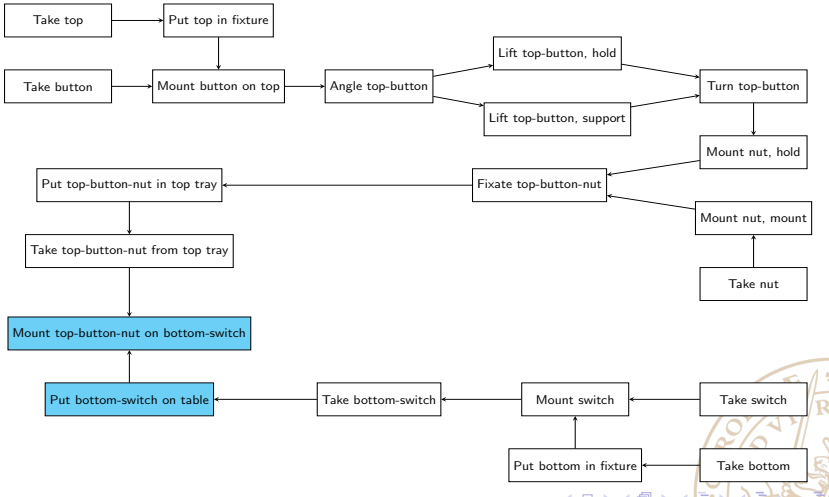



Undvika kollision:

- Individuella tasks får inte överlappa på fixtures, trays eller outputs
- 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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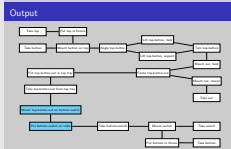

Output

# Tools

- Tools available
- Tool used by tasks

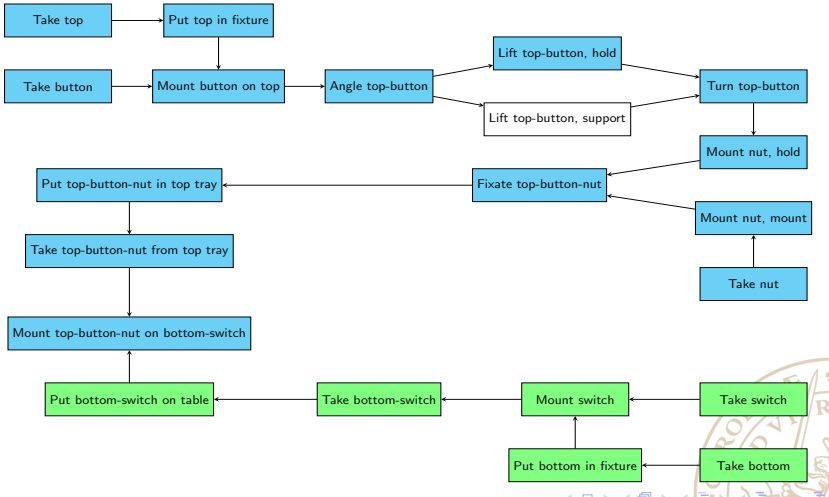
- För att veta när en tool change uppstår
- Antar att det finns en uppsättning av sagda tools för varje maskin





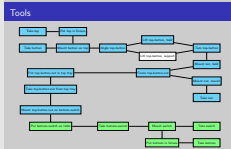
Tools
Tools available
Tool used by tasks

# Tools








- Notera att "Lift top-button" inte har tool specificerad → ger mer frihet med tool changes

# Action

Task actions

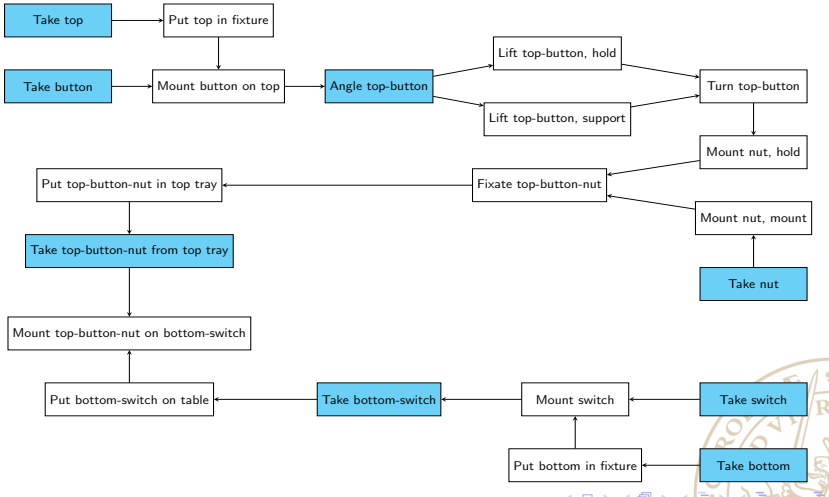
- Taking
- Mounting
- Putting
- Moving





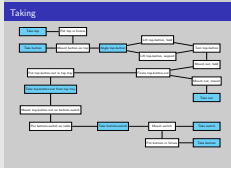
Action
Task actions
Taking
Mounting
Putting
Moving

# Taking



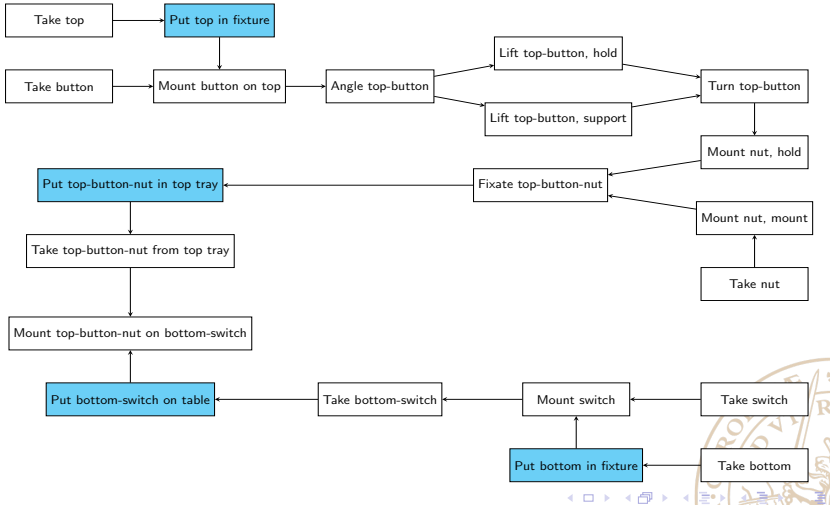




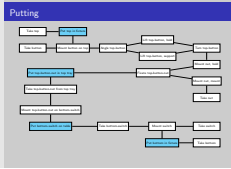

Angle skulle kunna delas in i två tasks, en taking och en moving

# Putting





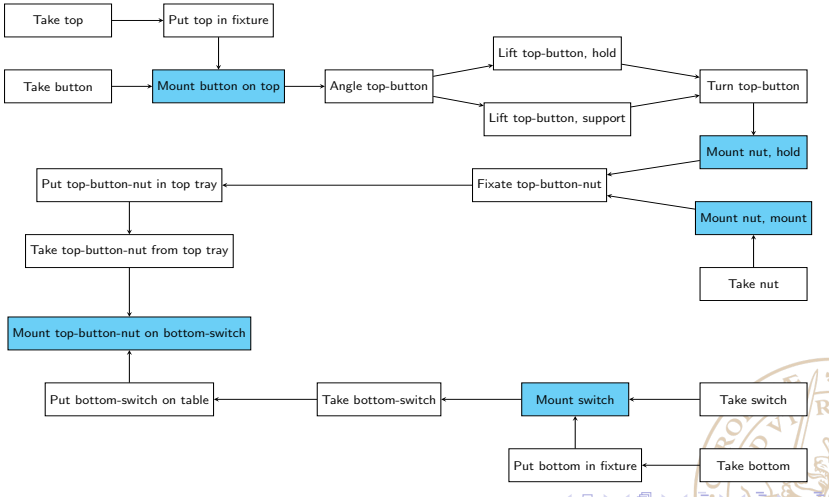



Ex. constraint

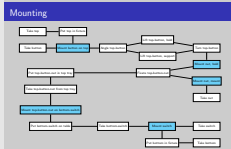
För tasks på en komponent, där det finns en take och en put, t.ex top (take top & put top in fixture), måste take:en vara predecessor till put:en

# Mounting





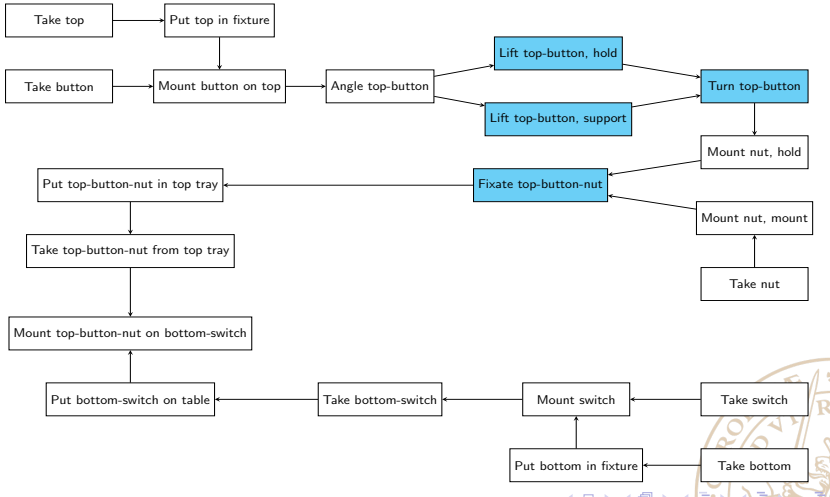



Ex. constraint

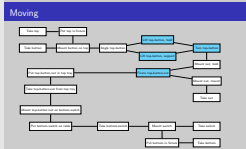
För tasks på en komponent, där det finns en take och en mount men ingen put, t.ex button (take button & Mount button on top), måste take:en vara predecessor till mount:en

# Moving








- Vi kan inte sätta upp constraint om ordning baserat på att tasks är move.
- T.ex. kan flera move hantera tasks med samma komponent (ex. highlight:ade) → kan inte säga något om ordningen.
- Så för att bl.a. lösa det: ↓

# Model

Group tasks

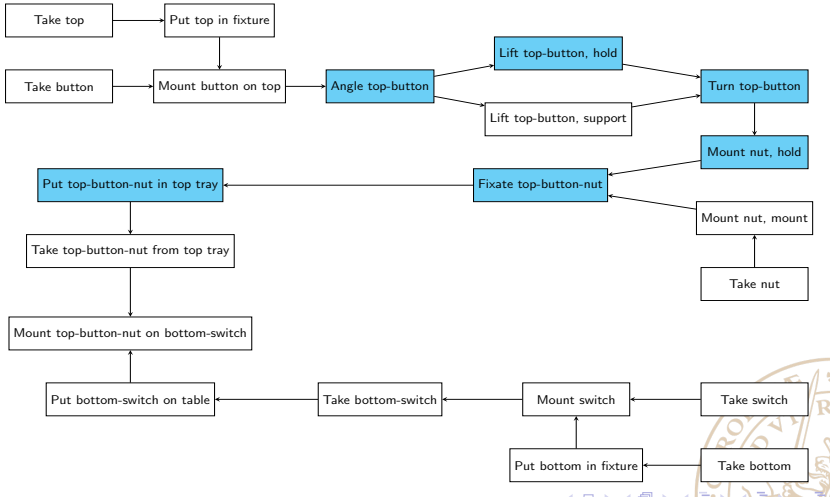
- Ordered group
- Concurrent group





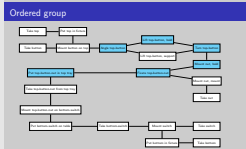
Model
Group tasks
Ordered group
Concurrent group

# Ordered group



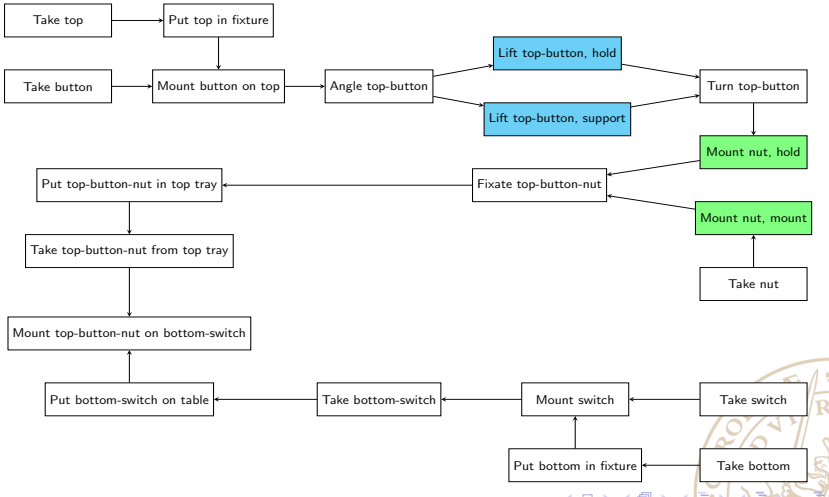




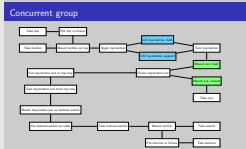

- Array med tasks
- Sätter upp predecessors

# Concurrent group







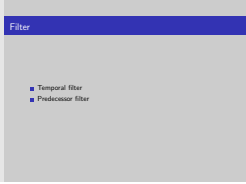

- Representera en task med flera maskiner
- En task med flera maskiner vs flera concurrent tasks
- En task med flera maskiner → tasks måste kunna ha flera predecessors → fungerar inte här

# 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:

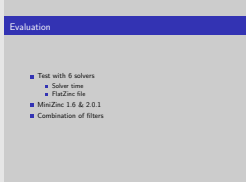
- Vi vet att put och mount tasks inte kan komma först, då komponenten måste plockas upp först
  → $pred(putTask/mountTask) \neq startTask$
- Då allting måste sitta i outputs i slutet av assemblyn
  → $pred(goalTask) \neq takeTask$
- Tasks som använder components som är sub-components i en annan task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

# Evaluation

- Test with 6 solvers
  - Solver time
  - FlatZinc file
- MiniZinc 1.6 & 2.0.1
- Combination of filters








FlatZinc file:

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

Reified:

- Kopplar ihop ett constraint med en variable("sanningsvärde") → 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

OM MINDRE ÄN 10 MINUTER KVAR, HOPPA SOLVERINTRODUKTIONER

# 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
- 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





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
- Gold medals 2013-2014





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

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.

- 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.

# 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





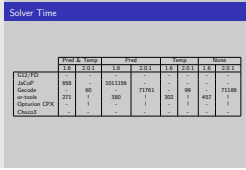
Assembly Times
Manual Time 516 t.u.
Solver Time 512 t.u.

# 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 | - | - | - | - | - | - | - | - |





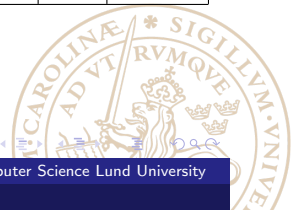



- Tid - Solvern hittade den optimala lösningen och avslutade sökninigen → konstaterade att det var den optimala, inom 4h
- ! - Fel i inläsning av FlatZinc
- - - Solvern avslutade inte sökningen inom 4h, men kan ha hittat lösningar(inklusive optimal)
- Notera Gecode och 2.0.1 vs 1.6
- 1011156 - 0:16:51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

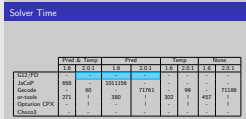
# Solver Time

| | 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 |
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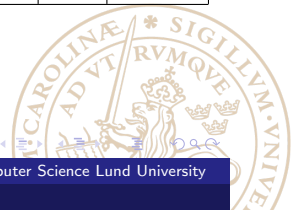
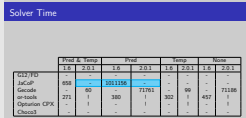
| Opturion CPX | - | ! | - | ! | - | ! | - | ! |
| Choco3 | - | - | - | - | - | - | - | - |







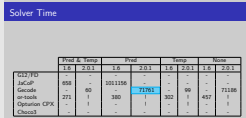



Hittar hittar alla lösningar, inklusive optimala

# 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 | - | - | - | - | - | - | - | - |





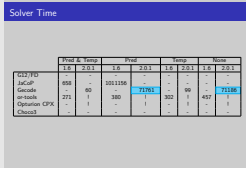

Hittar 3 lösningar, inklusive optimala

# 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 | - | - | - | - | - | - | - | - |







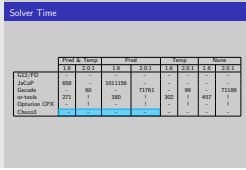

Hittar 1 lösning, den optimala, på ungefär samma tid som den tidigare

# 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 | - | - | - | - | - | - | - | - |

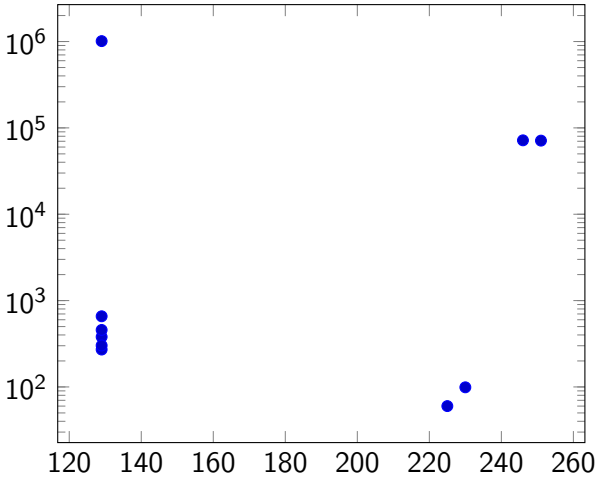






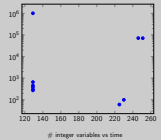

Hittar 2 lösningar direkt

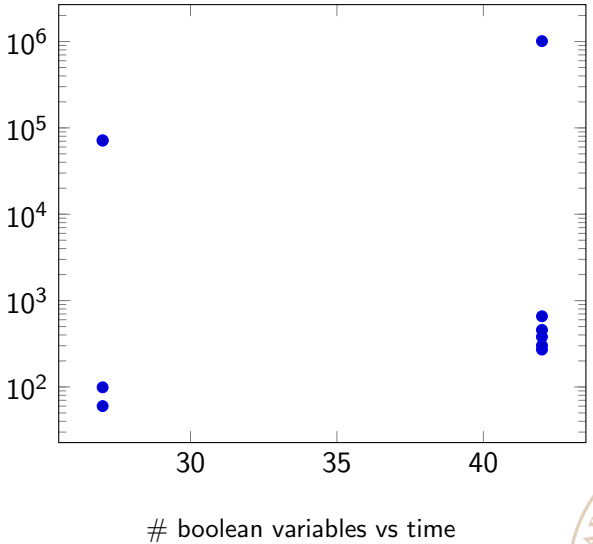
- np-komplett → kan inte garatera någon lösning
- Vi vet endast att de som avslutade sökningen i detta fallet kan avsluat sökninigen inom tid → vet inget om andra fall
- Även de solvers som inte avlsutade sökningen kan vara av värde i andra situationer


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



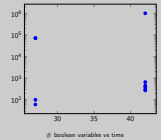


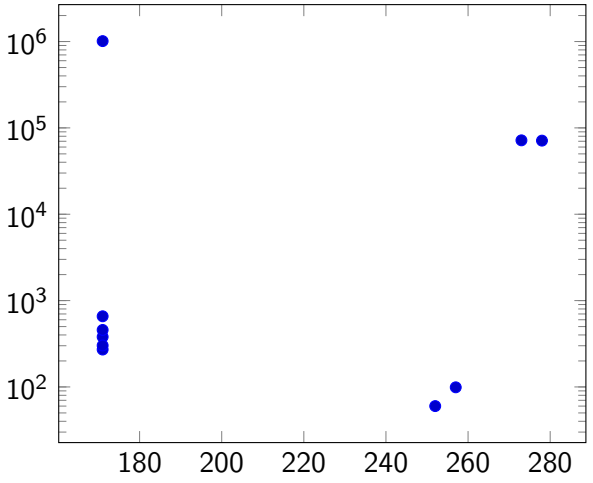



$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
30
35
40
# boolean variables vs time





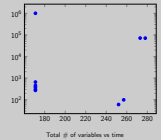


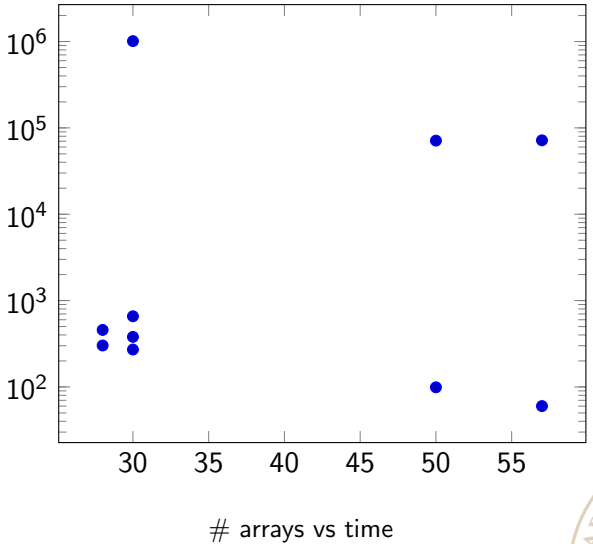



Total # of variables vs time



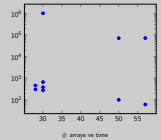


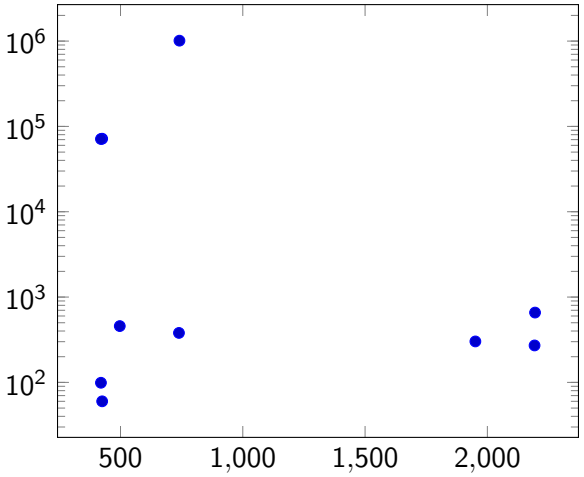



$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
30
35
40
45
50
55
# arrays vs time



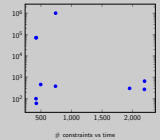


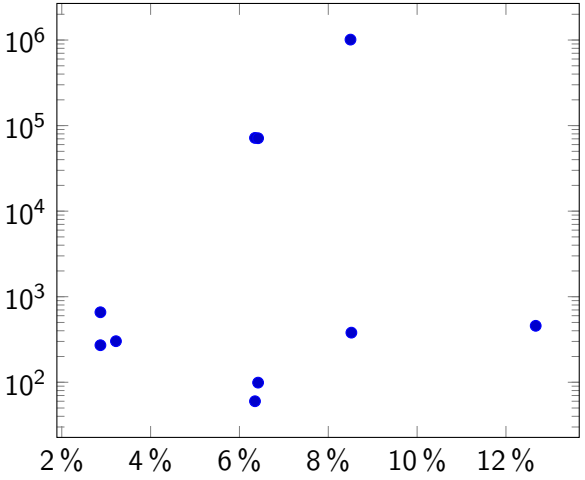



$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
500
1,000
1,500
2,000
# constraints vs time



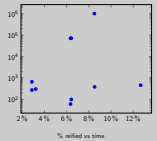


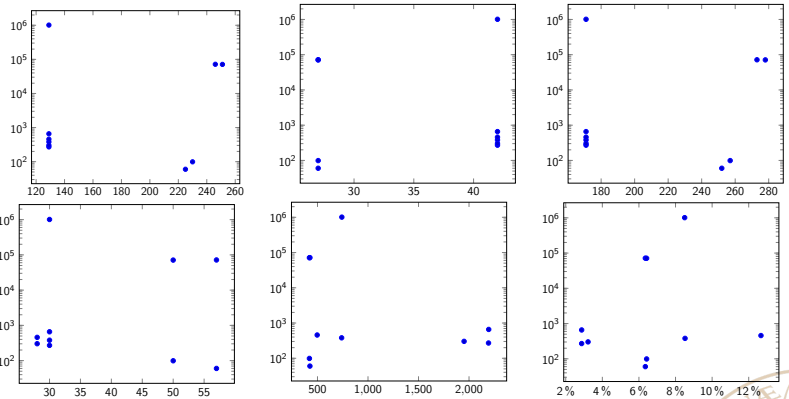



$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
2 %
4 %
6 %
8 %
10 %
12 %
% reified vs time



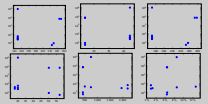





$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
120 140 160 180 200 220 240 260
30 35 40
180 200 220 240 260 280
30 35 40 45 50 55
500 1,000 1,500 2,000
2% 4% 6% 8% 10% 12%







# Conclusions

# Conclusions

- Model produces solution just as good as handmade solution





Conclusions
Model produces solution just as good as handmade solution

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- Model produces solution just as good as handmade solution
- Solver performance varies a lot





Conclusions
Model produces solution just as good as handmade solution
Solver performance varies a lot

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- Solver performance varies a lot
- Best performance: Gecode, all filters, MiniZinc 2.0.1





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Conclusions
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- Filters presented have a positive impact on runtime
- No relation between FlatZinc output and solver runtime

# Further work

- Test the result on a real robot
- Further testing of the filters
- More realistic representation of tools available
- Test solvers with more assemblies

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





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- More realistic representation of tools available
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