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# Experiments

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## Constraint Based Production Scheduling





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# Key Points



- This section describes the scheduling tool
  - This is a *preview* of the current state, not released yet!
- How to load/create data
  - From files
  - By instance generator
  - From benchmark problems
- How to run the solvers
  - Which solvers are supported
  - What to expect in terms of performance
- Experiments to try
  - Limited time
  - Possible "test before invest" continuation

# Outline



The Scheduling Tool

Under the hood

Input Data

Result Output

Instance Generator

Predefined Problem Sets

Some Suggested Experiments

Summary

# The Scheduling Tool



- We create the tool as basis for experiments
- To test ideas and solvers
- As a teaching tool
- Slightly higher standard than usual academic prototypes
  - This is a *preview*, not released yet
- Not a commercial tool
  - But can use commercial solvers
  - Also open-source solvers
- Written in Java, JavaFX
- Can also be used as a back-end scheduling server
- Uses our Java application framework generator
- Will become available in early 2025

# Outline



The Scheduling Tool

Under the hood

- Google CP Sat

- IBM CPOptimizer

- MiniZinc

- Which solver is better?

Input Data

Result Output

Instance Generator

Predefined Problem Sets



- Provide both open-source and commercial solver interfaces
- Allow experimentation without having to buy commercial tools straightaway
- Gives a level playing field to compare solvers and models
- Provides out-of-the-box, generic performance



- Open-Source tool provided by Google
- Available at [https://developers.google.com/optimization/cp/cp\\_solver](https://developers.google.com/optimization/cp/cp_solver)
- Probably best open-source CP solver for scheduling
- This solver is packaged with scheduler

## Example Problem

Below is a simple example of a job shop problem, in which each task is labeled by a pair of numbers  $(m, p)$  where  $m$  is the number of the machine the task must be processed on and  $p$  is the processing time of the task – the amount of time it requires. (The numbering of jobs and machines starts at 0.)

- Job 0 =  $\{(0, 3), (1, 2), (2, 2)\}$
- Job 1 =  $\{(0, 2), (2, 1), (1, 4)\}$
- Job 2 =  $\{(1, 4), (2, 3)\}$

In the example, job 0 has three tasks. The first,  $(0, 3)$ , must be processed on machine 0 in 3 units of time. The second,  $(1, 2)$ , must be processed on machine 1 in 2 units of time, and so on. Altogether, there are eight tasks.

## A solution for the problem

A solution to the job shop problem is an assignment of a start time for each task, which meets the constraints given above. The diagram below shows one possible solution for the problem:



You can check that the tasks for each job are scheduled at non-overlapping time intervals, in the order given by the problem.

The length of this solution is 12, which is the first time when all three jobs are complete. However, as you will see [below](#), this is not the optimal solution to the problem.

(from OR-Tools website)

# CP Optimizer from IBM



- Commercial tool of IBM
- <https://www.ibm.com/products/ilog-cplex-optimization-cplex-cp-optimizer>
- Part of optimization suite with Cplex, OPL
- We do **not** provide this solver, we allow to interface with it
- Academic licenses available
- Well-known for capabilities for scheduling

## Resources



### Applications of constraint programming

Explore applications of constraint programming including production problem and scheduling use cases.

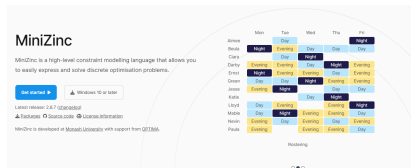
[Read the documentation](#) →

(from CPOptimizer website)

# MiniZinc from Monash University



- Modelling language and backend tools from Monash University in Melbourne, Australia
- Available from <https://www.minizinc.org/>
- Widely used for teaching
- Allows different backend solver to run from same model
- Generic CP tool, not optimized for scheduling
- Requires separate installation, open-source



(from MiniZinc Website)

# Which Solver is Better?



- We present results on a few benchmark types
- Fair comparison between solvers
  - Same hardware, Windows 11 laptop
  - CPU i7-10875H @ 2.3GHz, 64GB, four cores
  - Same timeout (600 s)
- Not a fair comparison to state-of-the-art
  - Uses out-of-the-box model
  - Significant improvements possible
  - More specific models
  - Parameter tuning
  - Unlimited runtime

# Taillard Job-Shop Benchmarks



Group	Nr	All Instances				Optimal Only		Non Optimal Only			
		Optimal (% of All Instances)				Time (% of VB)		Cost (% of VB)		Bound (% of VB)	
		Both	CPO	CPSat	None	CPO	CPSat	CPO	CPSat	CPO	CPSat
15/15	10	90.00	0.00	0.00	10.00	105.19	141.18	100.00	100.00	97.17	100.00
20/15	10	20.00	0.00	0.00	80.00	267.27	263.20	100.99	100.05	98.50	99.93
20/20	10	0.00	0.00	0.00	100.00	n/a	n/a	100.74	100.06	97.96	100.00
30/15	10	10.00	0.00	10.00	80.00	174.32	100.00	100.18	100.49	99.87	100.00
30/20	10	0.00	0.00	0.00	100.00	n/a	n/a	100.30	101.30	99.40	100.00
50/15	10	100.00	0.00	0.00	0.00	100.00	685.09	n/a	n/a	n/a	n/a
50/20	10	10.00	60.00	0.00	30.00	100.00	381.38	100.00	101.60	100.00	100.00
100/20	10	10.00	90.00	0.00	0.00	100.00	416.13	100.00	101.73	100.00	66.81

- Significant number of problems solved to optimality in 600s
- In terms of quality, solvers are quite similar
- CPO wins in terms of solution times for larger instances

# Results for Hybrid Flexible Flow-Shop



Group	Nr	All Instances				Optimal Only		Non Optimal Only			
		Optimal (% of All Instances)				Time (% of VB)		Cost (% of VB)		Bound (% of VB)	
		Both	CPO	CPSat	None	CPO	CPSat	CPO	CPSat	CPO	CPSat
20	25	76.00	0.00	20.00	4.00	100.00	580.71	100.00	100.00	96.52	100.00
25	25	80.00	0.00	8.00	12.00	101.65	238.02	100.00	100.37	97.67	100.00
30	25	60.00	0.00	4.00	36.00	100.35	264.69	100.18	101.05	100.00	100.00
40	25	4.00	16.00	0.00	80.00	100.00	2554.03	100.00	104.68	100.00	100.00
50	25	0.00	4.00	0.00	96.00	n/a	n/a	100.00	107.87	100.00	100.00
100	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	120.43	100.00	100.00
200	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	188.60	100.00	100.00
300	24	0.00	0.00	0.00	100.00	n/a	n/a	100.00	263.22	100.00	100.00
400	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	246.34	100.00	100.00

- Only smaller/medium instances solved to optimality
- For those problems, both solvers perform well
- CPO significantly better on large instances

# General Recommendations



- If you already have access to CPO, use it!
- For new problem types, do an evaluation with CPSat first
- Out of the box, CPO performs more consistently
- May be easier to extend CPSat with your own research
- Use multiple cores and memory to your advantage

# Outline



The Scheduling Tool

Under the hood

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Summary





- We have defined a specific JSON data format to describe scheduling problems
- This is different from the native/XML data format of the application (do not use)
- Load with menu `File - Load DataFile...`
- Save with menu `File - Save DataFile...`
- The format is described in a document

name	ProdID
Prod0	
Process 0	

name Process 0

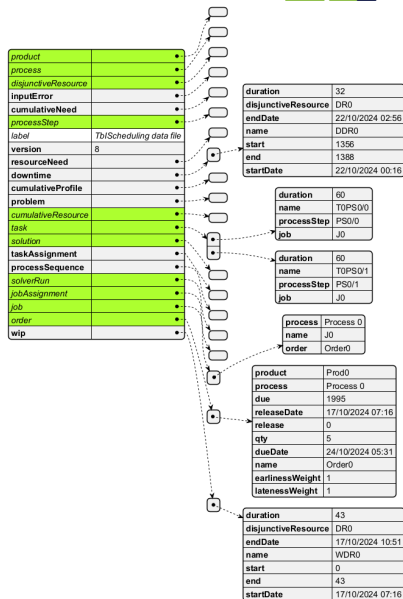
name DR0

- [illegible]

# Schedule Input Data



- Description of
  - Downtime
  - Task (x2)
  - Job
  - Order
  - WiP



# Outline



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- We use the same JSON format to describe the results of the schedule
- Added field types for SolverRun, Solution, assigned Jobs and Tasks

# Sample Results



- Description of
  - Solution
  - SolverRun
  - Job Assignment
  - Task Assignment

product	
process	
disjunctiveResource	
inputOrder	
constraintOrder	
resourceType	745:hourly:slot:file
version	0
resourceUsed	
downTime	
constraintOrder	
problem	
constraintResource	
task	
taskOrder	
taskAssignment	
resourceSequence	
disjunctive	
jobAssignment	
job	
unit	
unit	

totalSpan	163
totalEarliness	1832
maxTime	17/10/2024 20:51
totalWaitBefore	0
early	1
percentEarly	100
duration	129
maxEarliness	0
maxWaitAfter	0
early	0
job	0
jobOrder	Start
end	163
weightedEarliness	1832
totalLateness	0
maxWaitBefore	0
total	183
percentLate	Critical
start	43
totalWaitAfter	0
percentLate	0
weightedLateness	1832
maxEarliness	0
name	Set1
objectiveValue	163
maxTime	163
startDate	17/10/2024 10:51

duration	80
waitAfter	0
task	TOP00/1
disjunctiveResource	DRO
startDate	17/10/2024 19:51
name	TA8
start	43
end	103
jobAssignment	JAO
waitBefore	0
startDate	17/10/2024 19:51

duration	90
waitAfter	0
task	TOP00/1
disjunctiveResource	DRO
startDate	17/10/2024 20:51
name	TA1
start	103
end	163
jobAssignment	JAO
waitBefore	0
startDate	17/10/2024 19:51

enForce	2
weightEarliness	1
end	42
constraintOrder	None
weightLateness	1
problemCP	Critical
constraintOrder	Critical
description	
label	
resourceType	CPO
enforceMtg	51 hour
objectiveType	Minimize
constraint	20
weightDownTime	1
enforceCumulative	51 hour
name	Start
weightLateness	1
time	8:142
problemReport	Critical
enforceDownTime	51 hour
enforceLateness	Critical
enforceDueDate	51 hour
enforceDueDate	Critical

duration	129
solution	Set1
time	0
endDate	17/10/2024 20:51
name	JAO
start	43
end	163
job	20
early	1832
startDate	17/10/2024 10:51

# Outline



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Summary



- Application allows to generate different types of test problems
- Different types of resource models
- Different numbers of orders, resources, WiP, downtime
- Useful to generate more life-like examples combining different constraint types



# Instance Generator Dialog



- Resource Model
  - Select a resource model defining the overall structure of problem
- Nr Disjunctive Resources
  - Describe how many disjunctive resources are generated
- Resource Probability
  - The probability that a resource is compatible with a task
  - Only for some resource models

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. The 'Label' field is empty. The 'StartDate' is set to '01/10/2024' and the 'Start Time' is '0 : 00'. The 'Resource Model' is set to 'HybridFlowShop'. The 'Nr Disjunctive Resources' slider is set to 7. The 'Resource Probability' slider is set to 0.3. The 'Cumulative Resource' section is expanded, showing 'Nr Cumulative Resources' set to 1, 'Cumul Demand Range' set to 1, 'Profile Pieces' set to 3, and 'Cumul Capacity Range' set to 6. The 'Orders' section is also expanded, showing 'WIP', 'Downtime', and 'Other Parameters' sub-sections. At the bottom right are 'Run' and 'Cancel' buttons.

# Resource Models



- Flow-Shop
  - Multiple stages, all jobs use machines in same order
- Job-Shop
  - Multiple stages, jobs use machines in different order
- Open-Shop
  - Multiple stages, no predefined order of machines
- Hybrid Flow-Shop (default)
- Hybrid Job-Shop
- Hybrid Open-Shop
  - Like x-shop, but with multiple machines per stage
- Random
  - Multiple stages, each stage using a random subset of machines
- All
  - Multiple stages, each stage allowing all machines

# Instance Generator - Products



- Nr Products
  - Number of products to be generated
  - Products may be reused by multiple orders
- Stages Range
  - Range slider, sets lower and upper bound on number of stages

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. The 'Label' field is empty. The 'StartDate' is set to '01/10/2024' and the 'Start Time' is '0 : 00'. The 'Resource Model' is set to 'HybridFlowShop'. The 'Nr Disjunctive Resources' slider is set to 7. The 'Resource Probability' slider is set to 0.3. The 'Products' section is expanded, showing 'Nr Products' set to 10 and 'Stages Range' set to 4. Other sections like 'Duration', 'Cumulative Resource', 'Orders', 'WIP', 'Downtime', and 'Other Parameters' are collapsed. 'Run' and 'Cancel' buttons are at the bottom right.

Data Generator Parameters

Label:

StartDate:  Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

**Products**

Nr Products:

Stages Range:

► Duration

► Cumulative Resource

► Orders

► WIP

► Downtime

► Other Parameters

Run Cancel

# Instance Generator - Duration



- Duration Model
  - Different ways to link duration of processSteps
- Duration Range
  - Range slider to set lower and upper bounds on perUnit duration
- Duration Fixed Factor
  - How fixed and perUnit duration values are linked

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. At the top, there is a 'Label' field, a 'StartDate' field set to '01/10/2024', and a 'Start Time' field set to '0 : 00'. Below these is a 'Resource Model' dropdown menu set to 'HybridFlowShop'. There are two sliders: 'Nr Disjunctive Resources' with a range from 1 to 20 and a value of 7, and 'Resource Probability' with a range from 0 to 1 and a value of 0.3. A section titled 'Products' is expanded, showing a 'Duration' sub-section. Inside 'Duration', there is a 'Duration Model' dropdown set to 'Random', a 'Duration Range' slider with a range from 1 to 50 and a value of 16, and a 'Duration Fixed Factor' slider with a range from 0 to 5 and a value of 1. Below the 'Duration' section are several collapsed sections: 'Cumulative Resource', 'Orders', 'WIP', 'Downtime', and 'Other Parameters'. At the bottom right, there are 'Run' and 'Cancel' buttons.

# Instance Generator - Cumulative



- Nr Cumulative Resources
  - Number of cumulative resources generated
- Cumul Demand Range
  - Range slider to select lower and upper bound on cumulativeResource-Need demands
- Profile Pieces
  - Number of segments of CumulativeProfile generated for each resource
- Cumul Capacity Range
  - Range slider to select lower and upper bounds on cumulative profile

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. The 'Label' field is empty. 'StartDate' is set to '01/10/2024' and 'Start Time' is '0 : 00'. 'Resource Model' is set to 'HybridFlowShop'. 'Nr Disjunctive Resources' is a slider from 1 to 20, currently at 7. 'Resource Probability' is a slider from 0 to 1, currently at 0.3. The 'Cumulative Resource' section is expanded, showing 'Nr Cumulative Resources' (slider 1-5, at 3), 'Cumul Demand Range' (slider 1-10, at 3), 'Profile Pieces' (slider 1-5, at 3), and 'Cumul Capacity Range' (slider 1-30, from 6 to 11). Other sections like 'Products', 'Duration', 'Orders', 'WiP', 'Downtime', and 'Other Parameters' are collapsed. 'Run' and 'Cancel' buttons are at the bottom right.

# Instance Generator - Orders



- Nr Orders
  - Number of orders generated, each order is assigned a random product/process
- Qty Range
  - Range slider to select lower and upper bounds on quantity for each order

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. The 'Label' field is empty. The 'StartDate' is set to '01/10/2024' and the 'Start Time' is '0 : 00'. The 'Resource Model' is set to 'HybridFlowShop'. The 'Nr Disjunctive Resources' slider is set to 7. The 'Resource Probability' slider is set to 0.3. The 'Orders' section is expanded, showing 'Nr Orders' set to 50 and 'Qty Range' set to 1 to 11. Other sections like 'Products', 'Duration', 'Cumulative Resource', 'WIP', 'Downtime', and 'Other Parameters' are collapsed. 'Run' and 'Cancel' buttons are at the bottom right.

Data Generator Parameters

Label:

StartDate:  Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

► Products

► Duration

► Cumulative Resource

▼ Orders

Nr Orders:

Qty Range:

► WIP

► Downtime

► Other Parameters

Run Cancel

# Instance Generator - WiP (Work in Progress)



- WiP Probability
  - Probability of generating a WiP for a disjunctive resource
- WiP Range
  - Range slider to set lower and upper bound on WiP duration

A screenshot of the 'Data Generator Parameters' dialog box. It contains several input fields and sliders. The 'Label' field is empty. The 'StartDate' is set to '01/10/2024' and the 'Start Time' is '0 : 00'. The 'Resource Model' is set to 'HybridFlowShop'. The 'Nr Disjunctive Resources' slider is set to 7. The 'Resource Probability' slider is set to 0.3. The 'Products' section is expanded, showing 'Duration', 'Cumulative Resource', 'Orders', and 'WiP'. The 'WiP' section is further expanded, showing a 'WiP Probability' slider set to 1 and a 'WiP Range' slider set from 21 to 51. The 'Downtime' and 'Other Parameters' sections are collapsed. 'Run' and 'Cancel' buttons are at the bottom right.

# Instance Generator - Downtime



- Downtime Probability
  - Probability of generating a downtime for a disjunctive resource
- Downtime Range
  - Range slider to select lower and upper bounds on downtime duration

A screenshot of the 'Data Generator Parameters' dialog box. It contains fields for 'Label', 'StartDate' (01/10/2024), and 'Start Time' (0 : 00). The 'Resource Model' is set to 'HybridFlowShop'. There are two sliders: 'Nr Disjunctive Resources' (range 1 to 20, value at 7) and 'Resource Probability' (range 0 to 1, value at 0.3). A list of categories includes Products, Duration, Cumulative Resource, Orders, WIP, and Downtime (selected). Under 'Downtime', there is a 'Downtime Probability' slider (range 0 to 1, value at 0.5) and a 'Downtime Range' slider (range 1 to 100, values at 51 and 71). An 'Other Parameters' section is also visible. 'Run' and 'Cancel' buttons are at the bottom right.



# Instance Generator - Other Parameters



- Earliest Due
  - Smallest allowed value for a due date
- Horizon Days
  - What planning horizon to consider (in days)
- Time Resolution
  - In minutes, links internal and external time presentation
- Random Seed
  - Random seed to make reproducible random choices

A screenshot of the 'Data Generator Parameters' dialog box. It contains fields for 'Label', 'StartDate' (01/10/2024), 'Start Time' (0 : 00), 'Resource Model' (HybridFlowShop), 'Nr Disjunctive Resources' (slider from 1 to 20, set at 7), and 'Resource Probability' (slider from 0 to 1, set at 0.3). A tree view on the left shows categories: Products, Duration, Cumulative Resource, Orders, WIP, Downtime, and Other Parameters. The 'Other Parameters' section is expanded, showing 'Earliest Due' (20), 'Horizon Days' (20), 'Time Resolution' (5), and 'Random Seed' (42). 'Run' and 'Cancel' buttons are at the bottom right.

Data Generator Parameters

Label:

StartDate:  Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

► Products

► Duration

► Cumulative Resource

► Orders

► WIP

► Downtime

▼ Other Parameters

Earliest Due:

Horizon Days:

Time Resolution:

Random Seed:

Run Cancel

# Outline



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Taillard

SALBP

Test Scheduling



- Three datasets of different sizes
  - Job-shop
  - Flow-shop
  - Open-shop
- Load with menu `File - Load DataFile...` -  
Taillard -
- Larger instances need more solver time to reach good solutions (600 s)

# Simple Assembly Line Balancing Problem (SALBP)



- Will be discussed on more details as case study
- Design an assembly line setup by solving a scheduling problem
- Balance a set of operations across a number of stations of an assembly line
- Precedence graph is not a chain, can be very complex
- Specialized problem normally solved with specialized tools
- Load with menu `File - Load SALBP Problem...`

# Test Scheduling Benchmark set from ABB



- Will be discussed in more details as case study
- Schedule a set of tests on a number of machines, minimizing total duration
- Single stage tests, possibly large number of resources
- Closely related to bin-packing
- Load with menu `File - Load Test Scheduling Problem...`

# Outline



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Summary

# Experiment 1



- Start the application
  - Our running example will be automatically generated
- Look at the process diagram Window-Product-Process Diagram
- Run the solver Scenario - Run ScheduleJobs Solver
- Observe the results in Gantt Chart
- Customize display
- Look at Cumulative Resource Chart  
Window-Solution-Cumulative Resource Chart

# Experiment 2



- Re-run solver disabling cumulative constraint
- Observe result in Gantt chart
- See impact on Cumulative Resource chart
- Switch between solutions in charts



# Experiment 3



- Check Gantt chart display for delayed tasks, enabling lateness display
- Re-run solver, enforcing due-date constraints
- What impact does this have on objective

# Experiment 4



- Change objective to on-time delivery
- Results are very different, why?
- More explanations on this tomorrow

# Experiment 5



- Load one of the other example types
- For example, Taillard Job-shop 15x15
- Understand process diagram
- Run solver
- Look at intermediate solutions found

# Outline



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Summary

# Summary



- We presented an overview of our generic scheduling tool
- Discussed available solvers, both commercial and open-source
- Described the JSON data format for input and output
- Gave an overview of the instance generator provided
- Shows example problems included with tool
- Suggested some experiments to run