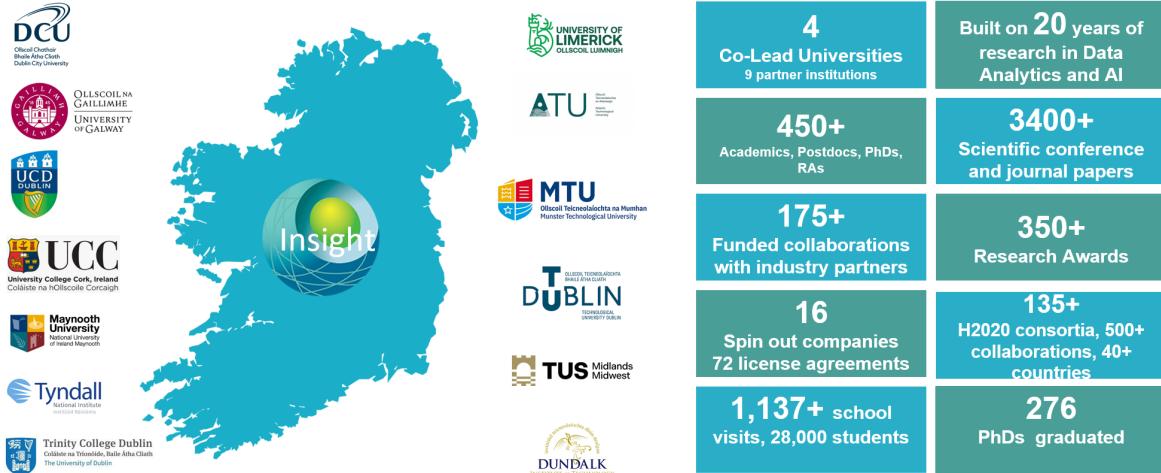


Note

- This is a document which combines all materials from the Scheduling course
- Files are also available individually in separate directories

Insight is one of the largest data research and innovation centres in Europe...



Background

- Mathematics @ TH Darmstadt
- 1986-1990 ECRC GmbH, Munich
- 1990-2000, Technical Director, Cosytec SA, Orsay
- 2000-2005, Imperial College London, Parc Technologies Ltd
- 2013-2014, President, Association for Constraint Programming
- Best Application Paper Awards, CP 2009, CP 2013
- Program Chair, CP 2020, CPAIOR 2014
- Distinguished Service Award, ACP



Part I

Introduction

Key Points

- Introducing a running example
- AI is more than LLM

- Stochastic vs. deductive AI methods
- Constraint Based Scheduling and its alternatives
- Key advantages
 - Compositional
 - Reusable
 - Explainable
- Course structure

1 A Running Example

Developing a Generic Scheduling Tool

- No programming, configured by JSON input data
- Compositional use of different constraint types
- Different commercial or open-source back-end solvers
- Developed in Java
- Interactive JavaFX front-end
- Can be used as back-end scheduling tool/server
- Instance generator included
- Readers for multiple benchmark types included
- Release planned early 2025
- Preview during the course, hands-on experience this afternoon

Introducing a Simple Scheduling Problem

- Will be used throughout the program
- Generated by instance generator
- 50 orders for different products, release and due dates
- 4 stages, always performed in the same sequence
- Two identical machines available for each stage
- Cumulative manpower constraint
- Complete description as JSON document

Excerpt of JSON Description

```

1  "order": [
2      {
3          "product": "Prod0",
4          "process": "Process 0",
5          "due": 5449,
6          "releaseDate": "1/10/2024 00:00",
7          "release": 0,
8          "qty": 7,
9          "dueDate": "19/10/2024 22:05",
10         "name": "Order0",
11         "earlinessWeight": 1,
12         "latenessWeight": 1
13     },

```

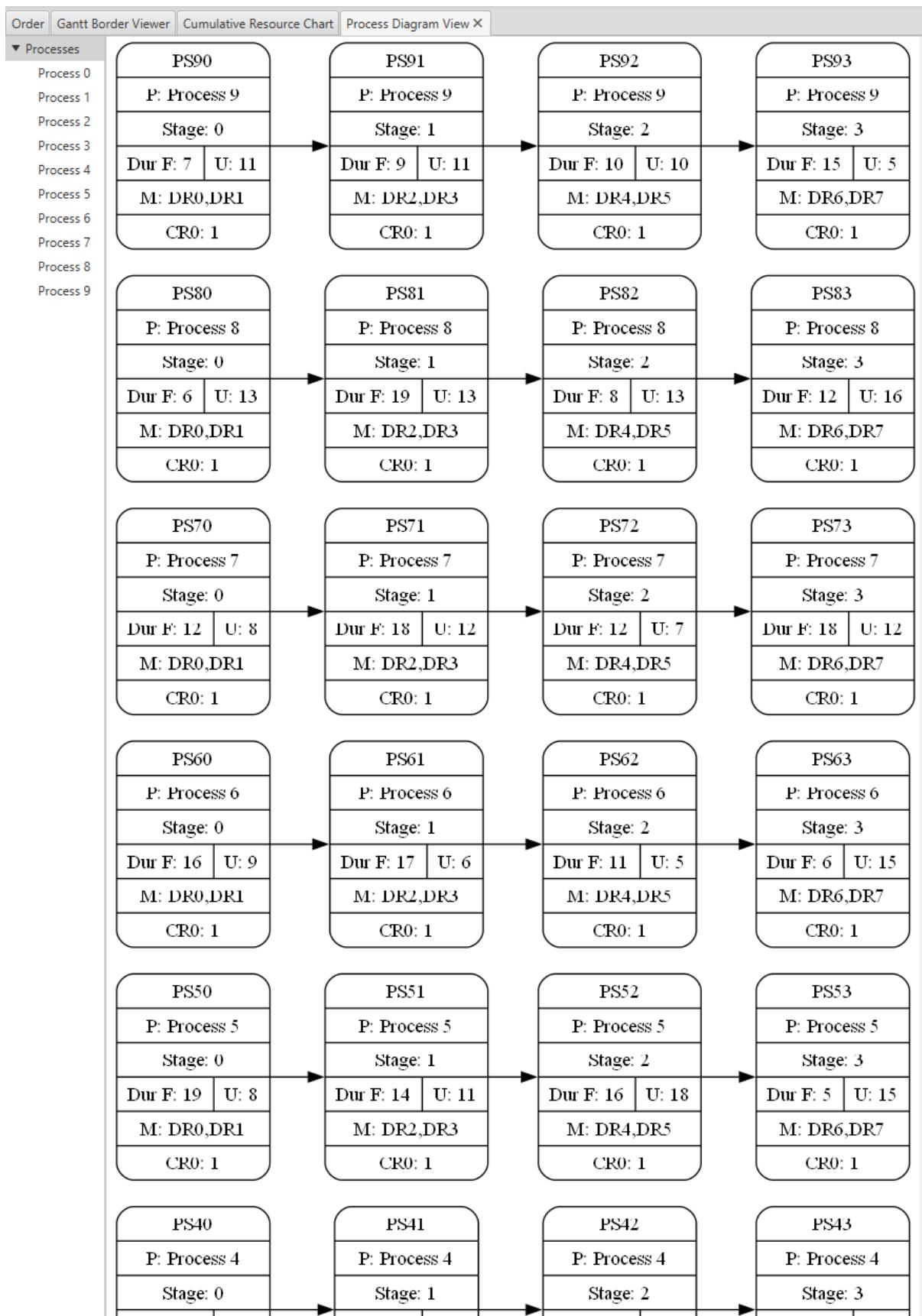
Orders Loaded

Order X	Name	Nr	Product	Process	Qty	Due	DueDate	Release	ReleaseDate	LatenessWeight	EarlinessWeight
Order0	0	Prod0	Process 0	7	5,449	19/10/2024 22:05	0	1/10/2024 00:00	1.0	1.0	
Order1	1	Prod1	Process 1	6	2,134	8/10/2024 09:50	0	1/10/2024 00:00	1.0	1.0	
Order2	2	Prod1	Process 1	7	1,266	5/10/2024 09:30	0	1/10/2024 00:00	1.0	1.0	
Order3	3	Prod1	Process 1	1	1,976	7/10/2024 20:40	0	1/10/2024 00:00	1.0	1.0	
Order4	4	Prod9	Process 9	5	2,866	10/10/2024 22:50	0	1/10/2024 00:00	1.0	1.0	
Order5	5	Prod9	Process 9	3	3,339	12/10/2024 14:15	0	1/10/2024 00:00	1.0	1.0	
Order6	6	Prod4	Process 4	9	1,676	6/10/2024 19:40	0	1/10/2024 00:00	1.0	1.0	
Order7	7	Prod5	Process 5	4	5,471	19/10/2024 23:55	0	1/10/2024 00:00	1.0	1.0	
Order8	8	Prod8	Process 8	1	1,966	7/10/2024 19:50	0	1/10/2024 00:00	1.0	1.0	
Order9	9	Prod8	Process 8	1	4,279	15/10/2024 20:35	0	1/10/2024 00:00	1.0	1.0	
Order10	10	Prod9	Process 9	6	5,733	20/10/2024 21:45	0	1/10/2024 00:00	1.0	1.0	
Order11	11	Prod4	Process 4	4	3,088	11/10/2024 17:20	0	1/10/2024 00:00	1.0	1.0	
Order12	12	Prod8	Process 8	9	2,569	9/10/2024 22:05	0	1/10/2024 00:00	1.0	1.0	
Order13	13	Prod7	Process 7	4	2,331	9/10/2024 02:15	0	1/10/2024 00:00	1.0	1.0	
Order14	14	Prod4	Process 4	9	3,290	12/10/2024 10:10	0	1/10/2024 00:00	1.0	1.0	
Order15	15	Prod3	Process 3	6	1,968	7/10/2024 20:00	0	1/10/2024 00:00	1.0	1.0	
Order16	16	Prod4	Process 4	8	1,579	6/10/2024 11:35	0	1/10/2024 00:00	1.0	1.0	
Order17	17	Prod1	Process 1	3	4,263	15/10/2024 19:15	0	1/10/2024 00:00	1.0	1.0	
Order18	18	Prod5	Process 5	9	4,491	16/10/2024 14:15	0	1/10/2024 00:00	1.0	1.0	
Order19	19	Prod3	Process 3	4	613	3/10/2024 03:05	0	1/10/2024 00:00	1.0	1.0	
Order20	20	Prod6	Process 6	2	5,034	18/10/2024 11:30	0	1/10/2024 00:00	1.0	1.0	
Order21	21	Prod7	Process 7	4	1,797	7/10/2024 05:45	0	1/10/2024 00:00	1.0	1.0	
Order22	22	Prod8	Process 8	7	4,286	15/10/2024 21:10	0	1/10/2024 00:00	1.0	1.0	
Order23	23	Prod9	Process 9	8	1,970	7/10/2024 20:10	0	1/10/2024 00:00	1.0	1.0	
Order24	24	Prod3	Process 3	4	1,286	5/10/2024 11:10	0	1/10/2024 00:00	1.0	1.0	
Order25	25	Prod6	Process 6	6	4,170	15/10/2024 11:30	0	1/10/2024 00:00	1.0	1.0	
Order26	26	Prod8	Process 8	4	5,481	20/10/2024 00:45	0	1/10/2024 00:00	1.0	1.0	
Order27	27	Prod1	Process 1	4	3,255	12/10/2024 07:15	0	1/10/2024 00:00	1.0	1.0	
Order28	28	Prod3	Process 3	7	1,021	4/10/2024 13:05	0	1/10/2024 00:00	1.0	1.0	
Order29	29	Prod5	Process 5	4	5,315	19/10/2024 10:55	0	1/10/2024 00:00	1.0	1.0	
Order30	30	Prod9	Process 9	7	5,075	18/10/2024 14:55	0	1/10/2024 00:00	1.0	1.0	
Order31	31	Prod1	Process 1	6	3,089	11/10/2024 17:25	0	1/10/2024 00:00	1.0	1.0	
Order32	32	Prod0	Process 0	8	3,324	12/10/2024 13:00	0	1/10/2024 00:00	1.0	1.0	
Order33	33	Prod7	Process 7	9	607	3/10/2024 02:35	0	1/10/2024 00:00	1.0	1.0	
Order34	34	Prod9	Process 9	1	2,914	11/10/2024 02:50	0	1/10/2024 00:00	1.0	1.0	

Process Diagram

- Processes describe how products are made
- Multiple process steps
- Not always in a straight sequence
- Duration formula based on quantity made
- Temporal constraints between steps

- Possible machines to run on
- Resource requirements (manpower, electricity,...)



Selecting Solver Options

- Which constraints to enforce
 - Here: do not enforce due dates
- Additional constraints to try
- Why solver to run
 - Here: Use open-source CPSat solver
- Which objective to use
 - Here: Makespan, overall project end
- What resources to use
 - Allow 30 seconds
 - Use 8 parallel threads

 Schedule Solver Parameters X

Label:

Description:

StartDate:

Start Time:

Enforce Release Date:

Enforce Due Date:

Enforce Cumulative:

Enforce WiP:

Enforce Downtime:

Enforce Setup:

Enforce Transport Time:

Relax Sequence:

Add Same Order:

Add NoWait:

Add Blocking:

Model Type:

Solver Backend:

Objective Type:

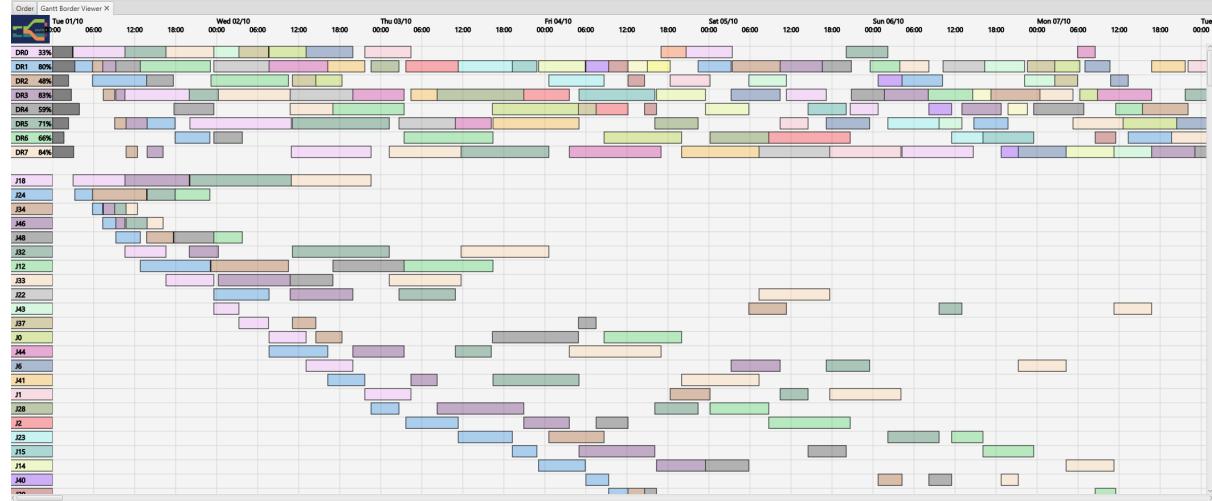
Weight Makespan:

Weight Flowtime:

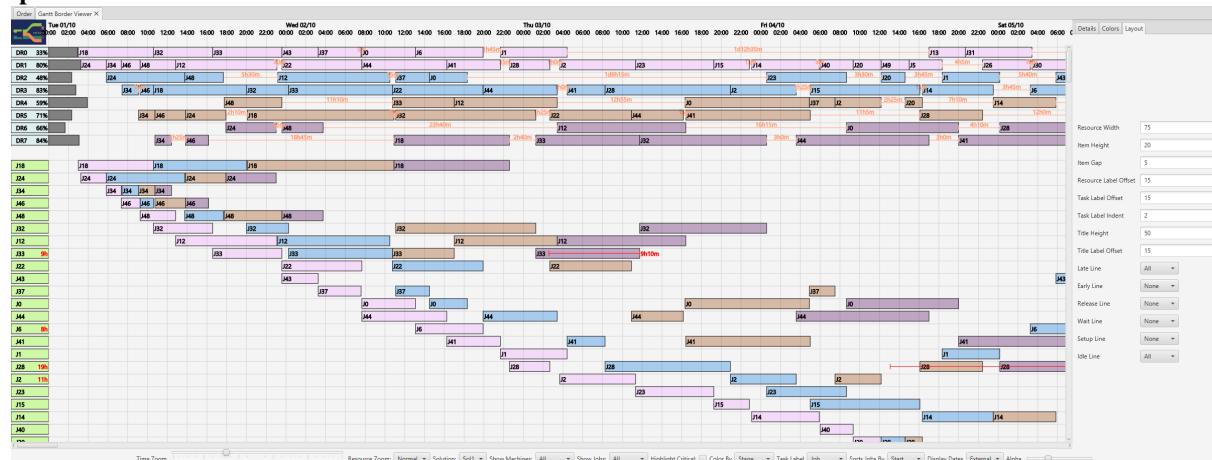
Weight Lateness: 8

Weight Earliness:

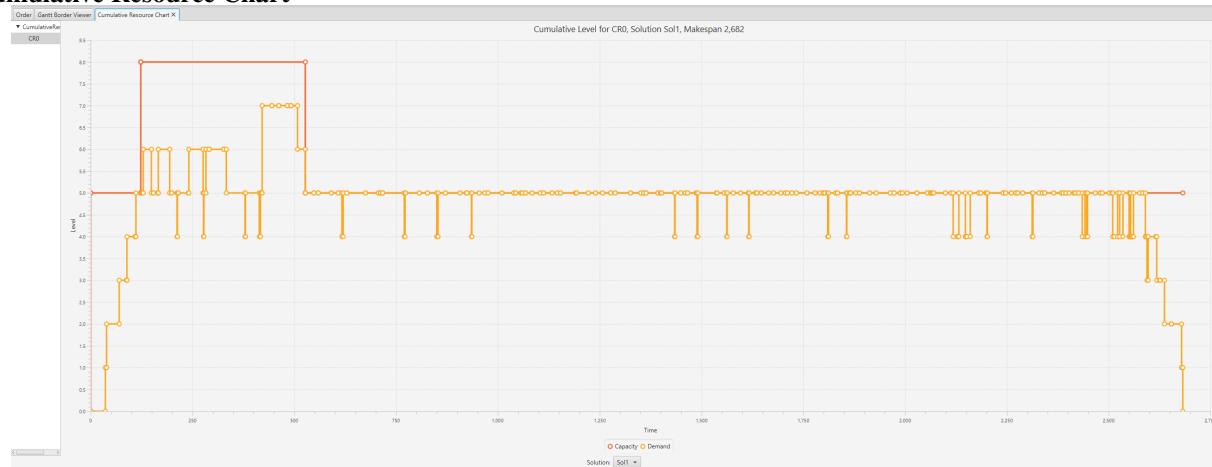
Schedule - Initial Gantt Chart



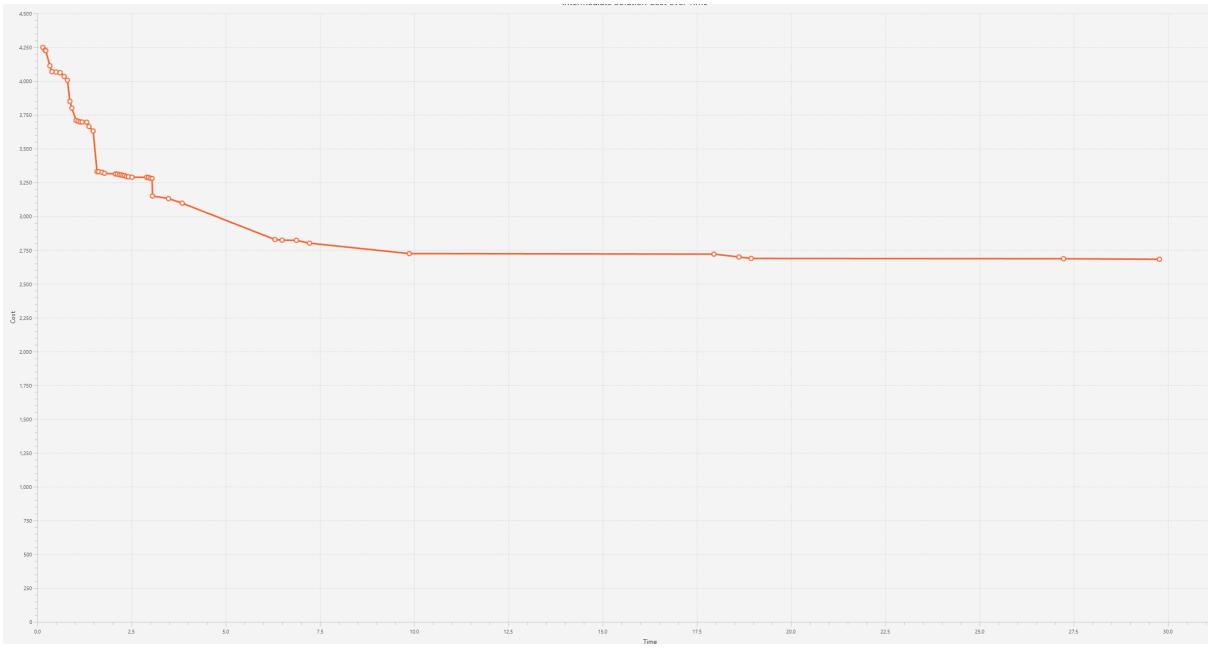
Adapted Gantt Chart



Cumulative Resource Chart



Intermediate Solutions Found



- Ongoing search for improved solutions
- Depends on time and resources, solver used

2 Artificial Intelligence

3 Scheduling

3.1 Constraint-Based Scheduling

Constraint Programming - in a nutshell

- Declarative description of problems with
 - *Variables* which range over (finite) sets of values
 - *Constraints* over subsets of variables which restrict possible value combinations
 - A *solution* is a value assignment which satisfies all constraints
- Constraint propagation/reasoning
 - Removing inconsistent values for variables
 - Detect failure if constraint can not be satisfied
 - Interaction of constraints via shared variables
 - Incomplete
- Search
 - User controlled assignment of values to variables
 - Each step triggers constraint propagation
- Different domains require/allow different methods

Constraint Programming is Different

- Declarative Programming
 - Concentrate on what you want
 - Not how to get there
 - Program != Algorithm
 - Program = Model
- Applied to Combinatorial Problems
 - No complete polynomial algorithms known (exist?)
 - CP less ad-hoc than heuristics
 - Models can evolve



A Subtractive Process

“Oh, bosh, as Mr. Ruskin says. Sculpture, per se, is the simplest thing in the world. All you have to do is to take a big chunk of marble and a hammer and chisel, make up your mind what you are about to create and chip off all the marble you don’t want.”-Paris Gaulois.

Source: <https://quoteinvestigator.com/2014/06/22/chip-away/>

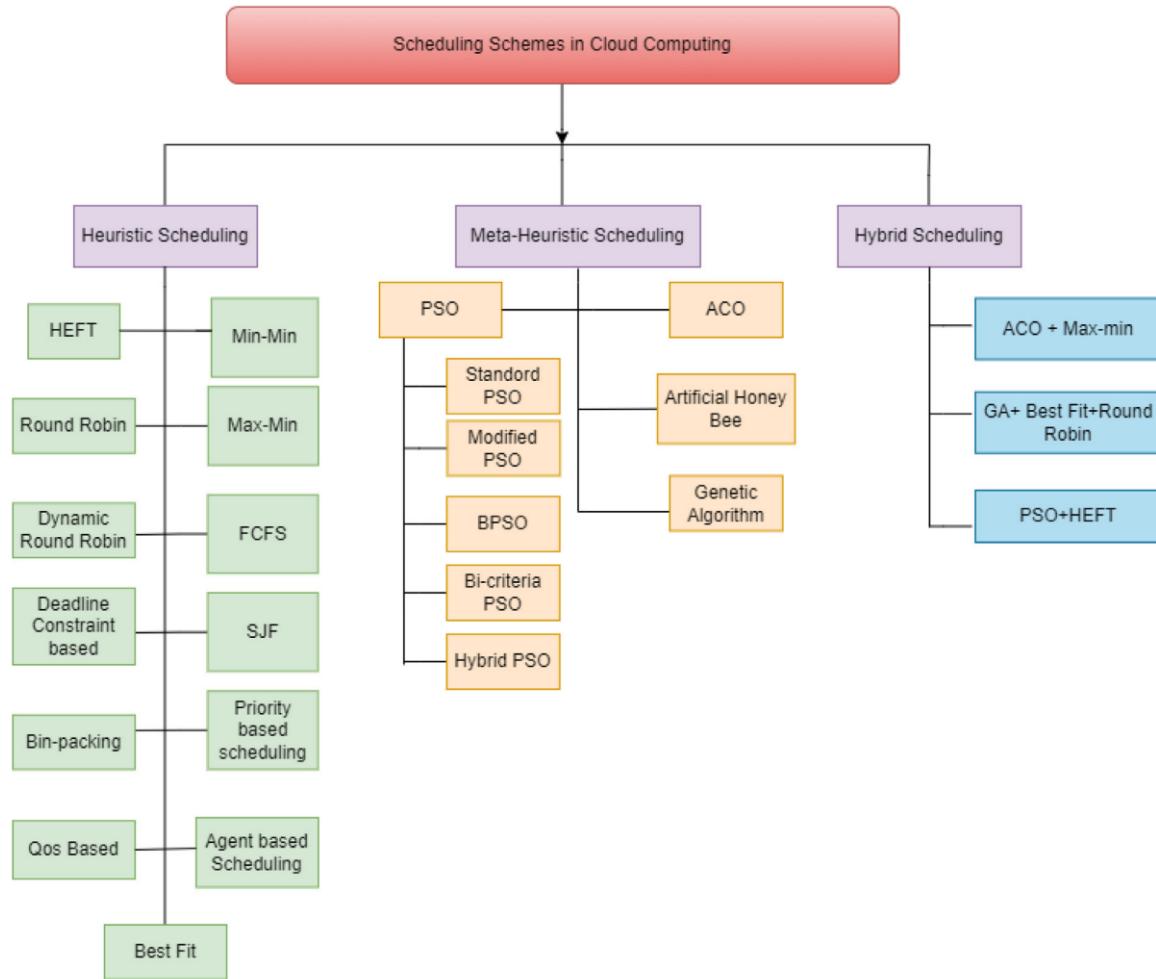
3.2 Other Scheduling Solution Approaches

Other Technologies

- Heuristics
- Integer Programming
- Local search
- Deep neural networks

Heuristics

- Do not try to explore the search space
- Find a good enough solution by making greedy choices
- More general meta-heuristics schemes
- Very good heuristics exist for specific problem types
- Not compositional, added constraints may destroy existing approach
- Often not reusable code base

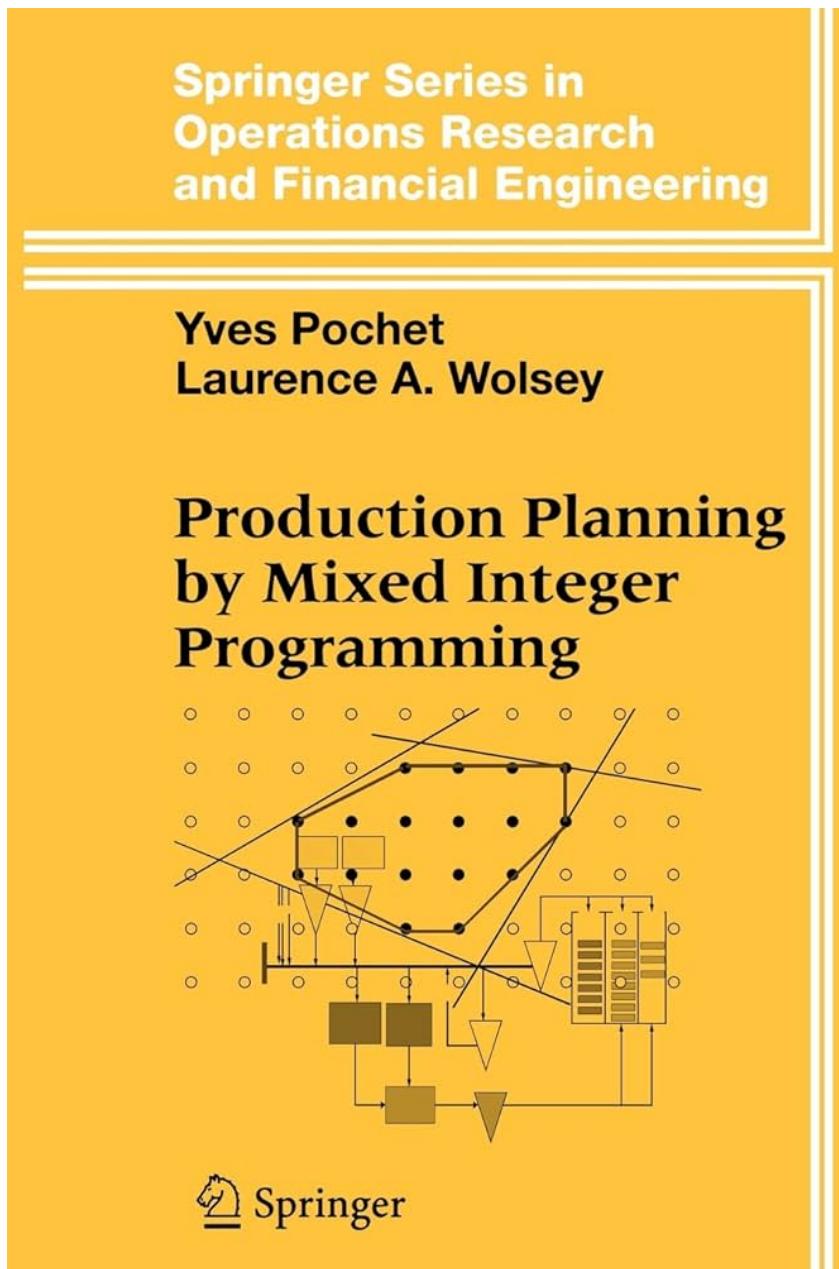


From: Singh, Kumar, and Singh: An empirical investigation of task scheduling and VM consolidation schemes in cloud environment, Computer Science review, 2023, <https://www.sciencedirect.com/science/article/pii/S1574013723000503>

Integer Programming

- Sub-class of constraint programming
- Restrict yourself to linear constraints
- Powerful reasoning on the complete set of constraints
 - Linear Programming
 - Cut generation

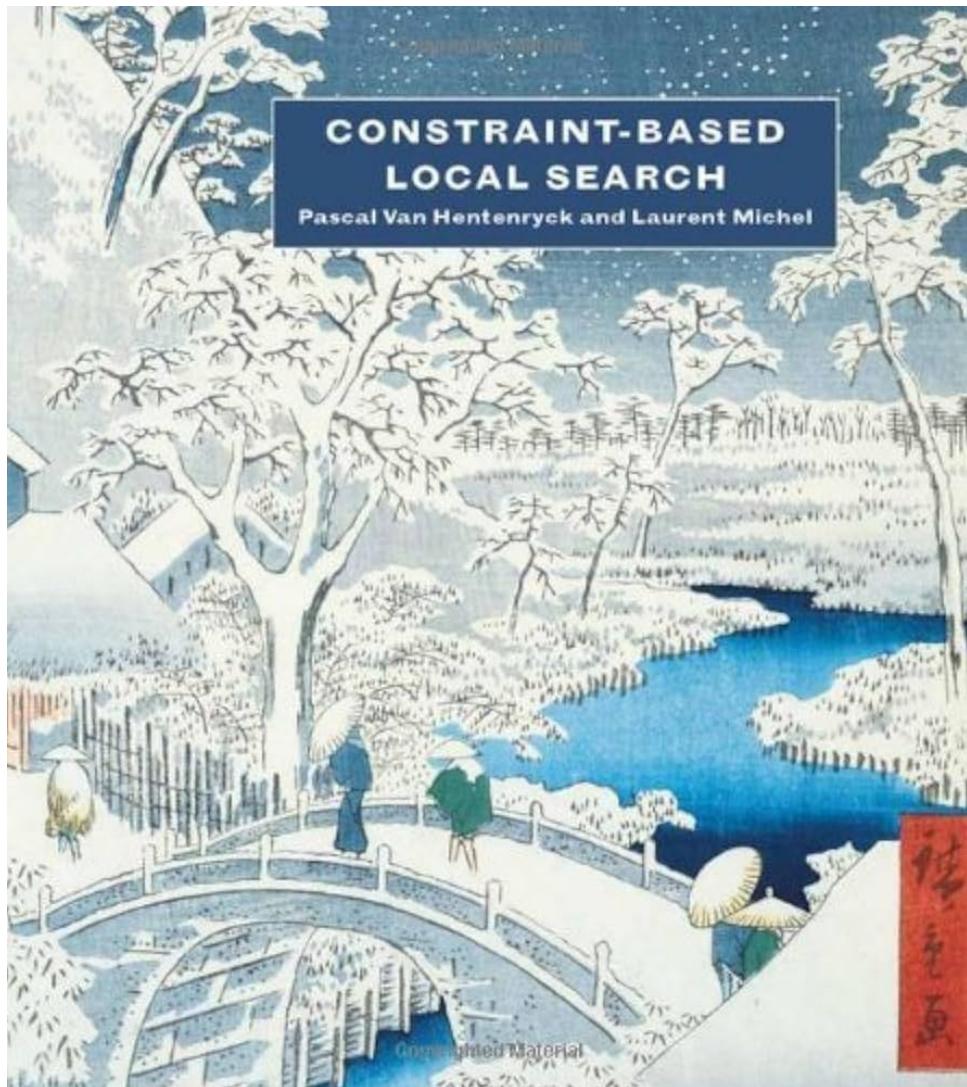
- Expressing scheduling constraints can be difficult
- Scalability issues



Local Search

- Start with an initial solution
- Try out changes that maintain feasibility
- Gradual improvement over time
- Not compositional
- No guarantee of solution quality

- Unifying approach: Constraint-Based Local Search



[constraint-based-local-search/](https://mitpress.mit.edu/9780262220774/)

4 Course Structure

Course Structure

Time	Day 1	Day 2
09:00-10:30	Introduction & Motivation	Costs & Objective Functions
10:30-11:00	Coffee	Coffee
11:00-12:30	Scheduling Concepts	Advanced Concepts
12:30-14:00	Lunch	Lunch
14:00-15:30	Machine Constraints	Case Studies
15:30-16:00	Coffee	Coffee & Close
16:00-17:00	Experiments	-

4.1 What is not covered?

What is not covered?

- How does it all work?
- How to integrate into an existing IT environment
- How to define and solve new constraints
- Interactive solving techniques

How does it all work?

- You don't really need to know this to use Constraint Programming
- Advantage of declarative, compositional formulation
- I teach an introductory course on Constraint Programming for CRT-AI
- Overview of courses, books and materials at <https://arxiv.org/abs/2403.12717>

5 Summary

Summary

- Why use Constraint Based Scheduling?
- Compared to other AI methods
- Compared to other solution approaches

Part II

Concepts

Key Points

- We introduce the core concepts used in scheduling
- Different layers of description
 - What we are doing (jobs, tasks, resources)
 - Why we are scheduling (orders, products, processes)
- Temporal Relations
- Process description
- Problem classification
- Visualization

6 Core Concepts

6.1 Jobs, Tasks and Resources

Most basic description of scheduling problem

- *Job*
 - Collection of activities required to manufacture one object/lot/order
 - Overall start/end determined by starts and ends of its tasks
- *Task*
 - Individual activities required for manufacture
 - Have defined start, end (typical: variables) and duration (sometimes fixed)
 - Often performed on one specific resource (more on that later)
- *Resources*
 - Resources are needed to perform the tasks
- Very compact representation of scheduling problem
- But, where does that information come from?

6.2 Orders, Products, Processes

Scheduling orders

- An *order* specifies a need for a certain *product* at a given time in a specific quantity
- There may be multiple ways of making the *product* (multiple *processes*)
- We assume that the process to use is decided when placing the order
- Each order corresponds to a job, with its constituent tasks
- There may be limited visibility of future orders

Process Description

- Each *process* consists of one or more *process steps*
- A process step contains a duration formula to describe how long it lasts
- The order of *process steps* is defined by *process sequences*
- The resources needed are defined by *resource needs* (described later on)
- Tasks are created for each process step, their duration is based on the duration formula and order quantity

Where do the orders come from?

- Made to order
 - Each order is caused by a customer request
 - Defines due date, release date often implied
- Made to stock
 - Orders are satisfied from stock
 - Inventory control strategy decides when to make product
 - Often called stock orders
 - More complex variant integrates production planning and detailed scheduling
 - Example later in course

7 Temporal Relations

Temporal Relations

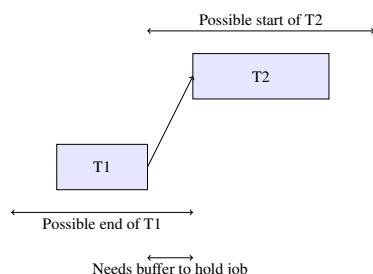
- Temporal constraints between tasks and/or jobs
- Defined by the manufacturing process
- In simple cases
 - A single sequence of process steps performed in that order
 - Each task must finish before the next one can start



7.1 Relations between Tasks

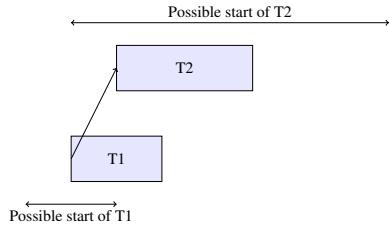
The Most Common Relation: EndBeforeStart ✓

- States that one task (T1) must end before the next one (T2) can start
- Typical for manufacturing process based on the same item
- Addition: offset
 - Wait at least offset units between end and start
 - For example cooling, drying time outside a machine



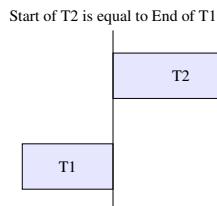
Less Common: StartBeforeStart ✓

- States that one task (T2) can start any time after the start of another task (T1)
- Uncommon in manufacturing, occurs in project management
- Example later on on assembly line balancing



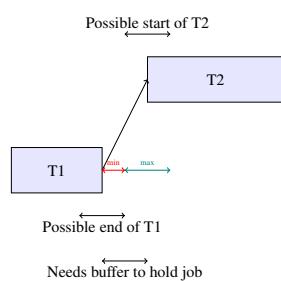
NoWait ✓

- Sometimes, two steps must follow each other immediately
- The item made would spoil
 - Product specific
- There is no space to hold item
 - Machine specific, buffers
- End of one task (T1) must be equal to start of next task (T2)
- May mean delay of start of task T1



MaxWait (✓)

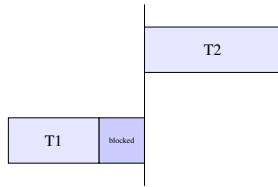
- Limit how long we can wait between tasks
 - Cooling enough, but not too much
 - Baking: rise time
- Impose both lower and upper waiting time limit
- Makes it more difficult to find solutions



Blocking ✓

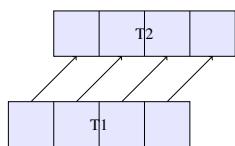
- Sometimes, two steps must follow each other immediately
- There is no space to store item between machines
- Keep item on previous machine until needed
- That machine is now *blocked*
- Duration of task T1 is extended until start of T2
- *Use with caution! Easy to deadlock*

Start of T2 is equal to End of T1



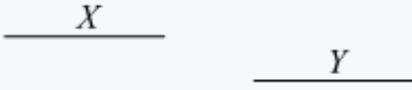
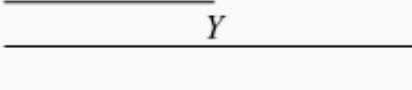
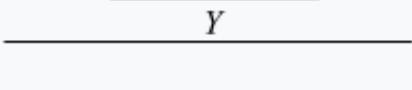
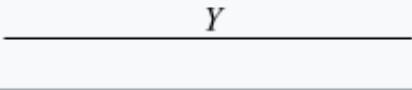
Special Case: Pipelining ✗

- Sometimes, we can start on the next task while the first is still running
- Possible if one job consists of multiple items (lots,...)
- As soon as the first item is finished, take it to the next machine to process it there
- Overlaps T1 and T2 as much as possible
- Details can get complex



More General: Relations between Intervals ✗

- First introduced by Allen (1983)
- 13 relations between intervals
- Allows composition of relations
- Constraint reasoning on sets of relations

Relation	Illustration	Interpretation
$X < Y$ $Y > X$		X precedes Y Y is preceded by X
$X \mathbf{m} Y$ $Y \mathbf{mi} X$		X meets Y Y is met by X (<i>i</i> stands for <i>inverse</i>)
$X \mathbf{o} Y$ $Y \mathbf{oi} X$		X overlaps with Y Y is overlapped by X
$X \mathbf{s} Y$ $Y \mathbf{si} X$		X starts Y Y is started by X
$X \mathbf{d} Y$ $Y \mathbf{di} X$		X during Y Y contains X
$X \mathbf{f} Y$ $Y \mathbf{fi} X$		X finishes Y Y is finished by X
$X = Y$		X is equal to Y

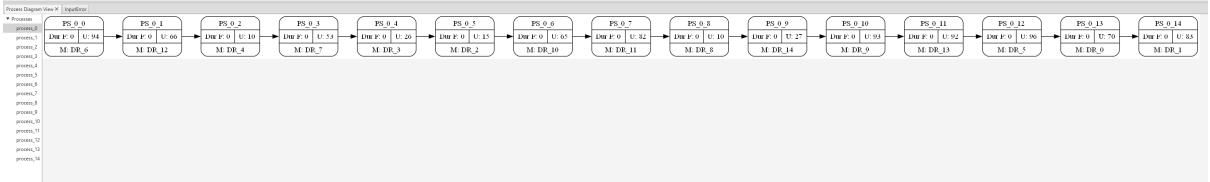
from Wikipedia: https://en.wikipedia.org/wiki/Allen%27s_interval_algebra

7.2 Relation between Tasks and Jobs

Start and End of Jobs ✓

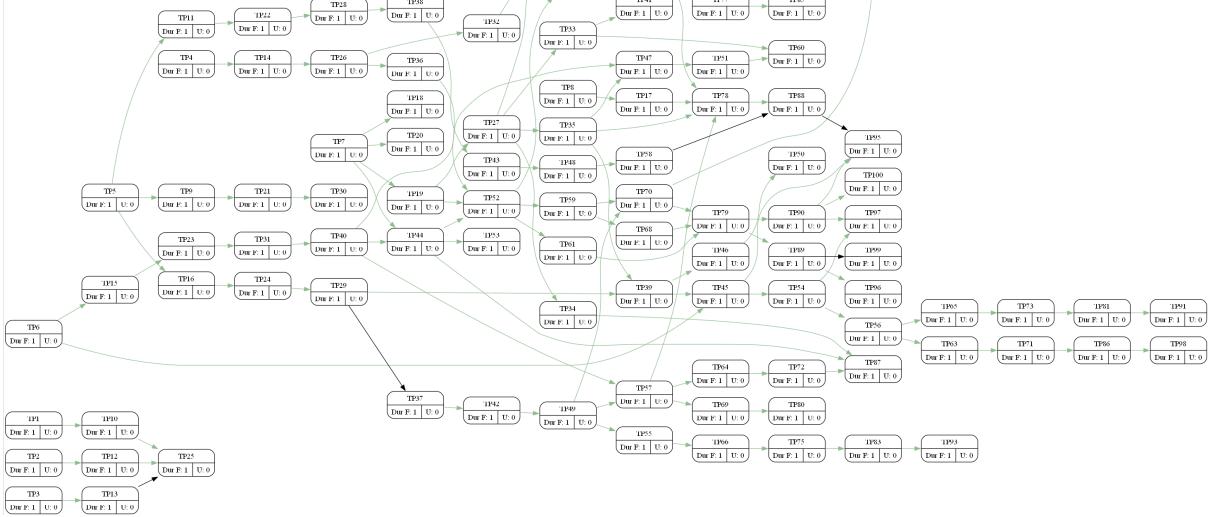
- The start of a job is equal to the start of the earliest task of the job
- The end of a job is equal to the latest end of any of its tasks
- Also called: the job *spans* its tasks
- Sometimes very simple
 - Start of job is start of first process step
 - End of job is end of last process step
 - But, do we know which steps will be first or last?

An Example of a Simple Process



- The steps form a precedence chain
- Easy to identify first and last step

An Example of a More Complex Process

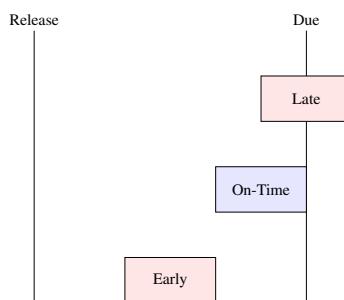


- There is no clear first or last process step

7.3 Jobs: Release and Due Date

Jobs: Release and Due Dates ✓

- The execution of a job may be constrained in time
- Release dates* states earliest time a job can start
- Due dates* states latest time a job can end
- These may or may not be hard constraints!
- A job will be *late* if it ends after the due date
- A job will be *early* if it ends before the due date
- A job will be *on-time* if it ends at the due date



7.4 Relations between jobs

Relations between Jobs ✎

- There may be relations between jobs as well
- For example, jobs for the same product may be arranged by due date
- Do not allow to run job for a later due date before any job with an earlier due date
- Orders for the same customer, but different products, may be constrained
- Most common:
 - Jobs for intermediate products must finish in time for their use later on

8 Alternative Processes, Bill of Materials

More Complexity

- We have ignored a lot of potential complications
 - Alternative processes
 - Alternative process paths
 - Alternative resources
- Intermediate products
- Impact of raw material availability

Intermediate products ✎

- Some production operations are assembly steps
- Combine multiple intermediate products together
- These intermediate products need to be made as well
- There are processes for those products

Raw materials ✎

- Sometimes, a process step needs certain raw materials
- These are not made within the scheduled part of the plant
- They come from stock, inventory control problem
- Do we schedule production and then order raw materials?
- Do we schedule based on the available raw materials?

Bill of Materials (BoM), Bill of Processes ✎

- Enterprise systems will describe which items are needed to make a product
- Tree like structure, indicates the intermediate product/raw material needed and its quantity
- *BoM explosion* derive all required input materials for a given set of orders
- We may want to know at which step of process we need which materials (Bill of processes)
- This is where you use SAP, big database, trivial calculation
- Becomes hard if processes not fixed

9 Problem Classification

Problem Classification

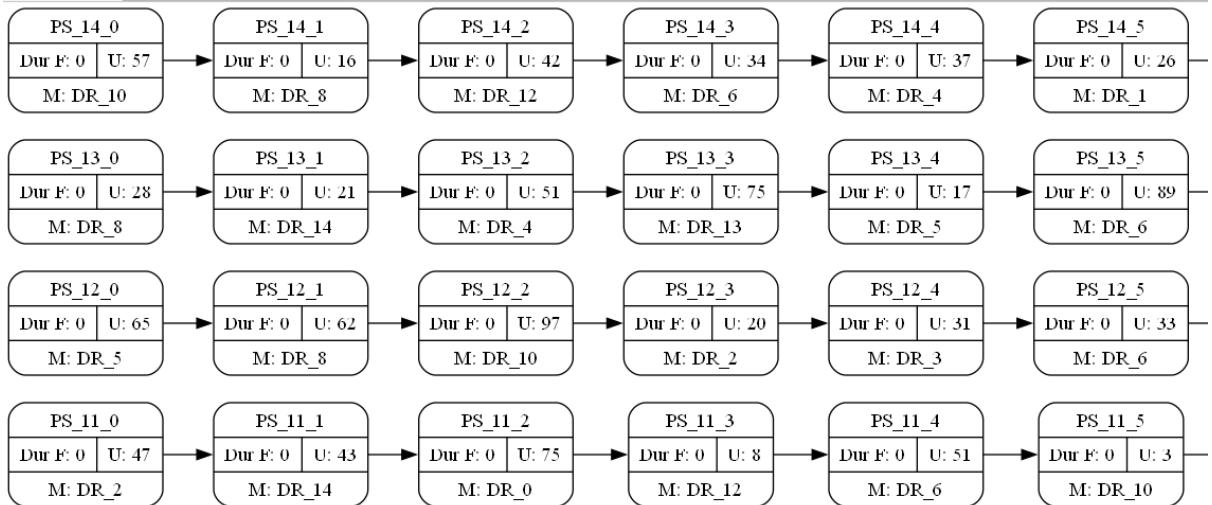
- Most real-world problems are messy, with many special conditions and exceptions
- Academic research prefers well-structured problems
- Scheduling research often focuses on well-structured problem types
 - Easier to understand
 - Possible to exploit structure
 - Easier to compare results
- A small number of problem types are very common in research

9.1 Job-Shop

Job-Shop ✓

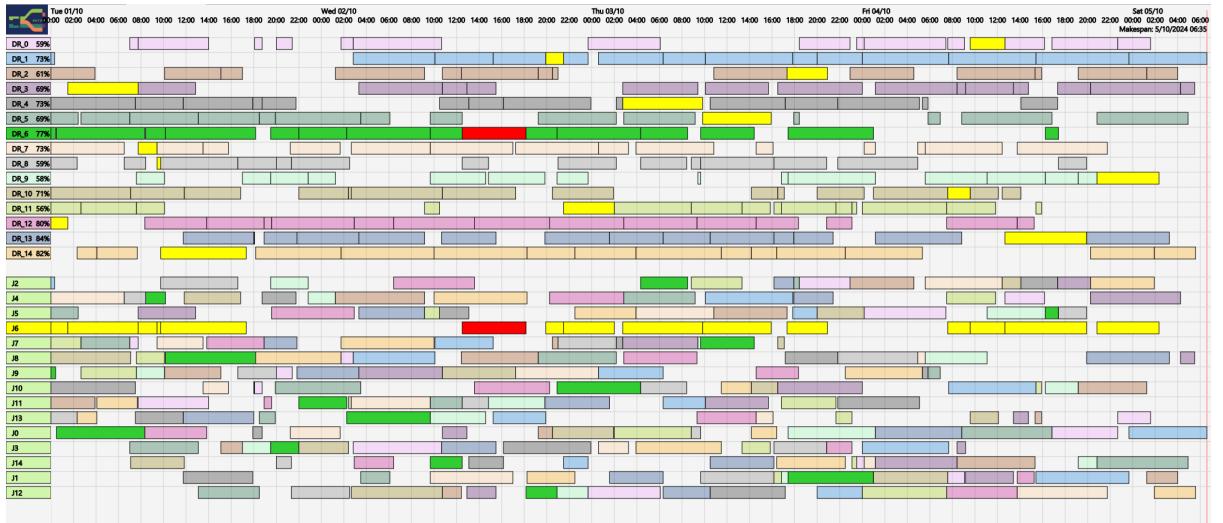
- Consists of a number of jobs and a number of machines
- Each job visits each machine, but possibly in a different order, depending on process
- Tasks of a job are linked as a precedence chain
- Objective is to minimize overall end, the *makespan*

Example Job-Shop Process



- Note that the order of machines visited is different for each process

Example Job-Shop Solution

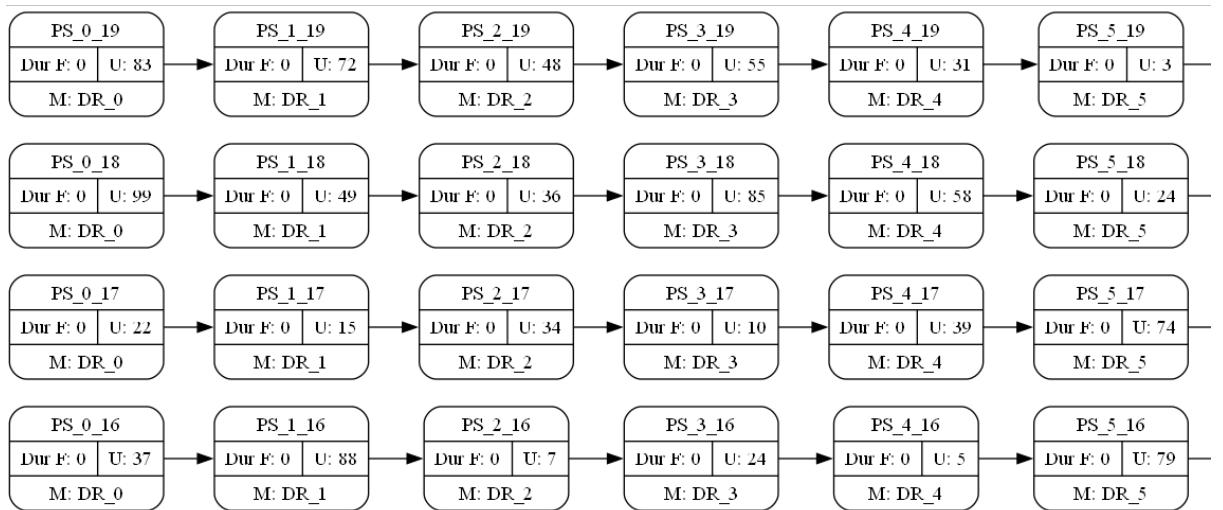


- One task is selected (in red), in both Machine and Job Gantt Chart

9.2 Flow-Shop ✓

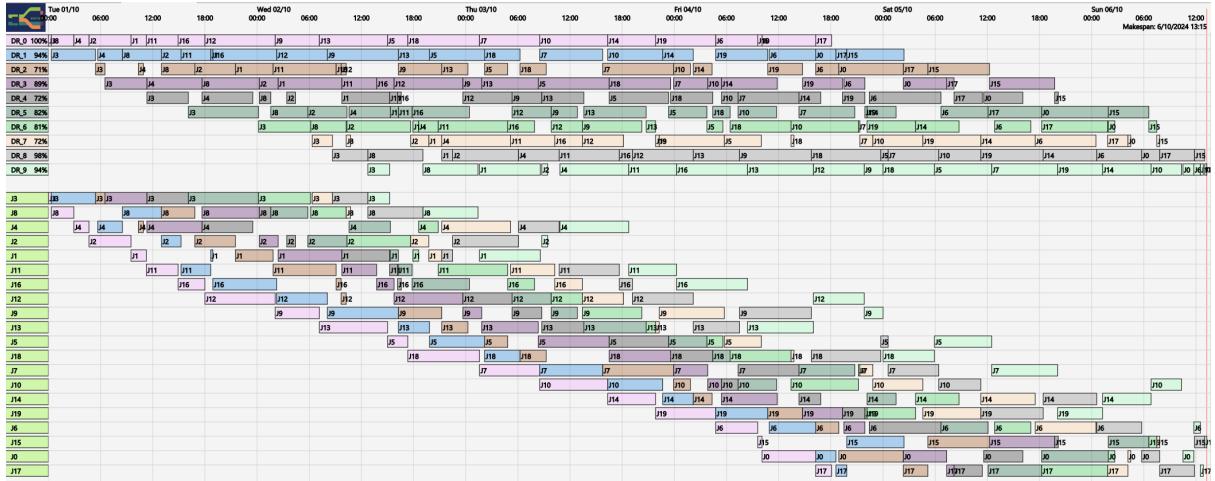
Flow-Shop ✓

- Consists of a number of jobs and a number of machines
- Each job visits each machine, all jobs in the same order
- Tasks of a job linked in a precedence chain
- Objective is to minimize overall end, the *makespan*



- Note that each process visits the machines in order DR_0, DR_1, ...

Example Flow-Shop Solution



- Tasks are colored by machine, note the regular pattern in the Job Gantt Chart

9.3 Open-Shop

Open-Shop ✓

- Consists of a number of jobs and a number of machines
- Each job visits each machine, we have to choose the sequence individually for each order
- There are no temporal constraints between tasks, but tasks of the same job cannot overlap
- Objective is to minimize overall end, the *makespan*

Open Shop Example Process

- Only showing details of one process
- No prescribed sequence between process steps
- Easier to find a task to run next
- Much larger search space

▼ Processes

process_0

process_1

process_2

process_3

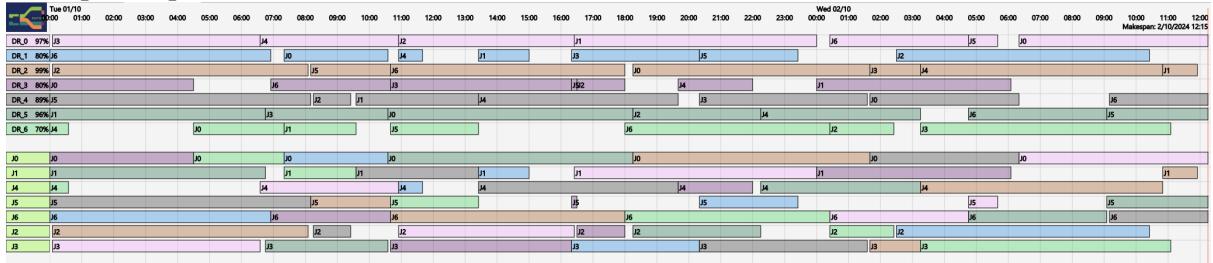
process_4

process_5

process_6

PS_0_6	
Dur F: 0	U: 56
M: DR_4	
PS_0_5	
Dur F: 0	U: 92
M: DR_5	
PS_0_4	
Dur F: 0	U: 71
M: DR_0	
PS_0_3	
Dur F: 0	U: 34
M: DR_6	
PS_0_2	
Dur F: 0	U: 54
M: DR_3	
PS_0_1	
Dur F: 0	U: 39
M: DR_1	
PS_0_0	
Dur F: 0	U: 89
M: DR_2	

Open-Shop Example Solution



- Example solution for 7x7 open shop example
- Order of tasks within jobs not constrained

9.4 RCPSP

Resource Constrained Project Scheduling Problem (RCPSP) (✓)

- Problem class from project management
- One project (one job), many tasks
- Precedence graph is arbitrary DAG
- Cumulative as well as disjunctive resources
- Variants with process alternatives

9.5 $\alpha/\beta/\gamma$ Notation

$\alpha/\beta/\gamma$ Notation

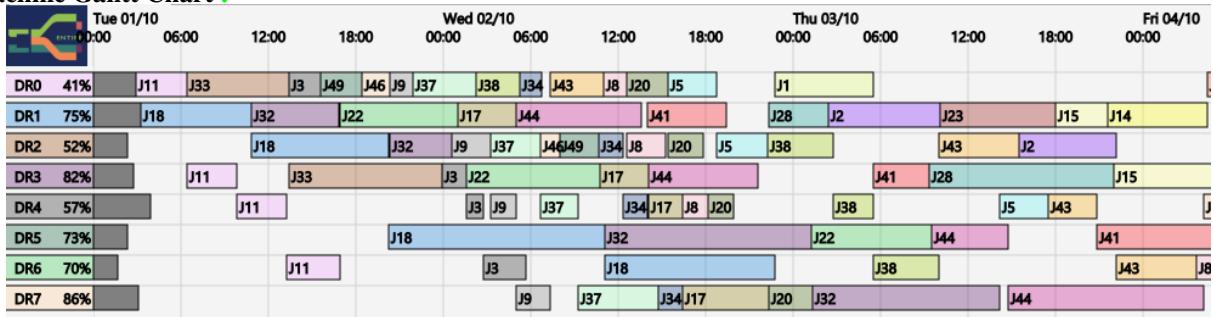
- The previous classes are good for research, but not very practical
- General scheme to describe problem type introduced in 1979
- Based on three parameters
 - α resource structure, stages
 - β temporal relations
 - γ objective
- $P2/r_j, \bar{d}_j/C_{\max}$: One stage, two identical parallel machines, hard release and due dates, objective makespan
- More detailed description at <https://encyclopedia.pub/entry/30497>

10 Key Visualization Methods

Visualization

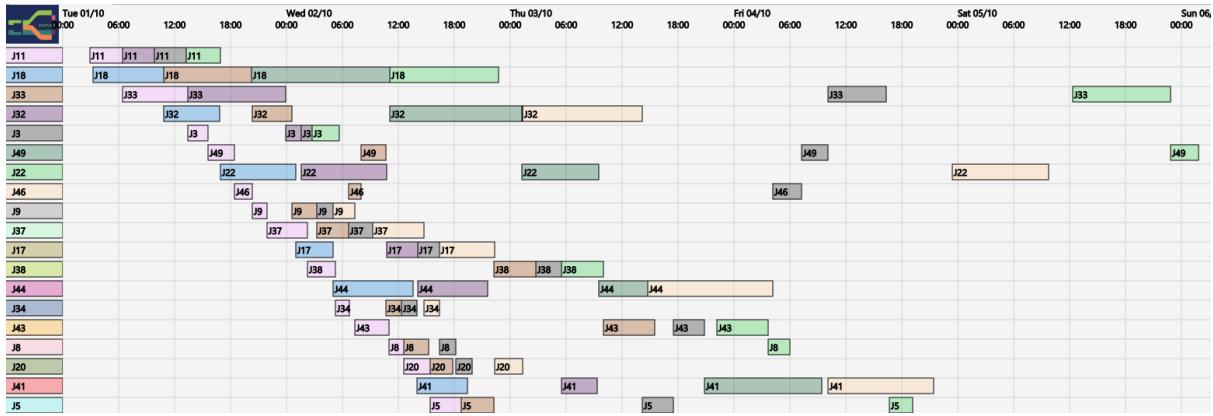
- Visualization is key to present and to understand results
- Many different ways to give an overview of schedule, and highlight problems
- Some diagrams types are used a lot, and are provided in our generic scheduling tool
- Customization is key

Machine Gantt Chart ✓



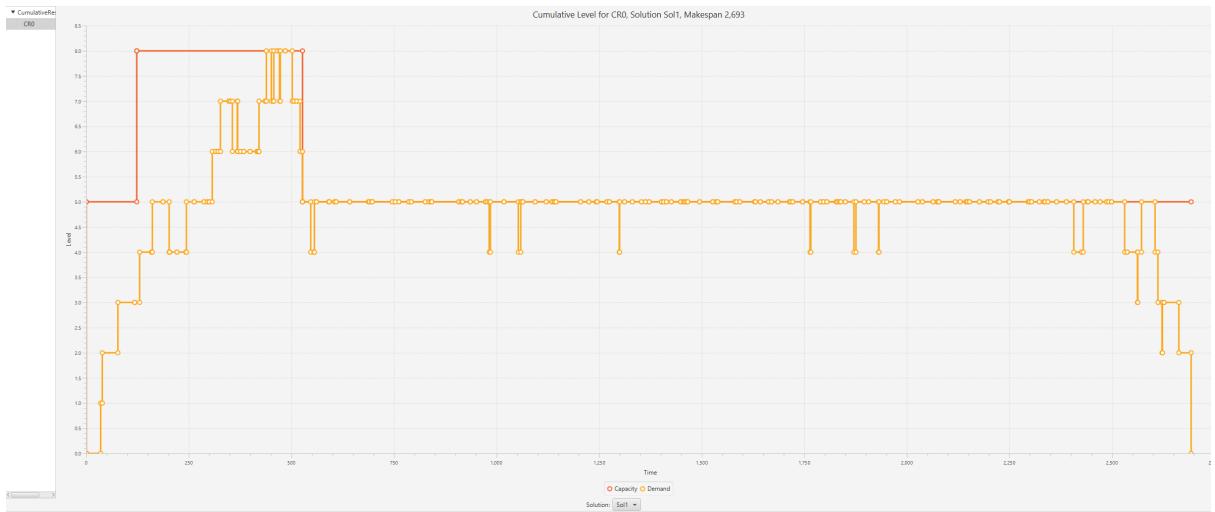
- Shows all tasks that are assigned to each machine
- Tasks should not overlap
- Also shows work in progress (WiP), down-times
- Optional display of setup and idle times

Job Gantt Chart ✓



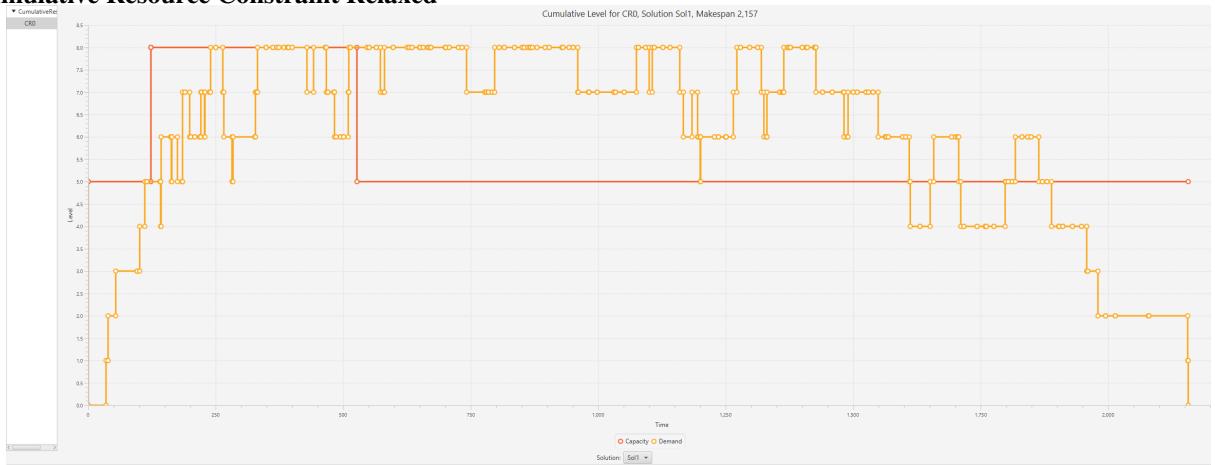
- Shows all tasks of a job in one line
- Only works for single chain of process steps
- Possible display of earliness, lateness
- Optional display of waiting and transport times

Cumulative Resource Chart ✓

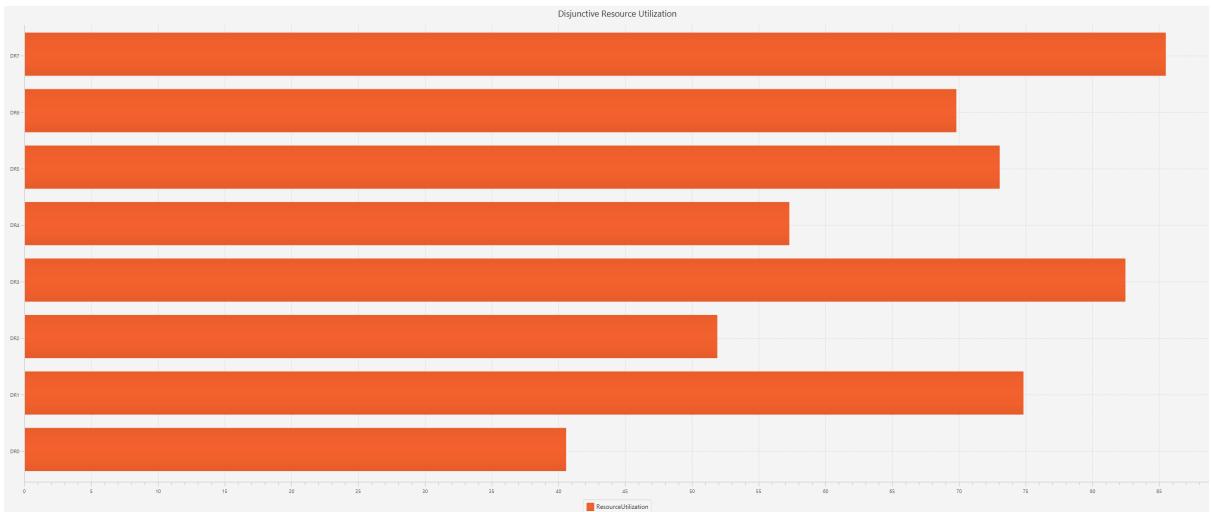


- Shows resource utilization of cumulative resource over time
- Utilization should be below capacity profile
- Unless we relax the cumulative resource constraint

Cumulative Resource Constraint Relaxed

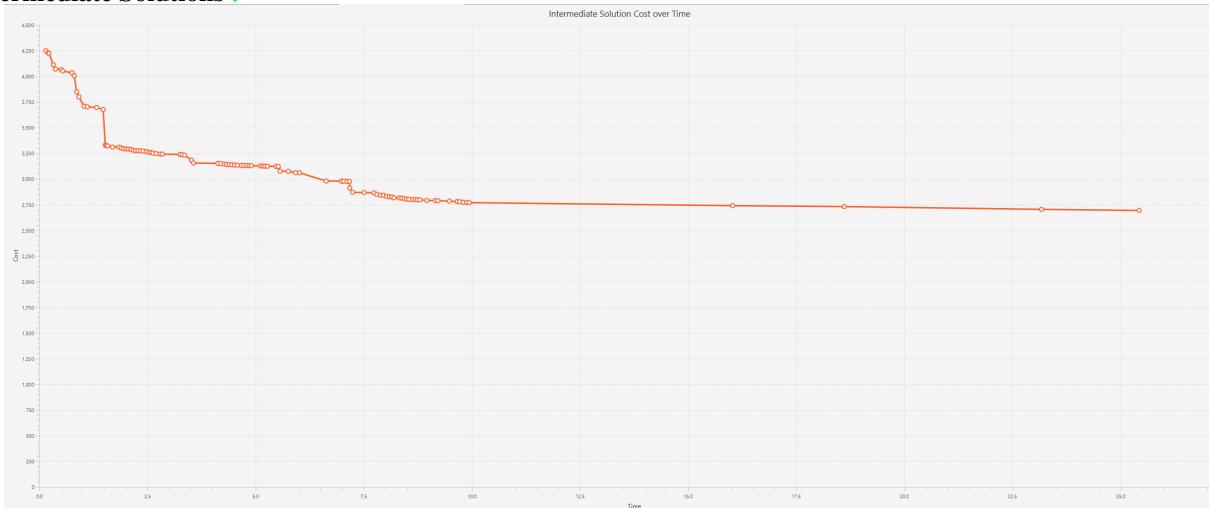


Resource Utilization ✓



- Shows utilization of machines as percentage of active time
- Helpful to identify bottleneck machines
- Information also shown in Machine Gantt

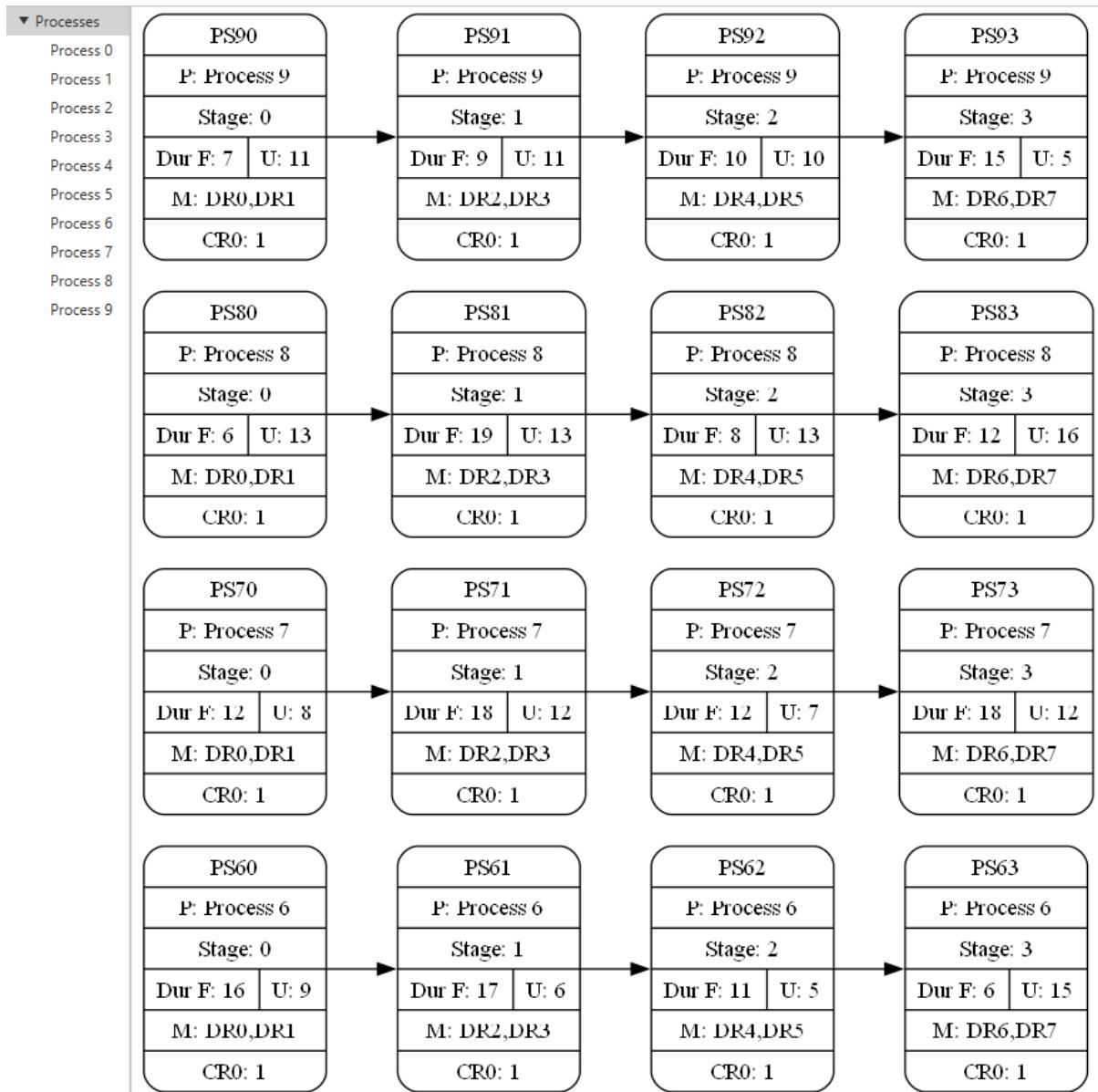
Intermediate Solutions ✓



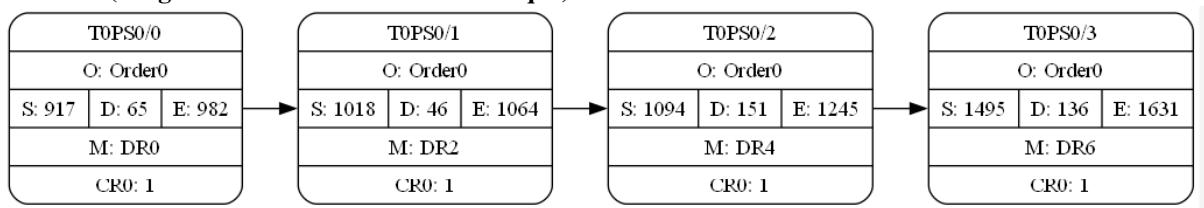
- Shows intermediate solutions found over time
- Useful to see if enough/too much time is allocated

Process Diagram ✓

- See all details of one process in one image
- Can also look at all processes in one diagram
- Options to show/hide different fields

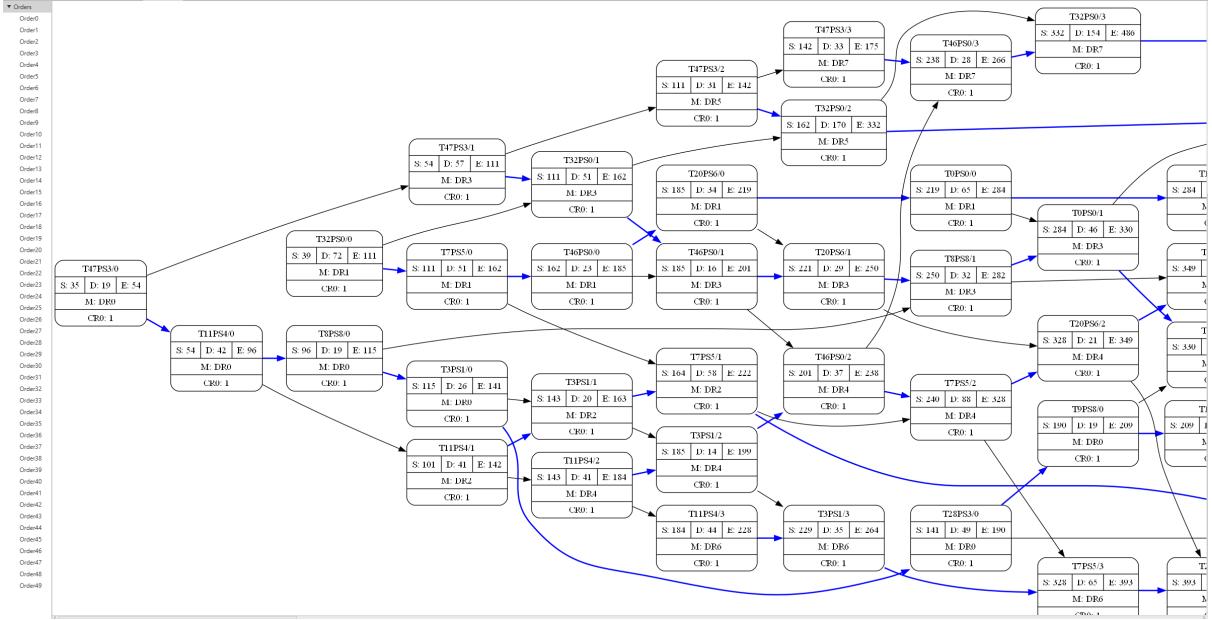


PERT Chart(Program Evaluation Review Technique) ✓



- Show details of job as a graph
- Useful if task graph is not a chain
- Often used in project management

PERT Charts become Confusing Quite Quickly



- Especially if all resource dependencies are included (in blue)

Calendars X

	Jan 22	Feb 22	Mar 22	Apr 22	May 22	Jun 22	Jul 22	Aug 22	Sep 22	Oct 22	Nov 22	Dec 22
Mon	3	3	3	3	3	3	3	3	3	3	3	3
Tue	3	3	3	3	3	3	3	3	3	3	3	3
Wed	3	3	3	3	3	3	3	3	3	3	3	3
Thu	3	3	3	3	3	3	3	3	3	3	3	3
Fri	3	3	3	3	3	3	3	3	3	3	3	3
Sat	3	3	3	3	3	3	3	3	3	3	3	3
Sun												

- Shows weekly structure for one or more years
- Indicates public holidays, shut-downs, etc
- Indicating working days, KPI for each day

11 Summary

Summary

- We introduced the key concepts for scheduling problems
- Orders, products, processes
- Jobs and tasks
- Existing problem classifications
 - Academic
 - Limited practical usefulness
 - Used for benchmarking
- Key visualization ideas

Part III

Machines and Resources

Key Points

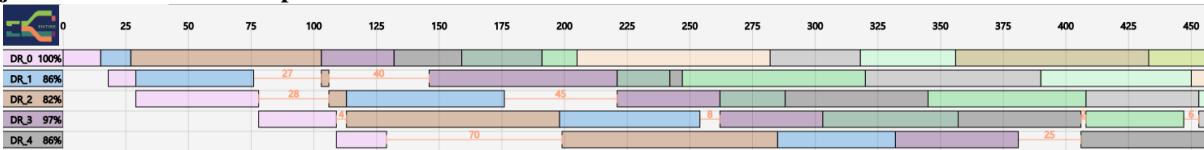
- Introduce different types of resources
- Disjunctive resources - one task at a time
- Cumulative resources - demands and capacity
- Machine choice - Use one of multiple machines
- Work in progress and planned downtimes
- Calendars - Not working all the time

12 Disjunctive Resources

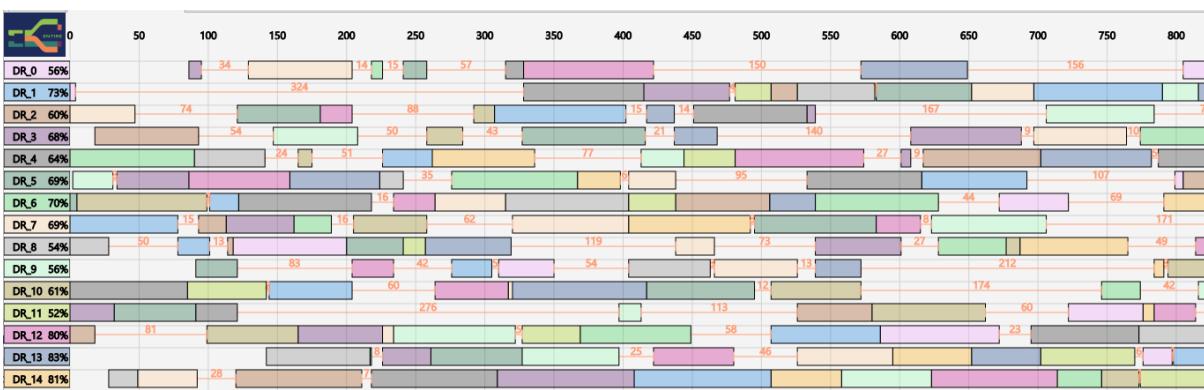
Disjunctive Resource ✓

- A *disjunctive resource* works on one task at a time
- Each task runs uninterrupted from start to end
- The machine may be *idle* between tasks
- The machine may be unused at start and end of schedule
 - Some of this may be unreachable, there is no work that can be done in these periods
 - Problem of cold start, especially for flow-shop type problems
- *Active time* is time between first and last use
- Resource utilization compares productive time to active or available time

Disjunctive Machines Examples



- Flow-Shop example, some unreachable time on later resources in process, some idle time



- Job-Shop example, a lot of idle time

12.1 Preemption

Preemption ✗

- Normal constraint for disjunctive constraints is one task at a time
- Once a task is started, it runs until it is finished
- *Preemption* allows to stop a task, run a different task, then resume the previous task to the end
- Example: This is how Operating Systems run tasks inside a computer
 - This works since cost of suspending a task is relatively low
 - Also needed as tasks continuously produce output which is expected
- In manufacturing, preemption often is an exception in an emergency
- Occurs a lot in project management, e.g. construction

How to Deal with Preemption in Scheduling

1. Handle this as manual intervention for critical situations
2. Dedicated preemptive scheduling constraints
3. Allow limited number of interruptions
 - Split each task into multiple pieces of unknown length
 - Normally, schedule all parts together for total duration
 - For preemption, schedule other task after first/second part
 - All parts of task must add up to total duration

13 Cumulative Resources

Cumulative Resources ✓

- A cumulative resource provides capacity over time, the sum of the demands at each timepoint cannot exceed the available capacity at that time
- Resource demand by one task is considered constant from start to end
 - Need to break task into smaller segments to model time variable demand
- In itself a hard problem, so full propagation not possible
 - Active research area since 1993, when the constraint was introduced in CHIP

13.1 Demand and Capacity

Specifying Cumulative Resources

- Describing a cumulative resource
 - The resource itself
 - The capacity profile over time
 - The demands per processStep
- Each task may or may not need a specific cumulative resource

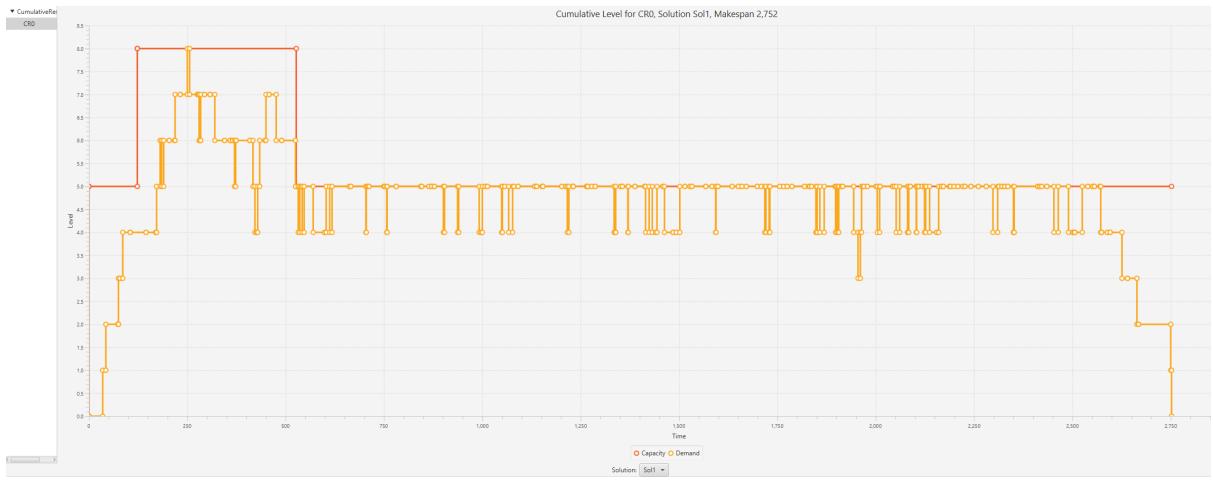
- The assumed total amount of work needed is constant
- We can calculate resource utilization by comparing demand to capacity

name	CR0
-------------	------------

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

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

Cumulative Resource Profile

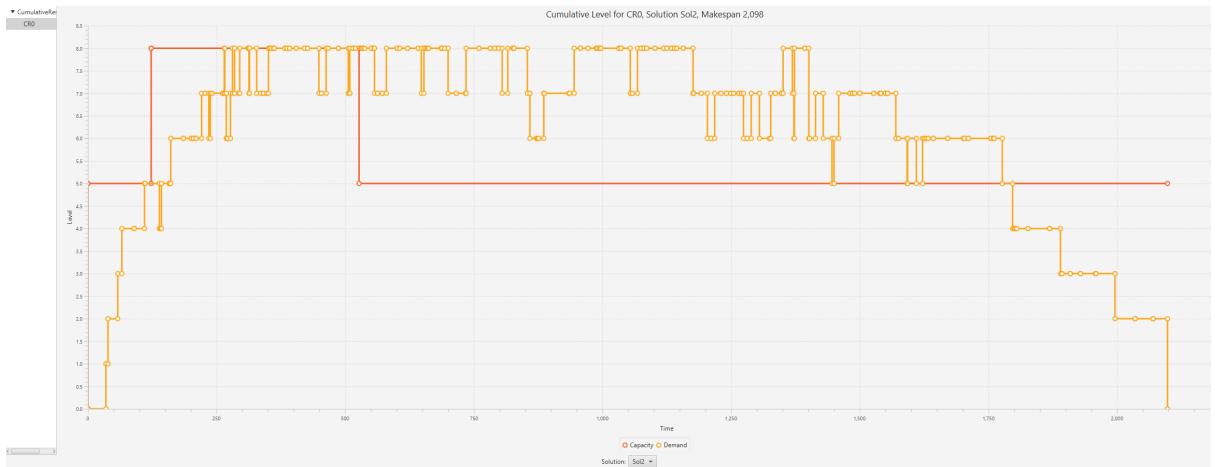


What is the Impact of the Cumulative?

- We want to understand what impact a cumulative resource has
- We can disable the constraint in the solver options
- Re-run the scheduler
- Observe the impact on the objective
- See where the capacity limit is not respected in new solution

Enforce Release Date:	<input checked="" type="checkbox"/>
Enforce Due Date:	<input type="checkbox"/>
Enforce Cumulative:	<input type="checkbox"/>
Enforce WiP:	<input checked="" type="checkbox"/>
Enforce Downtime:	<input checked="" type="checkbox"/>
Enforce Setup:	<input type="checkbox"/>
Enforce Transport Time:	<input type="checkbox"/>
<hr/>	
Relax Sequence:	<input type="checkbox"/>
Add Same Order:	<input type="checkbox"/>
Add NoWait:	<input type="checkbox"/>
Add Blocking:	<input type="checkbox"/>
<hr/>	
Model Type:	CPSat
Solver Backend:	None
<hr/>	
Objective Type:	Makespan

Cumulative Profile When Constraint is Disabled



- Objective reduced from 2,752 to 2,098
- Overall resource use now reaches 8 in period where capacity is limited to 5

13.2 Variants

Variant: Resource Limit as Objective ✗

- For some scheduling problems, the duration of the schedule is fixed
- The objective is: how many resources are needed to schedule all tasks within the available time?
- Capacity is a variable, part of objective function
- Example later on for assembly line balancing
 - Number of stations on line is fixed
 - Objective is to minimize *Takt*, the cycle time allocated for one step
- Consider solving this question with multiple scenarios, instead of different objective

Variant: Trading Time for Capacity ✗

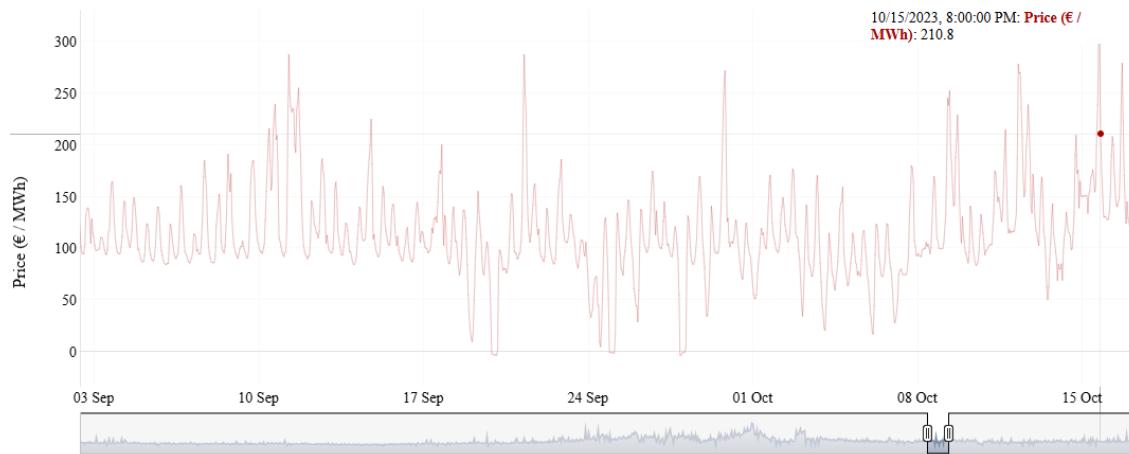
- In some cases, the duration of a task depends on how many resources are available
- Total amount of work (energy) is constant, higher demand (power) means lower duration
- In easiest case, fixed demand levels are assumed
 - Resources are assigned to task throughout duration
 - Example: assigning software engineers to projects
 - Remember Books's law
 - * Adding manpower to a late software project makes it later.
- Most general case, any profile is OK, as long total demand is covered
 - Cost of reassigning resource from one task to another is considered minimal

Variation: Time Variable Resource Cost X

- Resource cost may vary over time
- Example: Overtime cost for working on weekend
- Example: Energy cost with time variable tariff
- Avoid periods of high cost, use areas of low cost

Example: Electricity Price in Ireland

Hourly Irish Wholesale Electricity Price



from: <https://kilowatt.ie/wholesale-electricity-prices-ireland/>

Variant: Soft/Hard Limits X

- Often, some capacity is available for "free", sunk costs
- Resource use above that limit costs extra
- Example: Full-time staff/contract workers
- Example: In-house capacity/rented computing capacity
- Multiple profiles, each with its own cost per unit

Variant: Lower Utilization Limit X

- Sometimes, we also want to enforce a lower limit of the resource use
- We want to avoid resources being idle
- Express a lower limit on the resource use
- Can be hard to satisfy for specific demand and capacity values

14 Manpower

Manpower Constraints ✓

- Use cumulative constraints to express manpower limits
- Some tasks may need multiple workers
- Total capacity profile is number of workers available at each time
- Profile may change with shift-pattern (regular pattern)
- Holidays/sick-leave/training reduce available manpower at specific times
- Constraint does not assign workers, only checks that enough capacity is available

14.1 Nested Skill Levels

Skills ✗

- Not all workers have the same qualifications
- Workers may need to be trained/certified to perform certain tasks
- Each task may require specific skill(s)
- Nested resource constraints to cover the needed skills
 1. One worker may have all required skills, only one worker is needed
 2. Multiple workers needed to cover all required skills, no worker has all skills
 3. More than one worker needed anyway, the group must cover required skills
- Training/certification program may create its own scheduling problem

14.2 Assigned Operators

Alternative: Assigned Operators ✗

- In special cases, it may be required to assign specific workers to tasks
- Each worker can work on one tasks at a time (disjunctive constraint)
- Multiple workers are qualified to perform certain jobs (machine choice, one worker is assigned)
- Multiple workers are qualified to perform certain jobs (multiple workers with that skill are needed)
- Named individual must be assigned for traceability
 1. Is there a hand-over from one shift to the next?
 2. Complete work must be performed within one shift

14.3 Fractional Manpower Needs

Fractional Manpower Needs ✗

- Some tasks may not need a full-time operator
- Different scenarios
 - Operator only needed at start/end of task (setup, cleaning)
 - Operator is needed to load/unload items into machine
 - One operator can supervise three, but not four machines
- This gets too complex/too fragile very quickly

15 Machine Choice

Choosing which machine to use

- Problem with Job-shop/Flow-shop: There is only one machine per processStep
 - What happens if any of those machines stops working?
 - Do we stop production completely?
- Most plants have multiple machine for the same task
- Three fundamental alternatives
 - Multiple, identical machines
 - Multiple machines with different speeds
 - Preferences for specific machines, but viable alternatives exist
- On the other hand, sometimes identical machines are treated as different
 - Dedicated lines for major products, avoiding setup/cleaning times

15.1 Identical Machines

Identical Machines ✓

- Easiest case, several machines of same type
- You can choose any of the available machines
- Processing time is the same on all machines
- Product quality is identical
- Define which machines are available with ResourceNeed

15.2 Machine Dependent Speed

Machine Dependent Speed (✓)

- Duration of the task depends on machine on which it is run
- Two common scenarios
 1. Some machines are faster than others (new generation)
 2. Different processes are faster/slower on some machines
- Express task duration as part of ResourceNeed
- Prefer faster machines, but balance machine use

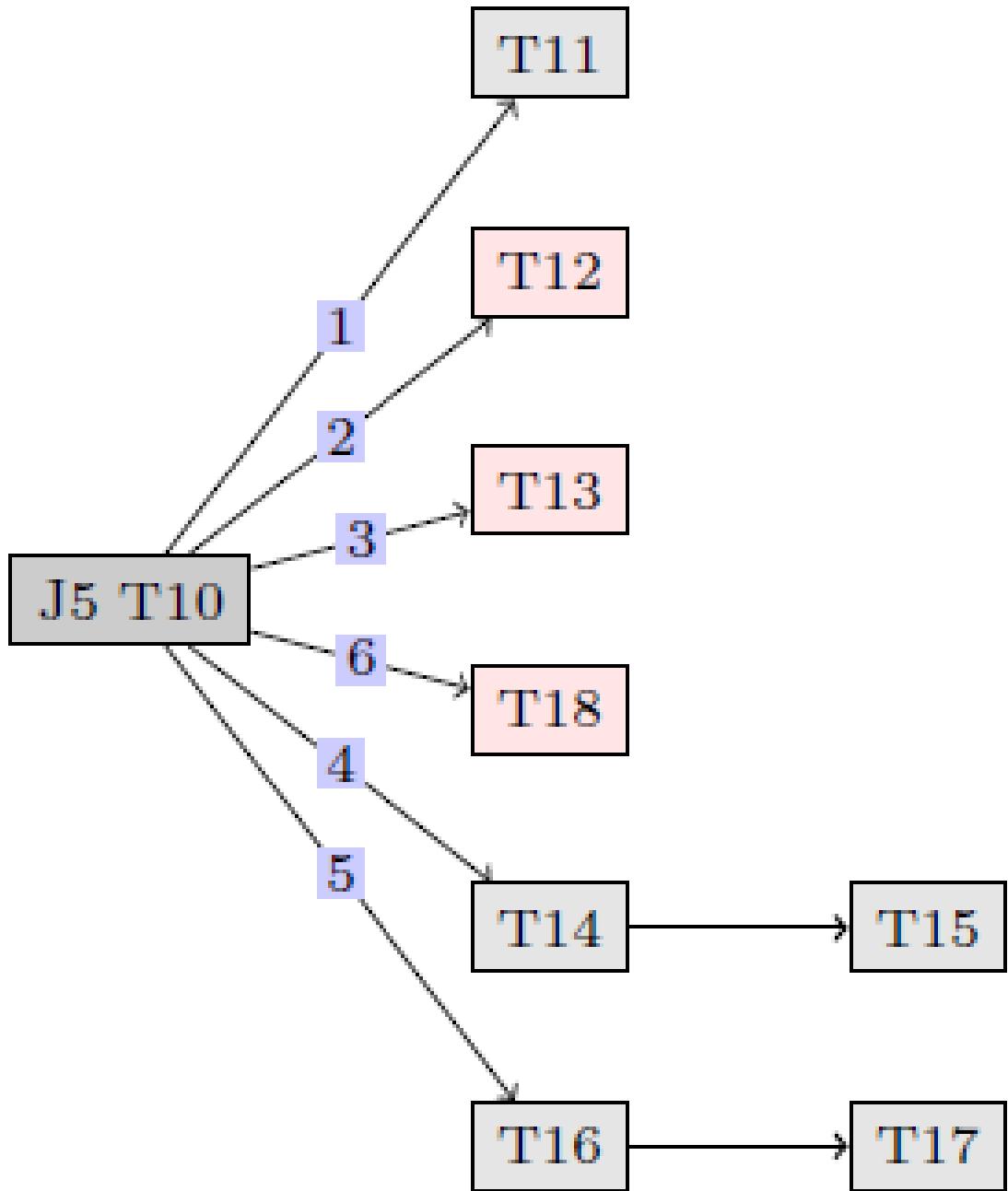
15.3 Machine Preferences

Machine Preference (✓)

- Each process step has a preference ranking of machines, from best to worst
- Potential Causes
 - Product quality
 - Production speed
 - Production cost
 - Skill level required
 - Scrap rate
- Handle preferences as part of objective
- Enforce certain levels of preference to understand impact

Example from Siemens Energy Case Study

- Six alternatives for task T10
- Preference ranking from one (best) to six (worst)
- Some alternatives require additional tasks
- Tasks in red are outsourced



16 Work in Progress and Planned Downtimes

Work in Progress ✓

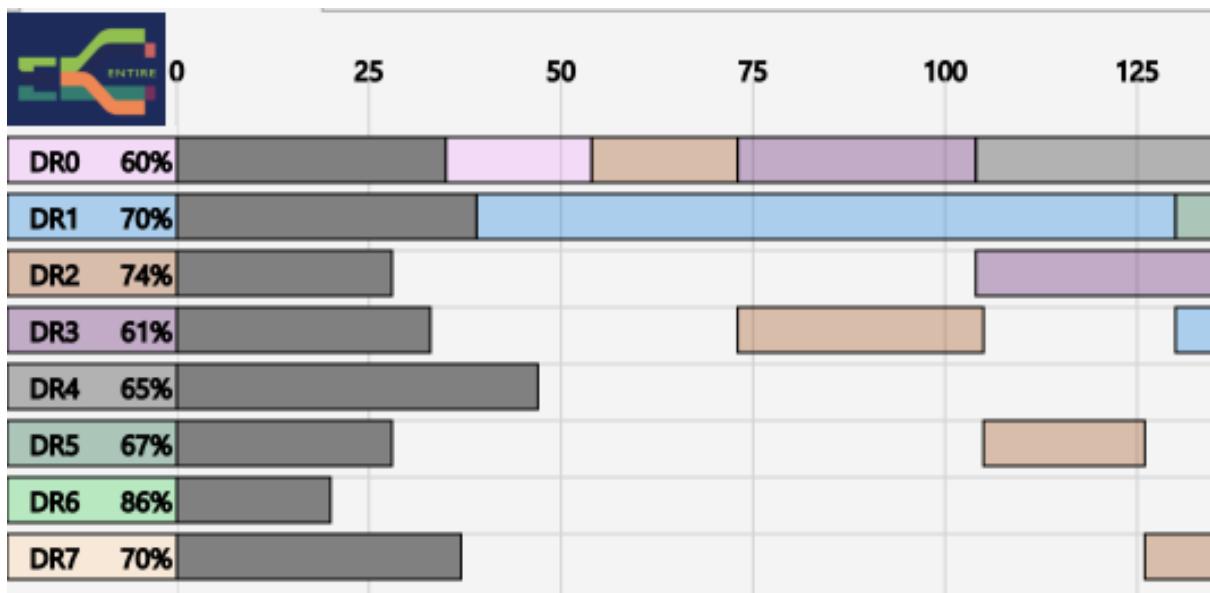
- Typically a plant does not start from scratch
- There is work currently running on machines
- This work must be finished before new work can be scheduled
- Called *Work in Progress (WiP)*

- Specified in input data

Name	DisjunctiveResource	Duration	Start	End	StartDate	EndDate	
WDR0	DR0	35	0	35	1/10/2024 00:00	1/10/2024 02:55	
WDR1	DR1	39	0	39	1/10/2024 00:00	1/10/2024 03:15	
WDR2	DR2	28	0	28	1/10/2024 00:00	1/10/2024 02:20	
WDR3	DR3	33	0	33	1/10/2024 00:00	1/10/2024 02:45	
WDR4	DR4	47	0	47	1/10/2024 00:00	1/10/2024 03:55	
WDR5	DR5	28	0	28	1/10/2024 00:00	1/10/2024 02:20	
WDR6	DR6	20	0	20	1/10/2024 00:00	1/10/2024 01:40	
WDR7	DR7	37	0	37	1/10/2024 00:00	1/10/2024 03:05	

Work in Progress ✓

- Typical a plant does not start from scratch
- There is work currently running on machines
- This work must be finished before new work can be scheduled
- Called *Work in Progress (WiP)*
- Specified in input data, shown in gray
- Part of the disjunctive constraints



Planned Downtimes ✓

- Sometimes, a machine is unavailable for a period of time
- Maintenance, upgrade
- Planned activity with fixed start and end
- This should be considered in schedule
- Given as input data
- Part of the disjunctive constraints
- Gaps may lead to loss of productivity

Name	DisjunctiveResource	Duration	Start	End	StartDate	EndDate
DDR1	DR1	51	3,749	3,800	14/10/2024 00:25	14/10/2024 04:40
DDR2	DR2	66	5,137	5,203	18/10/2024 20:05	19/10/2024 01:35
DDR4	DR4	52	2,888	2,940	11/10/2024 00:40	11/10/2024 05:00
DDR6	DR6	57	4,412	4,469	16/10/2024 07:40	16/10/2024 12:25

Variant: Scheduled Downtime ✗

- Sometimes, we can decide when the downtime should occur (within reason)
- We can schedule it like any other task
- Avoid unproductive gaps in schedule
- More complex case for regular, scheduled downtimes
 - Maintain the correct time gap between maintenance checks
- How is in control in scheduling these events?

Unplanned Downtime ✗

- A machine breaks down unexpectedly
- This is not reflected in current schedule (unplanned)
- How to react?
 - Extend current task until finished (if task continues after breakdown)
 - Create new task to complete work later on (if task is partially finished)
 - Scrap task, reintroduce order in next schedule (if task is scrapped by breakdown)

17 Calendars

Calendars

- A plant may not run 24/7, but shut down for regular/irregular periods
 - Overnight
 - Weekend
 - Public holidays/holidays/Christmas
- Some parts of plant may operate on different calendars
 - Office/lab may be working office hours only
- Considering multi-site, plants may be working in different time-zones
 - Common example: data centres around the world, follow the moon

Important Questions

- Which dates are expressed in working time, which in calendar time?
- Examples
 - Release/due dates typically expressed in calendar time
 - Task duration expressed in working time
 - Min/max waiting time expressed in calendar time

17.1 Factory Wide Calendars

Single, Factory-wide Calendar

- Three shift operation common
 - 06:00 - 14:00
 - 14:00 - 22:00
 - 22:00 - 06:00
- Start/end of weekend not obvious
- Handling of public holidays plant specific
- Lots of input data

Shift Pattern Definition X

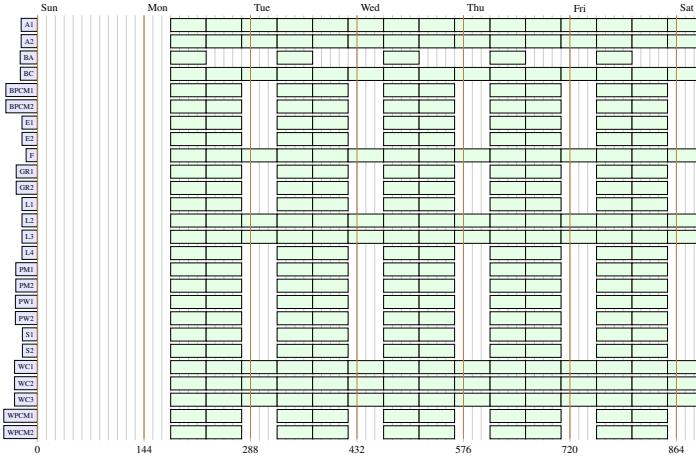
Name	Shift Model	Percentage	Start Date	End Date	Start Time	End Time	Mon	Tue	Wed	Thu	Fri	Sat	Sun
AV12	Shift 15 1	0.80	01/02/2022	01/11/2022	06:00	14:00	x	x	x	x	x	x	x
AV13	Shift 15 2	0.80	01/02/2022	01/11/2022	14:00	22:00	x	x	x	x	x	x	x
AV14	Shift 15 3	0.80	01/02/2022	01/11/2022	22:00	06:00	x	x	x	x	x	x	x
UV4	Shift 15 1	0.00	01/09/2022	30/09/2022	06:00	14:00	x	x	x	x	x	x	x
UV5	Shift 15 2	0.00	01/09/2022	30/09/2022	14:00	22:00	x	x	x	x	x	x	x
UV6	Shift 15 3	0.00	01/09/2022	30/09/2022	22:00	06:00	x	x	x	x	x	x	x

- Definition of three shifts for Mon-Fri, shut-down in September
- Plant does not shut-down for Bank holidays (marked /)

	Jan 22	Feb 22	Mar 22	Apr 22	May 22	Jun 22	Jul 22	Aug 22	Sep 22	Oct 22	Nov 22	Dec 22
Mon	/	3	3	3	3	3	3	3	3	3	3	3
Tue	3	3	3	3	3	3	3	3	3	3	3	3
Wed	3	3	3	3	3	3	3	3	3	3	3	3
Thu	3	3	3	3	3	3	3	3	3	3	3	3
Fri	3	3	3	3	3	3	3	3	3	3	3	3
Sat	/	3	3	3	3	3	3	3	3	3	3	3
Sun	/	/	/	/	/	/	/	/	/	/	/	/

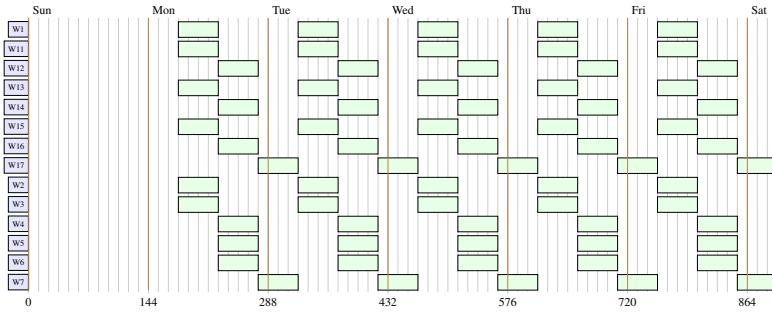
- Resulting shift calendar

Weekly Machine Dependent Calendar



- Note machines running one shift, two shifts, or three shifts

ShiftPattern for Workers



- Note different resource levels for morning, afternoon and night shift

17.2 Calendar Dependent Duration

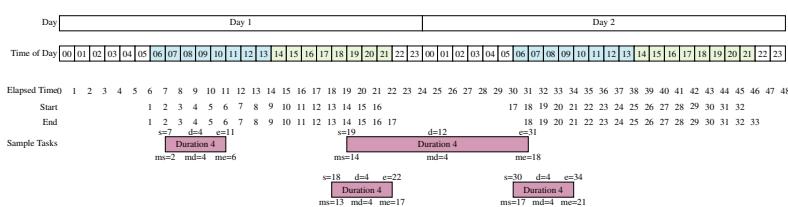
Calendar Dependent Duration X

- In some factories, tasks have different duration depending on when they are run
- During the night-shift fewer workers are available, tasks like cleaning take longer
- During holidays, most expert operators are absent, tasks take longer due to less experienced operators
- For every working period, define a utilization factor to define nominal capacity (0-100%)
 - Tasks take longer if work capacity is lower
 - Only supported in few solvers (CPO)

17.3 Task/Break Interaction

Tasks Stretching over Shutdown X

- When a machine does not run continuously, the duration of tasks in wall time may change



- Task starting at 07:00 has duration of 4 hours
- Same task starting at 19:00 stretches over nightly shutdown (22:00-06:00), extending its duration to 16 hours

18 Summary

Summary

- Introduced different resource types
 - Disjunctive resources
 - Cumulative resources
 - Machine choice
- Identifying resources is a key element of defining scheduling problem
- Many problem specific variants exist, also impacting the constraint reasoning
- Keep as simple as possible - as complex as required
- Not all described variants already in our generic tool

Part IV

Experiments

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

19 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

20 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

20.1 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

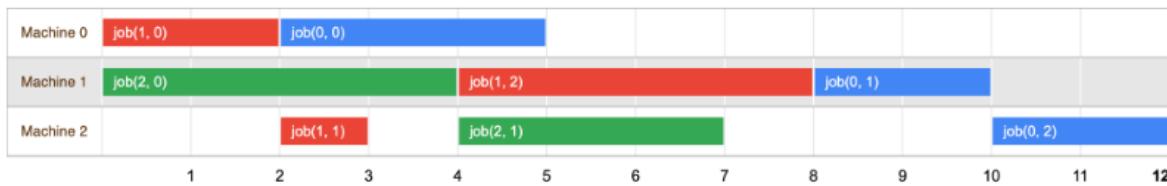
Below is a simple example of a job shop problem, in which each task is labeled by a pair of numbers (m, p) where m is the number of the machine the task must be processed on and p is the *processing time* of the task – the amount of time it requires. (The numbering of jobs and machines starts at 0.)

- 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)

20.2 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)

20.3 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

The screenshot shows the MiniZinc website. On the left, there's a 'Get started' button and a note about Windows 10 compatibility. Below that are links for the latest release (2.8.7), packages, source code, and license information. A note states that MiniZinc is developed at Monash University with support from OPTIMA. On the right, there's a large grid titled 'Rostering' showing a weekly schedule for ten people (Aimee to Paula) across five days (Mon to Fri). The grid uses colors to represent shifts: dark blue for Night, light blue for Day, and yellow for Evening. Some cells are empty. At the bottom right, there are three circular navigation icons.

(from MiniZinc Website)

20.4 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
15/15	10	90.00	0.00	0.00	10.00	105.19	141.18	100.00	100.00	97.17
20/15	10	20.00	0.00	0.00	80.00	267.27	263.20	100.99	100.05	98.50
20/20	10	0.00	0.00	0.00	100.00	n/a	n/a	100.74	100.06	97.96
30/15	10	10.00	0.00	10.00	80.00	174.32	100.00	100.18	100.49	99.87
30/20	10	0.00	0.00	0.00	100.00	n/a	n/a	100.30	101.30	99.40
50/15	10	100.00	0.00	0.00	0.00	100.00	685.09	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
100/20	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	CPO	CPSat	CPO	CPSat	CPO	CPSat
20	25	76.00	0.00	20.00	4.00	100.00	580.71	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
30	25	60.00	0.00	4.00	36.00	100.35	264.69	100.18	101.05	100.00
40	25	4.00	16.00	0.00	80.00	100.00	2554.03	100.00	104.68	100.00
50	25	0.00	4.00	0.00	96.00	n/a	n/a	100.00	107.87	100.00
100	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	120.43	100.00
200	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	188.60	100.00
300	24	0.00	0.00	0.00	100.00	n/a	n/a	100.00	263.22	100.00
400	25	0.00	0.00	0.00	100.00	n/a	n/a	100.00	246.34	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

21 Input Data

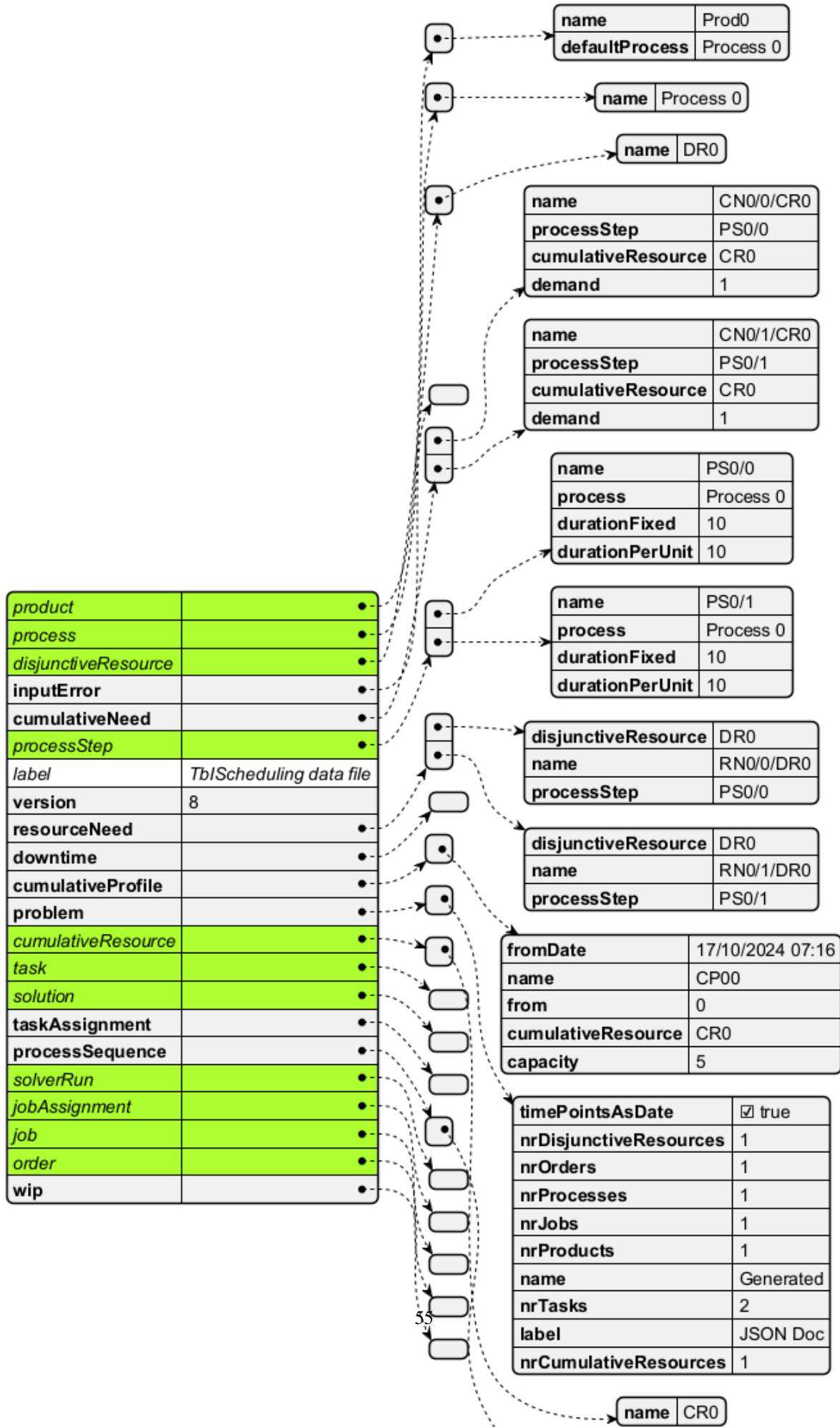
Input Data

- 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

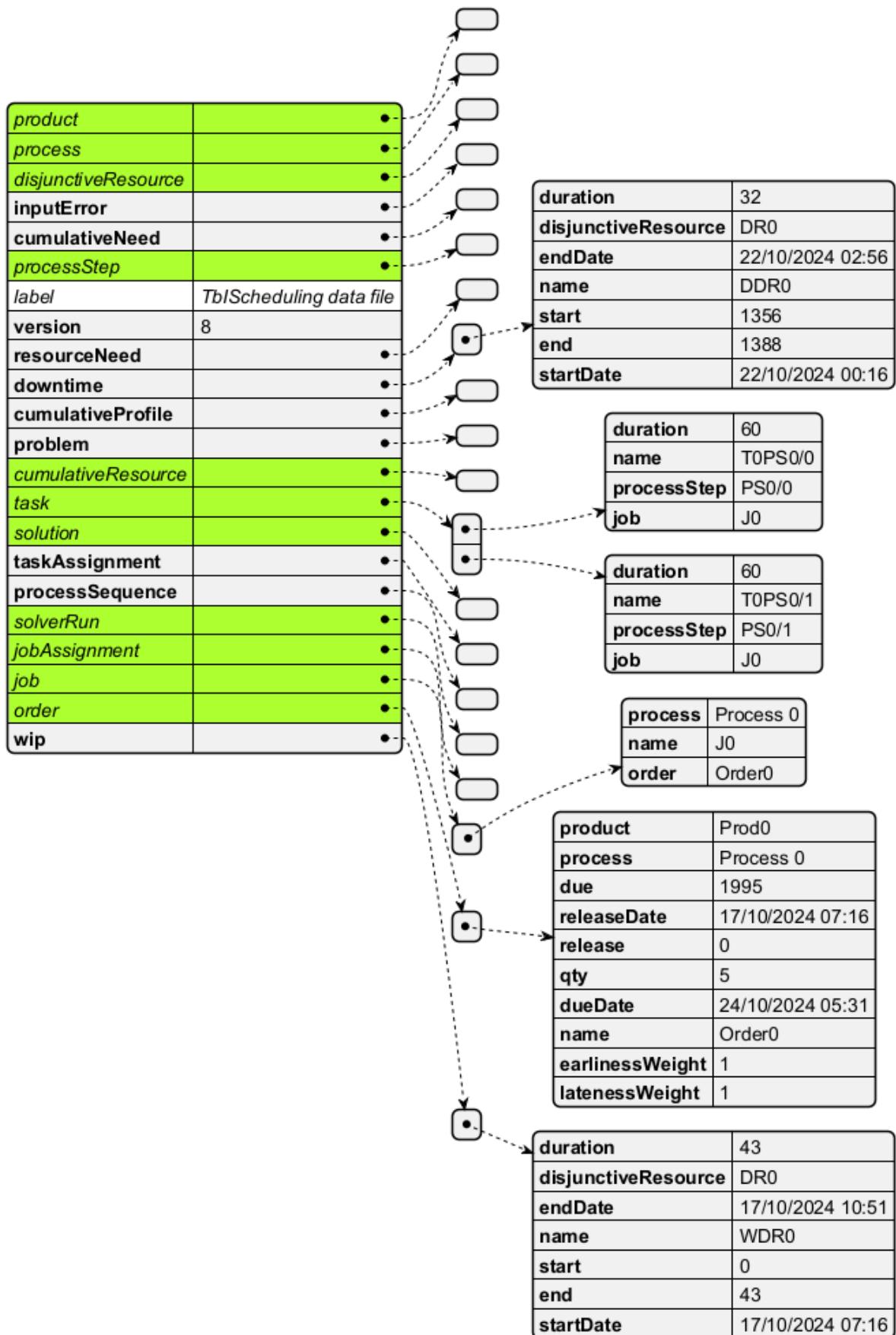
- Description of
 - Product
 - Process
 - DisjunctiveResource
 - CumulativeNeed
 - ProcessStep
 - ResourceNeed
 - CumulativeProfile
 - Problem
 - CumulativeResource

- ProcessSequence



Schedule Input Data

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



22 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



23 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

 Data Generator Parameters X

Label:

StartDate: Start Time: 0 : 00 Clock

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

Run Cancel

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: Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

Products

Nr Products:

Stages Range:

► Duration

► Cumulative Resource

► Orders

► WiP

► Downtime

► Other Parameters

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: Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

► Products

▼ Duration

Duration Model:

Duration Range:

Duration Fixed Factor:

► Cumulative Resource

► Orders

► WiP

► Downtime

► Other Parameters

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:

Nr Disjunctive Resources:

Resource Probability:

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

Label:

StartDate: Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

Products

Duration

Cumulative Resource

Orders

Nr Orders:

Qty Range:

WiP

Downtime

Other Parameters

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: Start Time:

Resource Model:

Nr Disjunctive Resources:

Resource Probability:

► Products

► Duration

► Cumulative Resource

► Orders

▼ WiP

WiP Probability:

WiP Range:

► 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

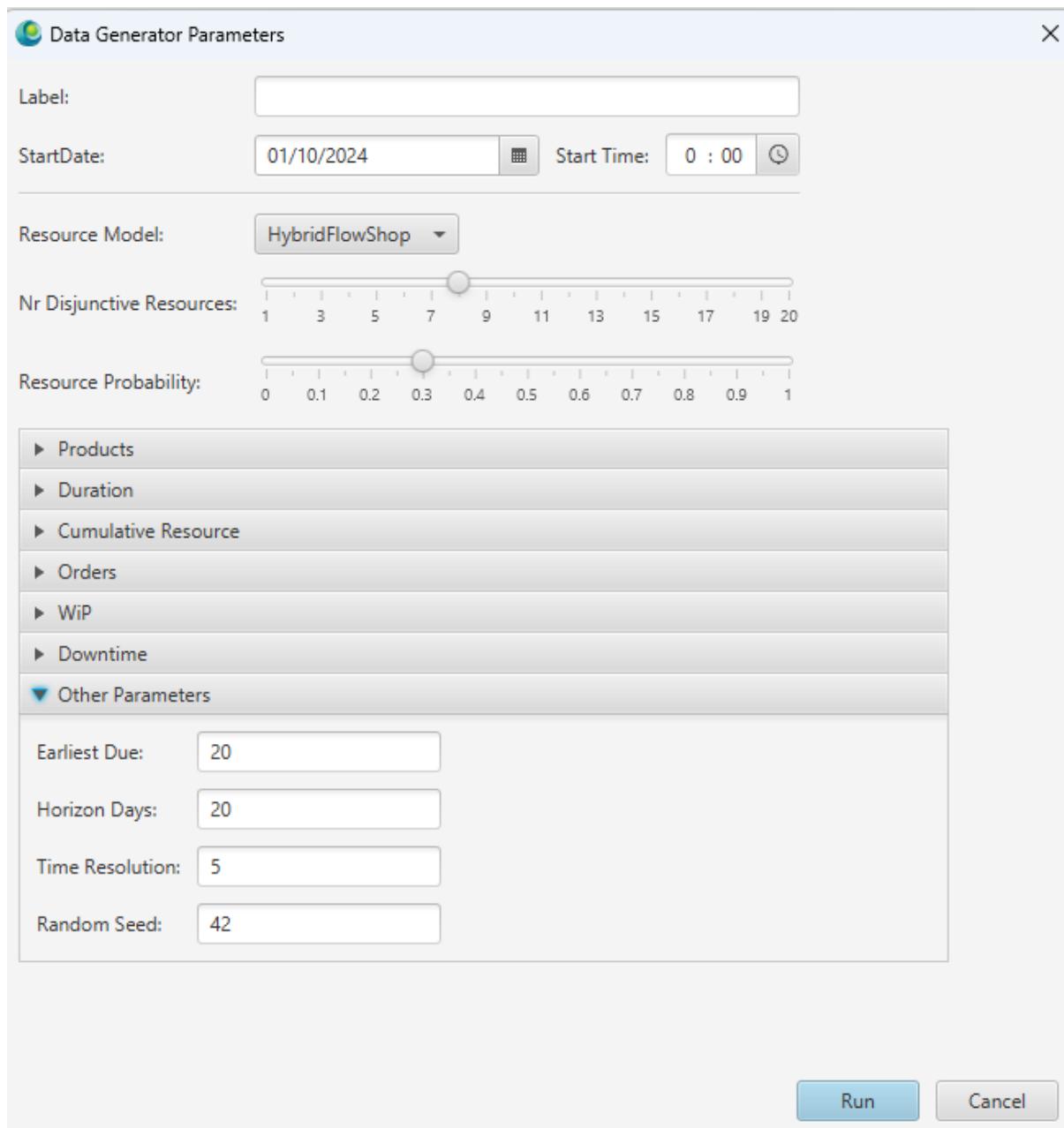
 Data Generator Parameters X

Label:	<input type="text"/>		
StartDate:	01/10/2024 <input type="button" value="..."/>	Start Time:	0 : 00 <input type="button" value="..."/>
Resource Model:	HybridFlowShop <input type="button" value="..."/>		
Nr Disjunctive Resources:	<input type="range" value="7"/> <div style="display: flex; justify-content: space-between;"> 13579111315171920 </div>		
Resource Probability:	<input type="range" value="0.3"/> <div style="display: flex; justify-content: space-between;"> 00.10.20.30.40.50.60.70.80.91 </div>		
<div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ► Products </div> <div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ► Duration </div> <div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ► Cumulative Resource </div> <div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ► Orders </div> <div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ► WiP </div> <div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ▼ Downtime </div>			
Downtime Probability:	<input type="range" value="0.5"/> <div style="display: flex; justify-content: space-between;"> 00.10.20.30.40.50.60.70.80.91 </div>		
Downtime Range:	<input type="range" value="51"/> <div style="display: flex; justify-content: space-between;"> 1112131415161718191100 </div>		
<div style="border: 1px solid #ccc; padding: 5px; margin-bottom: 5px;"> ► Other Parameters </div>			
		<input type="button" value="Run"/>	<input type="button" value="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



24 Predefined Problem Sets

24.1 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)

24.2 SALBP

Simple Assembly Line Balancing Problem (SALBP)

- Will be discussed in 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...`

24.3 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...`

25 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

26 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

Part V

Objectives

Key Points

- Why we search for good, but not always optimal solutions
- The different objectives provided in scheduling tool
- More complex optimization schemes involving multiple objectives
- Other criteria that might guide which solution we prefer
- An interesting research direction

27 Optimal vs. Good Solutions

Why have an Objective?

- For most scheduling problem, we define some form objective
- A mathematical formula that we evaluate on a schedule to compare it
- It is not always clear whether that formula represents some direct business benefit
- But, there are far more bad solutions than good solutions!
- The objective tells us if the solution is more "good" or "bad"
- Different stakeholders will have different views what makes a solution "good" or even "acceptable"

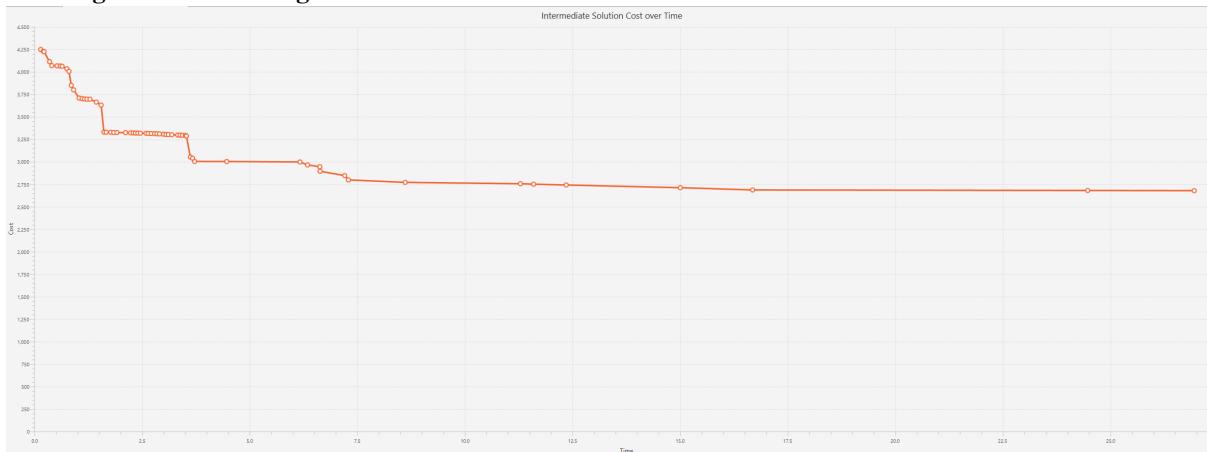
Minimizing Cost vs Maximizing Profit

- A lot of objectives aim to reduce cost of production
- This is not always a good thing
 - Doing nothing costs nothing
- But defining the profit obtained by a schedule is not easy
- Many intangible factors weigh in
 - Happiness of the customers (which customers are unhappy, does it matter?)
 - Happiness of personnel (Finding and retaining skilled personnel is critical)
 - Happiness of stakeholders (sales, production, inventory, management)

Timeliness

- How quickly do we need a solution?
 - Sometimes we need a solution right now
 - We may also have time to wait a bit, or even more
 - Waiting five minutes, having a short break for a coffee, will often be acceptable
 - For some problems, running a scheduler overnight is possible
 - Do we need the ultimate in solution quality, or an acceptable solution right now?
- Benchmarks are often run with unlimited resources
 - "We used four years of computer time to solve these problems"

Diminishing Returns Running a Solver



- Which compromise between quality and speed are we looking for?

27.1 Cost vs. Profit Based Objectives

28 Objective Types

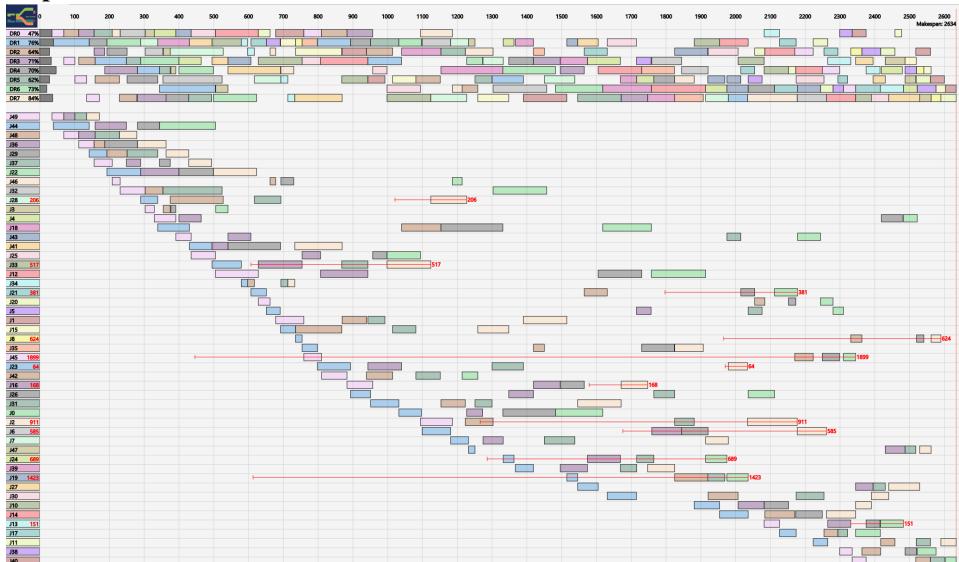
Setting the Objective

- We can select a predefined objective in solver dialog
- There are weight factors to give more impact to some cost terms in on-time and hybrid objectives

Objective Type: Makespan	Weight Makespan: 1
Weight Flowtime: 1	Weight Lateness: 1
Weight Earliness: 1	

28.1 Makespan ✓

Makespan ✓

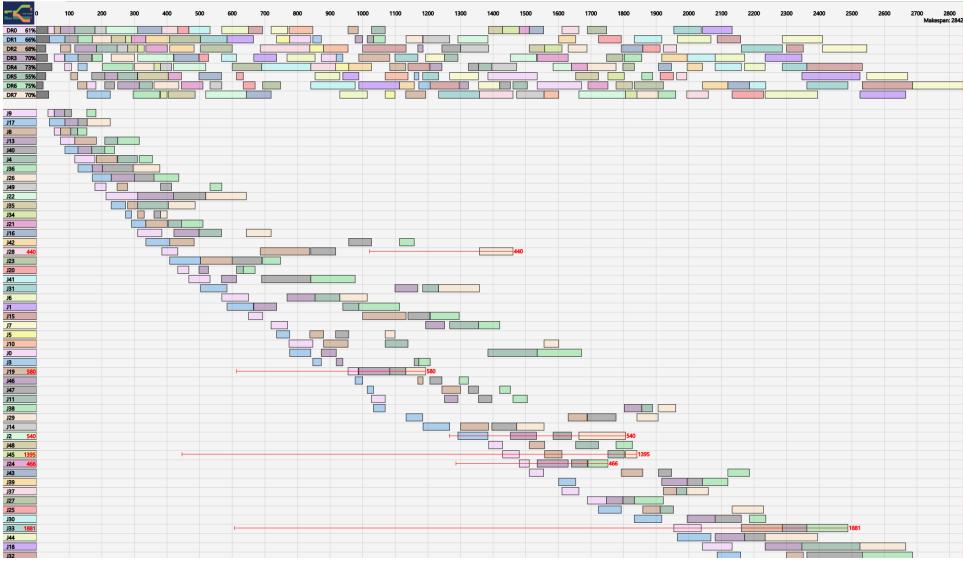


- Minimize the overall project end

- Very traditional objective in scheduling
 - Justified in project scheduling
 - Not so clearly justified in manufacturing
- A number of jobs are significantly late

28.2 Flowtime ✓

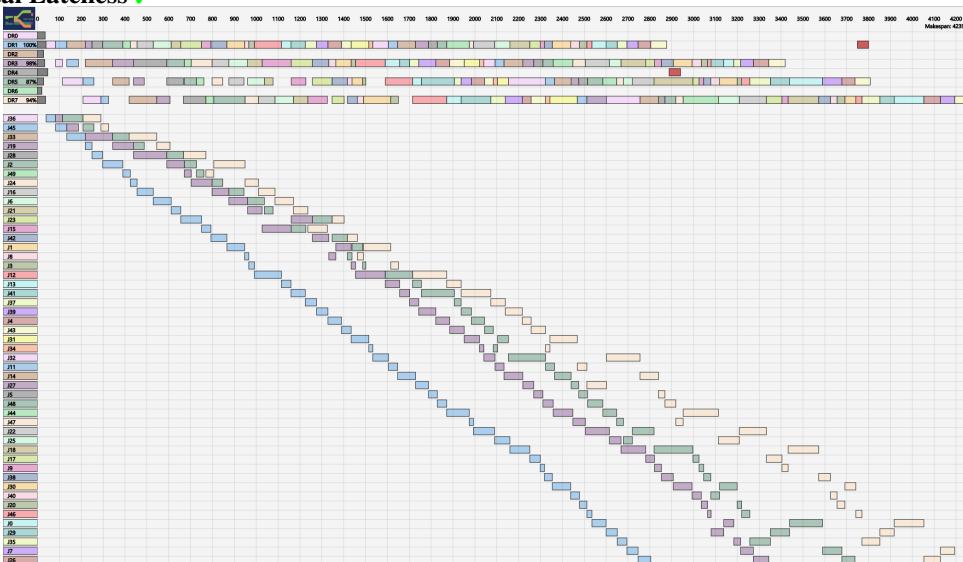
Flowtime ✓



- Minimize the sum of job ends
- Prefer any machine to end early
- Not always easy to find good solutions

28.3 Lateness

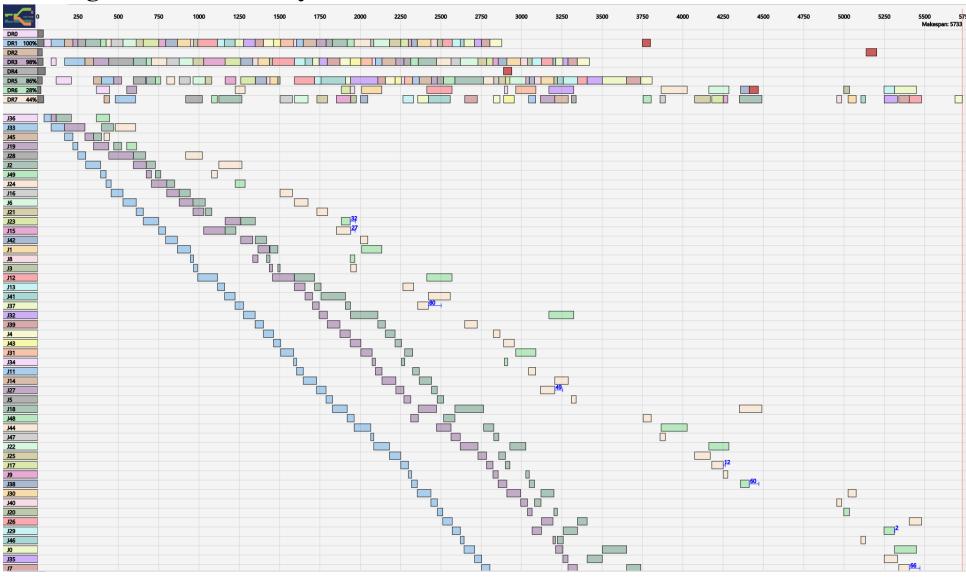
Total Lateness ✓



- Able to remove all delays on jobs
- Does not care about makespan or earliness

28.4 On-Time

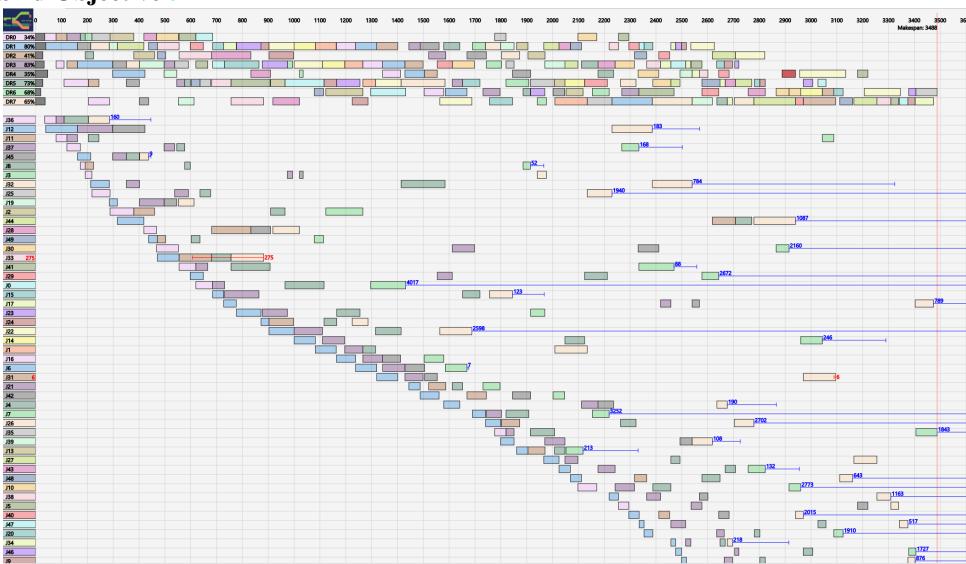
Maximizing On-Time Delivery ✓



- Weight 100 for lateness, weight 1 for earliness
- Removes all delays, very little earliness

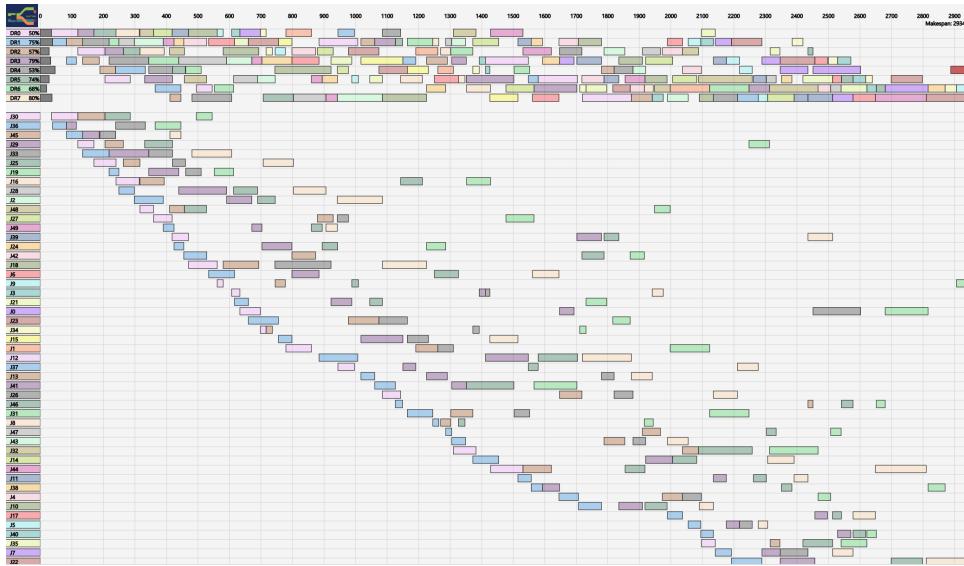
28.5 Hybrid

Hybrid Objective ✓



- Does not remove lateness completely
- Probably needs more time to improve

Hybrid Objective (Enforce Due Date) ✓



- Sometimes enforcing a constraint is more powerful
- Here require that due dates are respected
- Leads to overall better solution

28.6 Comparison

Comparing Solutions with Different Objectives

SolverRun	ObjectiveType	ObjectiveValue	SolverStatus	Bound	GapPercent	Makespan	Flowtime	TotalLateness	MaxLateness	NrLate	WeightedLateness	TotalEarliness	MaxEarliness	NrEarly	WeightedEarliness	PercentEarly	Percentlate
Run1	Makespan	2,634	Solution	1,050,00	60.14	2,634	86,339	7,618	1,899	12	7,618,00	76,688	4,887	38	76,688,00	76.00	24.00
Run2	Flowtime	66,356	Solution	39,248,00	40.85	2,842	66,356	5,575	1,881	7	5,575,00	94,628	5,045	43	94,628,00	86.00	14.00
Run3	TotalLateness	0	Optimal	0,00	NaN	4,239	119,745	0	0	0	0,00	35,664	1,494	50	35,664,00	100.00	0.00
Run4	OnTime	328	Optimal	328,00	0.00	5,733	155,081	0	0	0	0,00	328	80	8	328,00	16.00	0.00
Run5	Hybrid	3,554,610	Solution	1,150,697,00	67.63	3,488	117,180	281	275	2	281,00	38,510	4,017	34	38,510,00	68.00	4.00
Run6	Hybrid	2,992,627	Solution	1,155,981,00	61.37	2,934	96,782	0	0	0	0,00	58,627	4,530	43	58,627,00	86.00	0.00

- System tries to reduce the objective
- May mean other aspect of solution is poor
 - *Total Lateness* bad if just reducing *Makespan*
 - *Makespan* if just reducing *Total Lateness*
- Hybrid objectives can find better compromises
- Using constraints to restrict search can help
- Needs more work on lower bounds

28.7 Resource Levels

Optimizing Resource Levels X

- We have already discussed this in the Resources section
- Sometimes we aim to optimize resource use, not time or delay
- Typical is minimizing
 - The number of disjunctive machines needed
 - A cumulative resource capacity

- the manpower required to perform all tasks
- We may do this for understanding the problem
- The optimized schedules will be brittle

Multi-level Objectives

- In some situations, a hybrid objective combining different aspects is not enough
- We need to find the best compromises between the different objective types
 - Without an a-priori weight to state which is more important
- A solution *dominates* another solution, if for all objective types, it is better than the other
- Two solutions are *incomparable* if for some objective type one solution is better, but for some other objective, the other solution is better
- *Pareto frontier*: Set of all non-dominated, incomparable solutions

29 Other Quality Vectors

Other Quality Vectors

- There are other scales on which we may measure whether a solution is "good"
 - Fairness
 - Robustness
 - Product Quality
 - Customer Satisfaction

Fairness

- Typically involves humans
- If we assign operators, do we
 - Treat all operators in a fair way?
 - Give effective workers more work
 - Provide opportunities for training and skill development
 - De-risk dependency on key personnel
- Also, use multiple machines of same type consistently
 - Balanced
 - Not balanced

Robustness

- By scheduling, we create a plan
- Often, reality does not follow the plan
 - Unforeseen events, machine breakdowns, sick-leave
 - Delays in raw material delivery, inventory problems
 - Rush orders
 - Small variations in plan execution
- Can we protect the plan against certain types of unplanned events?
- Is the plan still useful when things change?
- Or, can we update the plan quickly enough to adapt to changes

Product Quality

- The tighter the schedule, the more risk there is of cutting corners
- If we minimize curing times to speed up production, quality may be affected
- The fastest machine is not always the best in terms of quality, cost

Customer Satisfaction

- Our objectives for minimizing lateness are lacking context
- Some customers are more important than others
- Some orders are more important to the customer than others
- A phone call by a human can capture more detail than an electronic order form
- We can adjust our schedule if we know what is important and what is not
 - But where do we get this information?
 - How do we avoid that a customer says "all my orders are critical"

30 Key Performance Indicators

Key Performance Indicators (KPI)

- Performance indicators can be computed from a given schedule, and allow to compare different schedules to each other
- Often, these are business oriented, not process driven
- There is a difference between an objective and a performance indicator
 - The objective drives the search for a solution
 - The KPI evaluates the quality of a solution, can be totally unrelated to objective
- Ideally, the KPI are expressed in such a way that solutions for different problems can be compared
 - Number of late orders, allows comparison of two solutions of the same problem
 - Percentage of late orders, allows comparison of two different schedules

KPIs for Sample Solutions

- Comparing different solutions of running example with enabling/disabling some constraints
- Compare *Makespan* to *On-time Delivery* objective
- There is no *Setup Time* constraint specified for this problem

Makespan	Flowtime	TotalLateness	MaxLateness	NrLate	WeightedLateness	TotalEarliness	MaxEarliness	NrEarly	WeightedEarliness	PercentEarly	PercentLate	Duration	Start	End		
2,688	83,425	10,083	1,959	11	10,083.00	82,067	4,938	39	82,067.00	78.00	22.00	2,653	35	2,688		
2,690	85,051	0	0	0	0.00	70,358	4,133	50	70,358.00	100.00	0.00	2,655	35	2,690		
2,136	58,403	0	0	0	0.00	97,006	4,956	50	97,006.00	100.00	0.00	2,101	35	2,136		
2,324	62,494	0	0	0	0.00	92,915	4,751	50	92,915.00	100.00	0.00	2,289	35	2,324		
5,733	154,918	0	0	0	0.00	491	122	10	491.00	20.00	0.00	5,538	195	5,733		
TotalWaitBefore	TotalWaitAfter	MaxWaitBefore	MaxWaitAfter	TotalIdleBefore	TotalIdleAfter	MaxIdleBefore	MaxIdleAfter	TotalSetupBefore	TotalSetupAfter	MaxSetupBefore	MaxSetupAfter	TotalActiveTime	TotalProductionTime	ActiveUtilization	SetupPercent	IdlePercent
23,297	23,297	1,943	1,943	6,823	6,823	435	435	0	0	0	0	19,917	13,094	65.74	0.00	34.26
24,903	24,903	1,611	1,611	5,901	5,901	342	342	0	0	0	0	18,995	13,094	68.93	0.00	31.07
12,081	12,081	449	449	785	785	80	80	0	0	0	0	13,879	13,094	94.34	0.00	5.66
0	0	0	0	4,211	4,211	111	111	0	0	0	0	17,305	13,094	75.67	0.00	24.33
0	0	0	0	26,641	28,641	773	773	0	0	0	0	41,735	13,094	31.37	0.00	68.63

KPIs Already Defined ✓

Makespan Max of job ends

Flowtime Sum of job ends

Total Lateness Sum of job lateness (tardiness)

Max Lateness Max of job lateness

NrLate Number of late jobs

WeightedLateness Weighted sum of job lateness

PercentLate percentage of late jobs

...Earliness same indicators, but for earliness

Duration Difference between overall start and overall end

Start start of earliest job

End end of last job

KPIs Already Defined (cont'd) ✓

TotalWait Sum of Wait time before/after a task of a job

MaxWait Max wait time before/after a task of a job

TotalIdle Sum of Idle times of disjunctive machines

MaxIdle Max Idle Time on a disjunctive machine

TotalSetup Total setup times

MaxSetup Max setup time

TotalActiveTime Total active time between first and last use of a machine

TotalProductionTime Sum of all task duration

ActiveUtilization Percentage of production time compared to active time

SetupPercent Percentage of setup time compared to active time

IdlePercent Percentage of idle time compared to active time

KPI Ranking ✎

- If we have multiple solutions, we want to rank them based on a comparison of different KPIs
- Different stakeholders will rank different KPIs in very different way
- This seems to require some customization of the formulas used
- We can also try to infer a ranking method based on some comparison queries asked to users
 - Do you prefer this or that solution?
 - With enough answer, we can postulate a ranking method

31 Interactive Scheduling

Interactive Scheduling ✎

- Some human schedulers are happy to accept a produced plan
 - Perhaps change some constraints, or weights
- Other human scheduler want to modify the plan by hand
 - This is not always easy to do
 - How can a scheduling tool handle this?
 - How much control is given to the user, who checks the constraints?
 - Do we allow the user to create invalid schedules?

Example: Moses System

- Scheduling application for Animal Feed mills in the UK
- Produces overnight schedule for delivery on next day
- Operator updates the schedule whenever a task is finished
- Change duration of task if it is delayed
- Move tasks by hand, changing sequence of tasks to be performed
 - System updates constraints, and warns if constraint is violated
- User can protect part of schedule from modification by system
 - Freeze all tasks up to the selected task
 - Unfreeze the schedule after the selected task
- Related to explainability

Summary

- Describe the need and role of objectives
- Presented different objectives available in the scheduling tool
- Discussed some more advanced possibilities for handling objectives
- Important to keep user on control of system

Part VI

Advanced Concepts

Key Points

-

32 Sequence Dependent Setup

33 Transportation Time

34 Human Resource Constraints

35 Energy Cost Aware Scheduling

36 Preemption

37 Inventory

38 Alternative Processes/Process Paths

39 Explainability

40 Summary

Summary

-

Part VII

Case Studies

Key Points

- We provide a number of scheduling case studies
- Use the methodology developed to describe problems
- Use scheduling tool to provide solutions

- Generic tool provides good, but not always best solutions
- Two case studies are not handled by scheduling tool (yet)

Case Studies Overview

- Production Planning and Detailed Scheduling
 - How to use detailed scheduling in a wider context
- Assembly Line Balancing
 - Scheduling to plan design of an assembly line
- Test Scheduling
 - Scheduling tests on resources
- Factory Design
 - Location of resources affects scheduling outcome
- Oven Scheduling
 - Solving one detailed scheduling problem is not enough
- Blades and Vanes
 - Capacity and production planning over a multi-year period

Summary

- See how the methodology can be applied to solve real-world problems
- Generic tool provides immediate solution of good quality
- Visualization of results is also provided
- Tool will be available in a few weeks time

Part VIII

Production Planning Case Study

Key Points

- Case study from industry
- Production planning and detailed scheduling
- Based on project with medical devices company in Cork
 - Real problem
 - Realistic data
- Solved in two stages
 - Production planning based on run-out days and safety stock levels
 - Scheduling using our generic scheduling tool

Product List

Name	ShortName	Nr	DailySales	InventoryAtStart	CalcDaysCover	LotSize	CycleTime	LotDuration	Machine	ProductType	SafetyStock	SafetyAlert
P1	P1	1	3.20	877	274.06	163	1.33	217	8	pt1	66	253.44
P2	P2	2	11.40	1,011	88.68	240	1.20	288	8	pt2	774	20.79
P3	P3	3	796.20	26,204	32.91	420	2.10	882	5,7,9,10,13,14,16	pt3	12,108	17.70
P4	P4	4	233.80	7,877	33.69	420	2.00	840	5,7,9,10,13,14,16	pt4	3,358	19.33
P5	P5	5	267.30	7,152	26.76	350	2.30	805	5,7,9,10,13,14,16	pt5	3,906	12.14
P6	P6	6	606.20	18,654	30.77	350	2.30	805	5,7,9,10,13,14,16	pt6	9,293	15.44
P7	P7	7	137.30	4,939	35.97	420	2.00	840	5,7,9,10,13,14,16	pt7	1,979	21.56
P8	P8	8	88.30	3,152	35.70	350	2.30	805	5,7,9,10,13,14,16	pt8	1,342	20.50
P9	P9	9	77.20	2,688	34.82	420	2.10	882	5,7,9,10,13,14,16	pt9	1,082	20.80
P10	P10	10	165.60	5,971	36.06	420	2.10	882	5,7,9,10,13,14,16	pt10	2,649	20.06
P11	P11	11	60.70	2,310	38.06	420	2.10	882	5,7,9,10,13,14,16	pt11	877	23.61
P12	P12	12	51.80	1,928	37.22	350	2.30	805	5,7,9,10,13,14,16	pt12	883	20.17
P13	P13	13	79.00	2,231	28.24	320	2.30	736	5,7,9,10,13,14,16	pt13	1,193	13.14
P14	P14	14	271.20	8,951	33.01	432	2.10	908	5,7,9,10,13,14,16	pt14	3,732	19.24
P15	P15	15	86.60	3,244	37.46	336	2.00	672	5,7,9,10,13,14,16	pt15	1,454	20.67
P16	P16	16	42.40	2,110	49.76	420	2.10	882	5,7,9,10,13,14,16	pt16	875	29.13
P17	P17	17	17.60	681	38.69	420	2.00	840	5,7,9,10,13,14,16	pt17	290	22.22
P18	P18	18	217.50	5,710	26.25	336	2.00	672	5,7,9,10,13,14,16	pt18	2,814	13.31
P19	P19	19	56.30	2,450	43.52	420	2.00	840	5,7,9,10,13,14,16	pt19	804	29.24
P20	P20	20	13.60	506	37.21	480	2.00	960	5,7,9,10,13,14,16	pt20	272	17.21
P21	P21	21	10.80	977	90.46	360	2.10	756	5,7,9,10,13,14,16	pt21	293	63.33
P22	P22	22	21.80	1,538	70.55	420	2.00	840	5,7,9,10,13,14,16	pt22	349	54.54
P23	P23	23	189.10	5,195	27.47	360	2.30	828	5,7,9,10,13,14,16	pt23	2,941	11.92
P24	P24	24	9.50	886	93.26	350	2.30	805	5,7,9,10,13,14,16	pt24	191	73.16
P25	P25	25	7.50	326	43.47	120	2.30	276	5,7,9,10,13,14,16	pt25	210	15.47
P26	P26	26	11.60	418	36.03	360	2.10	756	5,7,9,10,13,14,16	pt26	187	19.91
P27	P27	27	16.50	1,388	84.12	480	2.10	1,008	5,7,9,10,13,14,16	pt27	218	70.91

Product List (Sorted by Daily Sales)

Product X														
Name	ShortName	Nr	DailySales▼	InventoryAtStart	CalcDaysCover	LotSize	CycleTime	LotDuration	Machine	ProductType	SafetyStock	SafetyAlert		
P3	P3	3	796.20	26,204	32.91	420	2.10	882	5,7,9,10,13,14,16	pt3	12,108	17.70		
P6	P6	6	606.20	18,654	30.77	350	2.30	805	5,7,9,10,13,14,16	pt6	9,293	15.44		
P14	P14	14	271.20	8,951	33.01	432	2.10	908	5,7,9,10,13,14,16	pt14	3,732	19.24		
P53	P53	53	267.70	8,264	30.87	504	1.20	605	1,2,3,8	pt2	3,734	16.92		
P5	P5	5	267.30	7,152	26.76	350	2.30	805	5,7,9,10,13,14,16	pt5	3,906	12.14		
P124	P124	124	242.70	16,503	68.00	240	5.00	1,200	15,18,19	pt65	3,595	53.19		
P4	P4	4	233.80	7,877	33.69	420	2.00	840	5,7,9,10,13,14,16	pt4	3,358	19.33		
P123	P123	123	223.40	7,600	34.02	490	2.33	1,142	1,2,3,8	pt51	3,738	17.29		
P18	P18	18	217.50	5,710	26.25	336	2.00	672	5,7,9,10,13,14,16	pt18	2,814	13.31		
P23	P23	23	189.10	5,195	27.47	360	2.30	828	5,7,9,10,13,14,16	pt23	2,941	11.92		
P56	P56	56	168.20	4,824	28.68	504	1.20	605	1,2,3,8	pt2	2,660	12.87		
P10	P10	10	165.60	5,971	36.06	420	2.10	882	5,7,9,10,13,14,16	pt10	2,649	20.06		
P59	P59	59	152.80	5,666	37.08	420	1.33	559	1,2,3,8	pt51	3,095	16.83		
P7	P7	7	137.30	4,939	35.97	420	2.00	840	5,7,9,10,13,14,16	pt7	1,979	21.56		
P57	P57	57	134.80	5,358	39.75	588	1.10	647	1,2,3,8	pt53	2,294	22.73		
P36	P36	36	133.50	3,895	29.18	336	2.00	672	5,7,9,10,13,14,16	pt36	2,057	13.77		
P54	P54	54	122.40	5,059	41.33	480	1.33	639	1,2,3,8	pt51	1,965	25.28		
P121	P121	121	98.10	4,334	44.18	588	1.10	647	1,2,3,8	pt53	1,524	28.64		
P8	P8	8	88.30	3,152	35.70	350	2.30	805	5,7,9,10,13,14,16	pt8	1,342	20.50		
P125	P125	125	86.90	8,593	98.88	240	5.00	1,200	15,18,19	pt65	1,022	87.12		
P15	P15	15	86.60	3,244	37.46	336	2.00	672	5,7,9,10,13,14,16	pt15	1,454	20.67		
P100	P100	100	85.20	2,665	31.28	420	1.33	559	1,2,3,8	pt56	1,115	18.19		
P55	P55	55	79.50	2,876	36.18	441	2.33	1,028	1,2,3,8	pt52	1,367	18.98		
P13	P13	13	79.00	2,231	28.24	320	2.30	736	5,7,9,10,13,14,16	pt13	1,193	13.14		
P9	P9	9	77.20	2,688	34.82	420	2.10	882	5,7,9,10,13,14,16	pt9	1,082	20.80		
P47	P47	47	74.60	5,391	72.27	160	6.84	1,095	2,11	pt47	1,132	57.09		
P11	P11	11	60.70	2,310	38.06	420	2.10	882	5,7,9,10,13,14,16	pt11	877	23.61		
P61	P61	61	60.30	2,758	45.74	490	1.33	652	1,2,3,8	pt56	1,073	27.94		
P78	P78	78	57.60	2,234	38.78	588	1.10	647	1,2,3,8	pt59	824	24.48		
P19	P19	19	56.30	2,450	43.52	420	2.00	840	5,7,9,10,13,14,16	pt19	804	29.24		

Product List (Sorted by Days Cover)

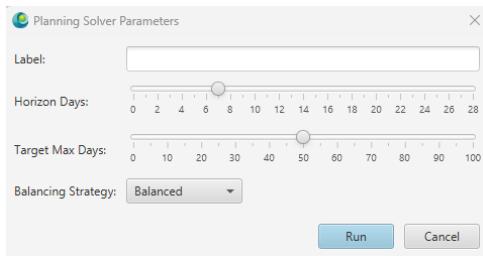
Product X														
Name	ShortName	Nr	DailySales	InventoryAtStart	CalcDaysCover	LotSize	CycleTime	LotDuration	Machine	ProductType	SafetyStock	SafetyAlert		
P35	P35	35	1.30	26	20.00	120	2.30	276	5,7,9,10,13,14,16	pt35	33	0.00		
P18	P18	18	217.50	5,710	26.25	336	2.00	672	5,7,9,10,13,14,16	pt18	2,814	13.31		
P5	P5	5	267.30	7,152	26.76	350	2.30	805	5,7,9,10,13,14,16	pt5	3,906	12.14		
P23	P23	23	189.10	5,195	27.47	360	2.30	828	5,7,9,10,13,14,16	pt23	2,941	11.92		
P13	P13	13	79.00	2,231	28.24	320	2.30	736	5,7,9,10,13,14,16	pt13	1,193	13.14		
P56	P56	56	168.20	4,824	28.68	504	1.20	605	1,2,3,8	pt2	2,660	12.87		
P58	P58	58	55.00	1,590	28.91	420	2.33	979	1,2,3,8	pt54	1,208	6.95		
P36	P36	36	133.50	3,895	29.18	336	2.00	672	5,7,9,10,13,14,16	pt36	2,057	13.77		
P6	P6	6	606.20	18,654	30.77	350	2.30	805	5,7,9,10,13,14,16	pt6	9,293	15.44		
P53	P53	53	267.70	8,264	30.87	504	1.20	605	1,2,3,8	pt2	3,734	16.92		
P100	P100	100	85.20	2,665	31.28	420	1.33	559	1,2,3,8	pt56	1,115	18.19		
P122	P122	122	45.40	1,421	31.30	490	1.33	652	1,2,3,8	pt56	725	15.33		
P3	P3	3	796.20	26,204	32.91	420	2.10	882	5,7,9,10,13,14,16	pt3	12,108	17.70		
P14	P14	14	271.20	8,951	33.01	432	2.10	908	5,7,9,10,13,14,16	pt14	3,732	19.24		
P4	P4	4	233.80	7,877	33.69	420	2.00	840	5,7,9,10,13,14,16	pt4	3,358	19.33		
P123	P123	123	223.40	7,600	34.02	490	2.33	1,142	1,2,3,8	pt51	3,738	17.29		
P77	P77	77	33.00	1,146	34.73	336	1.20	404	1,2,3,8	pt61	565	17.61		
P9	P9	9	77.20	2,688	34.82	420	2.10	882	5,7,9,10,13,14,16	pt9	1,082	20.80		
P8	P8	8	88.30	3,152	35.70	350	2.30	805	5,7,9,10,13,14,16	pt8	1,342	20.50		
P7	P7	7	137.30	4,939	35.97	420	2.00	840	5,7,9,10,13,14,16	pt7	1,979	21.56		
P26	P26	26	11.60	418	36.03	360	2.10	756	5,7,9,10,13,14,16	pt26	187	19.91		
P10	P10	10	165.60	5,971	36.06	420	2.10	882	5,7,9,10,13,14,16	pt10	2,649	20.06		
P55	P55	55	79.50	2,876	36.18	441	2.33	1,028	1,2,3,8	pt52	1,367	18.98		
P63	P63	63	42.40	1,565	36.91	490	1.33	652	1,2,3,8	pt51	689	20.66		
P59	P59	59	152.80	5,666	37.08	420	1.33	559	1,2,3,8	pt51	3,095	16.83		
P20	P20	20	13.60	506	37.21	480	2.00	960	5,7,9,10,13,14,16	pt20	272	17.21		
P12	P12	12	51.80	1,928	37.22	350	2.30	805	5,7,9,10,13,14,16	pt12	883	20.17		
P44	P44	44	5.50	205	37.27	360	2.10	756	5,7,9,10,13,14,16	pt44	126	14.36		
P15	P15	15	86.60	3,244	37.46	336	2.00	672	5,7,9,10,13,14,16	pt15	1,454	20.67		

Product List (Sorted by Safety Alert)

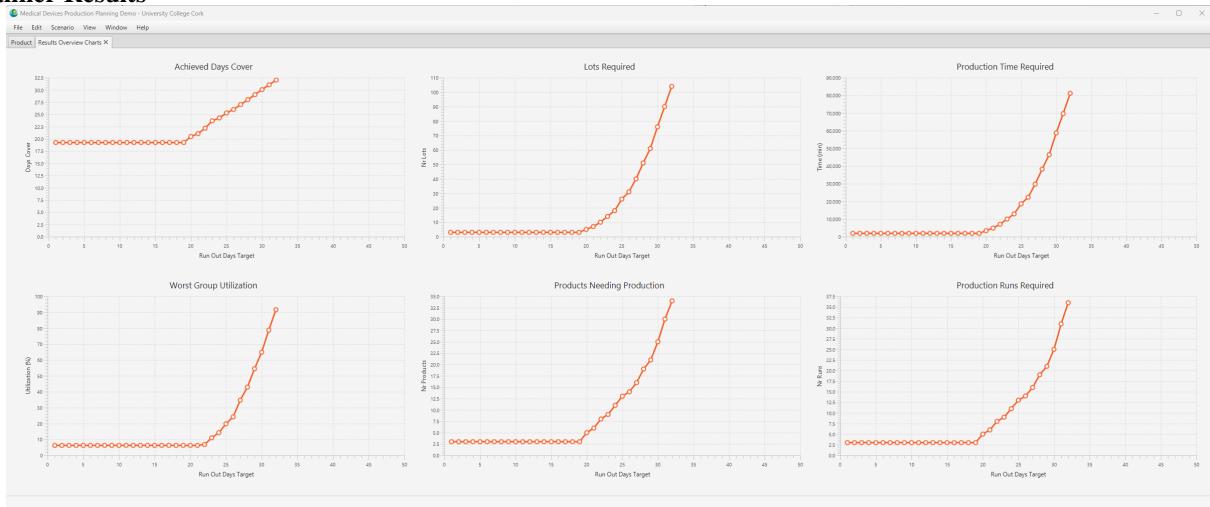
Product X															
Name	ShortName	Nr	DailySales	InventoryAtStart	CalcDaysCover	LotSize	CycleTime	LotDuration	Machine	ProductType	SafetyStock	SafetyAl...▲			
P35	P35	35	1.30	26	20.00	120	2.30	276	5,7,9,10,13,14,16	pt35	33	0.00			
P51	P51	51	5.70	405	71.05	140	4.50	630	2	pt50	381	4.21			
P58	P58	58	55.00	1,590	28.91	420	2.33	979	1,2,3,8	pt54	1,208	6.95			
P82	P82	82	6.10	259	42.46	441	1.33	587	1,2,3,8	pt51	189	11.48			
P23	P23	23	189.10	5,195	27.47	360	2.30	828	5,7,9,10,13,14,16	pt23	2,941	11.92			
P5	P5	5	267.30	7,152	26.76	350	2.30	805	5,7,9,10,13,14,16	pt5	3,906	12.14			
P56	P56	56	168.20	4,824	28.68	504	1.20	605	1,2,3,8	pt2	2,660	12.87			
P13	P13	13	79.00	2,231	28.24	320	2.30	736	5,7,9,10,13,14,16	pt13	1,193	13.14			
P18	P18	18	217.50	5,710	26.25	336	2.00	672	5,7,9,10,13,14,16	pt18	2,814	13.31			
P36	P36	36	133.50	3,895	29.18	336	2.00	672	5,7,9,10,13,14,16	pt36	2,057	13.77			
P44	P44	44	5.50	205	37.27	360	2.10	756	5,7,9,10,13,14,16	pt44	126	14.36			
P122	P122	122	45.40	1,421	31.30	490	1.33	652	1,2,3,8	pt56	725	15.33			
P6	P6	6	606.20	18,654	30.77	350	2.30	805	5,7,9,10,13,14,16	pt6	9,293	15.44			
P25	P25	25	7.50	326	43.47	120	2.30	276	5,7,9,10,13,14,16	pt25	210	15.47			
P59	P59	59	152.80	5,666	37.08	420	1.33	559	1,2,3,8	pt51	3,095	16.83			
P53	P53	53	267.70	8,264	30.87	504	1.20	605	1,2,3,8	pt2	3,734	16.92			
P112	P112	112	3.40	134	39.41	588	1.20	706	1,2,3,8	pt2	76	17.06			
P20	P20	20	13.60	506	37.21	480	2.00	960	5,7,9,10,13,14,16	pt20	272	17.21			
P32	P32	32	5.40	222	41.11	480	2.00	960	5,7,9,10,13,14,16	pt32	129	17.22			
P123	P123	123	223.40	7,600	34.02	490	2.33	1,142	1,2,3,8	pt51	3,738	17.29			
P99	P99	99	5.70	247	43.33	96	2.00	192	1,2,3,8	pt60	148	17.37			
P77	P77	77	33.00	1,146	34.73	336	1.20	404	1,2,3,8	pt61	565	17.61			
P3	P3	3	796.20	26,204	32.91	420	2.10	882	5,7,9,10,13,14,16	pt3	12,108	17.70			
P100	P100	100	85.20	2,665	31.28	420	1.33	559	1,2,3,8	pt56	1,115	18.19			
P55	P55	55	79.50	2,876	36.18	441	2.33	1,028	1,2,3,8	pt52	1,367	18.98			
P14	P14	14	271.20	8,951	33.01	432	2.10	908	5,7,9,10,13,14,16	pt14	3,732	19.24			
P80	P80	80	7.20	293	40.69	420	1.33	559	1,2,3,8	pt51	154	19.31			
P4	P4	4	233.80	7,877	33.69	420	2.00	840	5,7,9,10,13,14,16	pt4	3,358	19.33			
P49	P49	49	50.90	2,273	44.66	378	1.00	378	2	pt48	1,260	19.90			

Setup Matrix

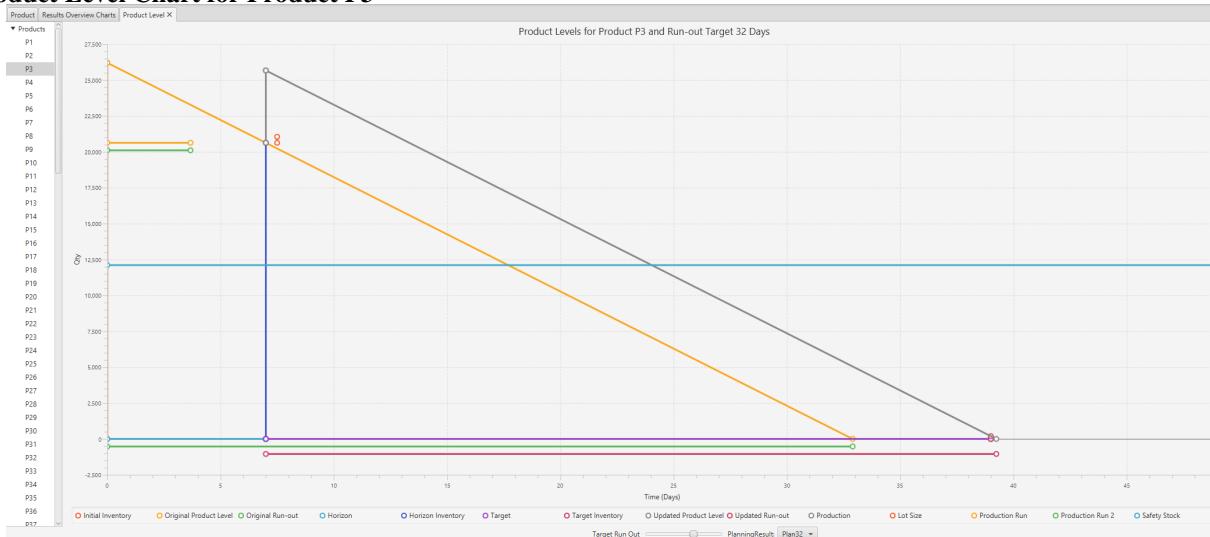
Row		Setup Matrix X	pt1	pt10	pt11	pt12	pt13	pt14	pt15	pt16	pt17	pt18	pt19	pt20	pt21	pt22	pt23	pt24	pt25	pt26	pt27	pt28	pt29	pt30	pt31	pt32	pt33	pt34	pt35	pt36	pt37	pt38	pt39	pt40	pt41	pt42	pt43	pt44	pt45	pt46	pt47	pt48	pt49	pt50	pt51	pt52	pt53	pt54	pt55	pt56	pt57	pt58	pt59	pt60	pt61	pt62	pt63	pt64	pt65	pt66	pt67	pt68	pt69	pt70	pt71	pt72	pt73	pt74	pt75	pt76	pt77	pt78	pt79	pt80	pt81	pt82	pt83	pt84	pt85	pt86	pt87	pt88	pt89	pt90	pt91	pt92	pt93	pt94	pt95	pt96	pt97	pt98	pt99	pt100	pt101	pt102	pt103	pt104	pt105	pt106	pt107	pt108	pt109	pt110	pt111	pt112	pt113	pt114	pt115	pt116	pt117	pt118	pt119	pt120	pt121	pt122	pt123	pt124	pt125	pt126	pt127	pt128	pt129	pt130	pt131	pt132	pt133	pt134	pt135	pt136	pt137	pt138	pt139	pt140	pt141	pt142	pt143	pt144	pt145	pt146	pt147	pt148	pt149	pt150	pt151	pt152	pt153	pt154	pt155	pt156	pt157	pt158	pt159	pt160	pt161	pt162	pt163	pt164	pt165	pt166	pt167	pt168	pt169	pt170	pt171	pt172	pt173	pt174	pt175	pt176	pt177	pt178	pt179	pt180	pt181	pt182	pt183	pt184	pt185	pt186	pt187	pt188	pt189	pt190	pt191	pt192	pt193	pt194	pt195	pt196	pt197	pt198	pt199	pt200	pt201	pt202	pt203	pt204	pt205	pt206	pt207	pt208	pt209	pt210	pt211	pt212	pt213	pt214	pt215	pt216	pt217	pt218	pt219	pt220	pt221	pt222	pt223	pt224	pt225	pt226	pt227	pt228	pt229	pt230	pt231	pt232	pt233	pt234	pt235	pt236	pt237	pt238	pt239	pt240	pt241	pt242	pt243	pt244	pt245	pt246	pt247	pt248	pt249	pt250	pt251	pt252	pt253	pt254	pt255	pt256	pt257	pt258	pt259	pt260	pt261	pt262	pt263	pt264	pt265	pt266	pt267	pt268	pt269	pt270	pt271	pt272	pt273	pt274	pt275	pt276	pt277	pt278	pt279	pt280	pt281	pt282	pt283	pt284	pt285	pt286	pt287	pt288	pt289	pt290	pt291	pt292	pt293	pt294	pt295	pt296	pt297	pt298	pt299	pt300	pt301	pt302	pt303	pt304	pt305	pt306	pt307	pt308	pt309	pt310	pt311	pt312	pt313	pt314	pt315	pt316	pt317	pt318	pt319	pt320	pt321	pt322	pt323	pt324	pt325	pt326	pt327	pt328	pt329	pt330	pt331	pt332	pt333	pt334	pt335	pt336	pt337	pt338	pt339	pt340	pt341	pt342	pt343	pt344	pt345	pt346	pt347	pt348	pt349	pt350	pt351	pt352	pt353	pt354	pt355	pt356	pt357	pt358	pt359	pt360	pt361	pt362	pt363	pt364	pt365	pt366	pt367	pt368	pt369	pt370	pt371	pt372	pt373	pt374	pt375	pt376	pt377	pt378	pt379	pt380	pt381	pt382	pt383	pt384	pt385	pt386	pt387	pt388	pt389	pt390	pt391	pt392	pt393	pt394	pt395	pt396	pt397	pt398	pt399	pt400	pt401	pt402	pt403	pt404	pt405	pt406	pt407	pt408	pt409	pt410	pt411	pt412	pt413	pt414	pt415	pt416	pt417	pt418	pt419	pt420	pt421	pt422	pt423	pt424	pt425	pt426	pt427	pt428	pt429	pt430	pt431	pt432	pt433	pt434	pt435	pt436	pt437	pt438	pt439	pt440	pt441	pt442	pt443	pt444	pt445	pt446	pt447	pt448	pt449	pt450	pt451	pt452	pt453	pt454	pt455	pt456	pt457	pt458	pt459	pt460	pt461	pt462	pt463	pt464	pt465	pt466	pt467	pt468	pt469	pt470	pt471	pt472	pt473	pt474	pt475	pt476	pt477	pt478	pt479	pt480	pt481	pt482	pt483	pt484	pt485	pt486	pt487	pt488	pt489	pt490	pt491	pt492	pt493	pt494	pt495	pt496	pt497	pt498	pt499	pt500	pt501	pt502	pt503	pt504	pt505	pt506	pt507	pt508	pt509	pt510	pt511	pt512	pt513	pt514	pt515	pt516	pt517	pt518	pt519	pt520	pt521	pt522	pt523	pt524	pt525	pt526	pt527	pt528	pt529	pt530	pt531	pt532	pt533	pt534	pt535	pt536	pt537	pt538	pt539	pt540	pt541	pt542	pt543	pt544	pt545	pt546	pt547	pt548	pt549	pt550	pt551	pt552	pt553	pt554	pt555	pt556	pt557	pt558	pt559	pt560	pt561	pt562	pt563	pt564	pt565	pt566	pt567	pt568	pt569	pt570	pt571	pt572	pt573	pt574	pt575	pt576	pt577	pt578	pt579	pt580	pt581	pt582	pt583	pt584	pt585	pt586	pt587	pt588	pt589	pt590	pt591	pt592	pt593	pt594	pt595	pt596	pt597	pt598	pt599	pt600	pt601	pt602	pt603	pt604	pt605	pt606	pt607	pt608	pt609	pt610	pt611	pt612	pt613	pt614	pt615	pt616	pt617	pt618	pt619	pt620	pt621	pt622	pt623	pt624	pt625	pt626	pt627	pt628	pt629	pt630	pt631	pt632	pt633	pt634	pt635	pt636	pt637	pt638	pt639	pt640	pt641	pt642	pt643	pt644	pt645	pt646	pt647	pt648	pt649	pt650	pt651	pt652	pt653	pt654	pt655	pt656	pt657	pt658	pt659	pt660	pt661	pt662	pt663	pt664	pt665	pt666	pt667	pt668	pt669	pt670	pt671	pt672	pt673	pt674	pt675	pt676	pt677	pt678	pt679	pt680	pt681	pt682	pt683	pt684	pt685	pt686	pt687	pt688	pt689	pt690	pt691	pt692	pt693	pt694	pt695	pt696	pt697	pt698	pt699	pt700	pt701	pt702	pt703	pt704	pt705	pt706	pt707	pt708	pt709	pt710	pt711	pt712	pt713	pt714	pt715	pt716	pt717	pt718	pt719	pt720	pt721	pt722	pt723	pt724	pt725	pt726	pt727	pt728	pt729	pt730	pt731	pt732	pt733	pt734	pt735	pt736	pt737	pt738	pt739	pt740	pt741	pt742	pt743	pt744	pt745	pt746	pt747	pt748	



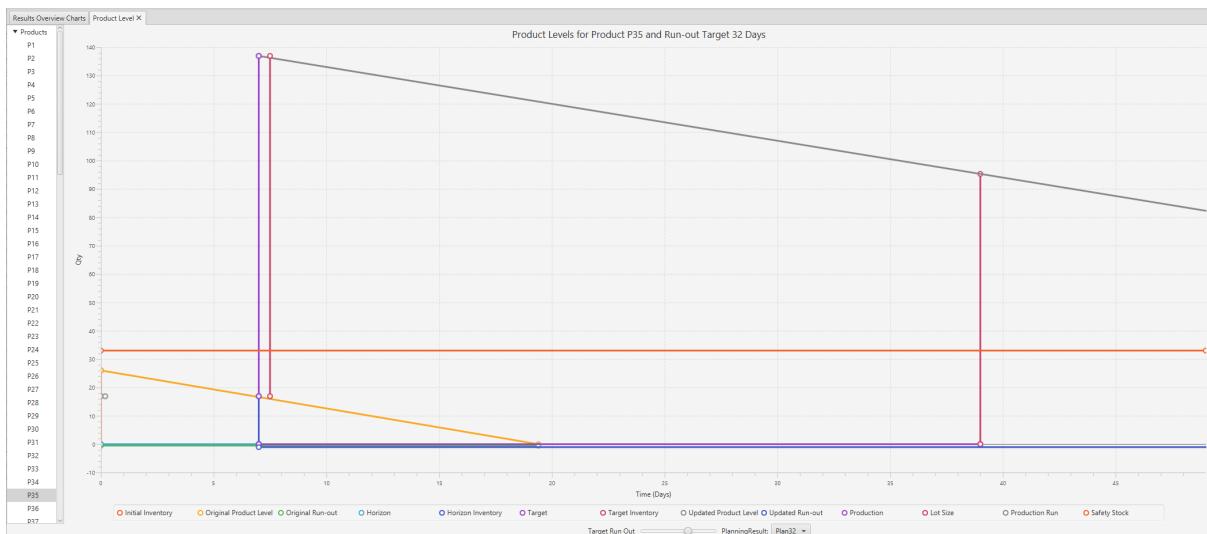
Planner Results



Product Level Chart for Product P3



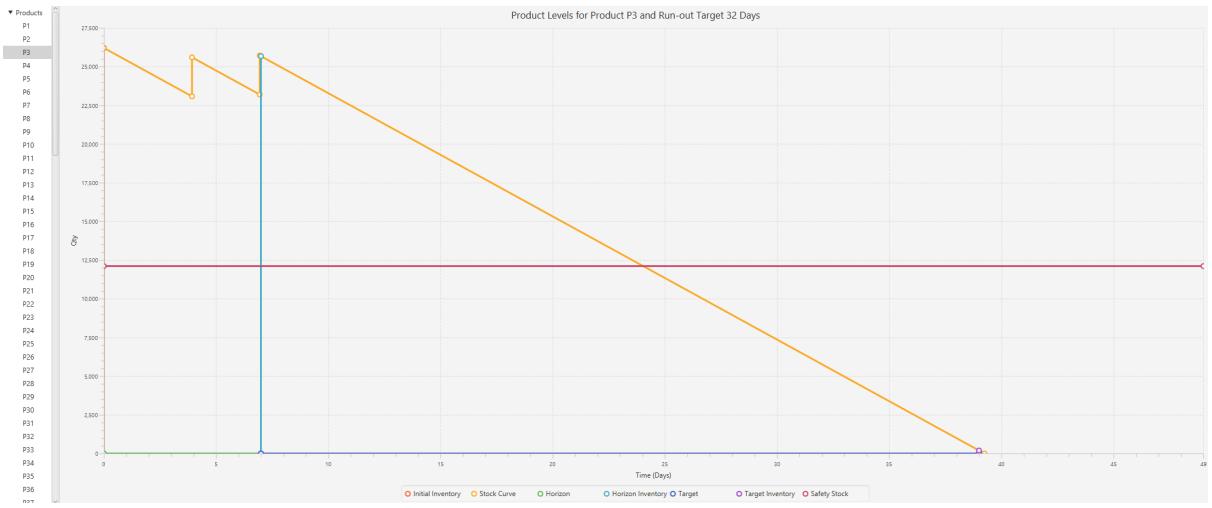
Product Level Chart for Product P35



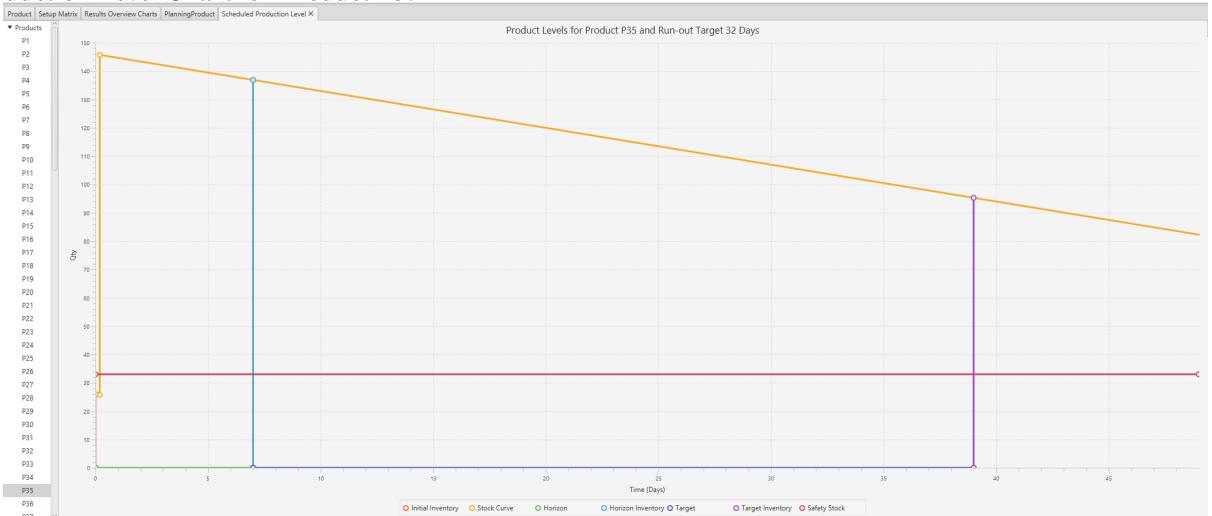
Scheduled Production Runs

Product	Results Overview Charts		Product Level		Scheduled Production Level		ProductionRun X		
Name	Product	NrLots	Qty	Due	Start	End	Duration	StartDay	EndDay
job3_0	P3	6	2,520	10,080	366	5,658	5,292	0.25	3.93
job3_1	P3	6	2,520	10,080	4,712	10,004	5,292	3.27	6.95
job4_0	P4	3	1,260	10,080	0	2,520	2,520	0.00	1.75
job5_0	P5	10	3,500	10,080	1,794	9,844	8,050	1.25	6.84
job6_0	P6	7	2,450	10,080	4,224	9,859	5,635	2.93	6.85
job6_1	P6	8	2,800	10,080	0	6,440	6,440	0.00	4.47
job7_0	P7	1	420	10,080	7,442	8,282	840	5.17	5.75
job8_0	P8	1	350	10,080	816	1,621	805	0.57	1.13
job9_0	P9	1	420	10,080	3,282	4,164	882	2.28	2.89
job10_0	P10	2	840	10,080	0	1,764	1,764	0.00	1.23
job11_0	P11	1	420	10,080	6,500	7,382	882	4.51	5.13
job12_0	P12	1	350	10,080	1,651	2,456	805	1.15	1.71
job13_0	P13	3	960	10,080	0	2,208	2,208	0.00	1.53
job14_0	P14	4	1,728	10,080	0	3,632	3,632	0.00	2.52
job15_0	P15	1	336	10,080	2,580	3,252	672	1.79	2.26
job17_0	P17	1	420	10,080	5,718	6,558	840	3.97	4.55
job18_0	P18	9	3,024	10,080	3,144	9,192	6,048	2.18	6.38
job20_0	P20	1	480	10,080	3,692	4,652	960	2.56	3.23
job23_0	P23	7	2,520	10,080	2,516	8,312	5,796	1.75	5.77
job26_0	P26	1	360	10,080	0	756	756	0.00	0.53
job35_0	P35	1	120	0	0	276	276	0.00	0.19
job36_0	P36	4	1,344	10,080	6,618	9,306	2,688	4.60	6.46
job44_0	P44	1	360	10,080	2,298	3,054	756	1.60	2.12
job46_0	P46	1	350	10,080	8,372	9,177	805	5.81	6.37
job51_0	P51	1	140	6,064	0	630	630	0.00	0.44
job53_0	P53	5	2,520	10,080	707	3,732	3,025	0.49	2.59
job55_0	P55	1	441	10,080	2,580	3,608	1,028	1.79	2.51
job56_0	P56	4	2,016	10,080	7,218	9,638	2,420	5.01	6.69
job58_0	P58	2	840	10,002	3,668	5,626	1,958	2.55	3.91
job59_0	P59	1	420	10,080	464	1,023	559	0.32	0.71
job63_0	P63	1	490	10,080	0	652	652	0.00	0.45
job77_0	P77	1	336	10,080	0	404	404	0.00	0.28
job78_0	P78	1	588	10,080	0	647	647	0.00	0.45

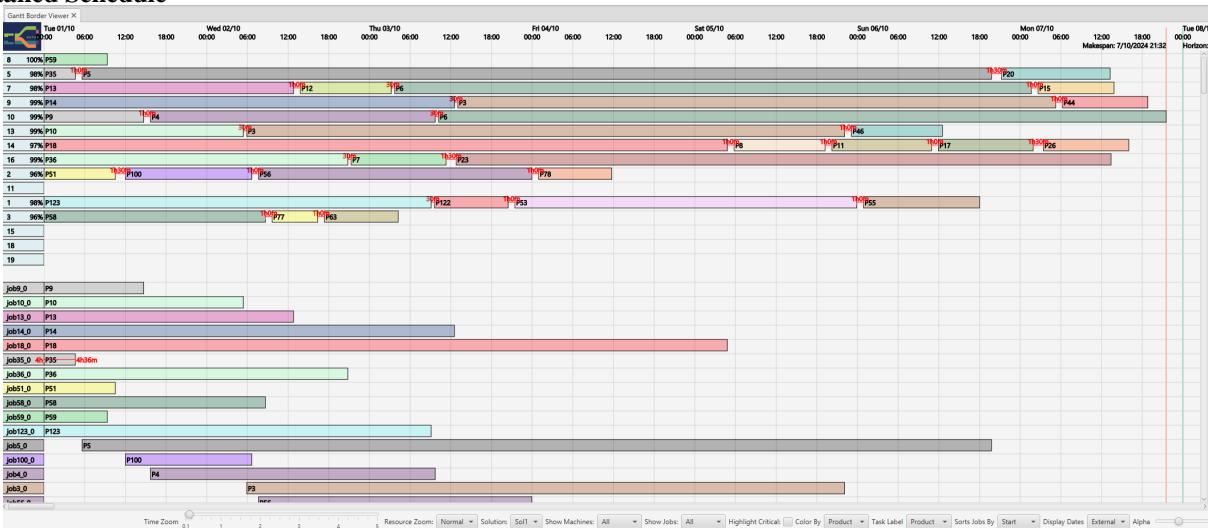
Production Level Chart for Product P3



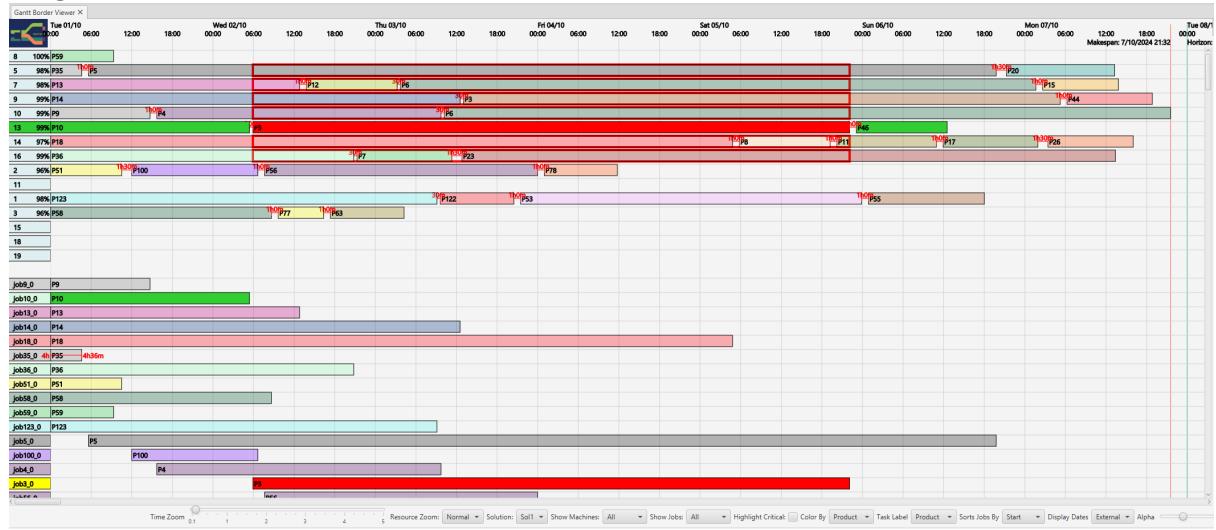
Production Level Chart for Product P35



Detailed Schedule



Showing Alternative Machines in Gantt Chart



Summary

- We demonstrated the use of our scheduling tool inside a production planning problem from industry
- Production planning decides which products to make in which quantity
 - Balance stock levels against projected demand
 - Allow for product specific safety stock levels
- Uses estimate of production capacity over planning horizon
- Use detailed scheduling to validate plan

Part IX

Assembly Line Balancing Case Study

Key Points

-

Problem Description

Feature Overview

Summary

-

Part X

Test Scheduling Case Study

Key Points

•

Problem Description

The problem arises in the context of a testing facility. A number of tests have to be performed in minimal time. Each test has a given duration and needs to run on one machine. While the test is running on a machine, no other test can use that machine. Some tests can only be assigned to a subset of the machines, for others you can use any available machine. For some tests, additional, possibly more than one, global resources are needed. While those resources are used for a test, no other test can use the resource. The objective is to finish the set of all tests as quickly as possible, i.e. all start times should be non-negative, and makespan should be minimized.

Feature Overview

Summary

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Part XI

Factory Design Case Study

Key Points

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Problem Description

Feature Overview

Summary

•

Part XII

Oven Scheduling Case Study

Key Points

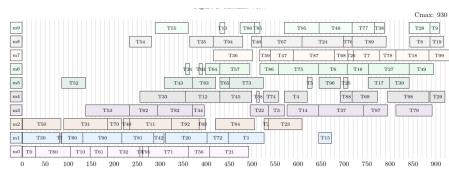
- Discusses two topics:
 - Solve a very specific industrial scheduling problem from the ASSISTANT EU project
 - Discuss the general issue of short-term scheduling vs. long-term objectives

Research Challenge

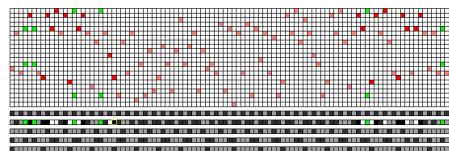
- Often the long-term business objectives are not visible in the operational decision problem
- We optimize a short-term objective without understanding the impact in the long term
- What choices should we make in short-term to improve overall result?
- Especially important when future data not yet visible
- Surprisingly, this problem is rarely discussed in literature

Examples

- Production Scheduling
- Nearly all scheduling benchmarks use c_{max} (makespan) as objective
- Why?
- Do we want to close factory as rapidly as possible?

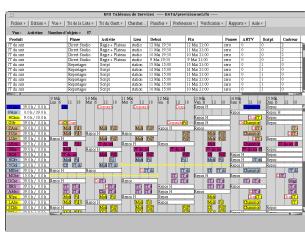


- Car Sequencing
- The best heuristics push difficult cars to the edge of schedule
- Because they are easier to schedule this way
- But: It makes it hard to schedule next day



Examples

- Personnel Rostering
- Satisfy working rules and demands for period
- But: rules apply on a rolling horizon
- Easy to over-constrain problem for next period



- Transportation Planning

- Build daily delivery tours, optimizing cost
- Where are your trucks at 10PM?
- Also, avoid cherry-picking at start of week



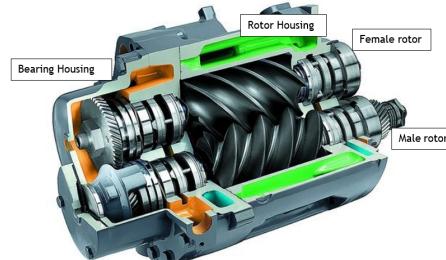
Problem Studied Here

- Example from the ASSISTANT EU project (ended last year)
- Oven schedule for one of the industrial partners
- Schedule tasks on a set of ovens
- Tasks can share oven only if they are compatible
- Conflicting objectives
 - Energy use of ovens very significant, reduce when ovens are used
 - Waiting for an oven affects quality of product
- Jobs only visible when previous process step starts
- Currently scheduled by hand, industry partner expressed strong need for change

What does this look like in the real world?



Industrial Oven



Rotors in Compressor

Solution Approach: Constraint Programming

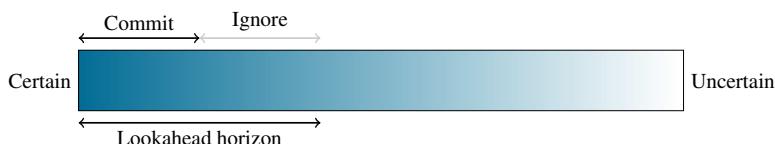
- Declarative modelling approach for combinatorial problems
 - Problem expressed in terms of variables and constraints
- Global constraints
 - Combines expressive modelling abstractions and powerful reasoning
 - Examples: disjunctive, cumulative, global_cardinality
- Compositional: Add constraints as required

- Main application areas
 - Scheduling, rostering, transportation
 - Also: test generation, verification, configuration



Overall Decomposition (Standard)

- We can only see that far into future
- We do not want to take decisions now that we might regret later
- We have to make some decisions now otherwise we never do anything
- *Rolling horizon* decomposition
 - We schedule up to *lookahead horizon* units into the future
 - We commit to implement resulting schedule only to up *commitHorizon*
 - We reschedule when we receive new information, or we reach the end of commitment
 - We solve each short-term sub problem based on short-term objectives



Short-Term Schedule Modelling

- Challenge: There is no global constraint to express the oven resource constraint
- We are not able to invest a lot of time/resources to develop such a constraint

- Two choices:
 - Two traditional models with variables linking them (Lackner et al, Constraints 2023)
 - Direct model expressing conditions as disjunctions of basic constraints

The Standard Pieces

- Jobs N consisting of multiple stages Q , tasks for each stage of each job, running on machines M
- Release dates r_i of jobs given by up-stream schedule
- WiP w_k on certain machines resulting from earlier schedule
- Machine m_{ij} and start variables s_{ij} for each task
- Precedence constraints between tasks of each jobs, with total waiting time c_i when waiting for resource
- Total number of ovens used in schedule $nrOvens$ by *nvalue* constraint

$$\text{nvalue}(\text{nrOvens}, [m_{ij} | i \in N, j \in Q] \text{++} [k | k \in M \text{ s.t. } w_k > 0])$$

Resource Constraints

We start from the basic decomposition of the disjunctive machine choice constraint

$$\begin{aligned} \forall_{i_1, i_2 \in N} \forall_{j_1, j_2 \in Q \text{ s.t. } <i_1, j_1> \neq <i_2, j_2>} : \quad m_{i_1 j_1} \neq m_{i_2 j_2} \vee \\ s_{i_1 j_1} \geq s_{i_2 j_2} + d_{i_2 j_2} \vee \\ s_{i_2 j_2} \geq s_{i_1 j_1} + d_{i_1 j_1} \end{aligned}$$

Express case where tasks share an oven (only when types and stages are the same)

$$\begin{aligned} \forall_{i_1, i_2 \in N \text{ s.t. } i_1 \neq i_2} \forall_{j \in Q} : \quad m_{i_1 j} \neq m_{i_2 j} \vee \\ s_{i_1 j} \geq s_{i_2 j} + d_{i_2 j} \vee \\ s_{i_2 j} \geq s_{i_1 j} + d_{i_1 j} \vee \\ (t_{i_1 j_1} = t_{i_2 j_2} \wedge m_{i_1 j} = m_{i_2 j} \wedge s_{i_1 j} = s_{i_2 j}) \end{aligned}$$

Limit stacking

Need binary variables $b_{i_1 i_2 j}$ to state that two jobs i_1 and i_2 share oven in stage j

$$\begin{aligned} \forall_{i_1, i_2 \in N \text{ s.t. } i_1 < i_2} \forall_{j \in Q} : \quad (b_{i_1 i_2 j} = 0 \wedge (m_{i_1 j} \neq m_{i_2 j} \vee \\ s_{i_1 j} \geq s_{i_2 j} + d_{i_2 j} \vee \\ s_{i_2 j} \geq s_{i_1 j} + d_{i_1 j})) \vee \\ (b_{i_1 i_2 j} = 1 \wedge t_{i_1 j_1} = t_{i_2 j_2} \wedge m_{i_1 j} = m_{i_2 j} \wedge s_{i_1 j} = s_{i_2 j}) \end{aligned}$$

Count how many jobs share stage j with job i

$$\forall_{i \in N} \forall_{j \in Q} : \quad z_{ij} = \sum_{i_1=1}^{i-1} b_{i_1 ij} + \sum_{i_2=i+1}^n b_{ii_2 j}$$

Limit how many tasks can be stacked together

$$\forall_{i \in N} \forall_{j \in Q} : \quad z_{ij} < \text{maxStacked}$$

This should not work!

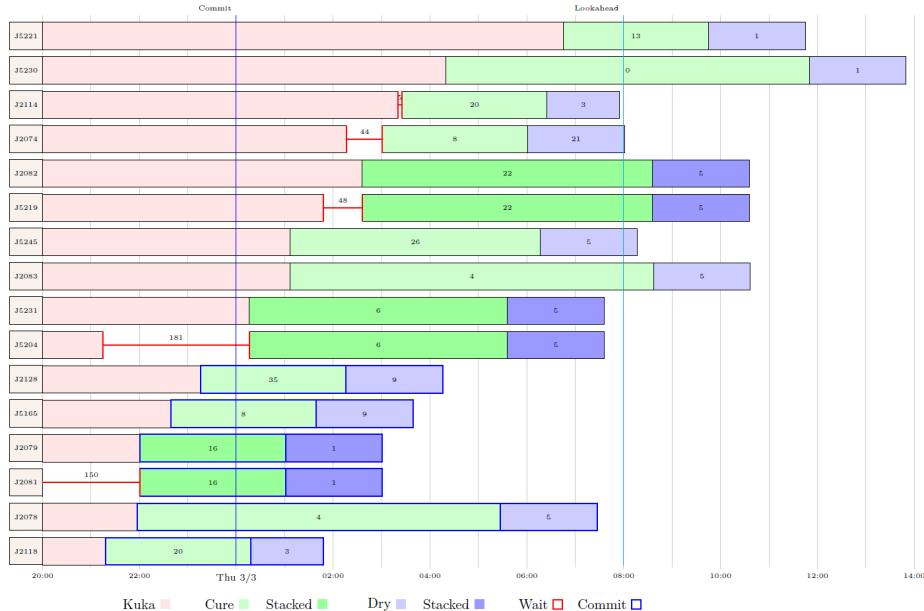
- Weakness of basic decomposition model was the reason to develop the scheduling constraints in the first place
- Does not scale well to thousands of tasks
- But model is well suited to some solvers
 - SAT based solvers, Chuffed, CP-SAT (OR-Tools)
 - MIP solvers
- This works (only) as long as problem size stays manageable

Compound Objective

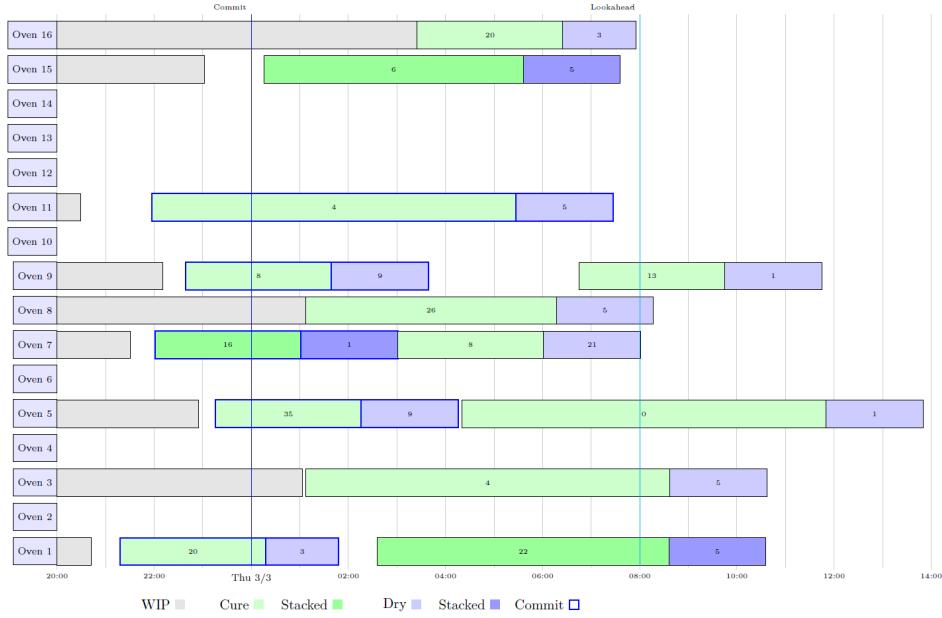
$$\min \alpha_1 \sum_{i \in N} c_i + \alpha_2 \text{nrOvens} + \alpha_3 \sum_{i \in N, j \in Q} z_{ij}$$

- Three conflicting elements
 - Total waiting time for jobs
 - Number of ovens used
 - Number of tasks stacked (negative coefficient)
- Reducing waiting time requires using more ovens
- Improved stacking will require for one job to wait until second is ready

Short-Term Schedule: Job View



Short Term Schedule: Resource View



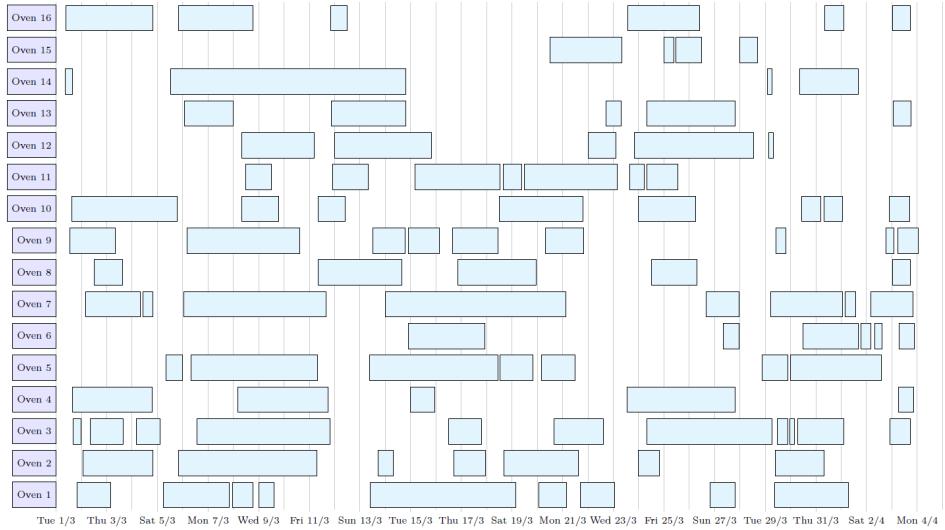
Are the short-term solutions good?

- We solve many problems to optimality, depending on solver
- Optimality gap is small, increasing search time helps a bit
- But are we optimizing the best possible objective?

Long Term Schedule: Detailed Schedule



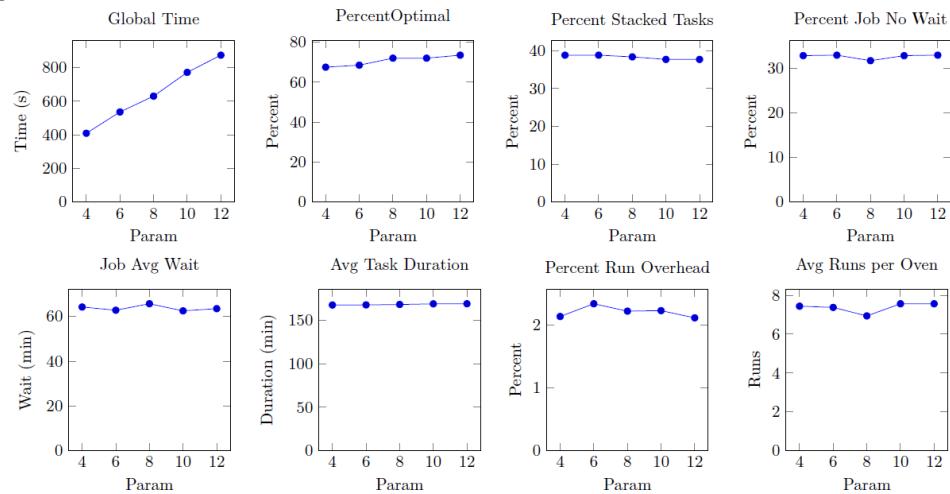
Long Term Schedule: Abstracted Oven Runs



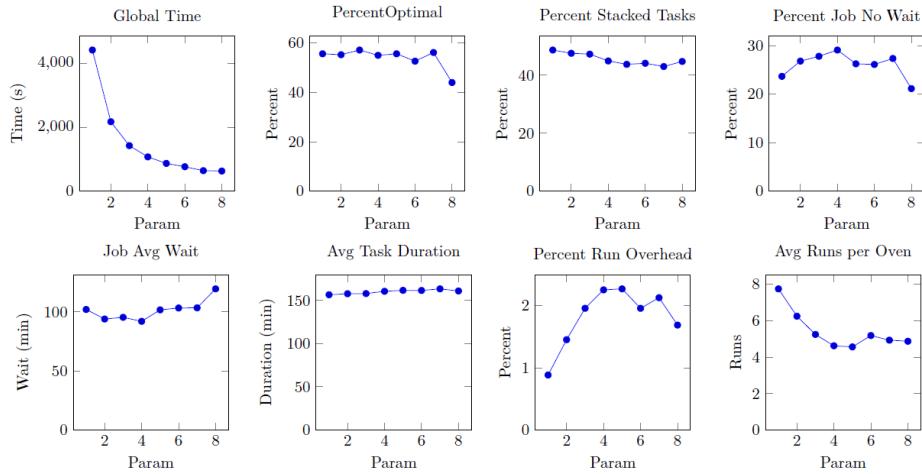
Is that a good global schedule? KPIs

Name	Unit	Explanation
Global Time	Seconds	Total time for solving all sub problems
Nr Jobs	-	Total number of jobs scheduled
Nr Tasks	-	Total number of tasks scheduled
Percent Optimal	Percentage (0-100)	How many sub problems were solved to optimality
Percent Stacked Tasks	Percentage (0-100)	Percentage of all tasks scheduled that were stacked
Percent Jobs No Wait	Percentage (0-100)	Percentage of jobs that were scheduled without any waiting time
Job Average Wait	Minutes	Average wait time over all jobs
Job Maximal Wait	Minutes	Largest waiting time for any job scheduled
Ovens Used	-	Total number of ovens used during period
Avg Task Duration	Minutes	Average tasks duration (influenced by stacking)
Oven Runs	-	Number of oven runs over total horizon
Run Overhead Percent	Percentage (0-100)	Overhead during oven runs when machine is idle
Avg Runs per Oven Used	-	Average number of oven runs per oven used

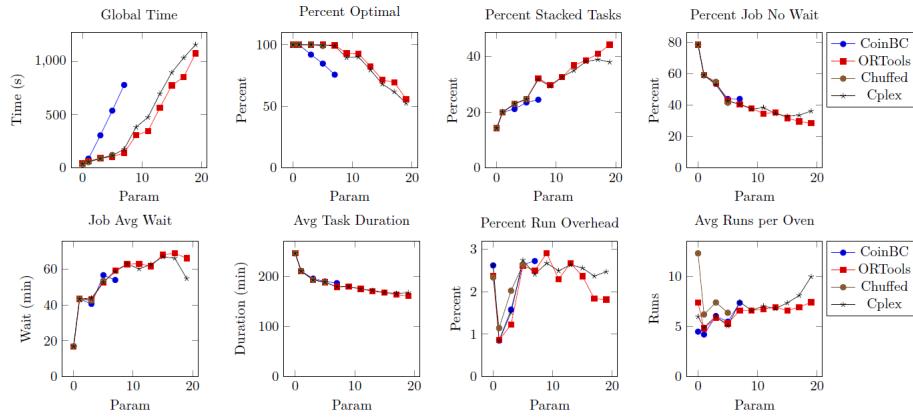
Impact of Lookahead Parameter



Impact of CommitHorizon Parameter



Comparing Different Solvers



Is the global solution really good?

- We schedule with limited information
- Hindsight is 20/20, we cannot expect best possible solution from partial information
- Process Challenge: Can we improve data visibility?
- Demand is variable over time, no steady-state solution
- Modelling Challenge: Can we define a short-term objective that produces better long-term solutions?
- Algorithm Challenge: Can we solve the global problem to optimality?
 - Assumes "a priori" visibility of data
 - This would provide a lower bound
 - But we need optimality to use as bound

Summary

- Discussed a non-standard oven scheduling problem from industry
- Models with decomposition of resource constraints
- Good/very good short-term solutions

- But is the overall schedule close to the global optimum?
- In any case, industry partner was happy with solution and analysis

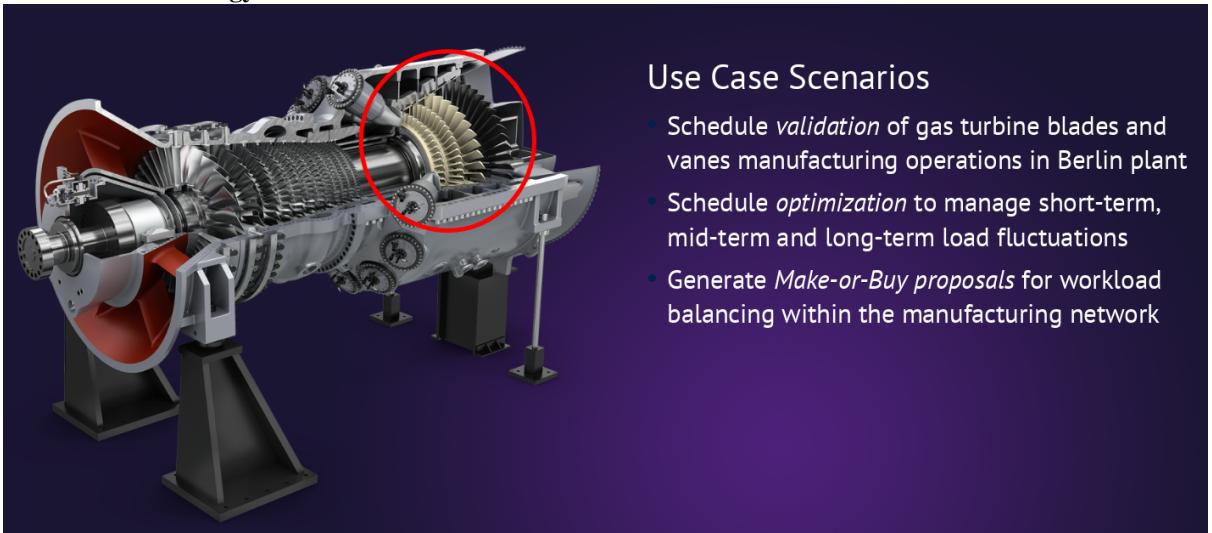
Part XIII

Blades and Vanes Production Case Study

Key Points

- Scheduling/Planning tool for manufacturing industry
- Developed as part of European ASSISTANT project
- Focused on key make-or-buy decisions
- Complex manufacturing process with alternative process paths
- Outperforms both current in-house tool and commercial simulator
- Key Technology: Optimization and Constraint Programming

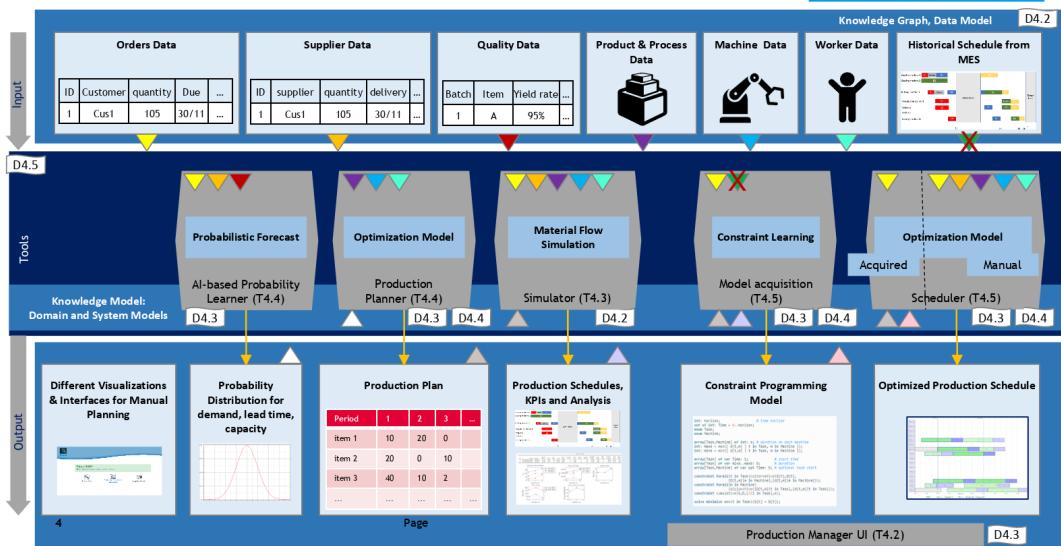
Assistant Siemens Energy Use Case



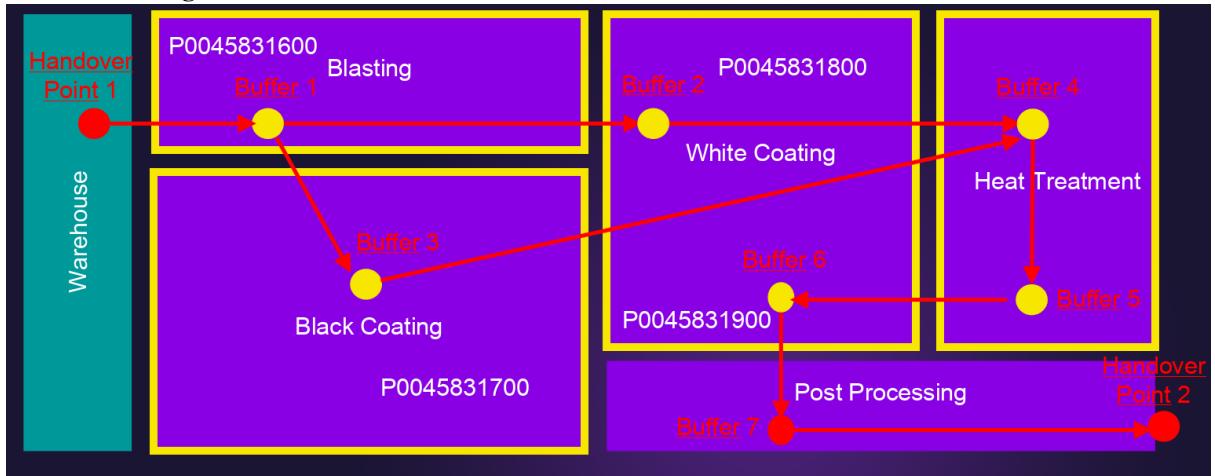
ASSISTANT Project Overview

Intelligent digital twin for process planning and scheduling

ASSISTANT



SE Product Routing



Test Datasets

Full Scale Datasets

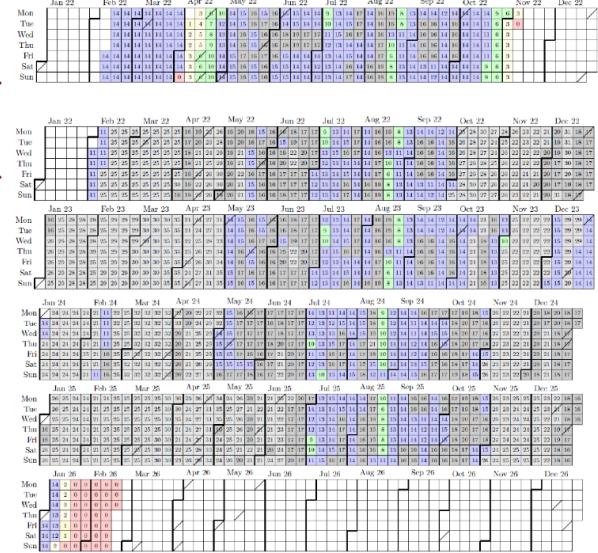
Berlin06: 96 orders, 9 months horizon, previous review

Berlin07: 450 orders, 4 years horizon

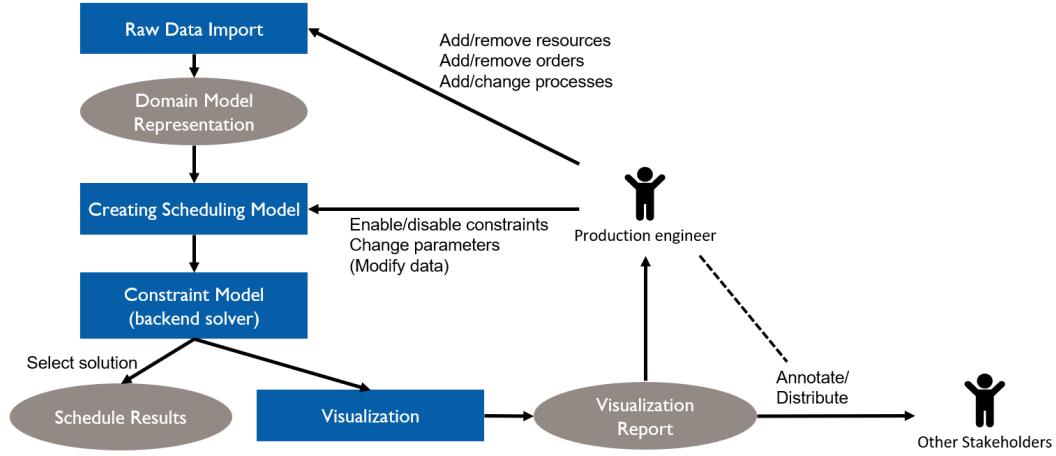
Berlin08: 559 orders, Christmas gap added

Berlin08a: 670 orders, filling gaps

Value in cell indicates active orders
Yellow and red colors indicate low order volume



Optimizer High Level Structure



Raw Data - Manual Data Entry Causes Problems

- Raw data come from spreadsheet
 - 20 tabs
- Excel is a particularly bad input data format
- Realistic, not real data
- Created by hand/automatically from existing test scenarios
- Series of files Berlin01 - Berlin05 were too inconsistent to run
- Berlin06 still contains some errors
- Optimizer explains all issues that it finds

ASSISTANT Project Siemens Energy Use Case - Insight SFI Centre for Data Analytics

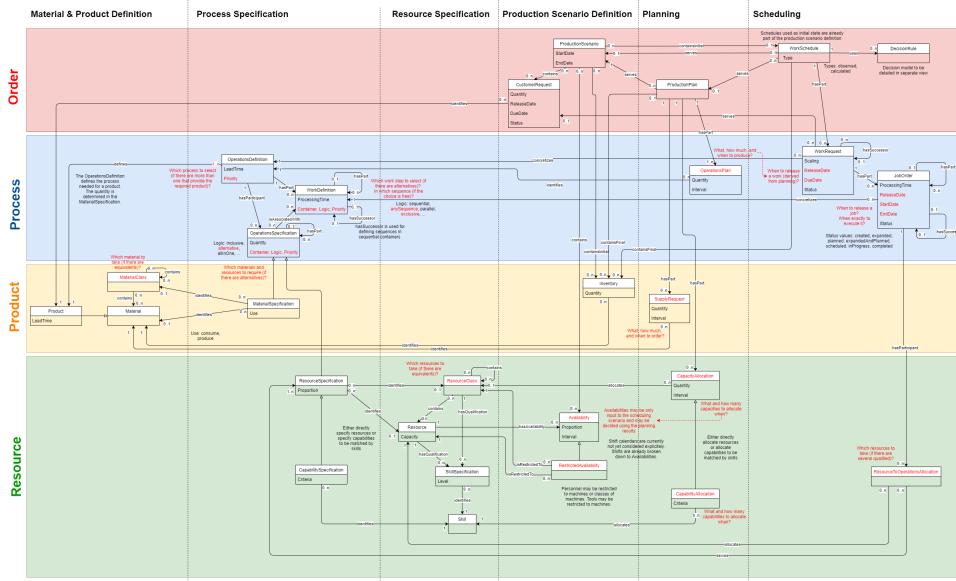
File Edit Scenario View Window Help

RawIssue X

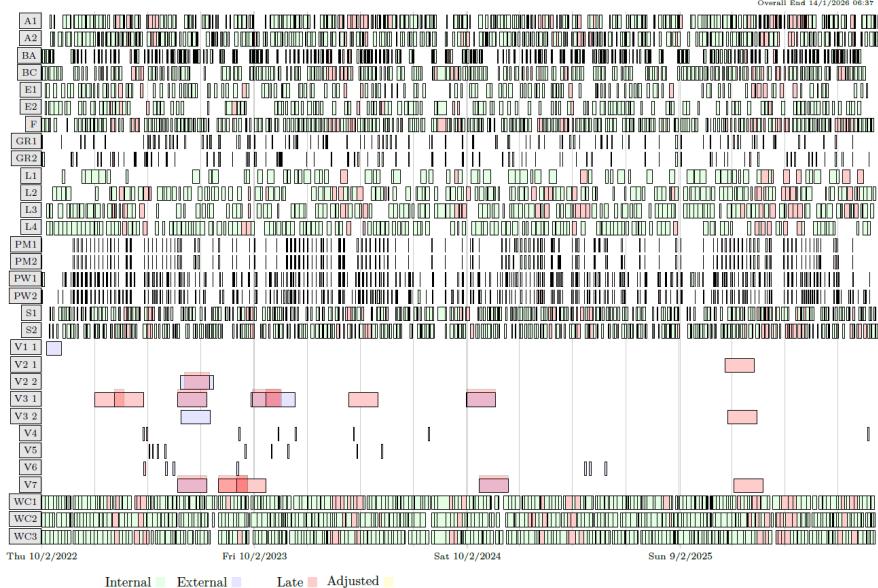
Name	Severity	Sheet	RowNr	ColNr	Description
Issue1	Major	t_Load	129	11	DateTime not formatted correctly, found 2022-02-2800:00:00 format yyyy-MM-dd'T'HH:mm:ss
Issue2	Minor	t_Products	1	15	Extra Empty Header
Issue3	Minor	t_Availabilities	1	8	Extra Empty Header
Issue4	Minor	t_Unavailabilities	1	8	Extra Empty Header
Issue5	Minor	t_Shift_Segments	1	6	Extra Empty Header
Issue6	Major	t_Shift_Segments	1	1	TimeOnly not formatted correctly, found 0.250000, format H:mm:ss
Issue7	Major	t_Shift_Segments	1	2	TimeOnly not formatted correctly, found 0.583333, format H:mm:ss
Issue8	Major	t_Shift_Segments	2	1	TimeOnly not formatted correctly, found 0.291667, format H:mm:ss
Issue9	Major	t_Shift_Segments	2	2	TimeOnly not formatted correctly, found 0.302083, format H:mm:ss
Issue10	Major	t_Shift_Segments	3	1	TimeOnly not formatted correctly, found 0.458333, format H:mm:ss
Issue11	Major	t_Shift_Segments	3	2	TimeOnly not formatted correctly, found 0.479167, format H:mm:ss
Issue12	Major	t_Shift_Segments	4	1	TimeOnly not formatted correctly, found 0.583333, format H:mm:ss
Issue13	Major	t_Shift_Segments	4	2	TimeOnly not formatted correctly, found 0.916667, format H:mm:ss
Issue14	Major	t_Shift_Segments	5	1	TimeOnly not formatted correctly, found 0.666667, format H:mm:ss
Issue15	Major	t_Shift_Segments	5	2	TimeOnly not formatted correctly, found 0.677083, format H:mm:ss
Issue16	Major	t_Shift_Segments	6	1	TimeOnly not formatted correctly, found 0.770833, format H:mm:ss
Issue17	Major	t_Shift_Segments	6	2	TimeOnly not formatted correctly, found 0.791667, format H:mm:ss
Issue18	Major	t_Shift_Segments	7	1	TimeOnly not formatted correctly, found 0.916667, format H:mm:ss
Issue19	Major	t_Shift_Segments	7	2	TimeOnly not formatted correctly, found 0.250000, format H:mm:ss
Issue20	Major	t_Shift_Segments	8	1	TimeOnly not formatted correctly, found 0.000000, format H:mm:ss
Issue21	Major	t_Shift_Segments	8	2	TimeOnly not formatted correctly, found 0.010417, format H:mm:ss
Issue22	Major	t_Shift_Segments	9	1	TimeOnly not formatted correctly, found 0.083333, format H:mm:ss
Issue23	Major	t_Shift_Segments	9	2	TimeOnly not formatted correctly, found 0.104167, format H:mm:ss
Issue24	Minor	t_Shift_Segments	10	0	First Column Empty
Issue25	Minor	t_Shift_Segments	11	0	First Column Empty
Issue26	Minor	t_Shift_Segments	12	0	First Column Empty
Issue27	Minor	t_Shift_Segments	13	0	First Column Empty
Issue28	Minor	t_Shift_Segments	14	0	First Column Empty
Issue29	Minor	t_Shift_Segments	15	0	First Column Empty
Issue30	Minor	t_Shift_Segments	16	0	First Column Empty
Issue31	Minor	t_Shift_Segments	17	0	First Column Empty
Issue32	Minor	t_Shift_Segments	18	0	First Column Empty
Issue33	Minor	t_Shift_Patterns	1	9	Extra Empty Header
Issue34	Minor	t_Shift_Patterns	7	0	First Column Empty
Issue35	Minor	t_Shift_Patterns	8	0	First Column Empty

▶ Filter

Domain Model - Knowledge Graph



Solution for Berlin 08a - Shows Only 20% of Tasks in Model



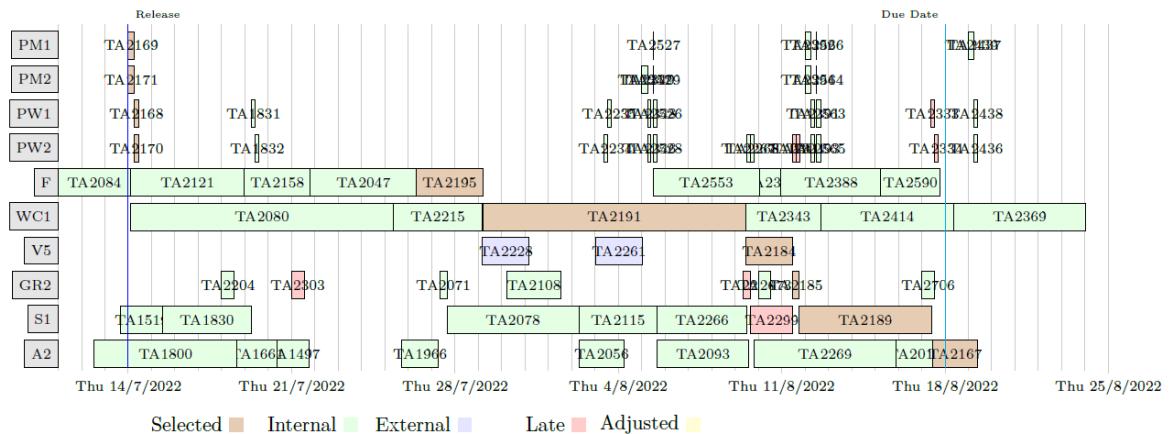
Implementation

- Requirement capture done inside project
- Data checking/cleaning most time consuming aspect
- Some specified functionality was rejected by Betriebsrat
- Built in Java
- Uses IBM's CPOptimizer back-end
- 120k LoC, 110k generated, 3k solver
- Outperforms both
 - Current in-house tool

- Simulation based tool based on commercial simulator
- System installed at SE site, but not in daily use

Explaining Late Delivery

- Explain why some orders are delivered late
- Find root-cause, show schedule in context



Evaluation - KPIs

KPI	Baseline	Optimizer
OTD	> 80 %	92 %
Bottleneck machine utilization	99.5 %	100 %
Manufacturing defects	10-15 %	< 10 %
Scenarios in 8 hours	15-20	> 100,000

Conclusion by Siemens Energy

“Within less than eight hours the ASSISTANT tools provided us thousands of manufacturing scenarios including different make-or-buy recommendations for making deliberate decisions on the way to proceed for strategic planning.”

from ASSISTANT final project review: Siemens Energy assessment

Summary

- Scheduling/Planning tool for manufacturing industry
- Developed as part of European ASSISTANT project
- Focused on key make-or-buy decisions
- Complex manufacturing process with alternative process paths
- Outperforms both current in-house tool and commercial simulator
- Key Technology: Optimization and Constraint Programming

Part XIV

Where to Go from Here

Key Points

- We are working on a survey of the existing CP & Scheduling literature
- Considers over 1200 papers
- Current version of survey available at <https://hsimonis.github.io/pthg24>

41 CP and Scheduling Literature Survey

A Survey of the Existing Literature

- Joint work with Cemalettin Ozturk, MTU
- What is out there
- Where to start
- Where to publish
- I'm interested in some specific topic, what is relevant

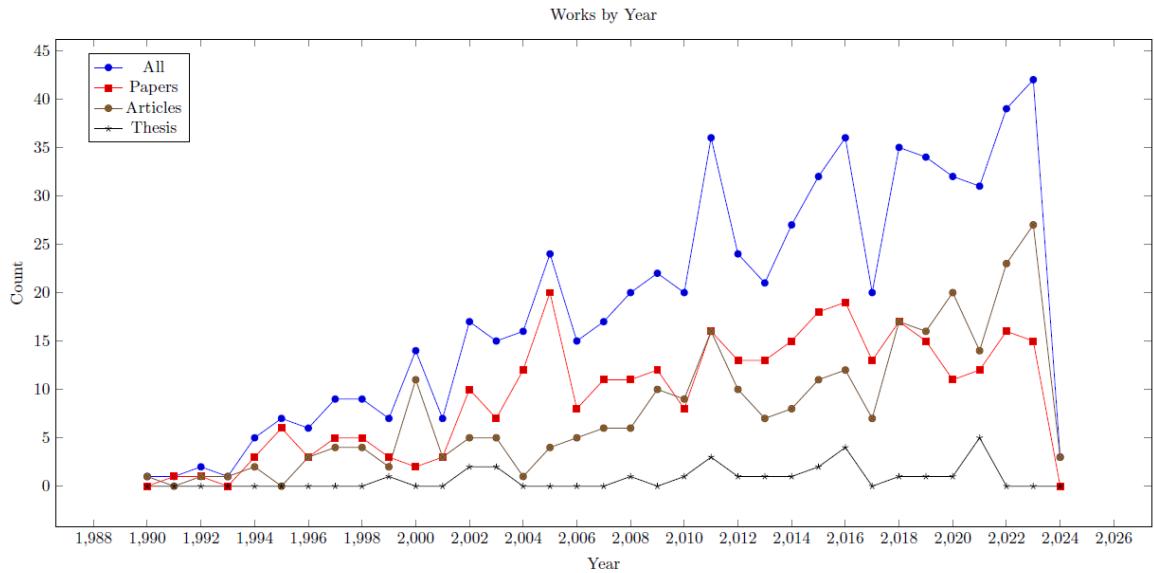
41.1 Methodology

Methodology

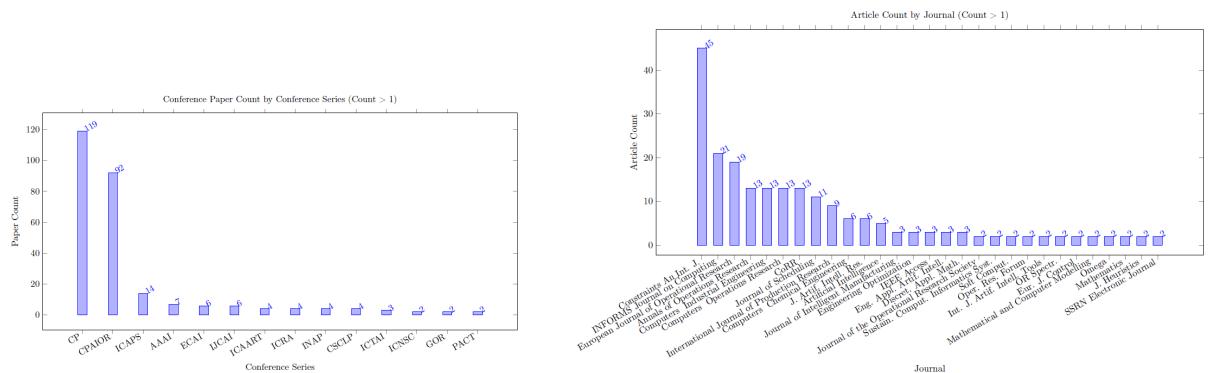
- Manually curated list of works, somewhat inclusive
- Starting with bibtex files
- Citation links through OpenCitations (open access)
- Content analysis on local copies of pdf files
- Closure of domain by analyzing missing cited and citing works
- Limited manual analysis of works (datasets, code)
- Results presented as LaTeX documents
- Open source analysis on git: <https://hsimonis.github.io/pthg24/>

41.2 Analysis Results

Overall Analysis (Based on 671 Works)



Origin of Papers/Articles



Most Recent Articles

Table 5: Works from bibtex (Total 274)

Key	Authors	Title	LC	Cite	Year	Conference /Journal	Pages	Nr Cites	Nr Refs	b	c
ForbesHJST24 ForbesHJST24	M. Forbes [M. Harris [H. Jansen [F.A. van der Schoot [T. Tamme]	Combining optimisation and simulation using logic-based Benders decomposition	Yes	[217]	2024	European Journal of Operational Research	15	0	26	1314	1496
PrataAN23 [PrataAN23]	Bruno A. Prata [Levi R. Abreu [Marcelo S. Nagano]	Applications of constraint programming in production scheduling problems: A descriptive bibliometric analysis	Yes	[509]	2024	Results in Control and Optimization	17	0	0	1427	1497
abs-2402-00459 abs-2402-00459	S. Nguyen [Dhananjay R. Thiruvady [Y. Sun [M. Zhang]	Genetic-based Constraint Programming for Resource Constrained Job Scheduling	Yes	[469]	2024	CoRR	21	0	0	1495	1498
AbreuNP23 [AbreuNP23]	Levi Ribeiro de Abreu [Marcelo Seido Nagano [Bruno A. Prata]	A two-stage constraint programming approach for open shop scheduling problem with machine blocking	Yes	[168]	2023	International Journal of Production Research	20	1	47	1243	1499
AbreuPNF23 AbreuPNF23	Levi R. Abreu [Bruno A. Prata [Marcelo S. Nagano [José M. Fratiman]	A constraint programming-based iterated greedy algorithm for the open shop with sequence-dependent processing times and makespan minimization	Yes	[3]	2023	Computers & Operations Research	12	0	46	1244	1500
Adelgren2023	N. Adelgren [Christen T. Maravillas]	On the use of production scheduling formulations including recent developments	Yes	[7]	2023	Computers & Industrial Engineering	12	0	43	1245	1501
AksarVP23	S. Aksar [Camino R. Vela [Juan José Palacios [L. González-Rodríguez]	Mathematical models and benchmarking for the fuzzy job shop scheduling problem	Yes	[8]	2023	Computers & Industrial Engineering	14	0	50	1246	1502
AkramNHSA23	Hilal Omar Akrami [Nor Kamariah Noordin [F. Hashmi [Mold Fadlee A. Rasid [Mustafa Ismail [Salman Abdurrahman M. Abdulghani	Joint Scheduling and Routing Optimization for Deterministic Hybrid Traffic in Time-Sensitive Networks Using Constraint Programming	Yes	[13]	2023	IEEE Access	16	0	0	1248	1503
AffieriGPS23	A. Affieri [M. Garrappa [E. Pastore [F. Salassa]	Permutation flowshop problems minimizing core processing time and core idle time	Yes	[15]	2023	Computers & Industrial Engineering	13	0	37	1249	1504
AffieriGPS23	A. Affieri [C. Quimper]	Scheduling through logic-based tools	Yes	[127]	2023	Constraints An. Int.	1	0	0	1287	1505
Caballer023 [Caballer023]	Jordi Coll Caballero	Constraint Programming for Flexible Flow Shop Scheduling Problem with Repeated Jobs and Repeated Operations	Yes	[159]	2023	Advances in Science and Technology Research Journal	14	0	0	1297	1506
CzerniachowskaW23	K. Czerniachowska [R. Wiczniarek [K. Zywicki]	Overload-Checking and Edge-Finding for Robust Cumulative Scheduling	No	[207]	2023	INFORMS Journal on Computing	null	0	16	No	1507
FahimiQ23 FahimiQ23	H. Fahimi [C. Quimper]	Job Scheduling and Job Shop Systems in Dynamic Environments: Mixed-Integer Linear Programming and Constraint Programming Approaches	Yes	[212]	2023	Omega	15	7	60	1312	1508
GhasemiMH23	S. Ghasemi [R. Tavakkoli-Moghaddam [M. Hamidi]	Operating room scheduling by emphasizing human factors and dynamic decision-making styles: a constraint programming method	No	[242]	2023	International Journal of Systems Science: Operations Logistics	null	0	104	No	1509
GuoZ23 GuoZ23	P. Guo [J. Zhu]	Capacity reservation for humanitarian relief: A logic-based Benders decomposition method with subgradient cut	Yes	[269]	2023	European Journal of Operational Research	29	0	112	1325	1510
GurPAE23 [GurPAE23]	S. Gür [M. Pinarbaşı [Haci Mehmet Alakas [T. Eren]	Operating room scheduling with surgical team: a new approach with constraint programming and goal programming	Yes	[270]	2023	Central. Eur. J. Oper. Res.	25	1	40	1327	1511
IsikYA23 IsikYA23	Eyüp Ensar Isik [Seyda Topaloglu Yıldız [Özge Satır Akpunar	Constraint programming models for the hybrid flow shop scheduling problem and its extensions	Yes	[321]	2023	Soft Comput.	28	0	127	1350	1512
JuvinHL23a	C. Juvin [L. Houssin [P. Lopez]	Logic-based Benders decomposition for the preemptive flexible job-shop scheduling problem	Yes	[331]	2023	Computers & Operations Research	17	0	40	1355	1513
LacknerMMWW23	M. Lackner [C. Mrkvicka [N. Musliu [D. Walkiewicz [F. Winter]	Exact methods for the Oven Scheduling Problem	Yes	[374]	2023	Constraints An. Int. J.	42	0	32	1371	1514

Automatically Extracted Article Features

Table 6: Automatically Extracted ARTICLE Properties (Requires Local Copy)

Work	Pages	Concepts	Classification	Constraints	Prog Languages	CP Systems	Areas	Industries	Benchmarks	Algorithm	a	c
Laborie03 [369]	38	task, precedence, order, cmax, machine, job, activity, re-scheduling, setup-time, release-date, inventory, preempt, job-shop, resource, scheduling, make-span		cycle, table constraint, cumulative, disjunctive	C++	Ilog Scheduler		benchmark		edge-finding, not-last, energetic reasoning, not-first, time-tabling	1201	1731
LaborieRSV18 [372]	41	release-date, job-shop, resource, activity, precedence, sequence, dependent setup, earliness, scheduling, machine, inventory, transportation, manpower, due-date, setup-time, batch process, order, tardiness, flow-shop, job, make-span, re-scheduling, task, distributed	psplib, parallel machine, RCPSP	alternative constraint, cumulative, noOverlap, disjunctive, span constraint, cycle, alwaysIn, endBeforeStart	C , Python, C++, Java	CHIP, Gecode, Ilog Solver, Cplex, Ilog Scheduler, OPL, Choco Solver, CPO	railway, container terminal, satellite, robot, pipeline, aircraft, shipping industry	chemical industry, petrochemical industry	real-world, CSPlib, benchmark	edge-finding	1080	1610
LacknerMMWW23 [374]	42	release-date, batch process, setup-time, job, order, due-date, tardiness, scheduling, make-span, machine, task, lateness, job-shop, earliness	parallel machine, OSP, single machine	alternative constraint, disjunctive, bin-packing, noOverlap, cumulative, endBeforeStart	Chuffed, Cplex, OPL, CPO, OR-Tools, MiniZinc, Gurobi	semiconductor oven scheduling	electronics industry, steel industry, manufacturing industry	random instance, industrial partner, benchmark, instance generator, zenodo, real-life real-life	time-tabling	984	1514	
LammaMM97 [377]	15	job-shop, resource, scheduling, precedence, order, task, job, distributed, no-wait		circuit, disjunctive	C++, Prolog	ECLAPSe, OPL, CHIP	railway				1230	1760
LetortCB15 [385]	52	machine, make-span, job, precedence, resource, scheduling, task, order	psplib	cumulative, cycle, bin-packing	Java, Prolog	Choco Solver, CHIP, SICStus		generated instance, Roadef, random instance	generated instance, Roadef, random instance	energetic reasoning, sweep, edge-finding	1110	1640
LiW08 [386]	18	precedence, activity, resource, completion-time, scheduling, make-span, scheduling, machine, preempt, job-shop, no preempt, job, re-scheduling, open-shop, due-date, task, order	RCPSP	disjunctive, cycle, bin-packing	Ilog Solver, OZ, Cplex, ECOPSe, CHIP			steel industry, manufacturing industry	real-world		1178	1708
LiessM08 [388]	12	precedent, resource, scheduling, machine, job, activity, precedence, job-shop, task, make-span, scheduling	RCPSP, psplib	disjunctive, cumulative	C++	OZ		benchmark	edge-finding		1179	1709
LimtanyakulS12 [393]	32	release-date, scheduling, order, completion-time, job, resource, activity, tardiness, machine, due-date, precedence		table constraint, disjunctive, bin-packing, cumulative	OZ, Ilog Scheduler, Cplex	robot, automotive	automotive industry	random instance, real-life generated instance, industrial partner, benchmark	not-last, energetic reasoning, not-first, edge-finding		1133	1663
LombardiM10s [402]	30	due-date, distributed, order, job, make-span, release-date, re-scheduling, task, completion-time, resource, activity, precedence, preempt, scheduling, machine	TCSP	cycle, constraint, span constraint, cumulative, disjunctive, table constraint	C	Cplex		real-world, benchmark, real-life	sweep		1160	1690

Manually Extracted Article Features

Table 4: Manually Defined PAPER Properties

Key	Title (Local Copy)	CP System	Bench	Links	Data Avail	Sol Avail	Code Avail	Related To	Classification	Constraints	a	b
AjlanPG23	Optimization of Short-Term Underground Mine Planning Using Constraint Programming	CP Opt	real-world	1	n	n	n	-	-	?	1	325
AjlanPG23 [1]	Enhancing Hybrid CP-SAT Search for Disjunctive Scheduling	ARIES	real-world, github, benchmark	1	y	y	-	JSSP OSSP	-	-	2	371
Bit-Monnot23	Predicting the Optimal Period for Cyclic Hoist Scheduling Problems	Mistral OR-Tools	benchmark, random instance, generated instance, real-life, industrial instance	3	n	n	-	CHSP	-	-	3	415
EfthymiouY23	An Efficient Constraint Programming Approach to Preemptive Job Shop Scheduling	CP Opt	supplementary material, github, benchmark	6	ref	y	PJSSP	endBeforeStart span noOverlap	-	-	4	476
JuvinHHL23	Constraint Programming for the Robust Two-Machine Flow-Shop Scheduling Problem with Budgeted Uncertainty	CP Opt Cplex	real-world	0	ref	n	-	Perm FSSP	endBeforeStart noOverlap sameSequence cumulative	-	5	477
KameugneFND23	Horizontally Elastic Edge Finder Rule for Cumulative Constraint Based on Slack and Density	?	benchmark	5	BL PSPLib	n	-	RCPSPs	-	-	6	480
KimCMILLP23	Iterated Greedy Constraint Programming for Scheduling Steelmaking Continuous Casting	Gurobi OR-Tools	real-world, benchmark, zenodo	0	y	n	-	SCC	alternative noOverlap	-	7	485
MehdiZadeh-Somarin23	A Constraint Programming Model for a Constrained Job Shop Scheduling Problem with Machine Availability	CP Opt	random instance	0	n	n	-	JSSP RMS	alternative endBeforeStart noOverlap table	-	8	529
MehdiZadeh-Somarin23 [430]	A Constraint Programming Model for Scheduling the Unloading of Trains in Ports	custom	real-world, generated instance	0	n	n	-	SUTP	PP-MS-MMRCPS/maximum disjunctive	-	9	553
PerezGSL23	Partially Preemptive Multi Skill/Mode Resource-Constrained Project Scheduling with Generalized Precedence Relations and Calendars	CP Opt MiniZinc Chuffed	real-world, benchmark, industrial instance, real-life	4	y	y	PP-MS-MMRCPS/maximum	-	-	10	557	
SquillaciPR23	Scheduling Complex Observation Requests for a Constellation of Satellites: Large Neighborhood Search Approaches	Cplex Studio	github, benchmark	2	y	n	-	EOSP	?	-	11	584
TardivoDFMP23	Constraint Propagation on GPU: A Case Study for the Cumulative Constraint	MiniCPP MiniZinc	bitbucket, github, benchmark, real-world	9	PSPLib BL Pack	y	-	RCPSP	cumulative	-	12	590
TasselGS23	An End-to-End Reinforcement Learning Approach for Job-Shop Scheduling Problems Based on Constraint Programming	custom Choco	industrial instance, real-world, supplementary material, github, benchmark	0	ref	y	-	JSSP	noOverlap	-	13	591
WangB23	Dynamic All-Different and Maximal Cliques Constraints for Fixed Job Scheduling	FaClLe	real-world, random instance	0	(y)	n	[628]	FJS	-	-	14	620
WangB23 [629]	A competitive constraint programming approach for the group shop scheduling problem	CP Opt	github, benchmark	0	ref	n	-	GSSP	noOverlap endBeforeStart	-	15	633

Extracted Features: Application Areas

Table 16: Works for Concepts of Type ApplicationAreas

Type	Keyword	High	Medium	Low
ApplicationAreas	COVID	[GuoZ23] [269]	[GelbingerKMMW21] [234]	[Fatemi-AnarakTFV23] [212], [MehdiZadeh-Somarin23] [430], [GurPAE23] [270], [JuvinHHL23a] [331], [OujanaAYB22] [487], [Lemos21] [381]
ApplicationAreas	HVAC	[LimHTB16] [399], [LimBTBB15] [391], [GrimesIOS14] [269]		[AkramNHRSA23] [13], [BenderWS21] [84], [HamPK21] [275], [Astrand21] [35], [QinWLS21] [511], [AstrandO21] [36], [MejaY20] [431]
ApplicationAreas	agriculture			
ApplicationAreas	aircraft	[PohlAF22] [629], [WangB20] [628], [TremDFWV21] [629], [Johann16] [205], [BalajestaniB13] [42], [LombardiM19] [405], [BalajestaniB11] [41], [FrankK05] [210], [Artiouchine305] [24], [Simonsu9] [553]	[WangB23] [629], [GombolayWS18] [253], [Ham18] [273], [Simonsu07] [559], [SakkoutW00] [529], [Simonsu95a] [556]	[PrataAN23] [509], [PovedaAA23] [508], [Adelgren2023] [7], [Etmane2023] [510], [NMS22] [224], [Bekerman22] [105], [ZarandiASC20] [554], [HanslerRPA20] [238], [abs-1902-09244] [283], [Hoeker9] [312], [LaboreiRSV18] [372], [HoekerH17] [314], [TranAB16] [554], [Lombardi10] [398], [Laborei09] [370], [Kowacs308] [355], [KrogLP110] [608], [MartinPV01] [427], [SimonsuK00] [560], [GruianK98] [264], [Darby-DownmanLM297] [163], [Wallace96] [625], [Simonsu95] [557], [BeniniBG06] [88], [KovacsV06] [360], [Wallace96] [625]
ApplicationAreas	automotive			[PovedaAA23] [509], [YuraszeczkMPV22] [650], [EndrZD22] [169], [Cerdeira21] [261], [LimtanayakulS17] [232], [SunLYL10] [562], [Lombardi10] [398], [BarlattCG08] [524], [SchildW00] [532]
ApplicationAreas	cable tree	[KochlerBFFHPSS21] [348]		[BeldiceanuC04] [78], [abs-2312-13682] [497], [PerrezGSL23] [499], [TouatBT22] [502], [CauwelaertDS20] [142], [Wallace20] [627], [ZarandiASC20] [554], [FallahAC20] [269], [Hoeker19] [312], [CauwelaertDMS20] [140], [Dejemeppe16] [172], [DejemeppeCS15] [172], [NovasH12] [476], [CorraileR07] [158], [LimRX00] [389]
ApplicationAreas	car manufacturing			[NaderiR22] [460], [WangB23] [628], [Adelgren2023] [7], [Etmane2023] [510], [GOMSS22] [122], [NaderiB22] [557]
ApplicationAreas	container terminal	[QinDCS20] [512], [SacramentoSP20] [526]	[AntuoriHHEN21] [22], [LaborieRSV18] [312]	[NaderiB22] [460], [AntuoriHHEN21] [22], [HubnerGSV21] [318], [AbreuAPN21] [168], [KoecherBFFHPSS21] [348], [VlkH121] [623], [BarzegaranZP20] [611], [GelbingerMM19] [236], [abs-1911-04768] [235], [BonfettiZLM16] [113], [Sialai5a] [552], [SchneiH15] [533], [AlesioNBG14] [181], [HarjunkoskiMBC14] [279], [BeniniBG06] [88], [KovacsV06] [360], [Wallace96] [625]
ApplicationAreas	crew-scheduling	[ZarandiASC20] [654], [PourDERB18] [505]		[BeldiceanuC04] [78], [abs-2312-13682] [497], [PerrezGSL23] [499], [TouatBT22] [502], [CauwelaertDS20] [142], [Wallace20] [627], [ZarandiASC20] [554], [FallahAC20] [269], [Hoeker19] [312], [CauwelaertDMS20] [140], [Dejemeppe16] [172], [DejemeppeCS15] [172], [NovasH12] [476], [CorraileR07] [158], [LimRX00] [389]
ApplicationAreas	dairies			[NaderiR22] [460], [WangB23] [628], [Adelgren2023] [7], [Etmane2023] [510], [GOMSS22] [122], [NaderiB22] [557]
ApplicationAreas	dairy	[EscobetPQPR19] [201]	[PrataAN23] [509], [HarjunkoskiMBC14] [279]	[NaderiB22] [460], [AntuoriHHEN21] [22], [HubnerGSV21] [318], [Lemee21] [331], [MohitazardehTNF20] [413], [TangIWSK18] [574], [HoekerH17] [314], [DoulashRP16] [190], [LipovetzkyvPS14] [394], [HachemiGH11] [272], [MilanoW09] [441], [WaB369] [643], [MilanoW06] [440], [BeldiceanuC02] [79], [JainG01] [323], [SimonsuK00] [560]
ApplicationAreas	datacenter	[HermenierDL11] [500]		[Bartak02] [54], [Bartak02a] [53], [Groletz21] [261]
ApplicationAreas	datacentre			[Zanella20] [652], [GalleguilloKSB19] [225], [Matl-WalaaOBM17] [418], [Letort13] [382], [IfrimOS12] [320], [LetortBC12] [383]
ApplicationAreas	day-ahead market			
ApplicationAreas	deep space			
ApplicationAreas	drone	[MontemanniD23a] [446], [MontemanniD23] [447], [Ham18] [273]		[HebrardALLCMR22] [285], [GuoZ23] [269], [JuvinHHL23a] [331], [Adelgren2023] [7], [ShalikhK23] [547], [EndoDZ22] [199], [Astrand21] [35], [AstrandO21] [36], [AntuoriHHEN21] [22], [ZarandiASC20] [554], [Ham18a] [274]

Prolific Authors

Table 8: Co-Authors of Articles/Papers

Author	Nr Works	Nr Cites	Entries
J. Christopher Beck	49	701	LuoB22 [416], ZhangBB22 [658], TangB20 [573], RoshanaiBAUB20 [521], TranPZLDB18 [597], TranVNB17 [599], TranVNB17a [600], CohenHB17 [154], BoothNB16 [113], KuiB16 [365], TranAB16 [594], TranWDRFOV16 [601], LuoVLM16 [415], TranDRFWOB16 [596], BajestaniB15 [43], KoschB14 [839], TerekhovTDB14 [831], LouieVN14 [412], HeinzB13 [294], HeinzKB13 [291], BajestaniB13 [42], TranTDB13 [598], HeinzB12 [290], TerekhovDOB12 [580], ZarandbiB12 [213], KovacsB11 [356], BeckFW11 [66], HeckmanB11 [289], BajestaniB11 [41], WuLB09 [643], BidotVLB09 [94], CarchraeB09 [131], WatsonB08 [632], KovacsB08 [553], BeckW07 [73], Beck07 [64], KovacsB07 [354], Beck06 [63], CarchraeBF06 [132], WuBBo5 [642], BeckW05 [72], BeckW04 [71], Beckf03 [70], BeckPS03 [69], BeckF00 [68], Beck99 [62], BeckF98 [67].
Michela Milano	31	297	
Andreas Schutt	27	322	YangS19 [24], KreterSS18 [86], CireH16 [125], MuslimS18 [455], KreterS17 [363], YoungFS17 [250], SchuttS16 [543], SchutTS17 [537], SchutTS16 [536], GuSS13 [265], SchutTS13 [536], GuS13 [265], SchutTSW13 [541], ChuGSW13 [147], SchutTSW12 [535], SchutTSW11 [540], SchutTS11 [534], SchutW10 [541], abs-1009-0347 [539], SchutTSW09 [538], SchutTSW08 [535], SchutTSW07 [535].
Michele Lombardi	25	194	BorghesiBLMB18 [115], CamerloherLMB18 [111], BridiBLMB16 [120], BridiBLBM16 [121], LombardiblMB15 [399], BartoliniBBM14 [60], BonfettiLMB14 [111], BonfettiLBM14 [109], BonfettiLMB13 [110], LombardiblMB13 [407], LombardiblMB12 [108], LombardiblMB12a [404], BonfettiLMB12 [112], BonfettiLBM11 [107], LombardiblMB11 [409], BeniniLMR11 [90], Milano11 [438], LombardiblM10 [403], LombardiblM10a [402], LombardiblMRB10 [408], LombardiblMRB10 [407], RuggieroBMA09 [525], MilanoW09 [441], BeniniLMR08 [89], BeniniGM06 [88], MilanoW06 [110], MilanoORT02 [439], LaminaMM97 [377], BrusonCLMM96 [121], BeniniLMR07 [90], BeniniLMR06 [89], BeniniLMR05 [88].
Peter J. Stuckey	24	453	YangS19 [644], DemirovićS18 [177], KreterSS18 [364], MuslimS18 [455], KreterS17 [363], SchutTS16 [543], BlomPS16 [100], KreterS15 [362], BlomPS15 [124], SchutTSW14 [542], BlomPS14 [364], LipovetzkyBPS14 [394], GuSSW14 [266], SchutTS13 [536], GuSS13 [265], SchutTSW13 [541], SchutTSW12 [536], GuSW12 [267], SchutTSW11 [540], BandaSC11 [170], abs-1009-0347 [539], SchutTSW09 [538], OhrnemannC09 [483].
John N. Hooker	19	1316	ElicOH22 [195], HookerI19 [312], Hooker17 [311], Hooker17 [314], HochenauerL18 [288], CireH16 [150], HarjunkoskiMBC14 [270], CireCH13 [149], CobanH11 [153], CobanH10 [153], CobanH10 [152], CobanH10 [151], CobanH10 [150], CobanH10 [149], CobanH10 [148], CobanH10 [147], CobanH10 [146], CobanH10 [145], CobanH10 [144], CobanH10 [143], CobanH10 [142], CobanH10 [141], CobanH10 [140], CobanH10 [139], CobanH10 [138], CobanH10 [137], CobanH10 [136], CobanH10 [135], CobanH10 [134], CobanH10 [133], CobanH10 [132], CobanH10 [131], CobanH10 [130], CobanH10 [129], CobanH10 [128], CobanH10 [127], CobanH10 [126], CobanH10 [125], CobanH10 [124], CobanH10 [123], CobanH10 [122], CobanH10 [121], CobanH10 [120], CobanH10 [119], CobanH10 [118], CobanH10 [117], CobanH10 [116], CobanH10 [115], CobanH10 [114], CobanH10 [113], CobanH10 [112], CobanH10 [111], CobanH10 [110], CobanH10 [109], CobanH10 [108], CobanH10 [107], CobanH10 [106], CobanH10 [105], CobanH10 [104], CobanH10 [103], CobanH10 [102], CobanH10 [101], CobanH10 [100], CobanH10 [99], CobanH10 [98], CobanH10 [97], CobanH10 [96], CobanH10 [95], CobanH10 [94], CobanH10 [93], CobanH10 [92], CobanH10 [91], CobanH10 [90], CobanH10 [89], CobanH10 [88], CobanH10 [87], CobanH10 [86], CobanH10 [85], CobanH10 [84], CobanH10 [83], CobanH10 [82], CobanH10 [81], CobanH10 [80], CobanH10 [79], CobanH10 [78], CobanH10 [77], CobanH10 [76], CobanH10 [75], CobanH10 [74], CobanH10 [73], CobanH10 [72], CobanH10 [71], CobanH10 [70], CobanH10 [69], CobanH10 [68], CobanH10 [67], CobanH10 [66], CobanH10 [65], CobanH10 [64], CobanH10 [63], CobanH10 [62], CobanH10 [61], CobanH10 [60], CobanH10 [59], CobanH10 [58], CobanH10 [57], CobanH10 [56], CobanH10 [55], CobanH10 [54], CobanH10 [53], CobanH10 [52], CobanH10 [51], CobanH10 [50], CobanH10 [49], CobanH10 [48], CobanH10 [47], CobanH10 [46], CobanH10 [45], CobanH10 [44], CobanH10 [43], CobanH10 [42], CobanH10 [41], CobanH10 [40], CobanH10 [39], CobanH10 [38], CobanH10 [37], CobanH10 [36], CobanH10 [35], CobanH10 [34], CobanH10 [33], CobanH10 [32], CobanH10 [31], CobanH10 [30], CobanH10 [29], CobanH10 [28], CobanH10 [27], CobanH10 [26], CobanH10 [25], CobanH10 [24], CobanH10 [23], CobanH10 [22], CobanH10 [21], CobanH10 [20], CobanH10 [19], CobanH10 [18], CobanH10 [17], CobanH10 [16], CobanH10 [15], CobanH10 [14], CobanH10 [13], CobanH10 [12], CobanH10 [11], CobanH10 [10], CobanH10 [9], CobanH10 [8], CobanH10 [7], CobanH10 [6], CobanH10 [5], CobanH10 [4], CobanH10 [3], CobanH10 [2], CobanH10 [1], CobanH10 [0].
Emmanuel Hebrard	17	71	JuvinHH23 [328], HebrardALLCMR22 [285], AntuoriHHEN21 [22], ArtiguesHQ21 [32], GodetLHS20 [247], AntuoriHHEN20 [21], HebrardHJMPV16 [286], SimoninAHL15 [555], SinalAH15 [553], GrimesH15 [551], BessiereHMQW14 [553], SimoninAHL12 [554], BilautHL12 [55], NattaAL17 [463], NattaALR16 [464], SimoninAHL15 [555], NattaAL15 [462], SimoninAHL12 [554], LahimerLH11 [555], TrojetHL11 [602], LopezAKY09 [410], TorresL00 [591].
Pierre Lopez	17	90	
Christian Artigues	16	203	PovedaAA23 [508], PohlarK22 [502], HebrardALLCMR22 [285], ArtiguesHQ21 [32], Polo-MejiaALB20 [503], NattaHKAL19 [466], NattaAL17 [463], NattaALR16 [464], SimoninAHL15 [555], NattaAL15 [462], SimoninAHL12 [554], NeronABCDD06 [481].
Pierre Schaus	15	79	CauwelaertDS20 [112], UllmannKS20 [656], HoumtJSW19 [316], CappartTSR18 [130], CauwelaertLS18 [141], CappartS17 [129], CauwelaertS16 [128], DMS16 [120], DujouinepsCS15 [173], GayHS15 [229], GayHS15 [230], GayHS15a [231], HoundsJWD14 [317], GaysS14 [232], SchausHM-CMD13 [531], Schauant10 [530].
Helmut Simonis	15	154	ArmstrongCOS22 [271], ArmstrongGOS21 [26], AntunesABD20 [20], AntunesABD19 [19], HurleyOS16 [310], GrimesIOS14 [266], IfrimOS12 [320], SimonisJ11 [662], SimonisJ09 [559], SimonisK09 [560], Simonis99 [558], Simonis95 [561], Simonis95 [557], Simonis95a [556], DinchevSH90 [184], Madi-WambalOBM17 [418], Madi-WambalOB16 [417], LetortCB15 [385], LetortCB13 [384], LetortCB12 [383], ClercqPB34 [151], BeldeceanuCDP11 [408], BeldeceanuCP08 [81], PoderB08 [500], BeldeceanuCP07 [82], PoderBS04 [501], BeldeceanuCP02 [79], AggounB93 [9], BorghesiBLMB18 [115], BridiBLMB16 [120], BridiBLMB16 [121], BonfettiBLM14 [109], LombardiblMB13 [407], BonfettiBLM12 [108], BonfettiBLM11 [107], LombardiblMB11 [406], BeniniLMR11 [90], LombardiblMRB10 [408], RuggieroBMA09 [529], BeniniLMR08 [89], BeniniGM06 [88].
Nicolas Beldiceanu	13	274	
Luca Benini	13	146	
Philippe Laborie	12	513	LunardiBLRV20 [413], LaborieTSV18 [372], Laborie18a [371], MelgarejoS15 [11], VilimS15 [621], Laborie09 [370], BidotVLB09 [94], BaptisteLPN06 [17], NeronABCDD06 [481], GodardLN05 [245], Laborie03 [369], FocacciaLN06 [215], BaptisteLPN06 [17], Baptiste09 [45], BaptisteLPN06 [47], NeronABCDD06 [481], ArtiouchnicheB05 [34], Baptiste02 [44], BaptistePN01 [50], BaptisteLPN00 [49], BaptisteLPN00 [49], BaptisteP97 [48], PapeB97 [49].
Philippe Baptiste	11	403	
Roman Barták	11	88	SvancaraB22 [569], JelmekB16 [325], BartakV15 [59], Bartak14 [55], BartakS11 [57], BartakCS10 [56], BartakSR10 [58], VilimBC04 [619], Bartak02 [54], Bartak02a [53].

41.3 Limitations

Limitations

- Limited coverage by OpenCitations
- Difficult to have local access to some publication types (book, incollection)
- Heavily biased towards publications in English
- More powerful NLP analysis of works possible?

Problem: Count for Most Cited Papers

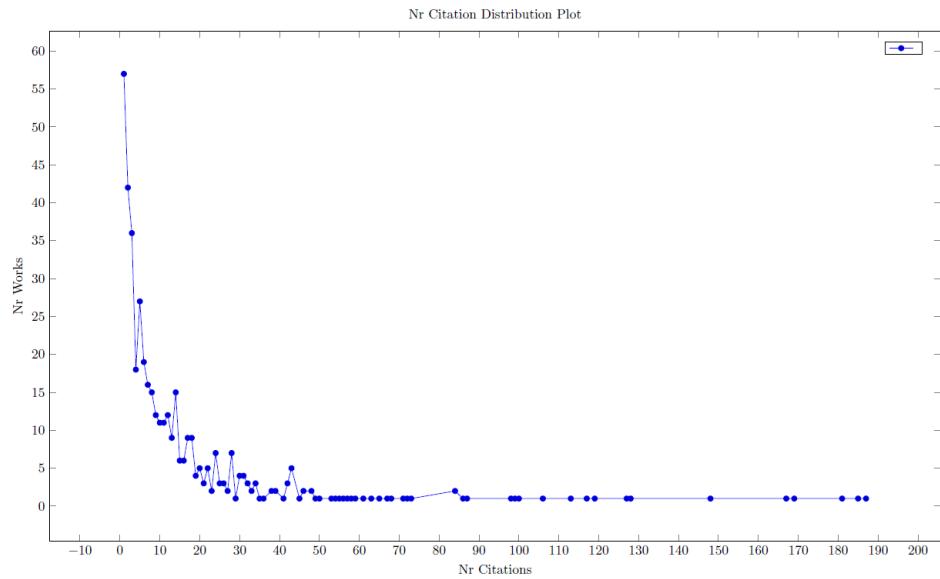
Table 9: Works from bibtex (Total 30)

Key	Authors	Title	LC	Cite	Year	Conference / Journal	Pages	Nr Cites	Nr Refs	b	c
JainM99 JainM99	A. Jain, S. Meeran	Deterministic job-shop scheduling: Past, present and future	Yes	[322]	1999	European Journal of Operational Research Computers Chemical Engineering	45	490	150	1352	1753
HarjunkoskiMBC14	I. Harjunkoski, Christos T. Maravillas, P. Bongers, Pedro M. Castro, S. Engell, Ignacio E. Grossmann, John N. Hooker, C. Méndez, G. Sand, L. Wassick	Scope for industrial applications of production scheduling models and solution methods	Yes	[279]	2014	European Journal of Operational Research Computers Chemical Engineering	33	381	176	1335	1649
BlazewiczDP96	J. Blazewicz, W. Domschke, E. Pesch	The job shop scheduling problem: Conventional and new solution techniques	Yes	[125]	1996	European Journal of Operational Research Mathematical Programming Book	33	344	127	1278	1762
HookerO03 HookerO03	John N. Hooker, G. Ottosson	Logic-based Benders decomposition	Yes	[319]	2003	Mathematical Programming Book	28	317	0	1347	1729
BaptistePN01	P. Baptiste, Claude Le Pape, W. Nuijten	Constraint-Based Scheduling	No	[50]	2001	INFORMS Journal on Computing Mathematical and Computer Modelling Book	null	296	0	No	n/a
JainG01 JainG01	V. Jain, Ignacio E. Grossmann	Algorithms for Hybrid MILP/CP Models for a Class of Optimization Problems	Yes	[233]	2001	INFORMS Journal on Computing Mathematical and Computer Modelling Book	19	279	23	1351	1738
AggounB93 AggounB93	A. Aggoun, N. Beldiceanu	Extending CHIP in order to solve complex scheduling and placement problems	Yes	[9]	1993	INFORMS Journal on Computing Mathematical and Computer Modelling Book	17	187	11	1247	1767
Hooker00 Hooker00	John N. Hooker	Logic-Based Methods for Optimization: Combining Optimization and Constraint Satisfaction	No	[304]	2000	Operations Research Planning and Scheduling by Logic-Based Benders Decomposition	null	185	0	No	n/a
Hooker07 Hooker07	John N. Hooker	Decomposition techniques for multistage scheduling problems using mixed-integer and constraint programming methods	Yes	[309]	2007	Operations Research Computers Chemical Engineering	29	181	19	1345	1715
HarjunkoskiG02	I. Harjunkoski, Ignacio E. Grossmann	Introducing Global Constraints in CHIP	Yes	[278]	2002	INFORMS Journal on Computing Mathematical and Computer Modelling Book	20	169	11	1334	1733
BeldiceanuC94	N. Beldiceanu, E. Contejean	IBM ILOG CP optimizer for scheduling - 20+ years of scheduling with constraints at IBM/ILOG	Yes	[78]	1994	INFORMS Journal on Computing Mathematical and Computer Modelling Book	27	167	8	1271	1765
LaborieRSV18	P. Laborie, J. Rogerie, P. Shaw, P. Vilim	Algorithms for propagating resource constraints in AI planning and scheduling: Existing approaches and new results	Yes	[372]	2018	INFORMS Journal on Computing Mathematical and Computer Modelling Book	41	148	35	1370	1610
Laborie03 Laborie03	P. Laborie	Propagation via lazy clause generation	Yes	[369]	2003	INFORMS Journal on Computing Mathematical and Computer Modelling Book	38	128	10	1369	1731
OhrimenkoSC09	O. Ohrimenko, Peter J. Stuckey, M. Codish	Mixed Integer Programming models for job shop scheduling: A computational analysis	Yes	[483]	2009	INFORMS Journal on Computing Mathematical and Computer Modelling Book	35	127	15	1417	1702
Kuhi16 Kuhi16	W. Ku, J. Christopher Beck	A constraint programming model for real-time train scheduling at junctions	Yes	[365]	2016	INFORMS Journal on Computing Mathematical and Computer Modelling Book	9	119	17	1367	1630
Rodriguez07 Rodriguez07	J. Rodriguez	Scheduling projects with multi-skilled personnel by a hybrid MILP/CP-benders decomposition algorithm	Yes	[520]	2007	INFORMS Journal on Computing Mathematical and Computer Modelling Book	15	117	6	1430	1716
LiW08 LiW08	H. Li, K. Womer	Scheduling and routing of automated guided vehicles: A hybrid approach	Yes	[386]	2008	INFORMS Journal on Computing Mathematical and Computer Modelling Book	18	113	31	1374	1708
CorreiaLR07	Ayoub Inna Correia, A. Langevin, L. Rousseau	Mixed-Integer linear programming and constraint programming formulations for solving distributed flexible job shop scheduling problem	Yes	[158]	2007	INFORMS Journal on Computing Mathematical and Computer Modelling Book	20	106	20	1296	1714
MengZRZL20	L. Meng, C. Zhang, Y. Ren, B. Zhang, C. Lv	Earth Observation Satellite Management	Yes	[355]	2020	INFORMS Journal on Computing Mathematical and Computer Modelling Book	13	100	62	1393	1574
BensanaLV99	E. Bensana, M. Lemaitre, G. Verfaillie	Propagating constraints via lazy clause generation	Yes	[91]	1999	INFORMS Journal on Computing Mathematical and Computer Modelling Book	7	99	0	1276	1752

OpenCitation Count Compared to Google Scholar

Key	Type	Google	OC	Ratio
JainM99	article	1116	490	2.28
HarjunkoskiMBC14	article	588	381	1.54
BlazewiczDP96	article	796	344	2.31
BaptistePN01	book	1039	296	3.51
AggounB93	article	502	187	2.68
LaborieRSV18	article	309	148	2.09
BensanaLV99	article	251	99	2.54
DincbasSH90	article	271	86	3.15
Thorsteinsson01	paper	205	67	3.06
DincbasSH88	paper	287	0	(?)

Problem: Citation Count Distribution



42 Summary

Summary

- Use the survey to find
 - Most important works on Constraint Based Scheduling
 - Specialized papers on the constraint reasoning for scheduling
 - Works in specific application domains or specific industries