Experiments

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Constraint Based Production Scheduling

Acknowledgments

This publication was developed as part of the ENTIRE EDIH project, which received funding from Enterprise Ireland and the European Commission.

Part of this work is based on research conducted with the financial support of Science Foundation Ireland under Grant number 12/RC/2289-P2 at Insight the SFI Research Centre for Data Analytics at UCC, which is co-funded under the European Regional Development Fund.

Part of this work is based on research conducted within the ASSISTANT European project, under the framework program Horizon 2020, ICT-38-2020, Artificial intelligence for manufacturing, grant agreement number 101000165.

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

1 The Scheduling Tool

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

2 Under the hood

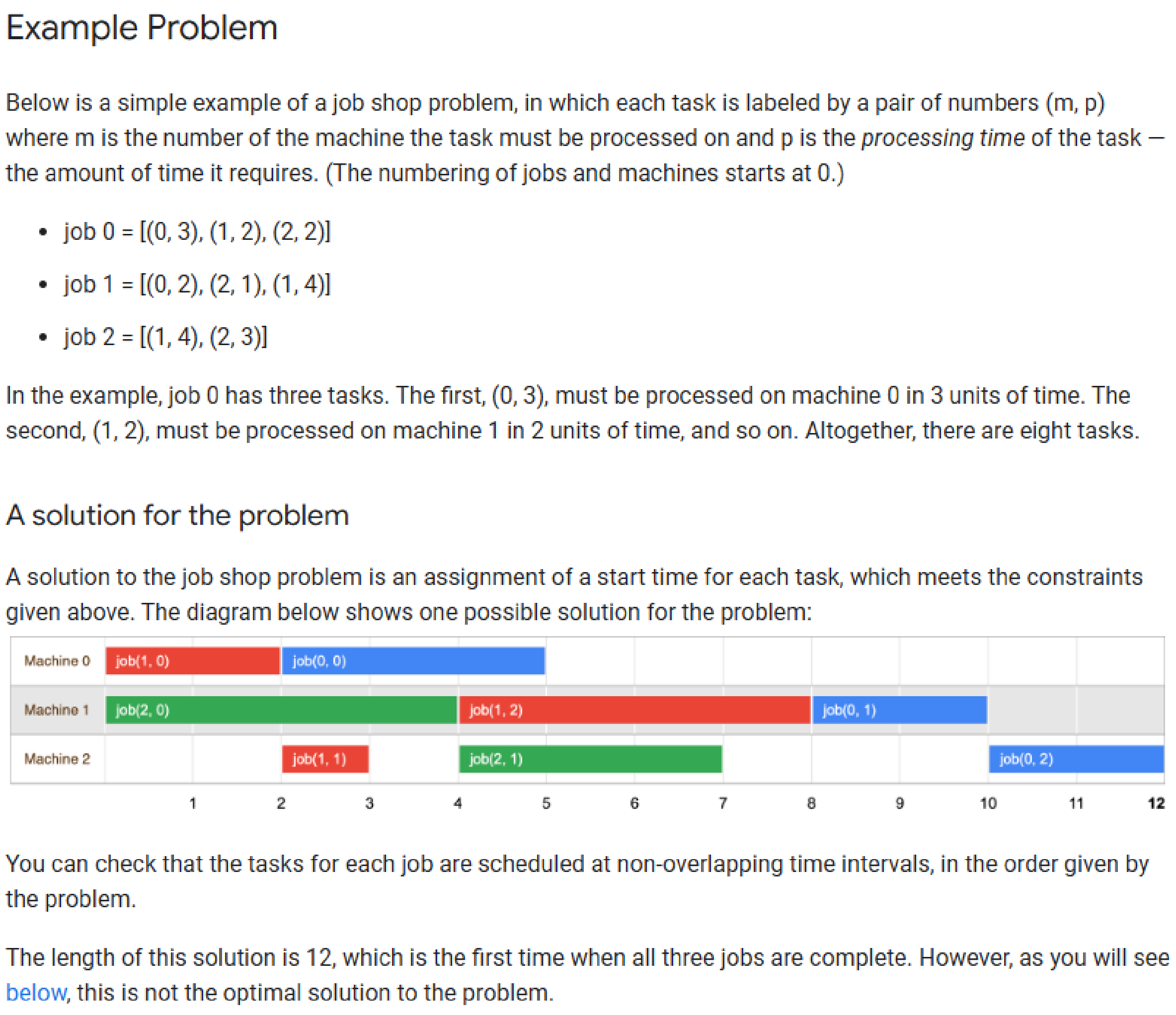
Back-end solvers

- 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

2.1 Google CPSat

Google OR-Tools CPSat Solver

- Open-Source tool provided by Google
- Available at `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.

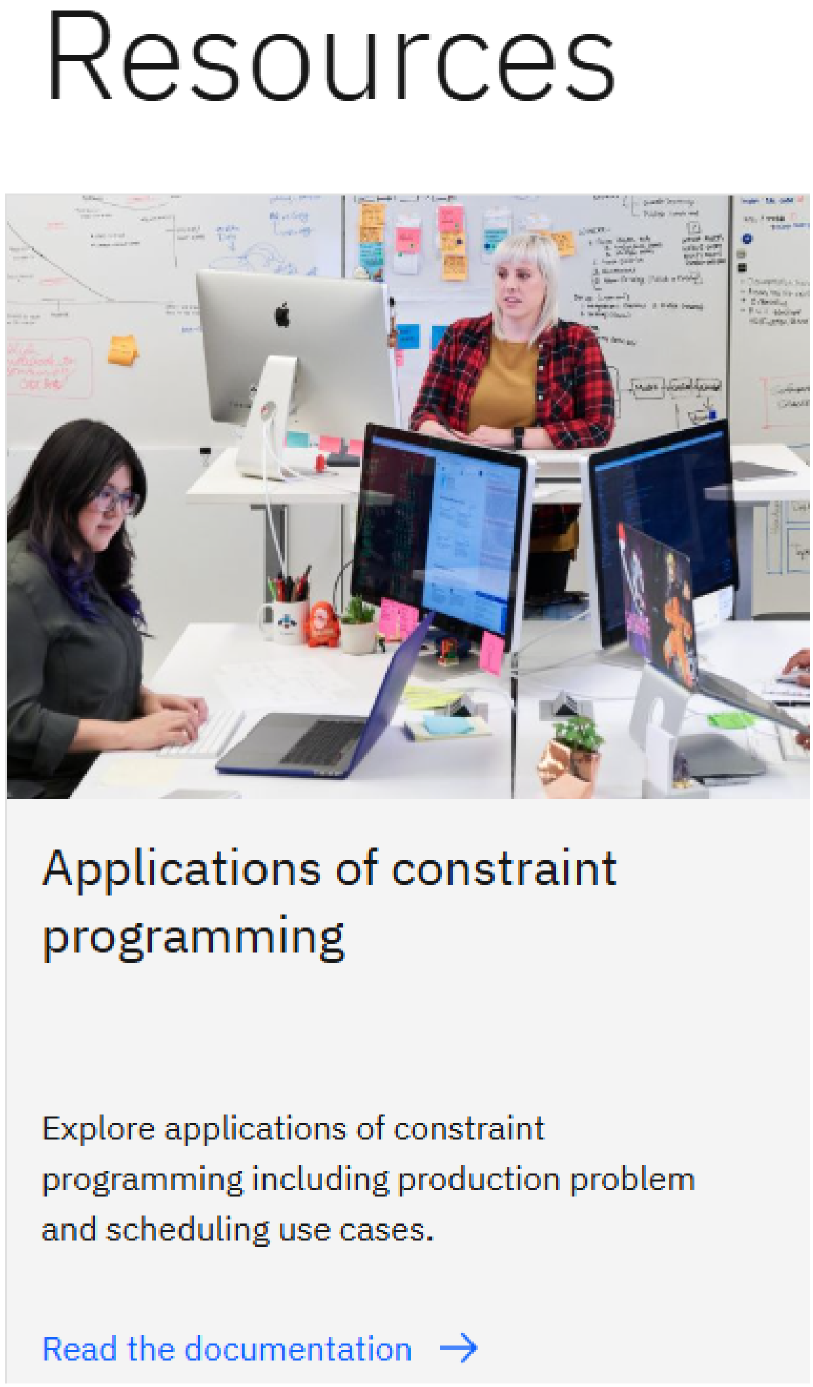
(from OR-Tools website)

2.2 IBM CPOptimizer

CP Optimizer from IBM

- Commercial tool of IBM
- `https://www.ibm.com/products/ilog-cplex-optimization-studio/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 →

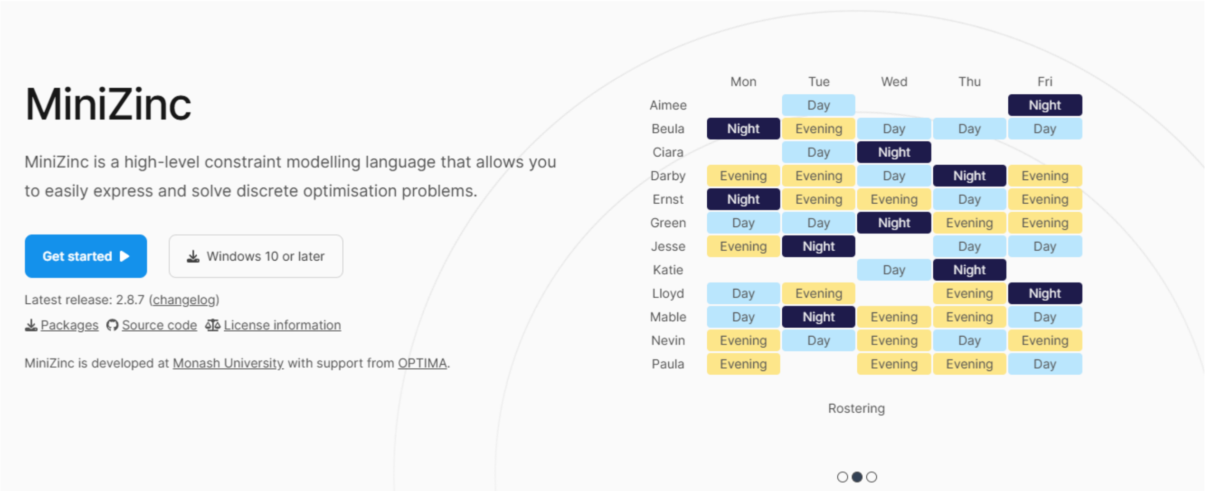
(from CPOptimizer website)

2.3 MiniZinc

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



MiniZinc

MiniZinc is a high-level constraint modelling language that allows you to easily express and solve discrete optimisation problems.

Latest release: 2.8.7 (changelog)

Packages Source code License information

MiniZinc is developed at Monash University with support from OPTIMA.

	Mon	Tue	Wed	Thu	Fri
Aimee		Day			Night
Beula	Night	Evening	Day	Day	Day
Ciara		Day	Night		
Darby	Evening	Evening	Day	Night	Evening
Ernst	Night	Evening	Evening	Day	Evening
Green	Day	Day	Night	Evening	Evening
Jesse	Evening	Night		Day	Day
Katie			Day	Night	
Lloyd	Day	Evening		Evening	Night
Mable	Day	Night	Evening	Evening	Day
Nevin	Evening	Day	Evening	Day	Evening
Paula	Evening		Evening	Evening	Day

Rostering

(from MiniZinc Website)

2.4 Which solver is better?

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

		All Instances				Optimal Only		Non Optimal Only			
		Optimal (% of All Instances)				Time (% of VB)		Cost (% of VB)		Bound (% of VB)	
Group	Nr	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

		All Instances				Optimal Only		Non Optimal Only			
		Optimal (% of All Instances)				Time (% of VB)		Cost (% of VB)		Bound (% of VB)	
Group	Nr	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

3 Input Data

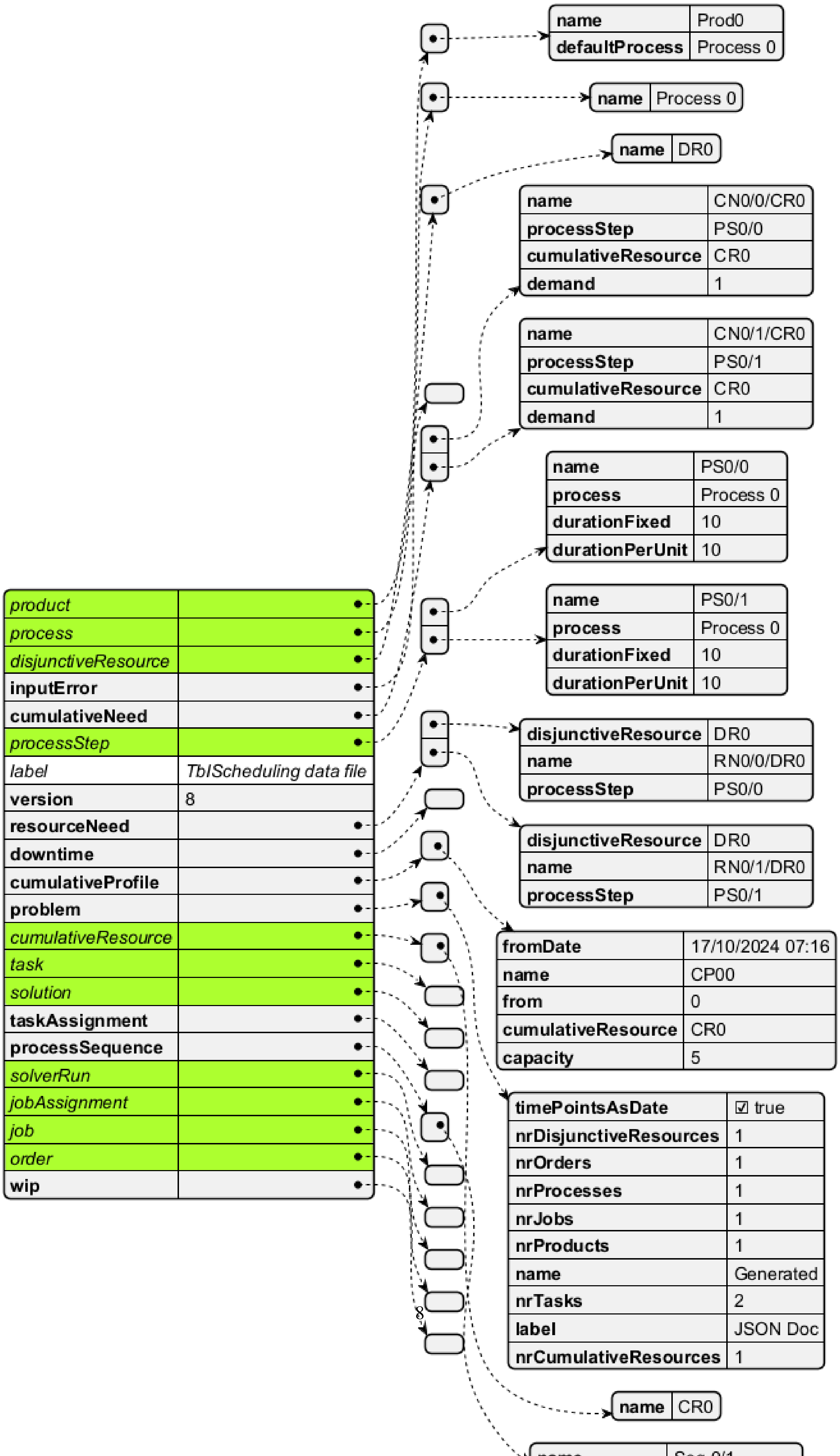
Input Data

- 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

Base Data

- Description of
  - Product
  - Process
  - DisjunctiveResource
  - CumulativeNeed
  - ProcessStep
  - ResourceNeed
  - CumulativeProfile
  - Problem
  - CumulativeResource

- ProcessSequence



product	●
process	●
disjunctiveResource	●
inputError	●
cumulativeNeed	●
processStep	●
label	*TblScheduling data file*
version	8
resourceNeed	●
downtime	●
cumulativeProfile	●
problem	●
cumulativeResource	●
task	●
solution	●
taskAssignment	●
processSequence	●
solverRun	●
jobAssignment	●
job	●
order	●
wip	●

name	Prod0
defaultProcess	Process 0

name	Process 0

name	DR0

name	CN0/0/CR0
processStep	PS0/0
cumulativeResource	CR0
demand	1

name	CN0/1/CR0
processStep	PS0/1
cumulativeResource	CR0
demand	1

name	PS0/0
process	Process 0
durationFixed	10
durationPerUnit	10

name	PS0/1
process	Process 0
durationFixed	10
durationPerUnit	10

disjunctiveResource	DR0
name	RN0/0/DR0
processStep	PS0/0

disjunctiveResource	DR0
name	RN0/1/DR0
processStep	PS0/1

fromDate	17/10/2024 07:16
name	CP00
from	0
cumulativeResource	CR0
capacity	5

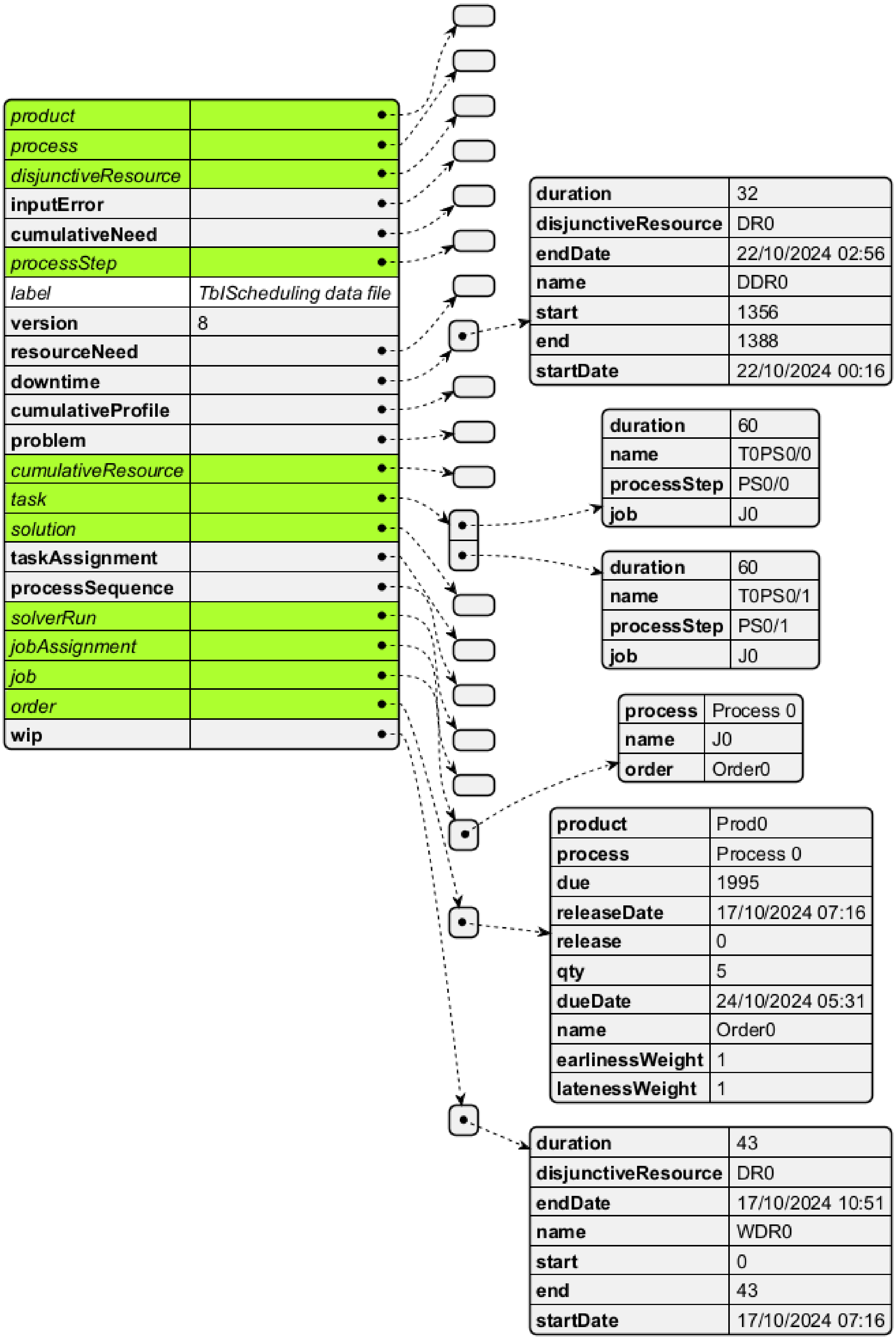
timePointsAsDate	☑ true
nrDisjunctiveResources	1
nrOrders	1
nrProcesses	1
nrJobs	1
nrProducts	1
name	Generated
nrTasks	2
label	JSON Doc
nrCumulativeResources	1

name	CR0

name	Seq 0/1

Schedule Input Data

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



product	•
process	•
disjunctiveResource	•
inputError	•
cumulativeNeed	•
processStep	•
label	*TblScheduling data file*
version	8
resourceNeed	•
downtime	•
cumulativeProfile	•
problem	•
cumulativeResource	•
task	•
solution	•
taskAssignment	•
processSequence	•
solverRun	•
jobAssignment	•
job	•
order	•
wip	•

duration	32
disjunctiveResource	DR0
endDate	22/10/2024 02:56
name	DDR0
start	1356
end	1388
startDate	22/10/2024 00:16

duration	60
name	T0PS0/0
processStep	PS0/0
job	J0

duration	60
name	T0PS0/1
processStep	PS0/1
job	J0

process	Process 0
name	J0
order	Order0

product	Prod0
process	Process 0
due	1995
releaseDate	17/10/2024 07:16
release	0
qty	5
dueDate	24/10/2024 05:31
name	Order0
earlinessWeight	1
latenessWeight	1

duration	43
disjunctiveResource	DR0
endDate	17/10/2024 10:51
name	WDR0
start	0
end	43
startDate	17/10/2024 07:16

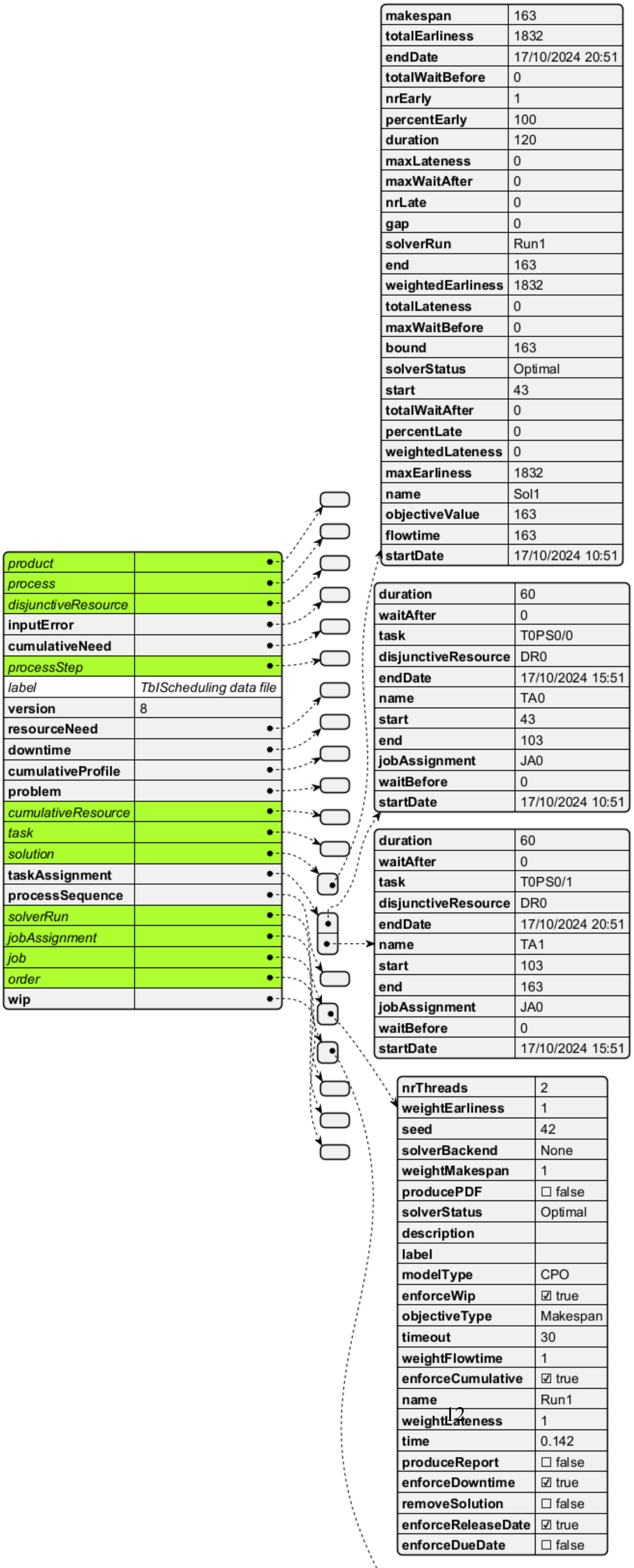
4 Result Output

Result Data

- 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	●
inputError	●
cumulativeNeed	●
processStep	●
label	*TblScheduling data file*
version	8
resourceNeed	●
downtime	●
cumulativeProfile	●
problem	●
cumulativeResource	●
task	●
solution	●
taskAssignment	●
processSequence	●
solverRun	●
jobAssignment	●
job	●
order	●
wip	●

makespan	163
totalEarliness	1832
endDate	17/10/2024 20:51
totalWaitBefore	0
nrEarly	1
percentEarly	100
duration	120
maxLateness	0
maxWaitAfter	0
nrLate	0
gap	0
solverRun	Run1
end	163
weightedEarliness	1832
totalLateness	0
maxWaitBefore	0
bound	163
solverStatus	Optimal
start	43
totalWaitAfter	0
percentLate	0
weightedLateness	0
maxEarliness	1832
name	Sol1
objectiveValue	163
flowtime	163
startDate	17/10/2024 10:51

duration	60
waitAfter	0
task	T0PS0/0
disjunctiveResource	DR0
endDate	17/10/2024 15:51
name	TA0
start	43
end	103
jobAssignment	JA0
waitBefore	0
startDate	17/10/2024 10:51

duration	60
waitAfter	0
task	T0PS0/1
disjunctiveResource	DR0
endDate	17/10/2024 20:51
name	TA1
start	103
end	163
jobAssignment	JA0
waitBefore	0
startDate	17/10/2024 15:51

nrThreads	2
weightEarliness	1
seed	42
solverBackend	None
weightMakespan	1
producePDF	☐ false
solverStatus	Optimal
description	
label	
modelType	CPO
enforceWip	☑ true
objectiveType	Makespan
timeout	30
weightFlowtime	1
enforceCumulative	☑ true
name	Run1
weightLateness	1
time	0.142
produceReport	☐ false
enforceDowntime	☑ true
removeSolution	☐ false
enforceReleaseDate	☑ true
enforceDueDate	☐ false

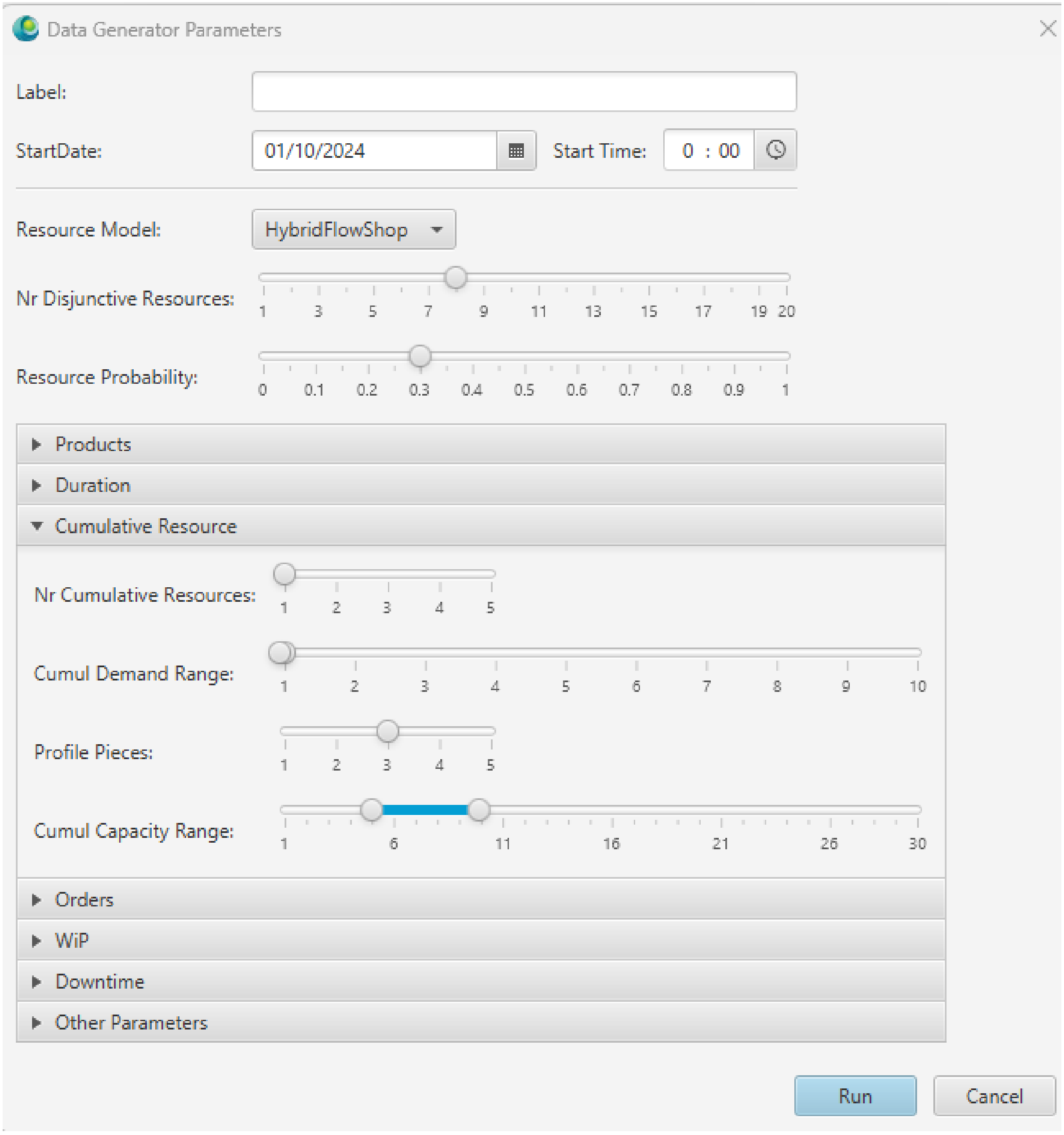
5 Instance Generator

Instance Generator

- 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



Label:

StartDate: 01/10/2024

Start Time: 0 : 00

Resource Model: HybridFlowShop

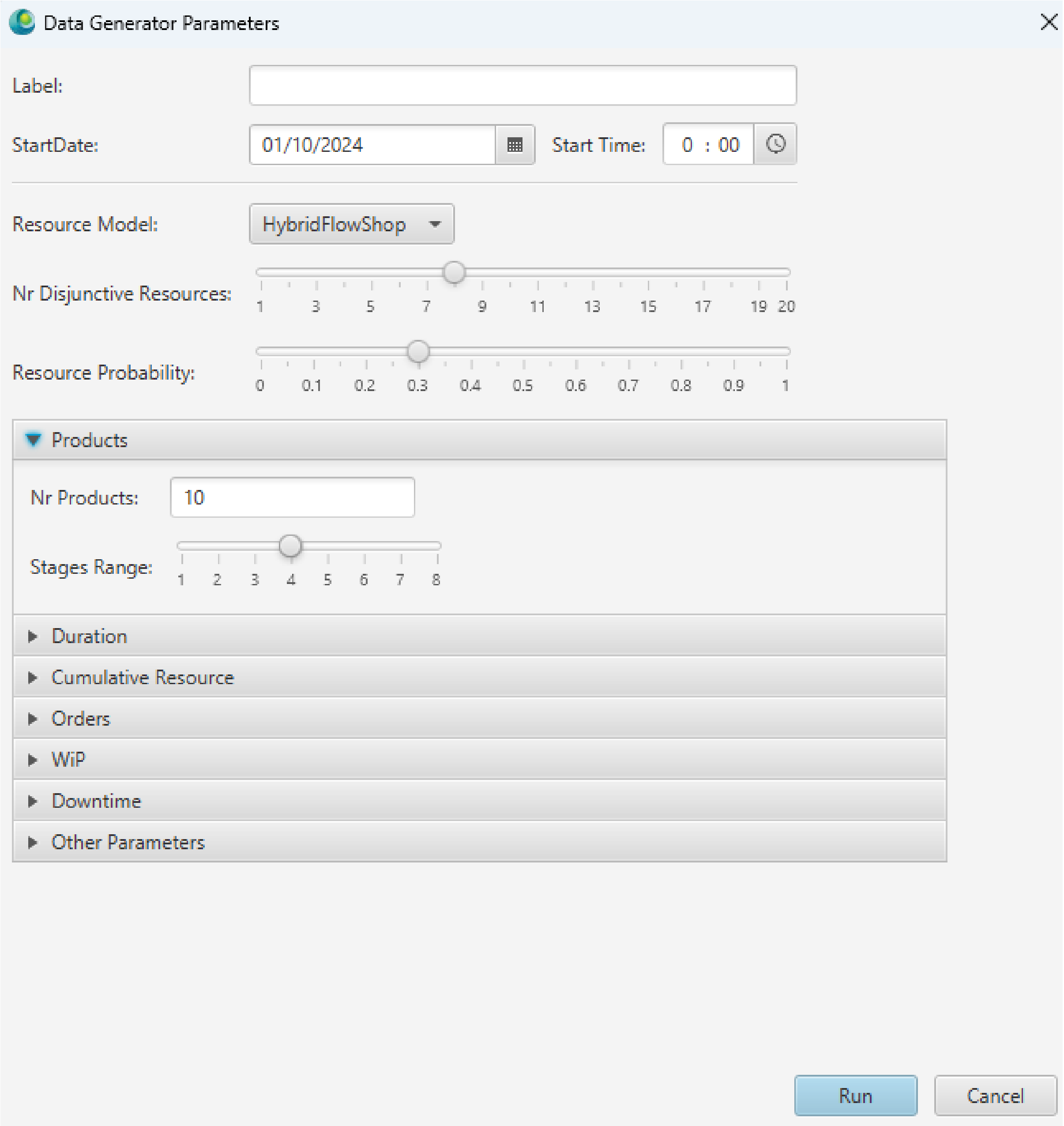
Resource Models

- 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



Data Generator Parameters

Label:

StartDate: 01/10/2024 Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

Resource Probability:

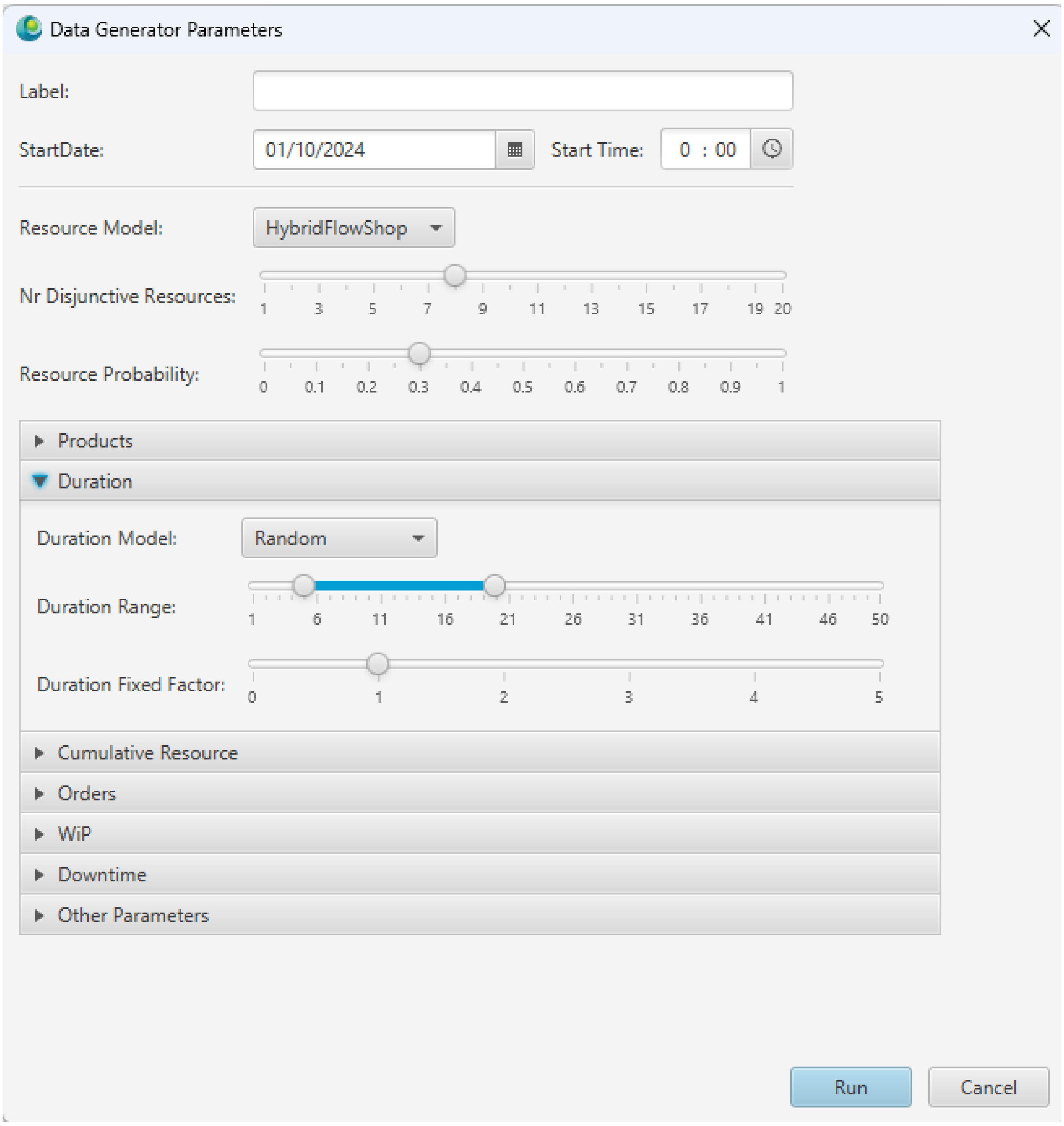
Products

Nr Products: 10

Stages Range:

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



Data Generator Parameters

Label:

StartDate: 01/10/2024 Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

Resource Probability:

Duration Model: Random

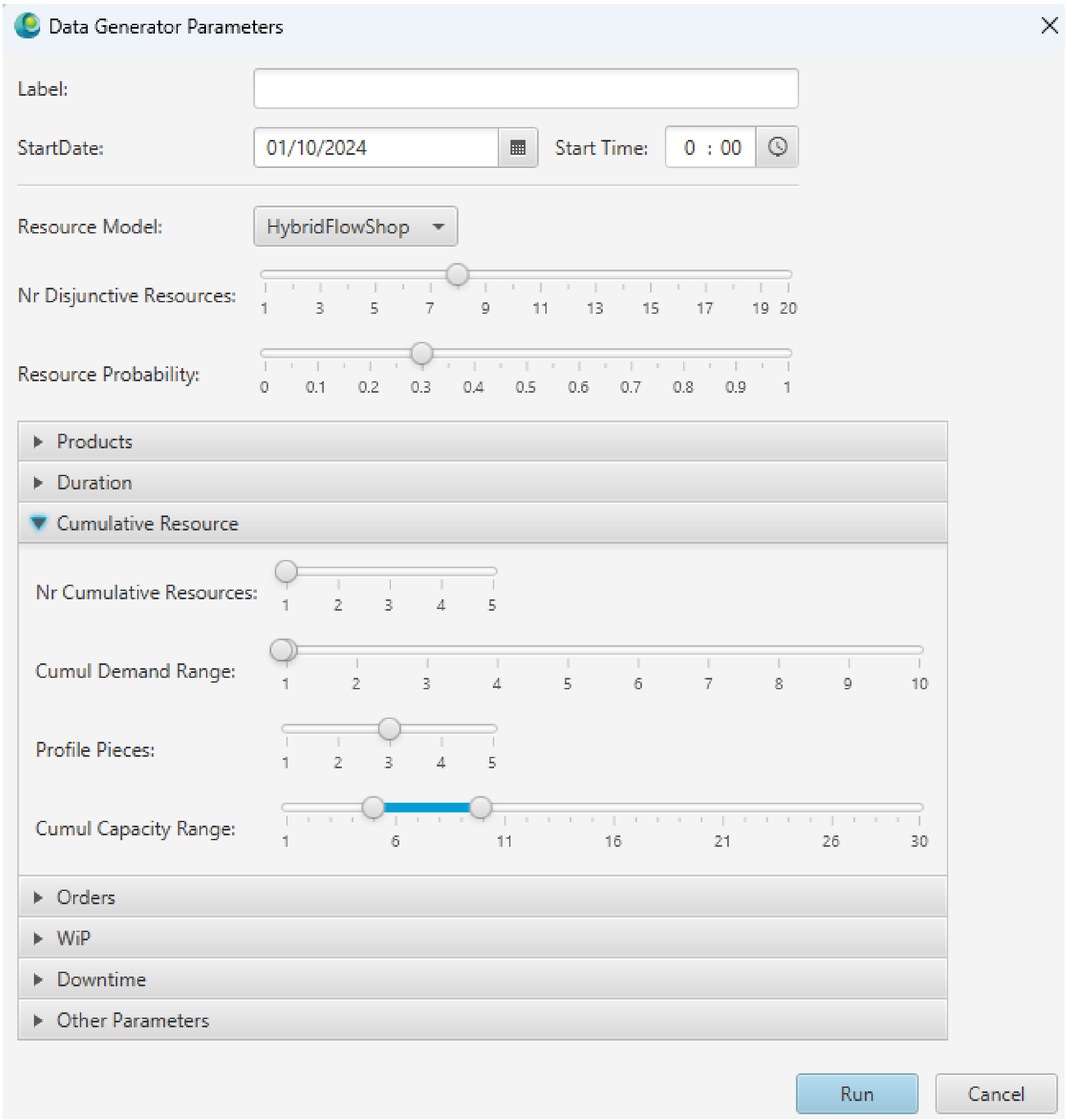
Duration Range:

Duration Fixed Factor:

Instance Generator - Cumulative

- Nr Cumulative Resources
  - Number of cumulative resources generated
- Cumul Demand Range
  - Range slider to select lower and upper bound on cumulativeResourceNeed 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 capacity values



Data Generator Parameters

Label:

StartDate: 01/10/2024 Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

Resource Probability:

Cumulative Resource

Nr Cumulative Resources:

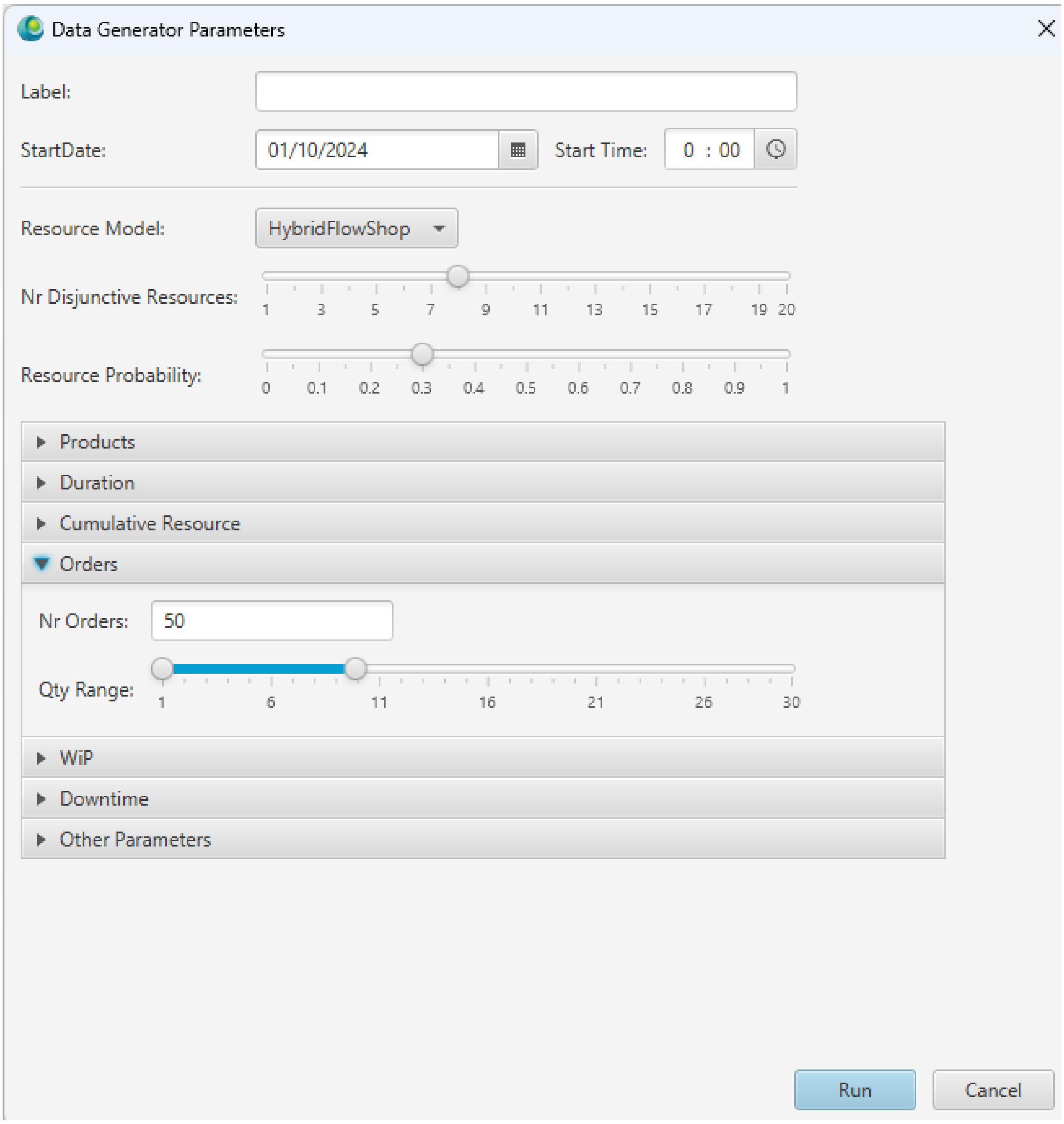
Cumul Demand Range:

Profile Pieces:

Cumul Capacity Range:

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



Data Generator Parameters

Label:

StartDate: 01/10/2024

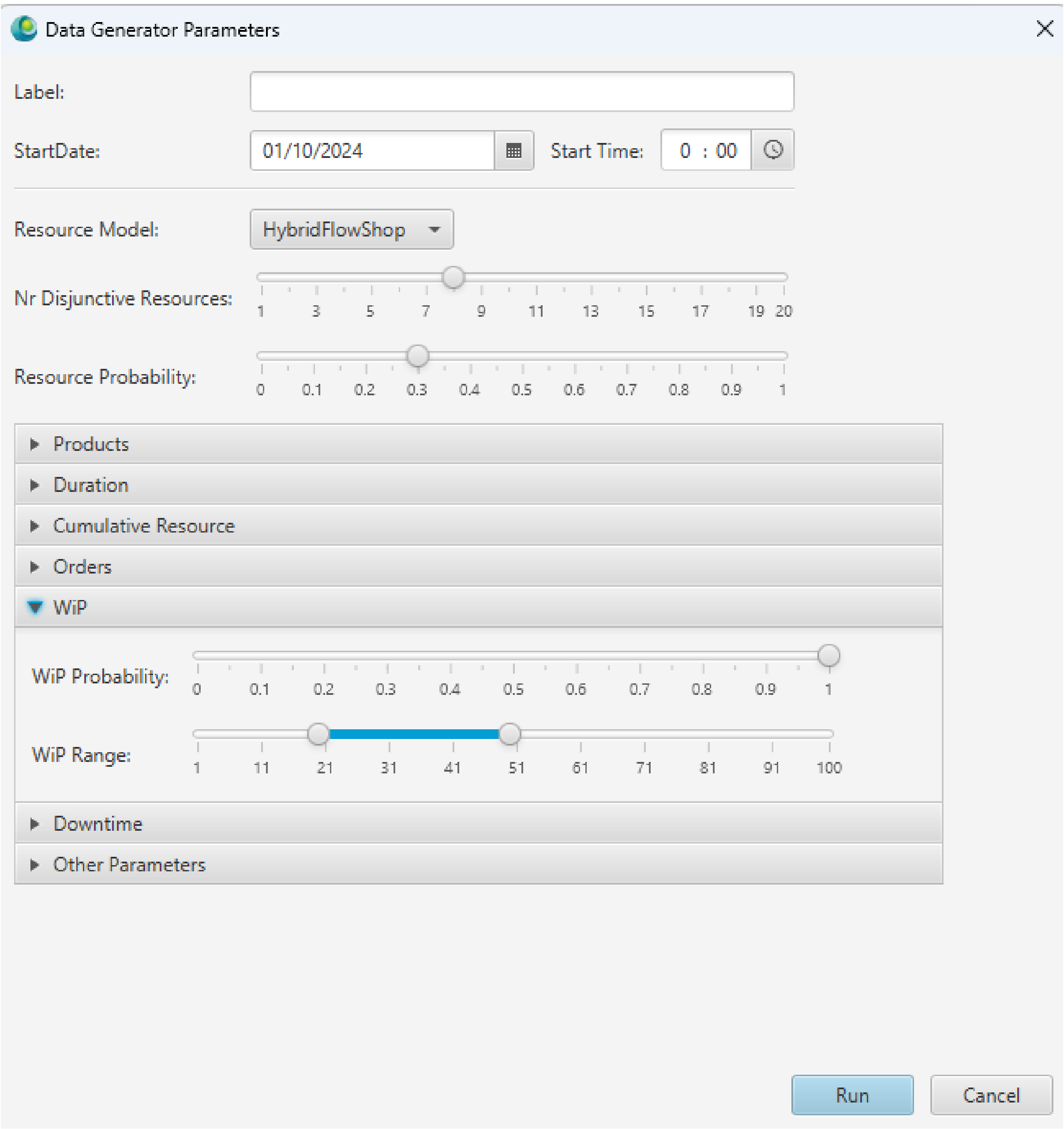
Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Orders: 50

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



Data Generator Parameters

Label:

StartDate: 01/10/2024 Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

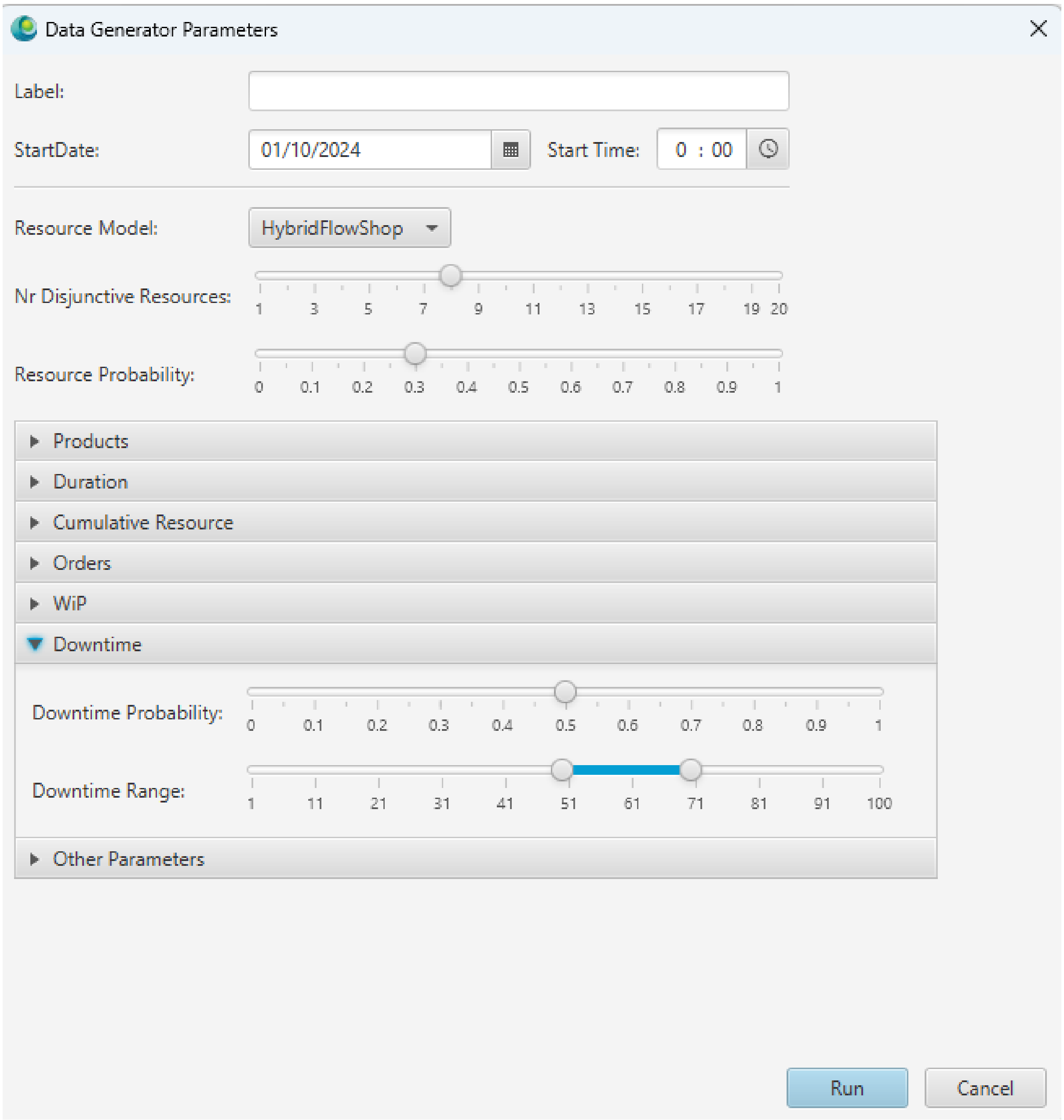
Resource Probability:

WiP Probability:

WiP Range:

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



Data Generator Parameters

Label:

StartDate: 01/10/2024

Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

Resource Probability:

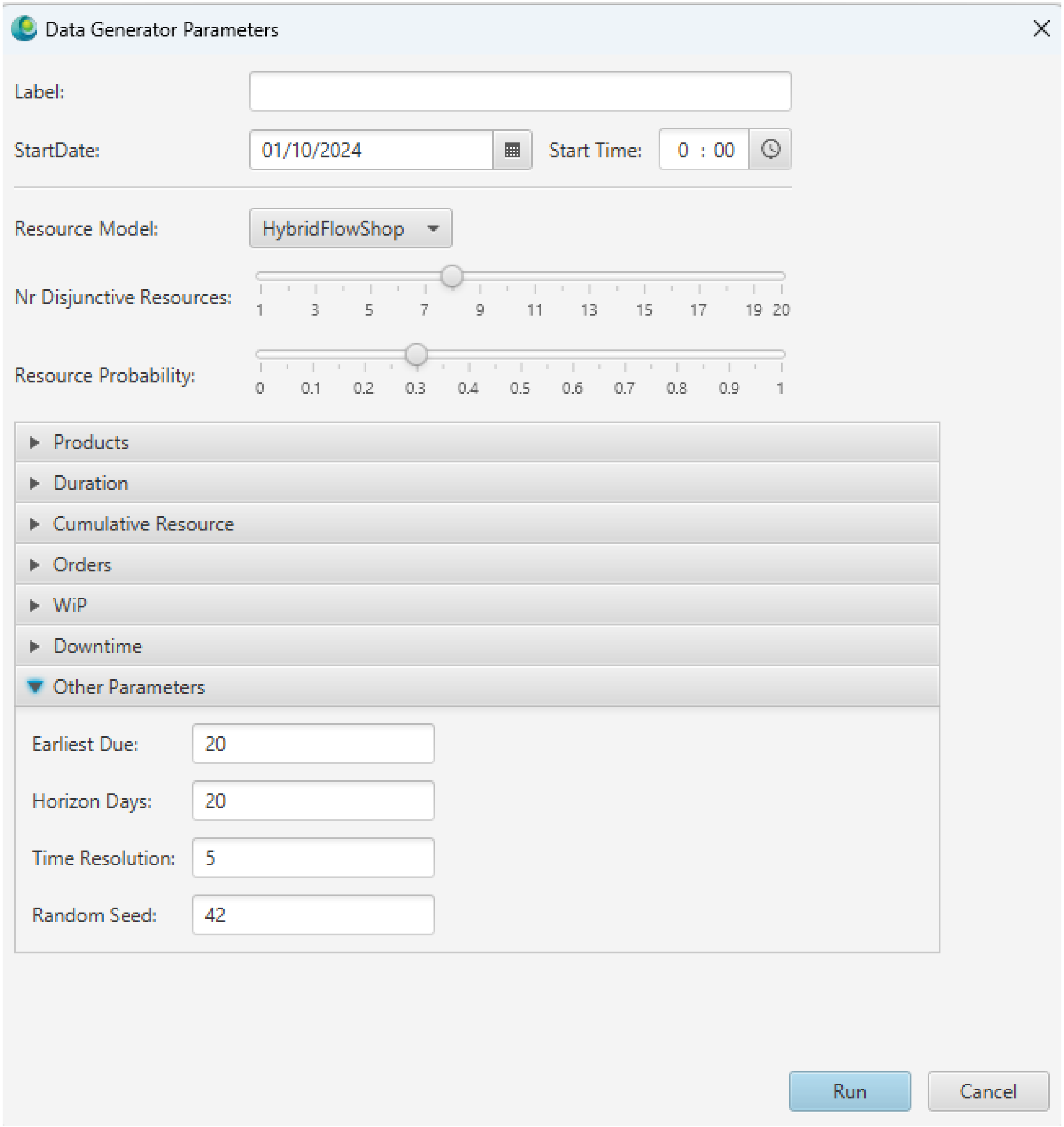
Downtime Probability:

Downtime Range:

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



Data Generator Parameters

Label:

StartDate: 01/10/2024

Start Time: 0 : 00

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

Resource Probability:

Earliest Due: 20

Horizon Days: 20

Time Resolution: 5

Random Seed: 42

6 Predefined Problem Sets

6.1 Taillard

Taillard Scheduling Benchmarks

- 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)

6.2 SALBP

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...`

6.3 Test Scheduling

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...`

7 Some Suggested Experiments

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

8 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