Introduction and Motivation

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Constraint Based Production Scheduling

Acknowledgments

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

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

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

Key Points

- 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 by 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

```
  "order": [
    {
      "product": "Prod0",
      "process": "Process 0",
      "due": 5449,
      "releaseDate": "1/10/2024 00:00",
      "release": 0,
      "qty": 7,
      "dueDate": "19/10/2024 22:05",
      "name": "Order0",
      "earlinessWeight": 1,
      "latenessWeight": 1
    },
```

Orders Loaded

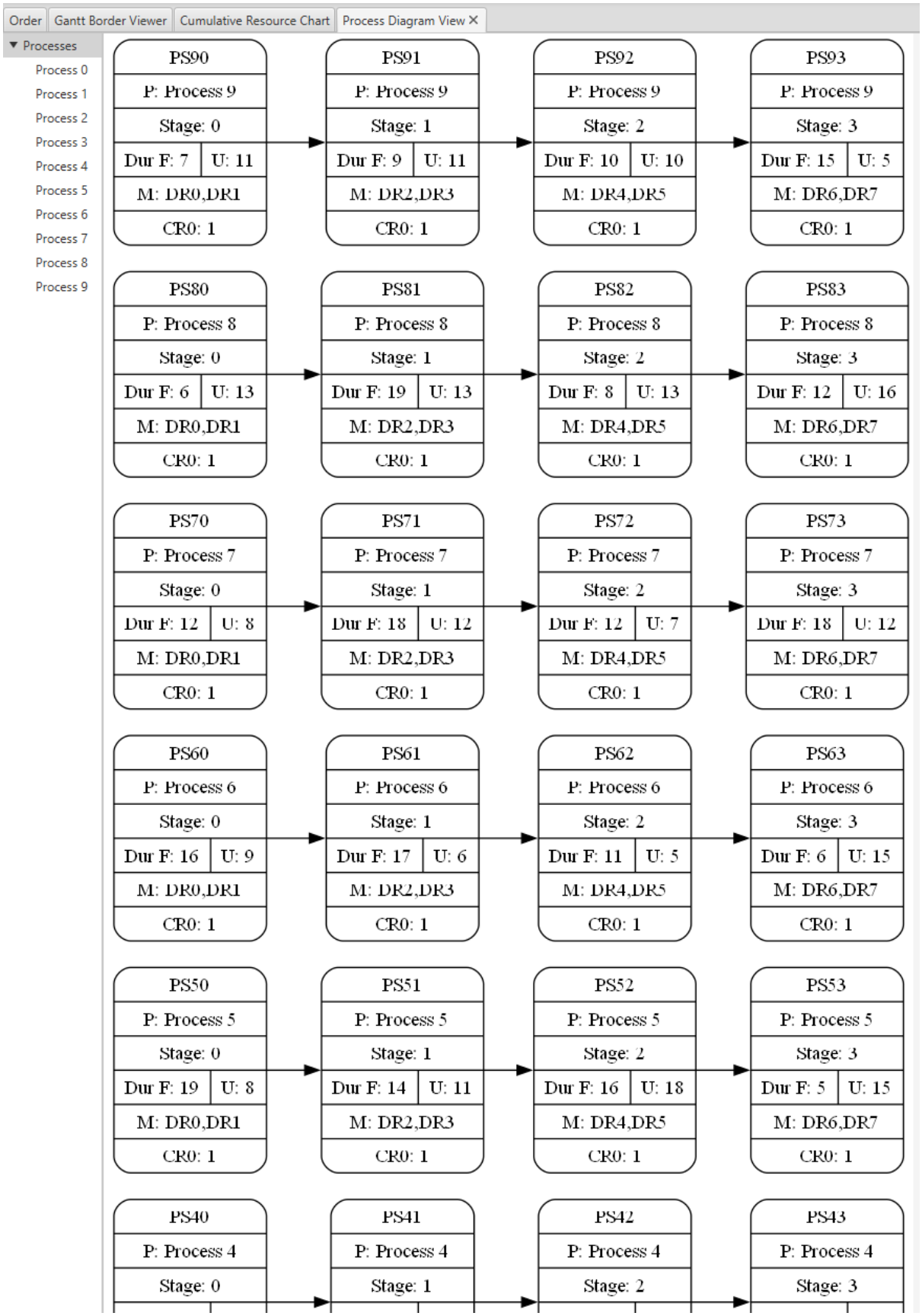
Order ×

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

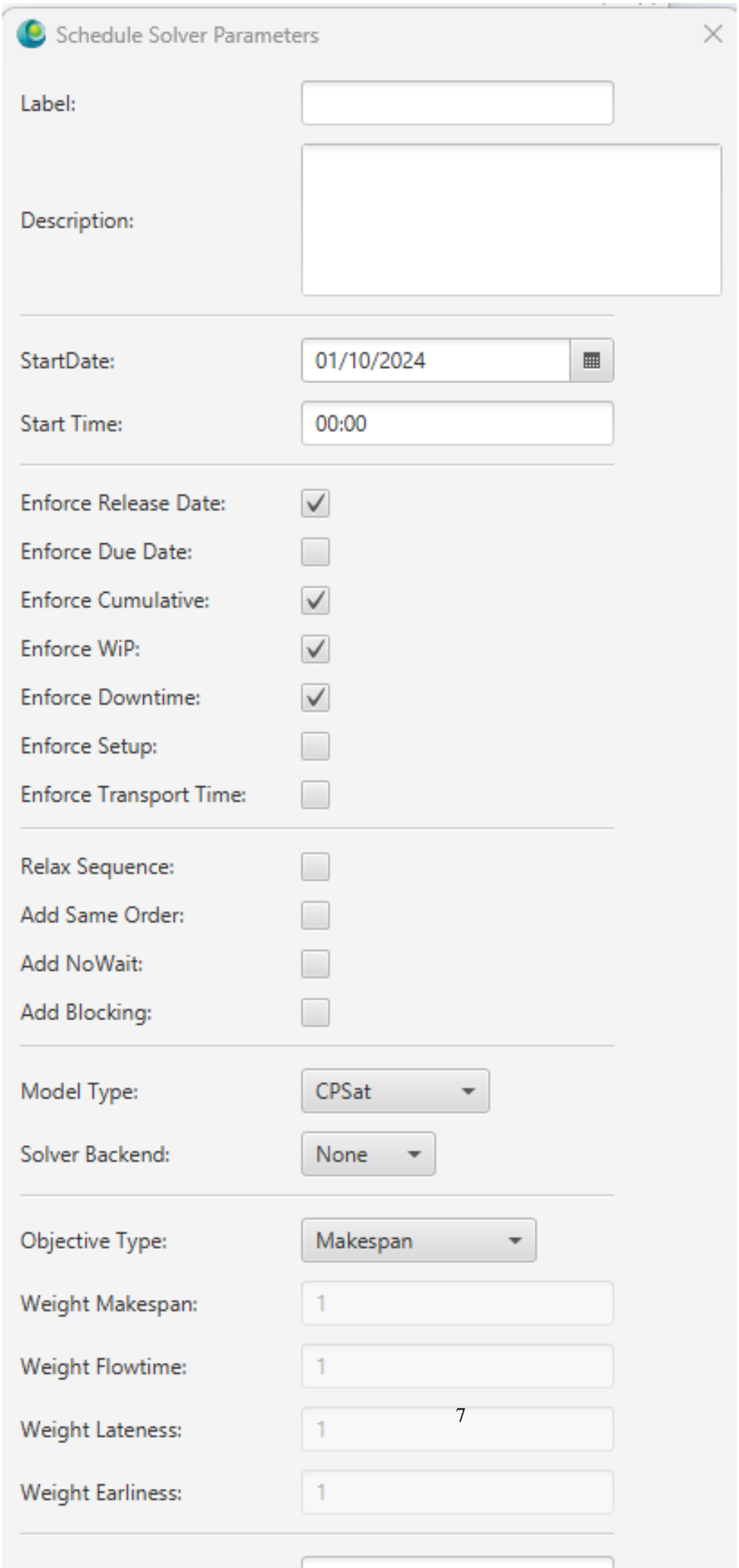
- Processes describe how products are made
- Multiple process steps
- Not always in a straight sequence
- Duration formula based on quantity made
- Temporal constraints between steps

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

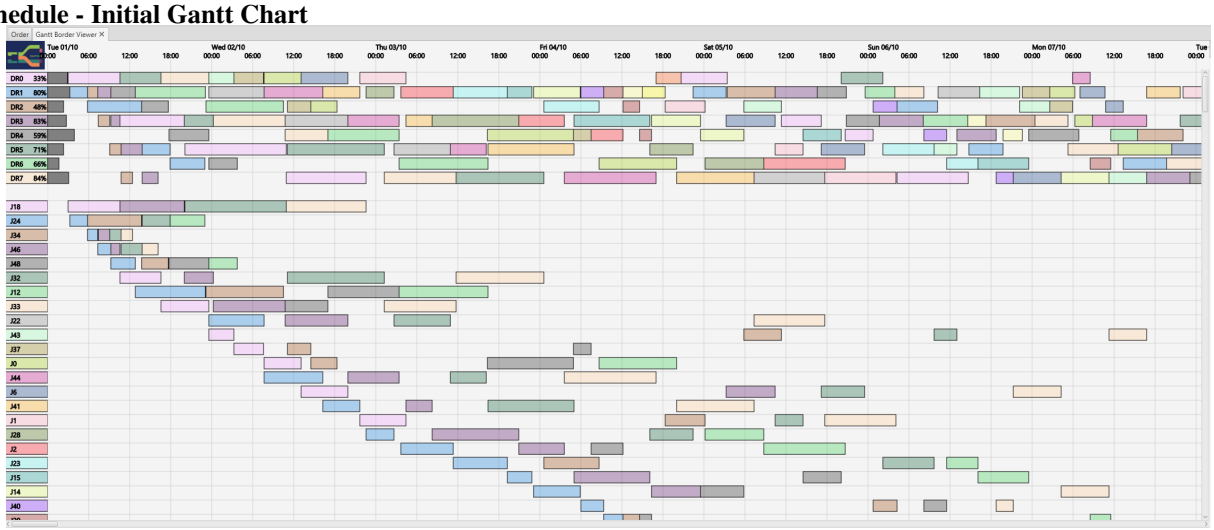

Order
Gantt Border Viewer
Cumulative Resource Chart
Process Diagram View
Processes
Process 0
Process 1
Process 2
Process 3
Process 4
Process 5
Process 6
Process 7
Process 8
Process 9
PS90
P: Process 9
Stage: 0
Dur F: 7
U: 11
M: DR0,DR1
CR0: 1
PS91
P: Process 9
Stage: 1
Dur F: 9
U: 11
M: DR2,DR3
CR0: 1
PS92
P: Process 9
Stage: 2
Dur F: 10
U: 10
M: DR4,DR5
CR0: 1
PS93
P: Process 9
Stage: 3
Dur F: 15
U: 5
M: DR6,DR7
CR0: 1
PS80
P: Process 8
Stage: 0
Dur F: 6
U: 13
M: DR0,DR1
CR0: 1
PS81
P: Process 8
Stage: 1
Dur F: 19
U: 13
M: DR2,DR3
CR0: 1
PS82
P: Process 8
Stage: 2
Dur F: 8
U: 13
M: DR4,DR5
CR0: 1
PS83
P: Process 8
Stage: 3
Dur F: 12
U: 16
M: DR6,DR7
CR0: 1
PS70
P: Process 7
Stage: 0
Dur F: 12
U: 8
M: DR0,DR1
CR0: 1
PS71
P: Process 7
Stage: 1
Dur F: 18
U: 12
M: DR2,DR3
CR0: 1
PS72
P: Process 7
Stage: 2
Dur F: 12
U: 7
M: DR4,DR5
CR0: 1
PS73
P: Process 7
Stage: 3
Dur F: 18
U: 12
M: DR6,DR7
CR0: 1
PS60
P: Process 6
Stage: 0
Dur F: 16
U: 9
M: DR0,DR1
CR0: 1
PS61
P: Process 6
Stage: 1
Dur F: 17
U: 6
M: DR2,DR3
CR0: 1
PS62
P: Process 6
Stage: 2
Dur F: 11
U: 5
M: DR4,DR5
CR0: 1
PS63
P: Process 6
Stage: 3
Dur F: 6
U: 15
M: DR6,DR7
CR0: 1
PS50
P: Process 5
Stage: 0
Dur F: 19
U: 8
M: DR0,DR1
CR0: 1
PS51
P: Process 5
Stage: 1
Dur F: 14
U: 11
M: DR2,DR3
CR0: 1
PS52
P: Process 5
Stage: 2
Dur F: 16
U: 18
M: DR4,DR5
CR0: 1
PS53
P: Process 5
Stage: 3
Dur F: 5
U: 15
M: DR6,DR7
CR0: 1
PS40
P: Process 4
Stage: 0
PS41
P: Process 4
Stage: 1
PS42
P: Process 4
Stage: 2
PS43
P: Process 4
Stage: 3

Selecting Solver Options

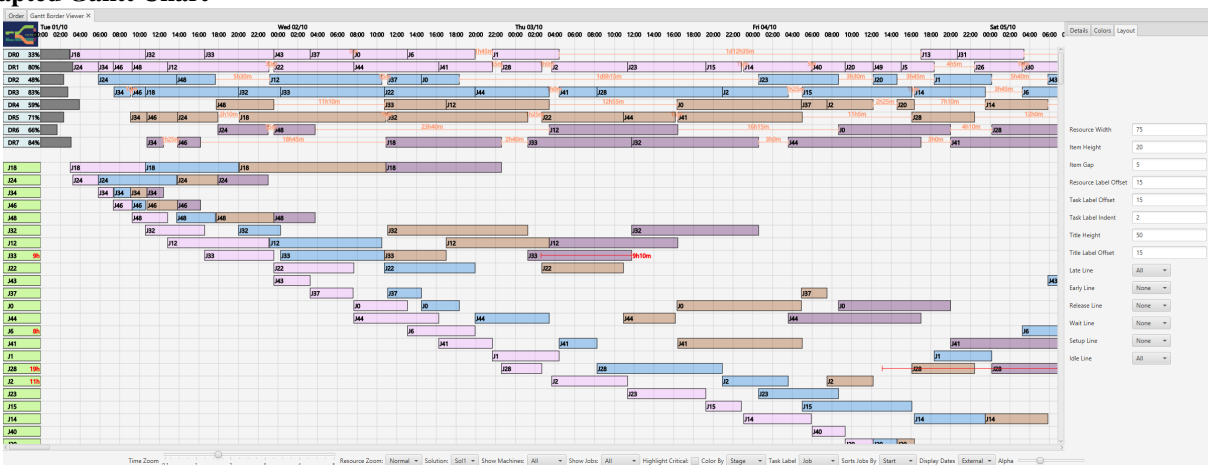
- Which constraints to enforce
  - Here: do not enforce due dates
- Additional constraints to try
- Why solver to run
  - Here: Use open-source CPSat solver
- Which objective to use
  - Here: Makespan, overall project end
- What resources to use
  - Allow 30 seconds
  - Use 8 parallel threads


Schedule Solver Parameters
Label:
Description:
StartDate:
01/10/2024
Start Time:
00:00
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:
CPSat
Solver Backend:
None
Objective Type:
Makespan
Weight Makespan:
1
Weight Flowtime:
1
Weight Lateness:
1
Weight Earliness:
1

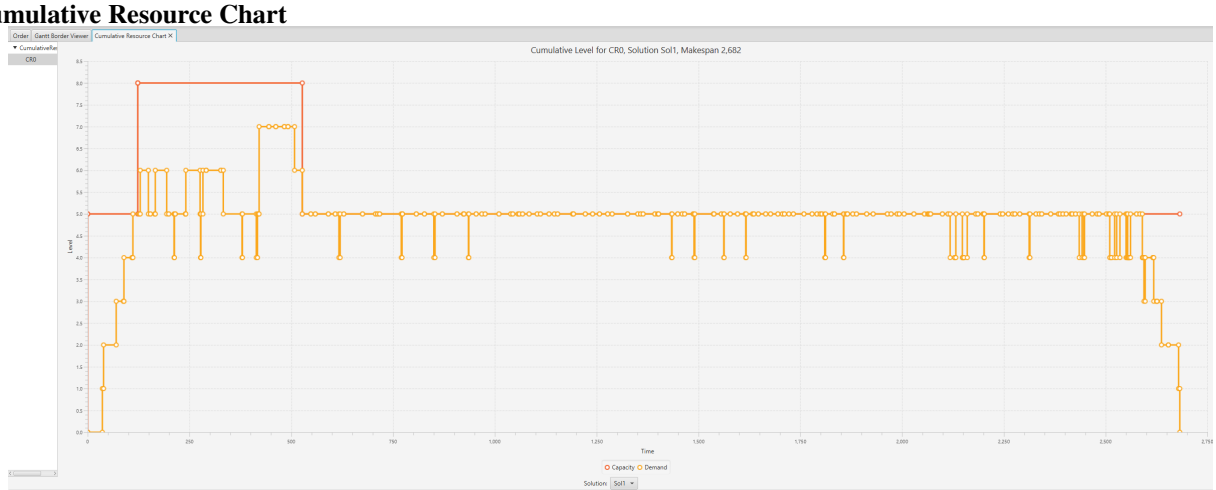
Schedule - Initial Gantt Chart



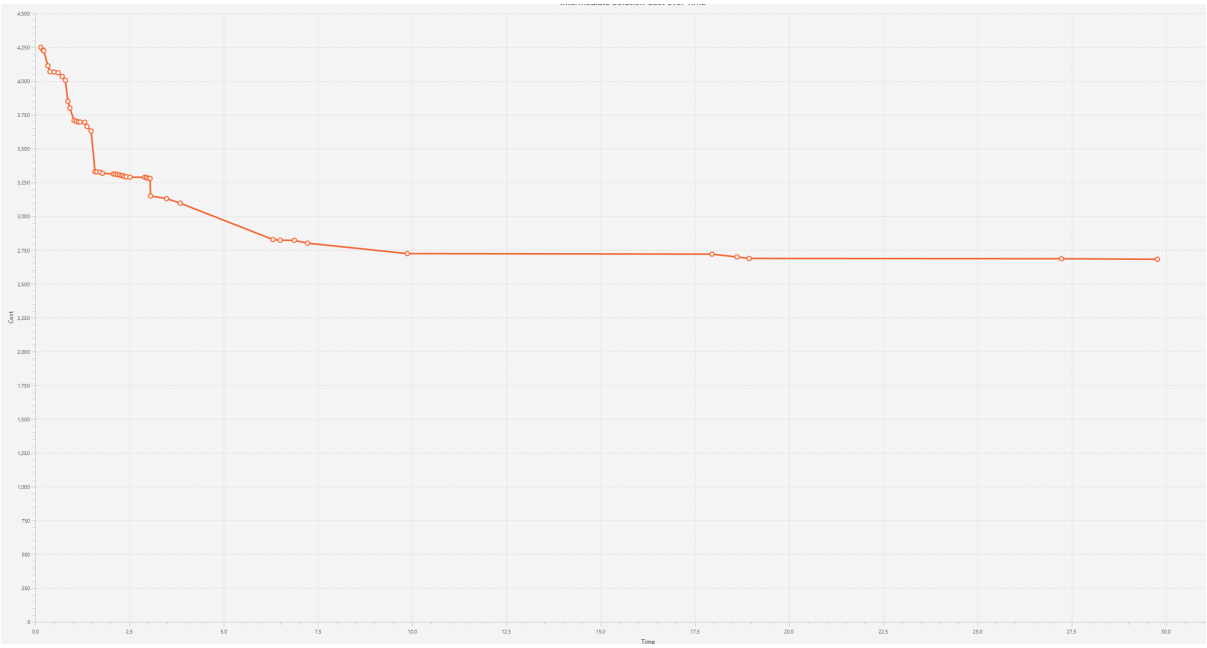
Adapted Gantt Chart



Cumulative Resource Chart



Intermediate Solutions Found



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

2 Artificial Intelligence

What is Artificial Intelligence?

> Artificial intelligence, or AI, is the field that studies the synthesis and analysis of computational agents that act intelligently.

David Poole, Alan Mackworth. Artificial Intelligence, Cambridge University Press, 3rd Edition, 2023.

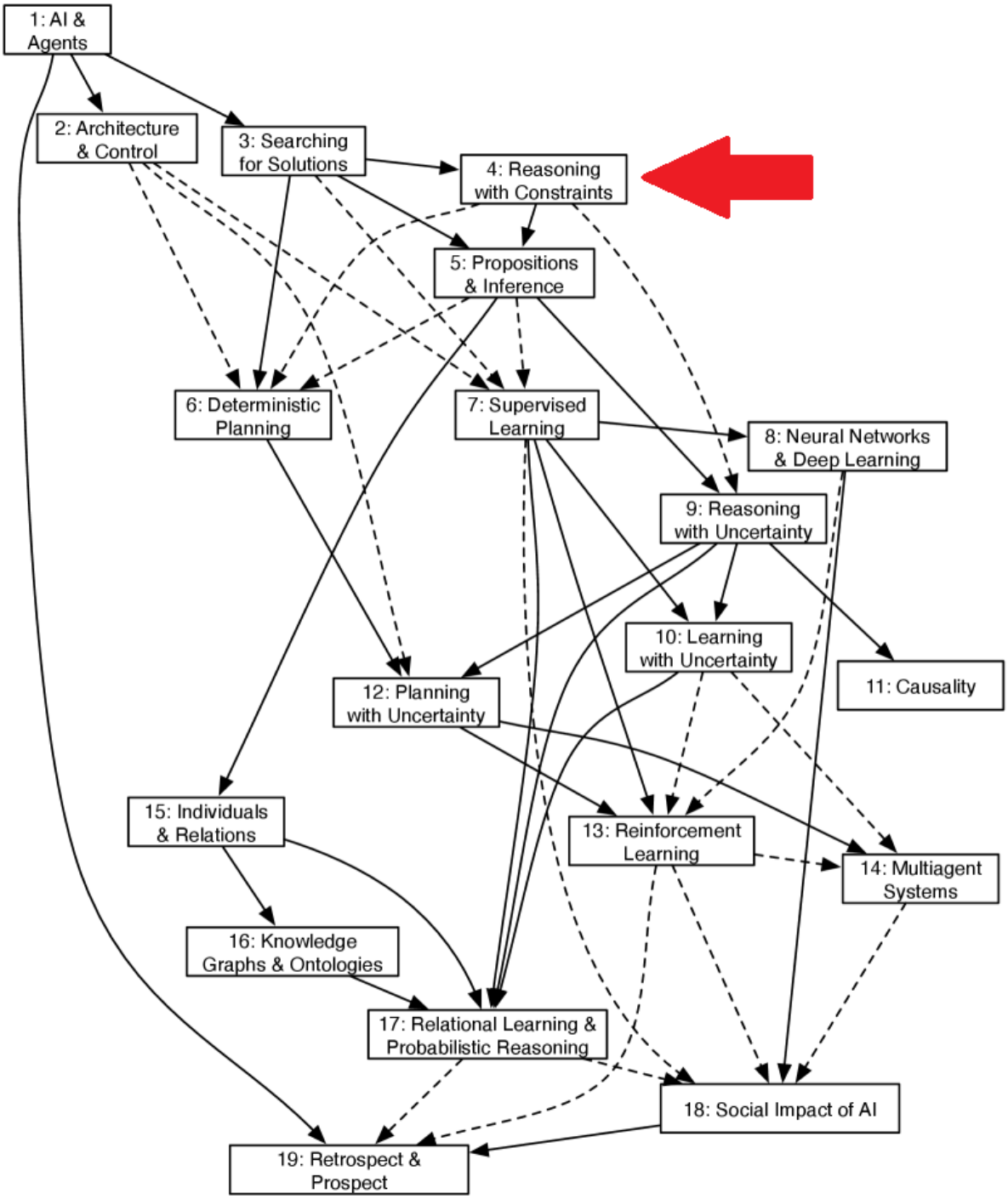
- This definition leaves a lot of questions.

The Great Divide

- Two fundamentally different approaches to AI
  - Reasoning based
  - Stochastic
- Currently, the stochastic methods get all the attention
- But they have their problems
  - Impossible to understand what is happening inside
  - Hallucinations, making up convincing false statements
  - Enormous resource requirements
  - Privacy/IP of training data
  - Really limited to a few multi-nationals

Topics in AI

- Chapter Structure of AI Book
- Shows importance of deductive/search based approaches



What is Constraint Programming?

Constraint programming technology is used to find solutions to scheduling and combinatorial optimization problems. It is based primarily on computer science fundamentals, such as logic programming and graph theory, in contrast to mathematical programming, which is based on numerical linear algebra.

Constraint programming is invaluable when dealing with the complexity of many real-world sequencing and scheduling problems.

IBM (https://ibmdecisionoptimization.github.io/docplex-doc/cp.html)

3 Scheduling

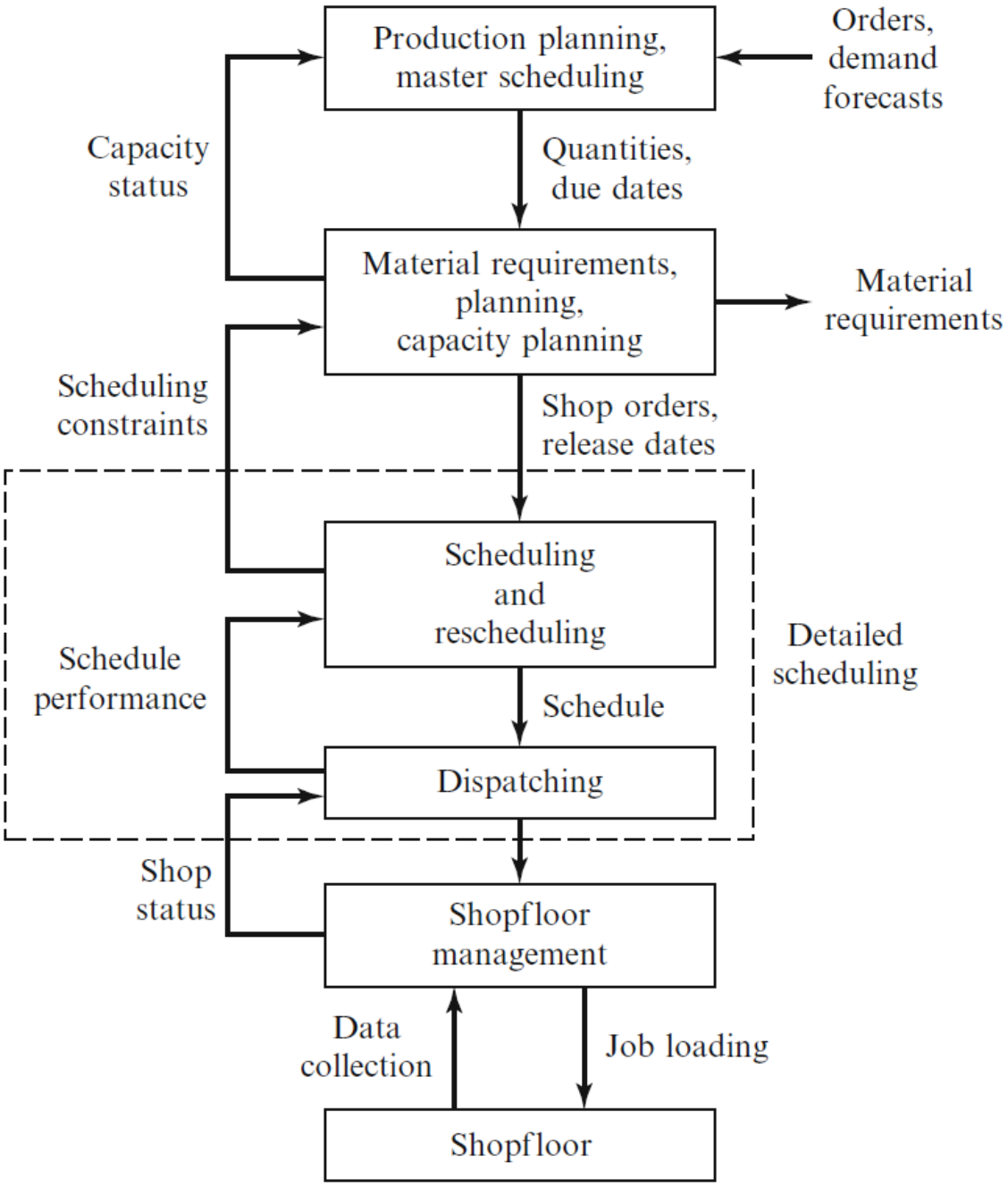
What is Scheduling?

Scheduling is a decision-making process that is used on a regular basis in many manufacturing and services industries. It deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives.

Michael Pinedo. Scheduling. Springer, 5th edition, 2016.

Information Flow Diagram in a Manufacturing System

- According to Pinedo, page 5.
- We focus on what is shown as *detailed scheduling*



3.1 Constraint-Based Scheduling

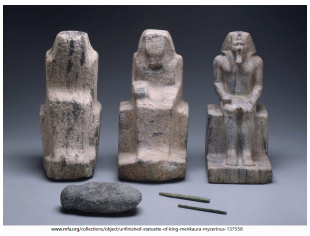
Constraint Programming - in a nutshell

- 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/

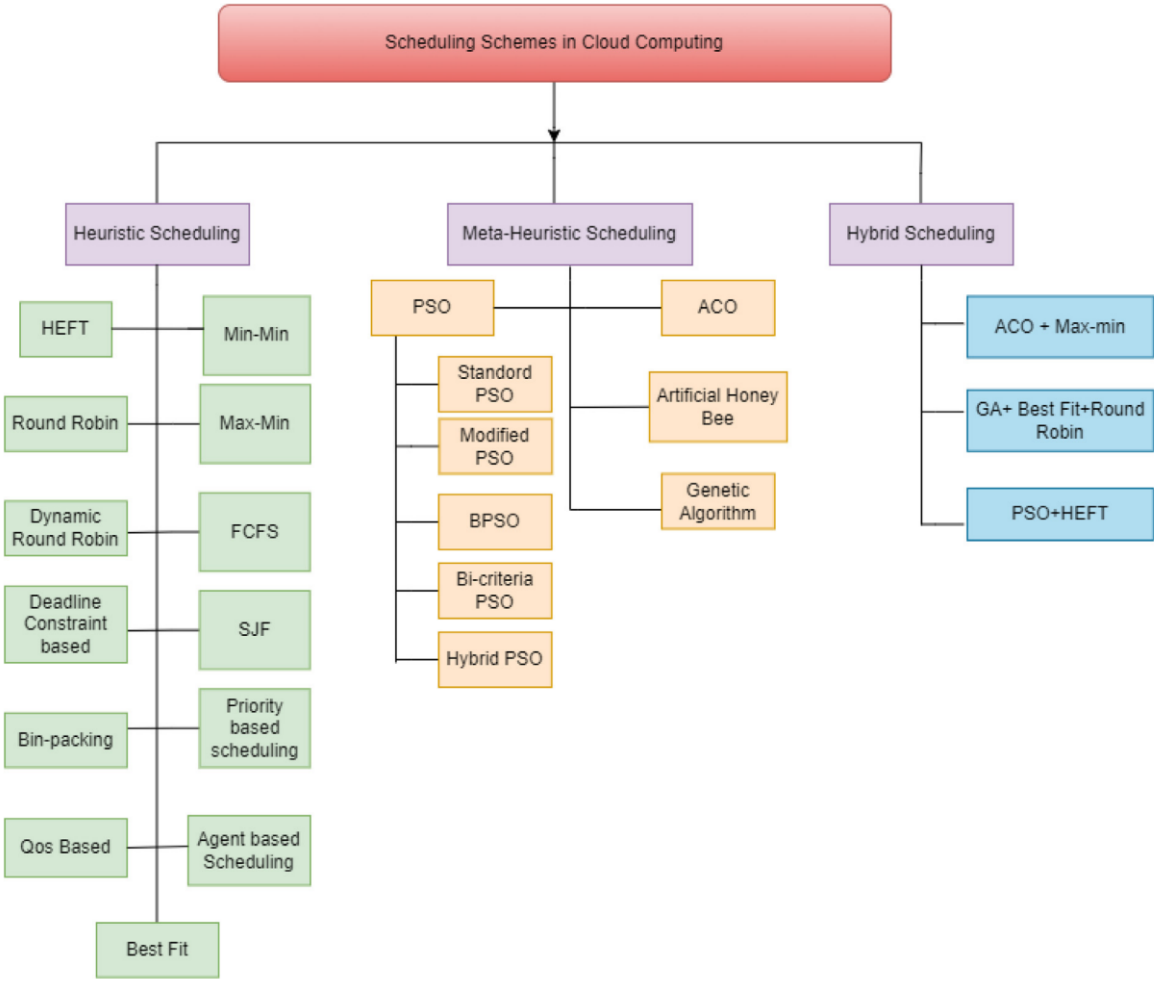
3.2 Other Scheduling Solution Approaches

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

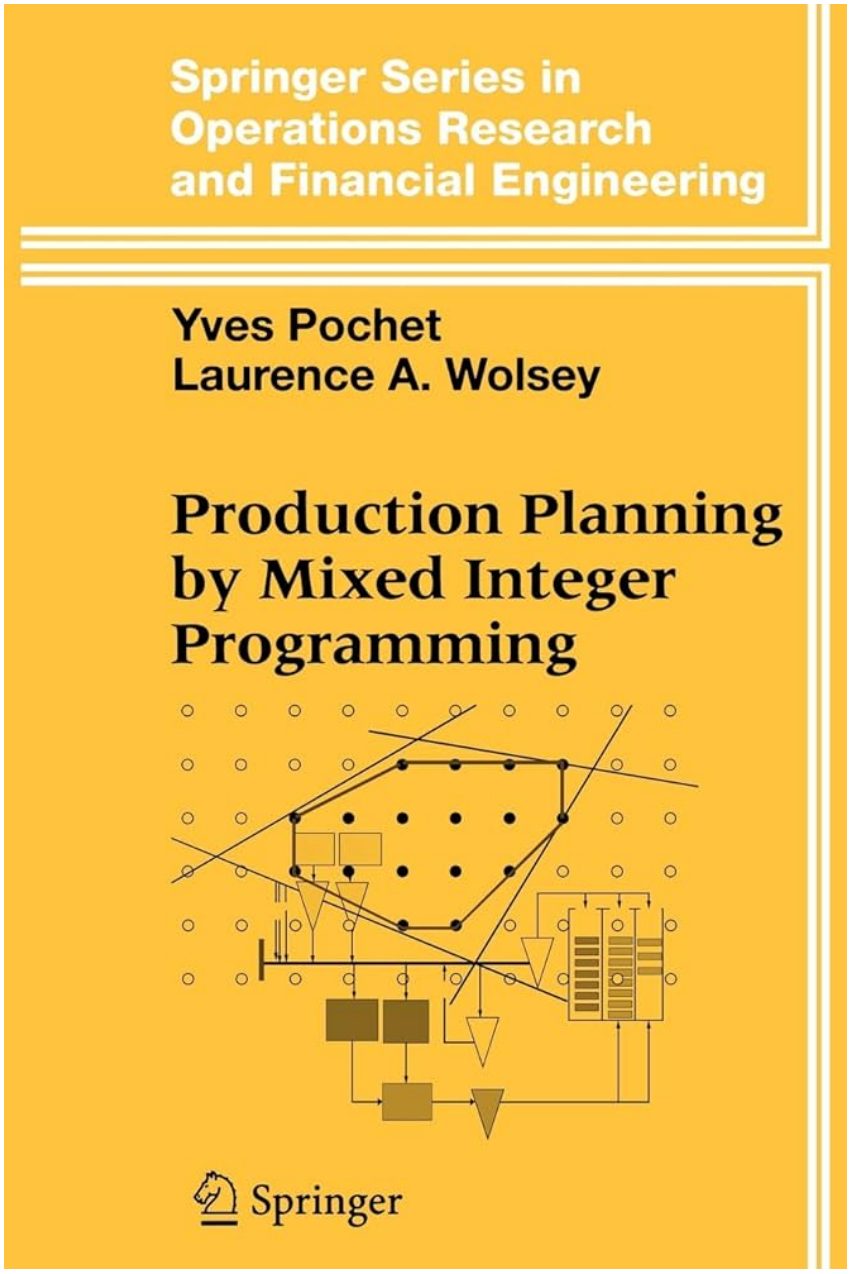


From: Singh, Kumar, and Singh: An empirical investigation of task scheduling and VM consolidation schemes in cloud environment, Computer Science review, 2023, https://www.sciencedirect.com/science/article/pii/S1574013723000503

Integer Programming

- Restrict yourself to linear constraints
- Powerful reasoning on the complete set of constraints
  - Linear Programming
  - Cut generation
- Expressing scheduling constraints can be difficult

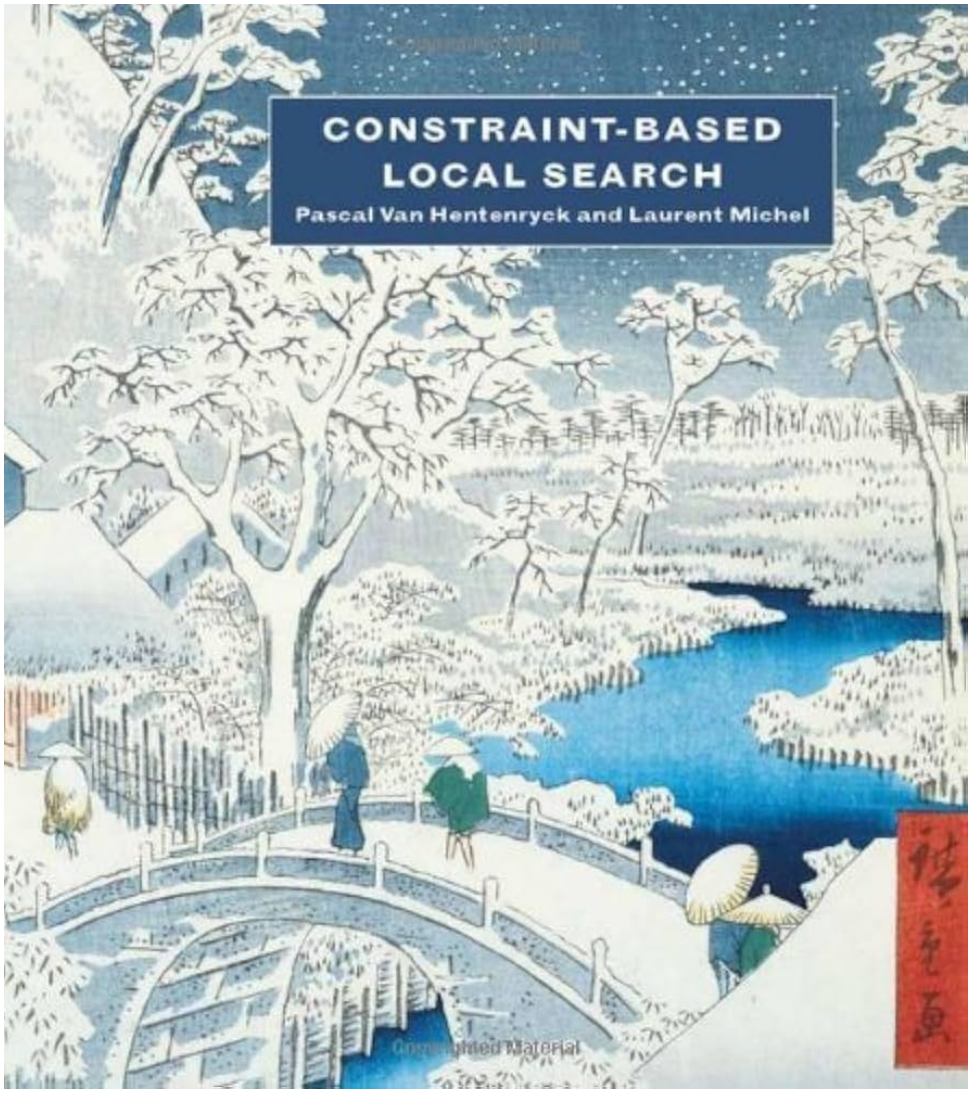
- Scalability issues for detailed scheduling



https://link.springer.com/book/10.1007/0-387-33477-7

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



https://mitpress.mit.edu/9780262220774/constraint-based-local-search/

4 Course Structure

4.1 Timetable

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	-

4.2 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
  - Ask for details if interested
- 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