

Experiments

Helmut Simonis

email: `helmut.simonis@insight-centre.org`
homepage: `http://http://insight-centre.org/`

ENTIRE EDIH
Insight SFI Centre for Data Analytics
School of Computer Science and Information Technology
University College Cork
Ireland

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

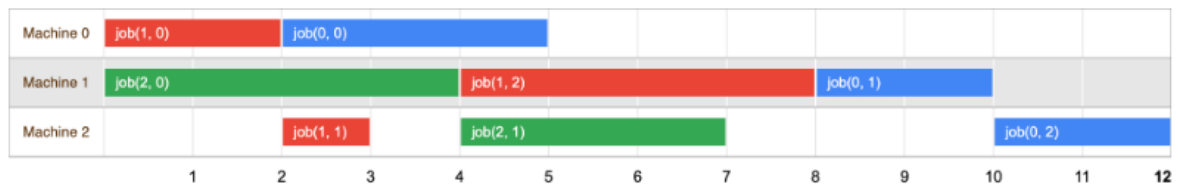
Below is a simple example of a job shop problem, in which each task is labeled by a pair of numbers (m, p) where m is the number of the machine the task must be processed on and p is the *processing time* of the task – the amount of time it requires. (The numbering of jobs and machines starts at 0.)

- 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.

[Get started](#) [Windows 10 or later](#)

Latest release: 2.8.7 ([changelog](#))

[Packages](#) [Source code](#) [License information](#)

MiniZinc is developed at [Monash University](#) with support from [OPTIMA](#).

(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

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

3 Input Data

Input Data

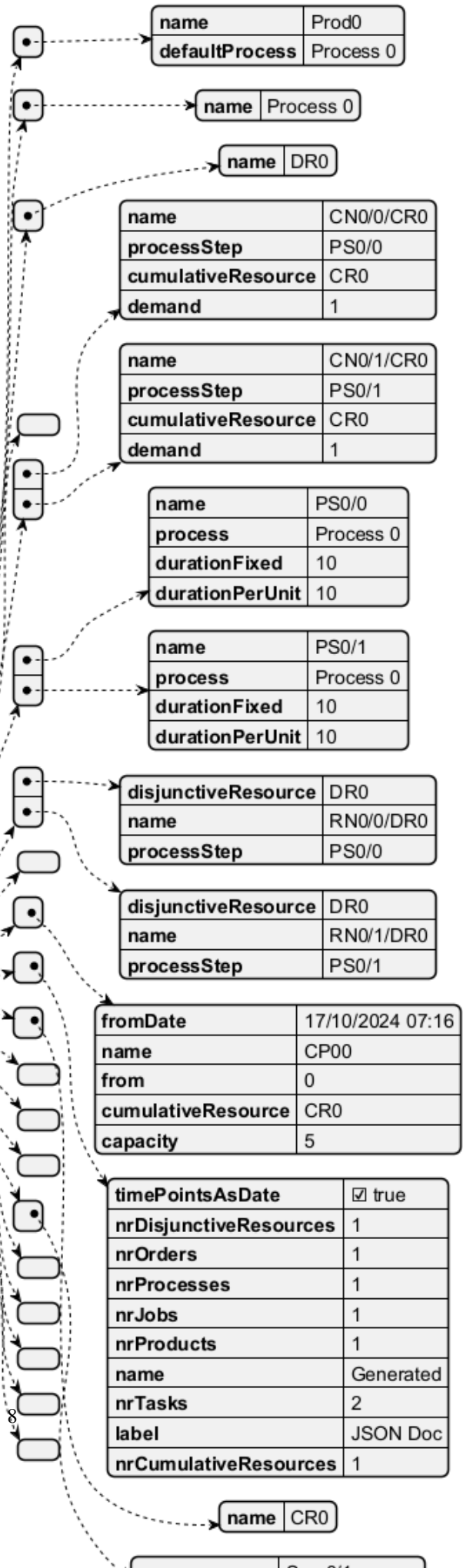
- We have defined a specific JSON data format to describe scheduling problems
- This is different from the native/XML data format of the application (do not use)
- Load with menu `File - Load DataFile...`
- Save with menu `File - Save DataFile...`
- The format is described in a document

Base Data

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

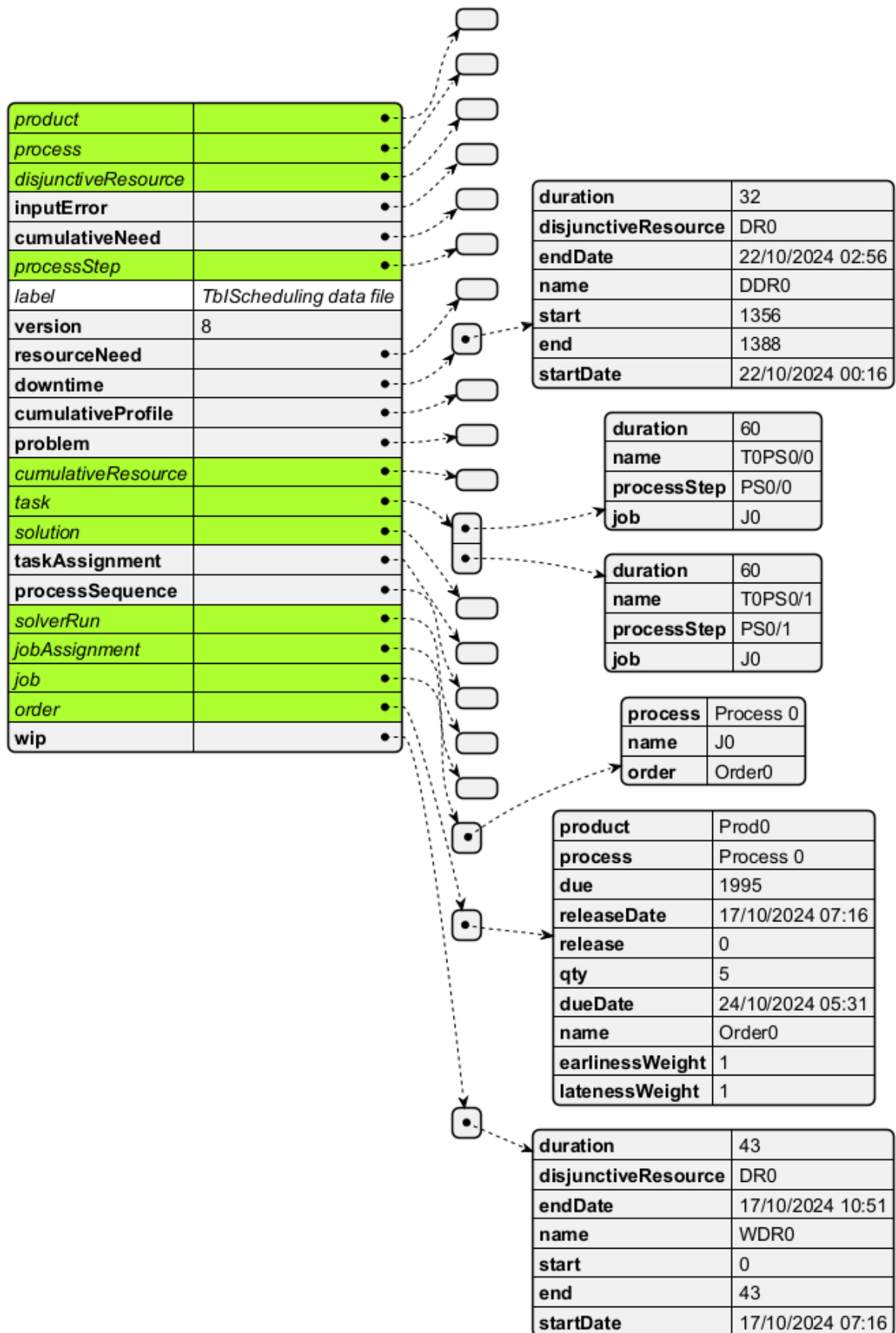
– ProcessSequence

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		•



Schedule Input Data

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



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	TbIScheduling 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	<input type="checkbox"/> false
solverStatus	Optimal
description	
label	
modelType	CPO
enforceWip	<input checked="" type="checkbox"/> true
objectiveType	Makespan
timeout	30
weightFlowtime	1
enforceCumulative	<input checked="" type="checkbox"/> true
name	Run1
weightLateness	1
time	0.142
produceReport	<input type="checkbox"/> false
enforceDowntime	<input checked="" type="checkbox"/> true
removeSolution	<input type="checkbox"/> false
enforceReleaseDate	<input checked="" type="checkbox"/> true
enforceDueDate	<input type="checkbox"/> false

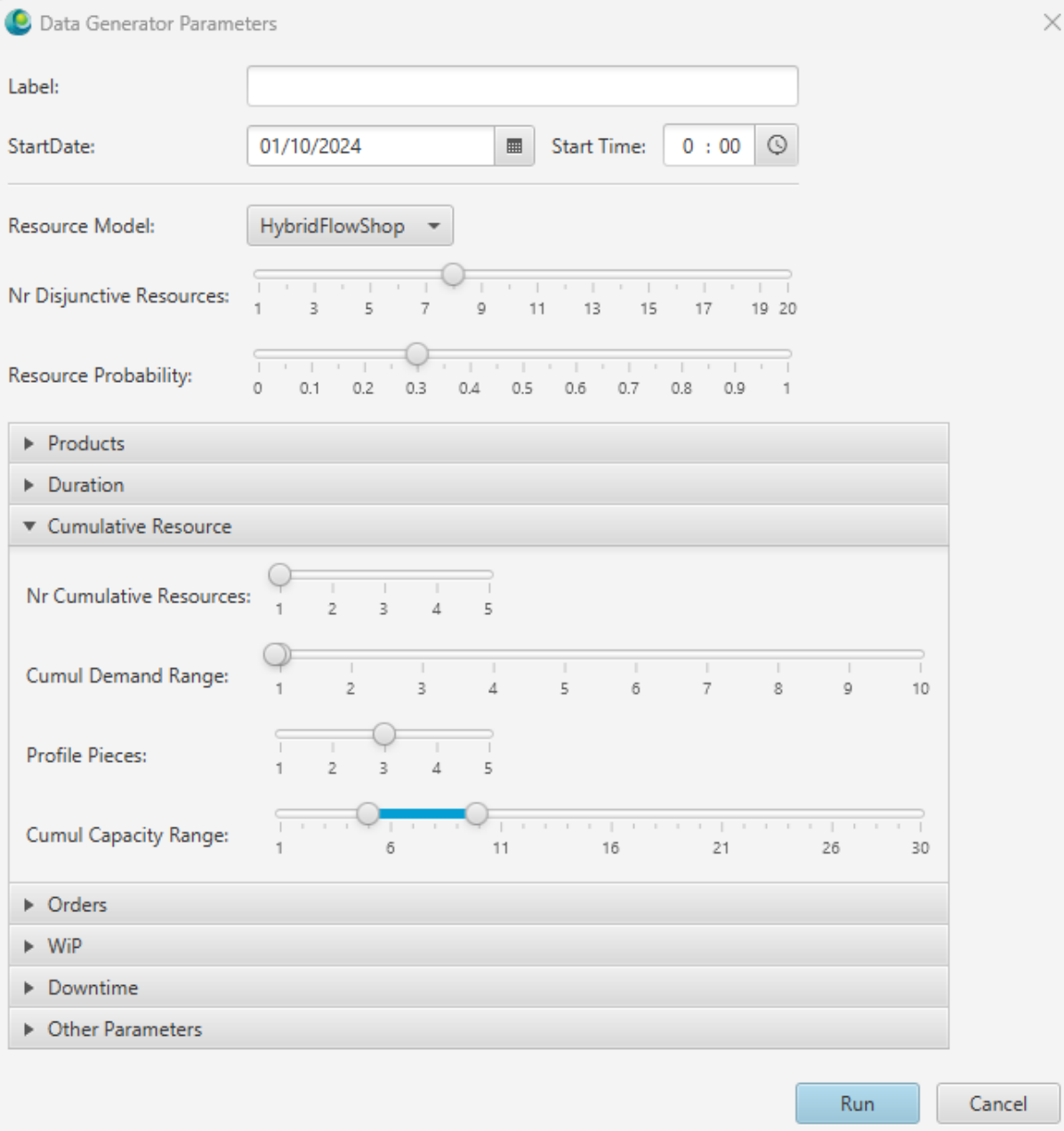
5 Instance Generator

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

The image shows a software window titled "Data Generator Parameters". It contains several input fields and sliders. At the top, there is a "Label:" text box. Below it, "StartDate:" is set to "01/10/2024" with a calendar icon, and "Start Time:" is set to "0 : 00" with a clock icon. The "Resource Model:" is a dropdown menu currently showing "HybridFlowShop". Below this, "Nr Disjunctive Resources:" has a slider from 1 to 20 with a value of approximately 8. "Resource Probability:" has a slider from 0 to 1 with a value of approximately 0.3. A large section contains expandable categories: "Products", "Duration", "Cumulative Resource" (expanded), "Orders", "WiP", "Downtime", and "Other Parameters". Under "Cumulative Resource", there are four sliders: "Nr Cumulative Resources:" (1 to 5, value ~1.5), "Cumul Demand Range:" (1 to 10, value ~1.5), "Profile Pieces:" (1 to 5, value ~3), and "Cumul Capacity Range:" (1 to 30, range from ~5 to ~10). At the bottom right are "Run" and "Cancel" buttons.

Data Generator Parameters

Label:

StartDate:  Start Time: 

Resource Model: HybridFlowShop ▾

Nr Disjunctive Resources:

Resource Probability:

► Products

► Duration

▼ Cumulative Resource

Nr Cumulative Resources:

Cumul Demand Range:

Profile Pieces:

Cumul Capacity Range:

► Orders

► WiP

► Downtime

► Other Parameters

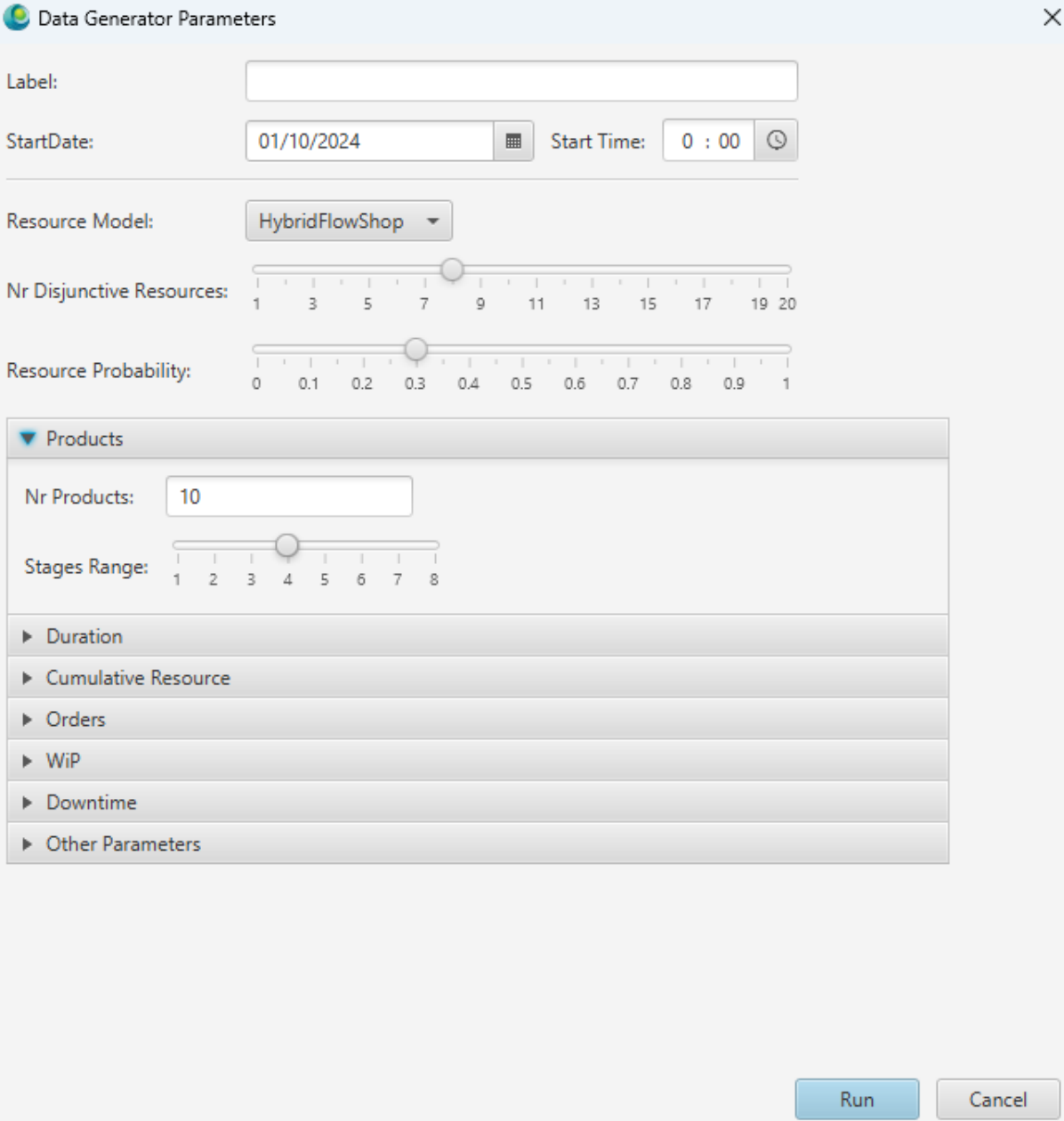
Resource Models

- 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

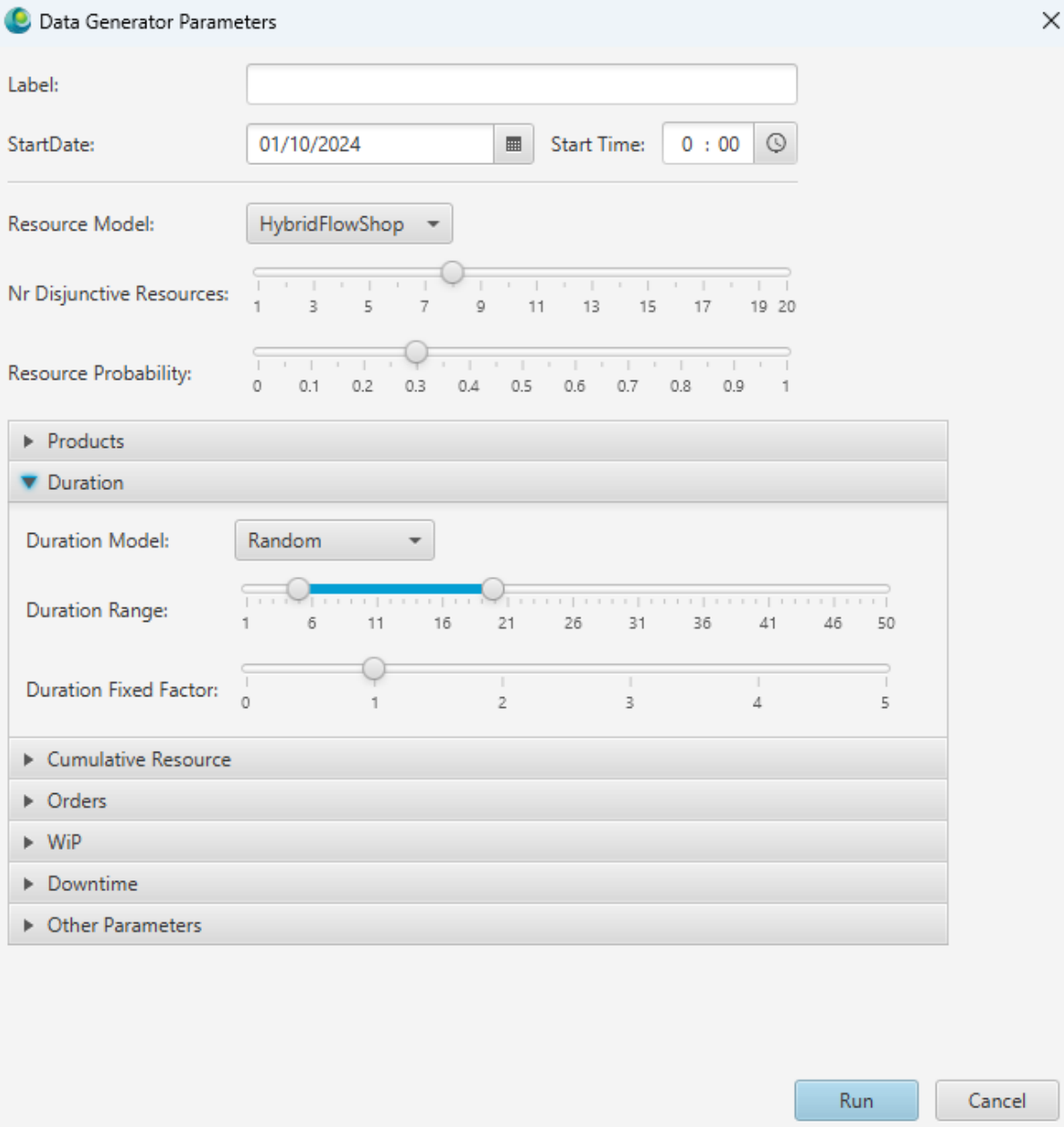
- Nr Products
 - Number of products to be generated
 - Products may be reused by multiple orders
- Stages Range
 - Range slider, sets lower and upper bound on number of stages



The image shows a software window titled "Data Generator Parameters". It contains several input fields and sliders for configuring data generation. At the top, there is a "Label" text box. Below it, "StartDate" is set to "01/10/2024" with a calendar icon, and "Start Time" is set to "0 : 00" with a clock icon. The "Resource Model" is a dropdown menu currently showing "HybridFlowShop". Below this, there are two sliders: "Nr Disjunctive Resources" with a range from 1 to 20 and a slider knob at 7, and "Resource Probability" with a range from 0 to 1 and a slider knob at 0.3. A section titled "Products" is expanded, showing "Nr Products" as 10 and a "Stages Range" slider from 1 to 8 with a knob at 4. Below the "Products" section are several expandable categories: "Duration", "Cumulative Resource", "Orders", "WiP", "Downtime", and "Other Parameters". At the bottom right, there are "Run" and "Cancel" buttons.

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



The image shows a software window titled "Data Generator Parameters". It contains several input fields and sliders for configuring data generation. At the top, there is a "Label" text box, a "StartDate" date picker set to "01/10/2024", and a "Start Time" time picker set to "0 : 00". Below these, the "Resource Model" is set to "HybridFlowShop" via a dropdown menu. Two sliders follow: "Nr Disjunctive Resources" (ranging from 1 to 20, with a slider at 8) and "Resource Probability" (ranging from 0 to 1, with a slider at 0.3). A section titled "Products" is expanded, showing a "Duration" sub-section. In "Duration", the "Duration Model" is set to "Random", and there are two sliders: "Duration Range" (ranging from 1 to 50, with a range from 6 to 21 highlighted in blue) and "Duration Fixed Factor" (ranging from 0 to 5, with a slider at 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 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: Start Time:

Resource Model: HybridFlowShop

Nr Disjunctive Resources:

Resource Probability:

► Products

► Duration

▼ Cumulative Resource

Nr Cumulative Resources:

Cumul Demand Range:

Profile Pieces:

Cumul Capacity Range:

► Orders

► WiP

► Downtime

► Other Parameters

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 [X]

Label:

StartDate: [Calendar Icon] Start Time: [Clock Icon]

Resource Model: HybridFlowShop ▾

Nr Disjunctive Resources: (1 to 20)

Resource Probability: (0 to 1)

▶ Products

▶ Duration

▶ Cumulative Resource

▼ Orders

Nr Orders:

Qty Range: (1 to 30)

▶ 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

Data Generator Parameters [X]

Label:

StartDate: [Calendar Icon] Start Time: [Clock Icon]

Resource Model: HybridFlowShop ▾

Nr Disjunctive Resources: (1 to 20)

Resource Probability: (0 to 1)

▸ Products

▸ Duration

▸ Cumulative Resource

▸ Orders

▾ **WiP**

WiP Probability: (0 to 1)

WiP Range: (1 to 100)

▸ Downtime

▸ Other Parameters

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 [X]

Label:

StartDate: [Calendar Icon] Start Time: [Clock Icon]

Resource Model: HybridFlowShop ▾

Nr Disjunctive Resources: (1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 20)

Resource Probability: (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1)

▶ Products

▶ Duration

▶ Cumulative Resource

▶ Orders

▶ WiP

▼ Downtime

Downtime Probability: (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1)

Downtime Range: to (1, 11, 21, 31, 41, 51, 61, 71, 81, 91, 100)

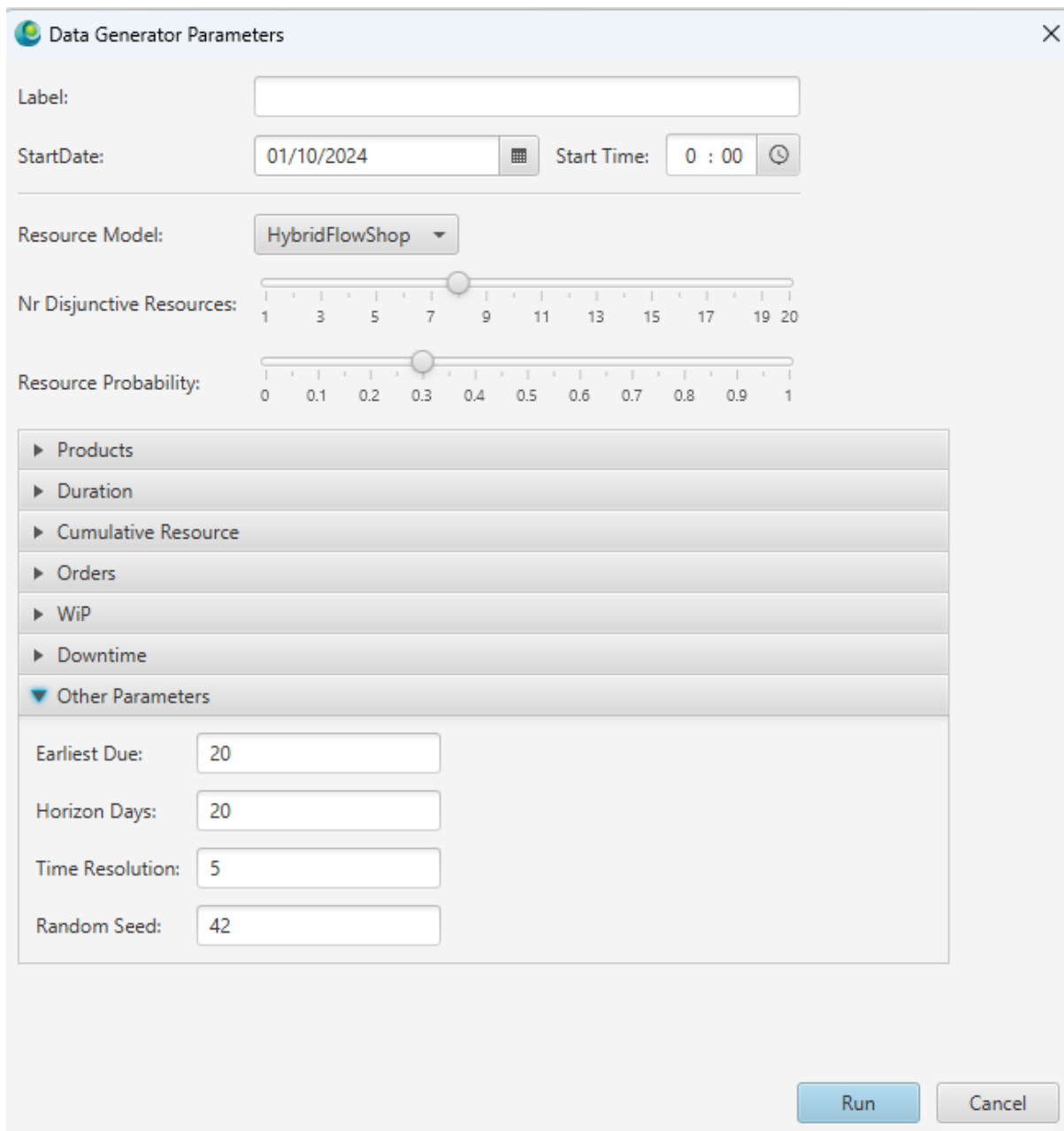
▶ Other Parameters

Run Cancel

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



The image shows a software dialog box titled "Data Generator Parameters". It contains several input fields and sliders for configuring a data generator. The fields include "Label" (empty), "StartDate" (01/10/2024), "Start Time" (0 : 00), "Resource Model" (HybridFlowShop), "Nr Disjunctive Resources" (slider at 7), and "Resource Probability" (slider at 0.3). Below these are expandable sections for "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). At the bottom right are "Run" and "Cancel" buttons.

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

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