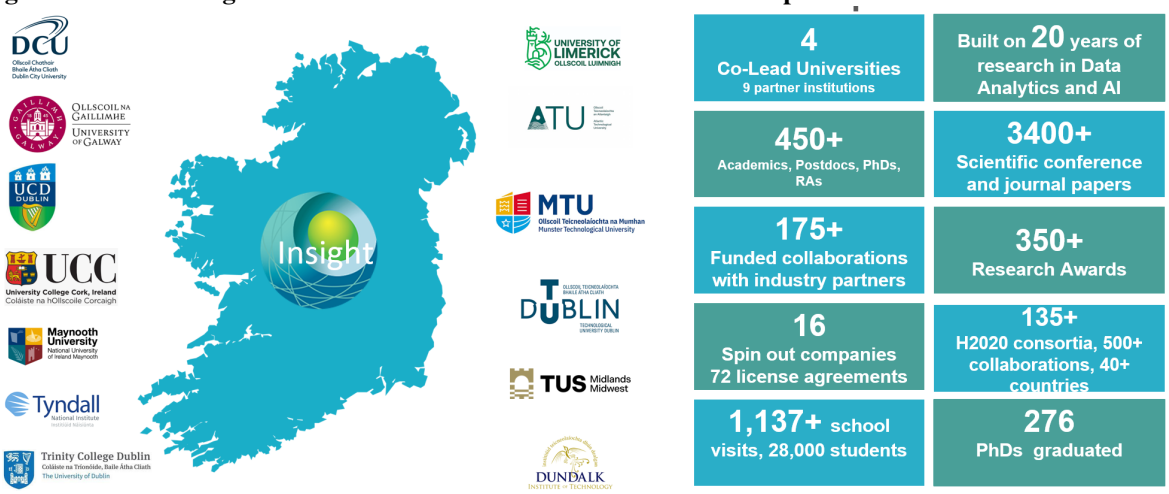
**Note**

- This is a document which combines all materials from the Scheduling course
- Files as 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 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

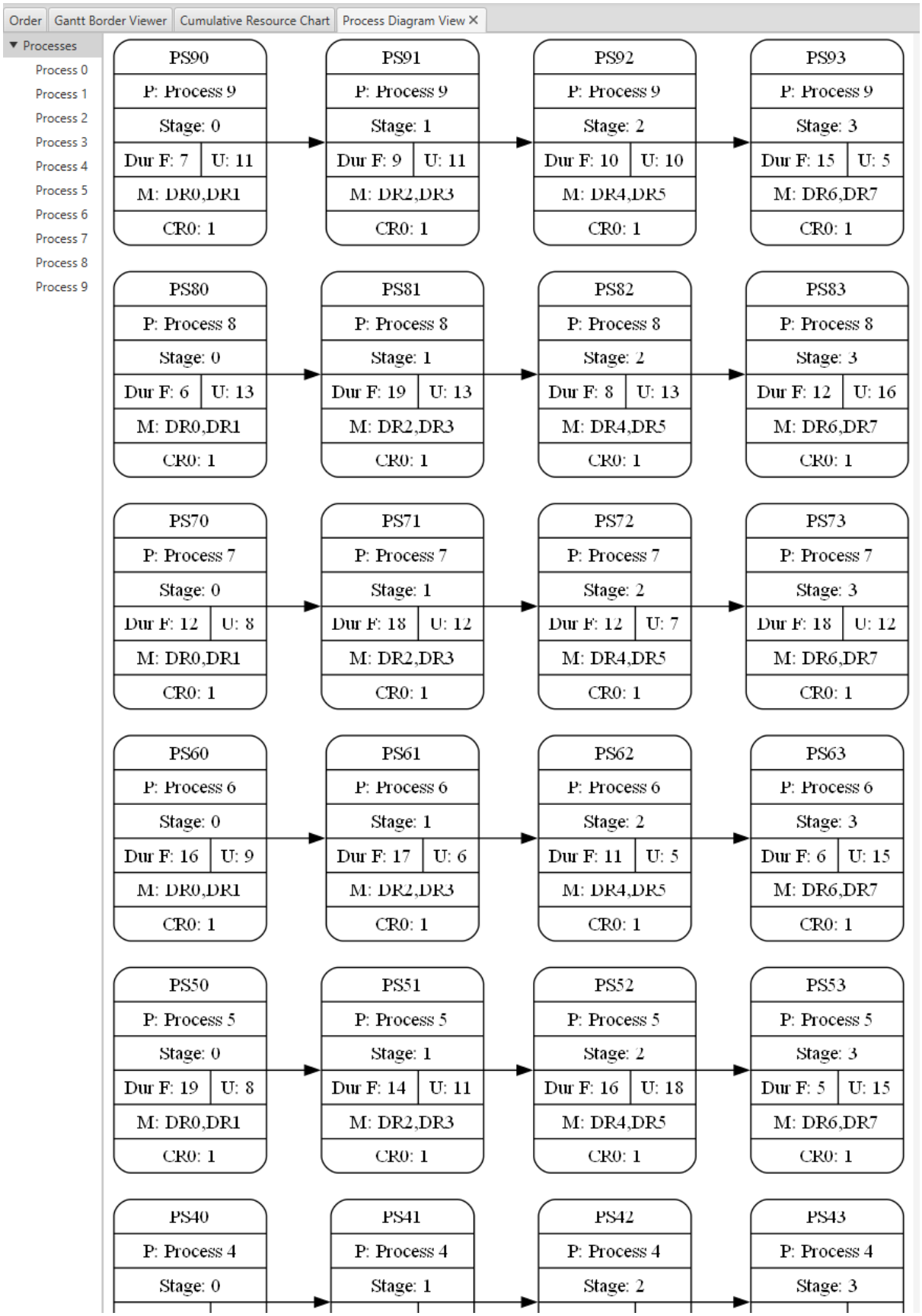
Order ×

| 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

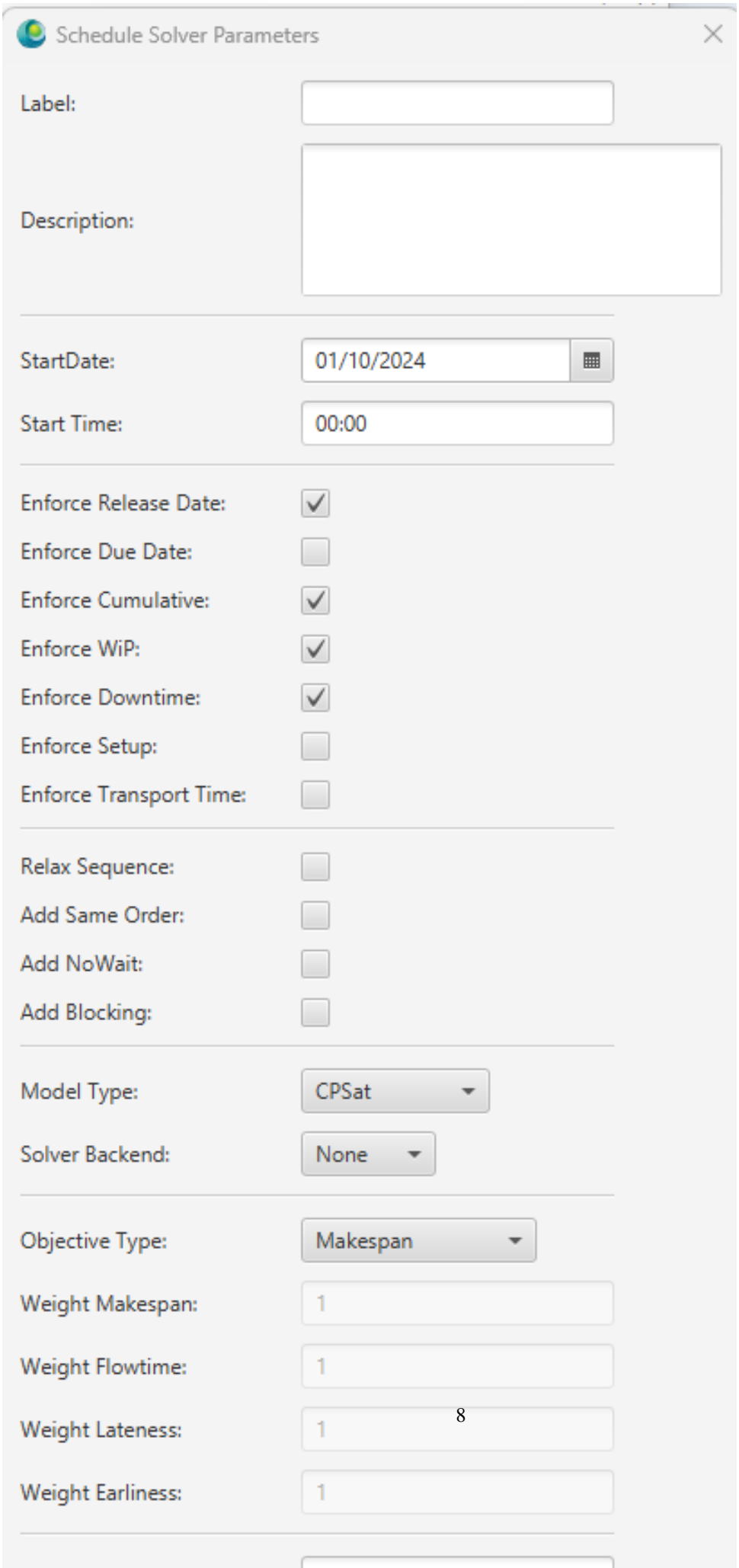
- Processes describe how products are made
- Multiple process steps
- Not always in a straight sequence
- Duration formula based on quantity made
- Temporal constraints between steps

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

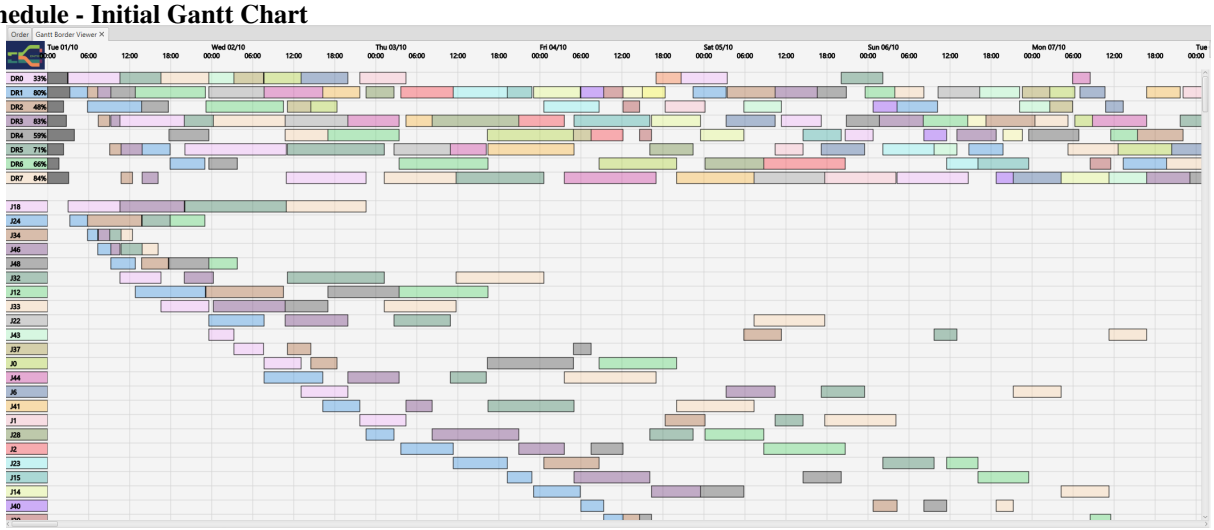

Order
Gantt Border Viewer
Cumulative Resource Chart
Process Diagram View
Processes
Process 0
Process 1
Process 2
Process 3
Process 4
Process 5
Process 6
Process 7
Process 8
Process 9
PS90
P: Process 9
Stage: 0
Dur F: 7
U: 11
M: DR0,DR1
CR0: 1
PS91
P: Process 9
Stage: 1
Dur F: 9
U: 11
M: DR2,DR3
CR0: 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**

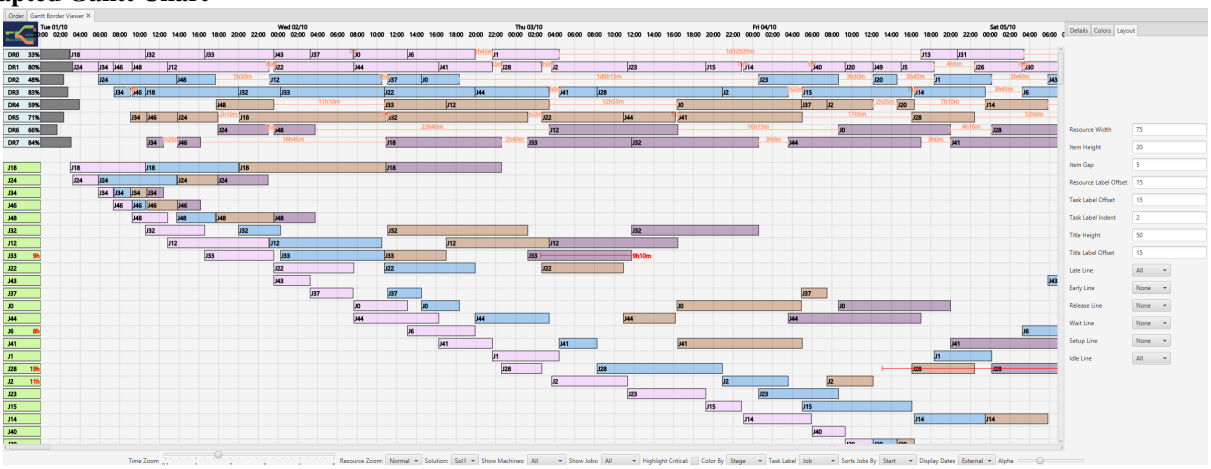
- Which constraints to enforce
  - Here: do not enforce due dates
- Additional constraints to try
- Why solver to run
  - Here: Use open-source CPSat solver
- Which objective to use
  - Here: Makespan, overall project end
- What resources to use
  - Allow 30 seconds
  - Use 8 parallel threads


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

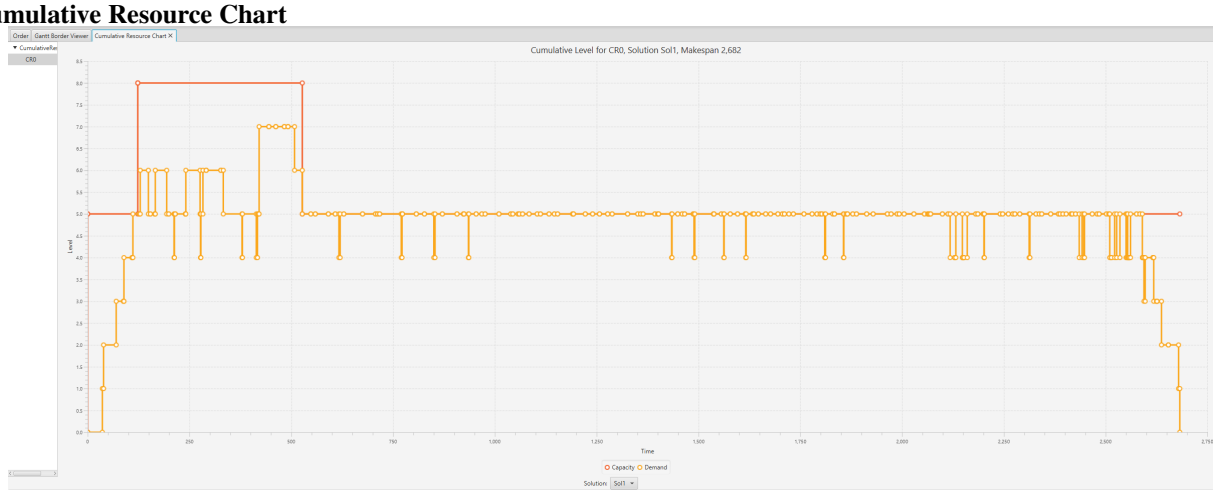
## Schedule - Initial Gantt Chart



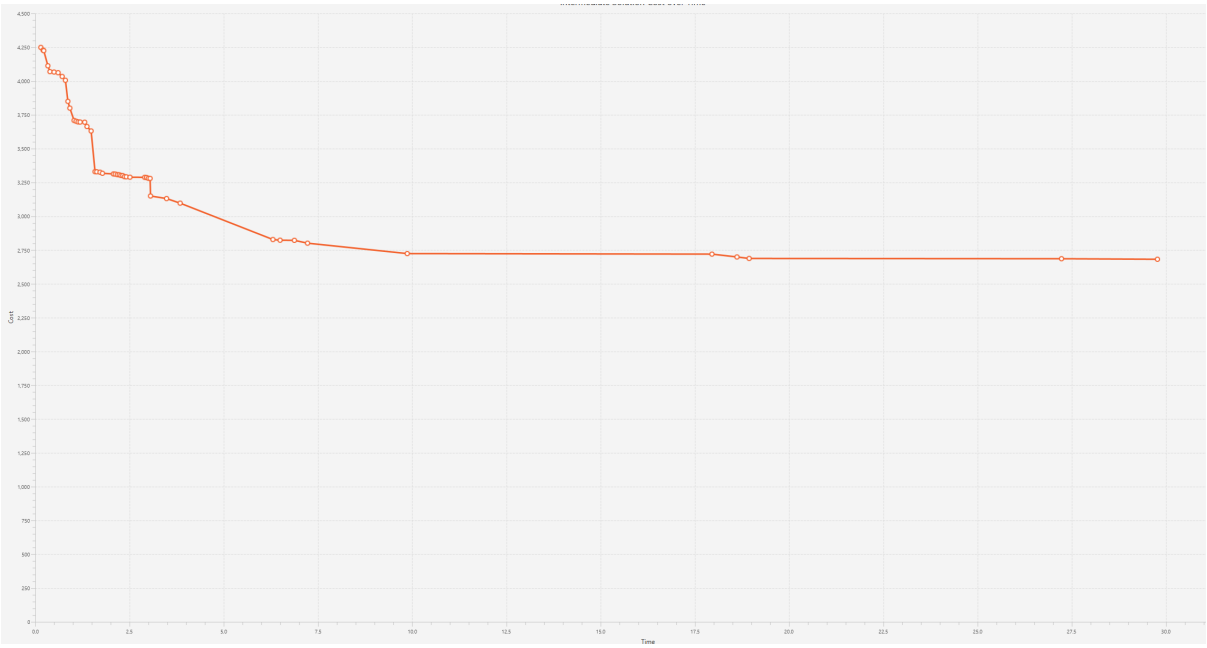
## Adapted Gantt Chart



## Cumulative Resource Chart




## Intermediate Solutions Found



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

# 2 Artificial Intelligence

# 3 Scheduling

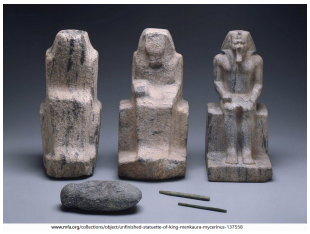
## 3.1 Constraint-Based Scheduling

**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/`

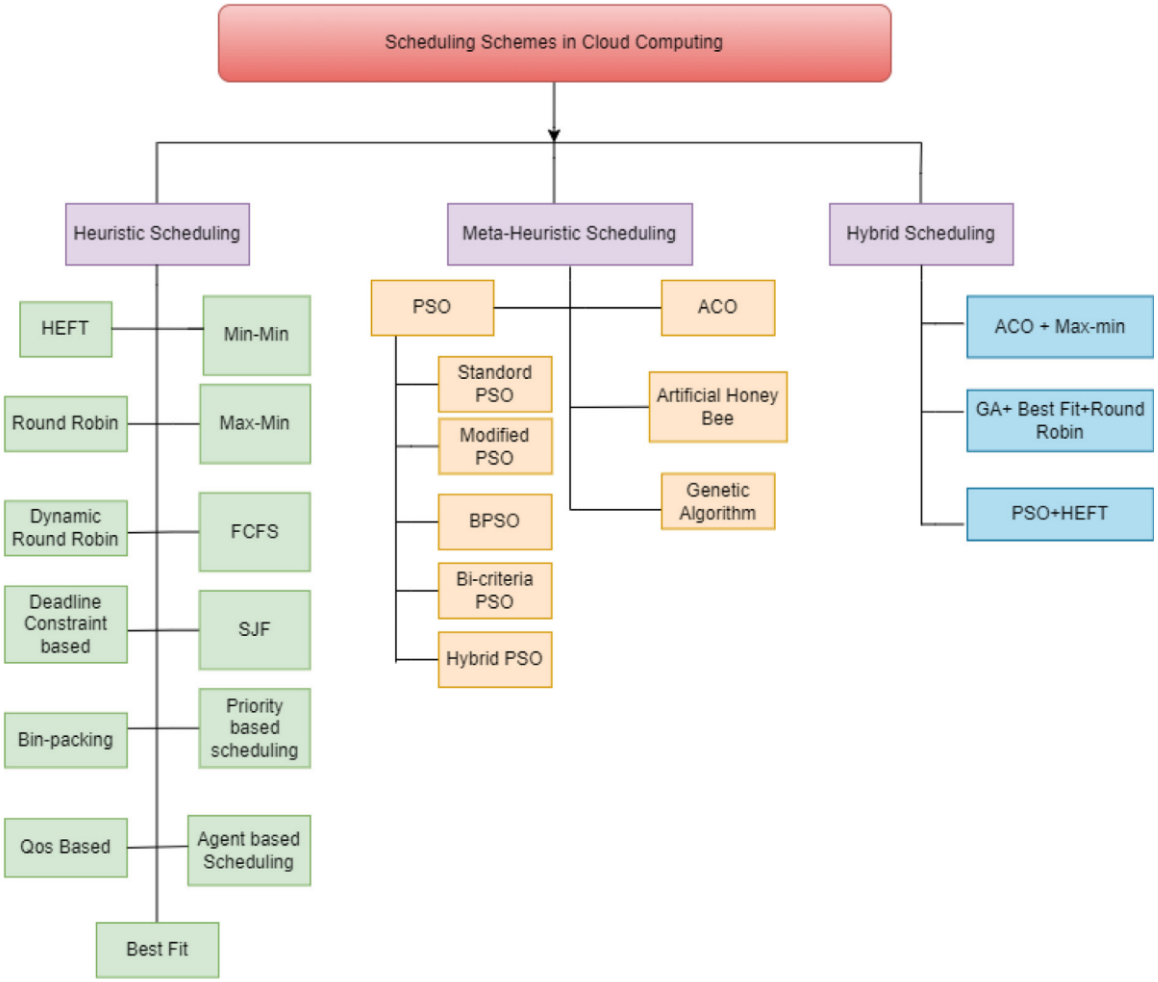
## 3.2 Other Scheduling Solution Approaches

### 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

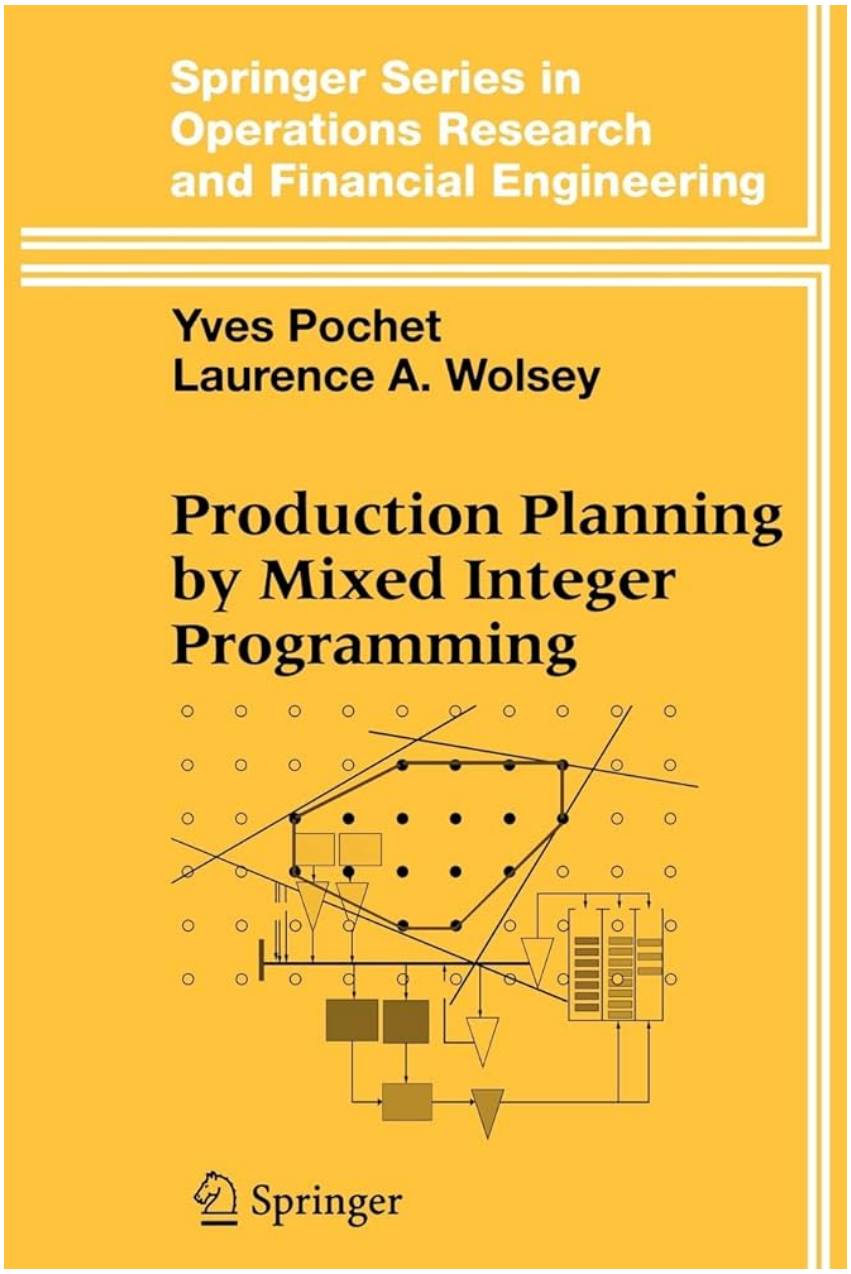



From: Singh, Kumar, and Singh: An empirical investigation of task scheduling and VM consolidation schemes in cloud environment, Computer Science review, 2023, https://www.sciencedirect.com/science/article/pii/S1574013723000503

### 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

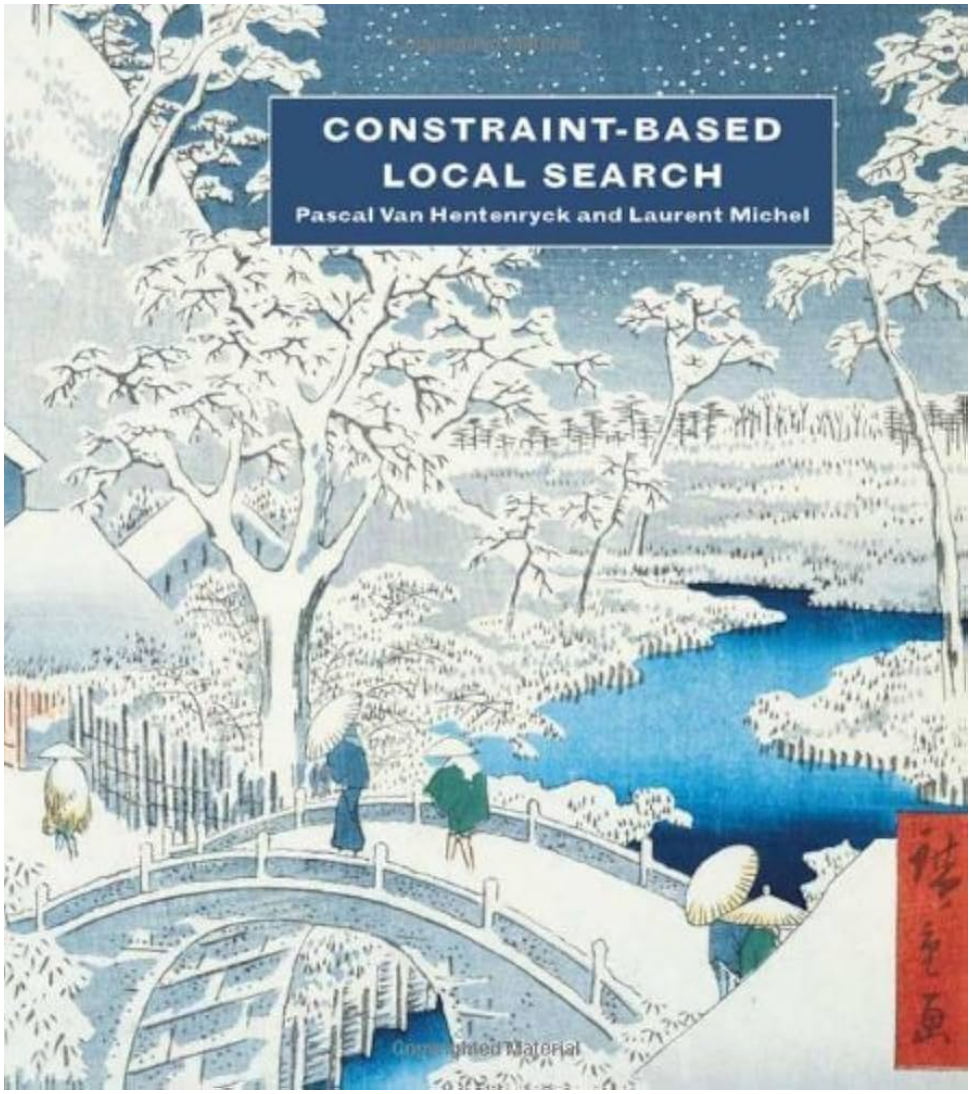


https://link.springer.com/book/10.1007/0-387-33477-7

**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

**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
  - Why we are scheduling (orders, products, processes)
  - What we are doing (jobs, tasks)
- Temporal Relations
- Process description
- Problem classification
- Visualization

# 6 Core Concepts

## 6.1 Orders, Products, Processes

## 6.2 Jobs and Tasks

# 7 Temporal Relations

## 7.1 Release and Due Date

# 8 Processes, Bill of Materials

# 9 Problem Classification

## 9.1 Job-Shop

## 9.2 Flow-Shop

## 9.3 Open-Shop

## 9.4 RCPSP

## 9.5 $\alpha$, $\beta$, $\gamma$ Notation

# 10 Key Visualization Methods

# 11 Summary

**Summary**

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

# Part III
# Machines and Resources

**Key Points**

-

## 12 Disjunctive Resources

## 13 Cumulative Resources

## 14 Machine Choice

### 14.1 Identical Machines

### 14.2 Machine Dependent Speed

### 14.3 Machine Preferences

## 15 Work in Progress and Planned Downtimes

## 16 Calendars

## 17 Summary

**Summary**

-

# Part IV
# Experiments

**Key Points**

-

18 The Scheduling Tool

19 Data Input

20 Result Output

21 Instance Generator

22 Predefined Problem Sets

22.1 Taillard

22.2 SALBP

22.3 Test Scheduling

22.4 Hybrid Flexible Flowshop

23 Creating Your Own Tests

24 Summary

**Summary**

-

# Part V
# Objectives

**Key Points**

-

## 25 Why Have an Objective?

### 25.1 Cost vs. Profit Based Objectives

## 26 Objective Types

### 26.1 Makespan

### 26.2 Flowtime

### 26.3 Lateness

### 26.4 Earliness

### 26.5 Just-In-Time

### 26.6 Hybrid

### 26.7 Resource Levels

## 27 Multi-Level

## 28 Interactive Scheduling

**Summary**

-

# Part VI
# Advanced Concepts

**Key Points**

-

## 29 Sequence Dependent Setup

## 30 Transportation Time

## 31 Human Resource Constraints

## 32 Energy Cost Aware Scheduling

## 33 Premption

## 34 Inventory

## 35 Alternative Processes/Process Paths

## 36 Explainability

## 37 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 ×

| 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 ×

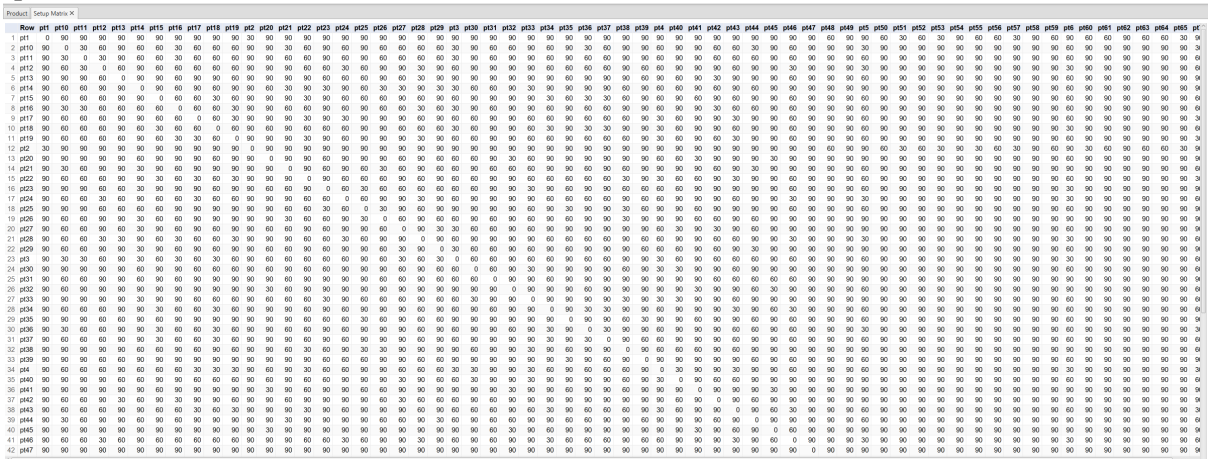
| Name | ShortName | Nr | DailySales | InventoryAtStart | CalcDaysCover | LotSize | CycleTime | LotDuration | Machine | ProductType | SafetyStock | SafetyAlert |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P35 | P35 | 35 | 1.30 | 26 | 20.00 | 120 | 2.30 | 276 | 5,7,9,10,13,14,16 | pt35 | 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)**

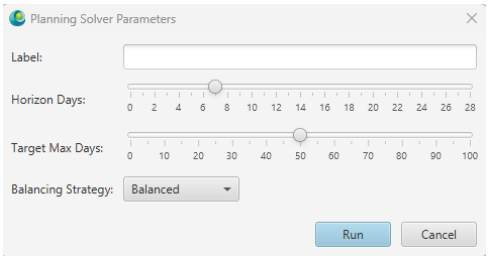
Product ×

| 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 |

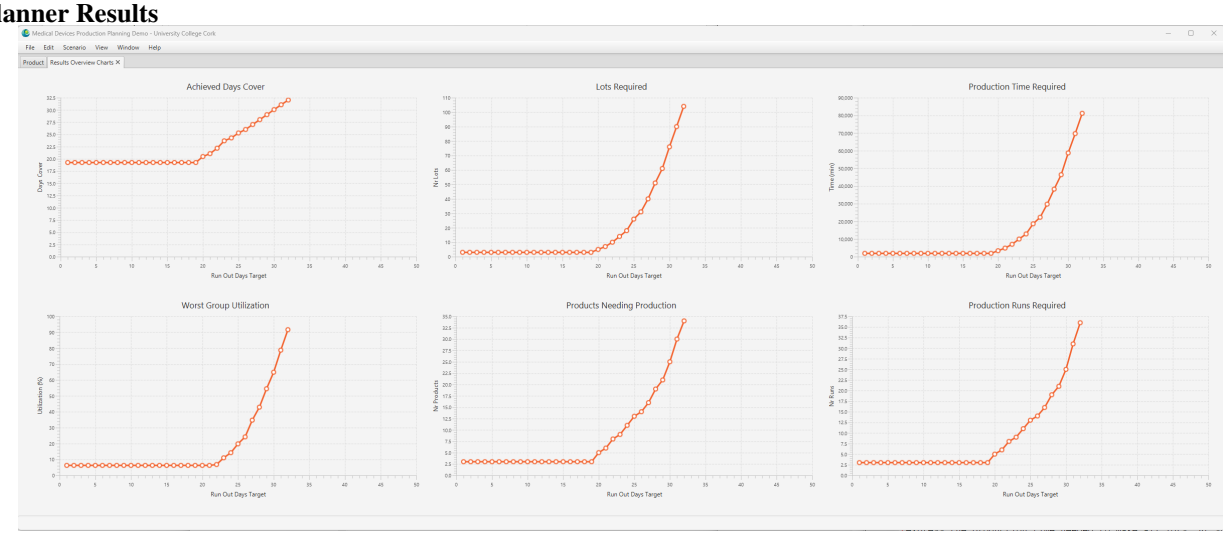
## Setup Matrix



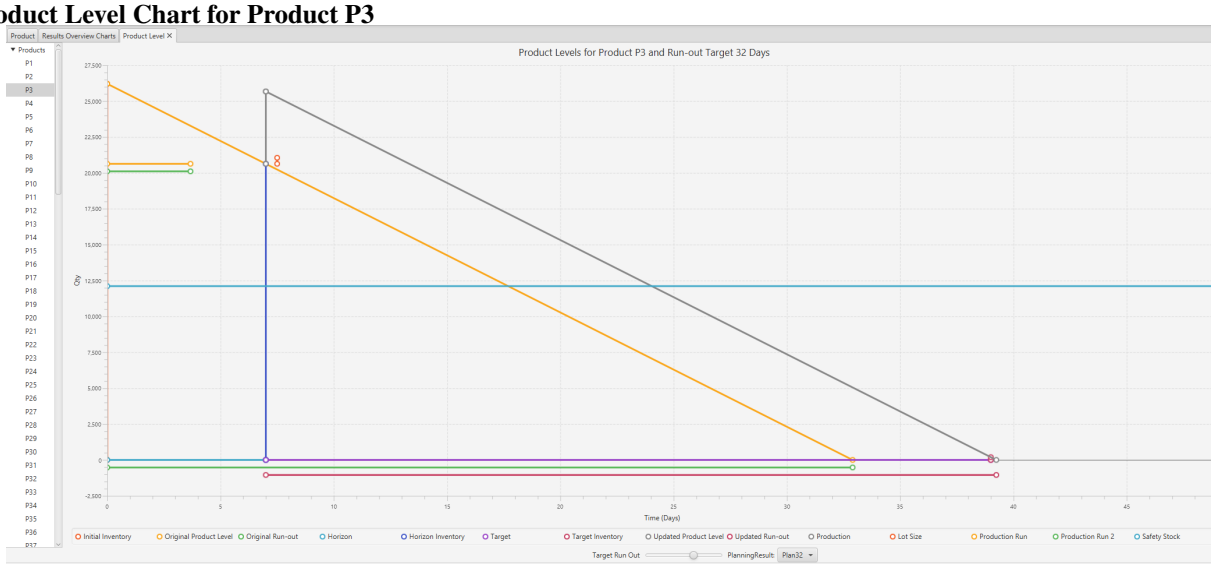
## Running the Planning Solver



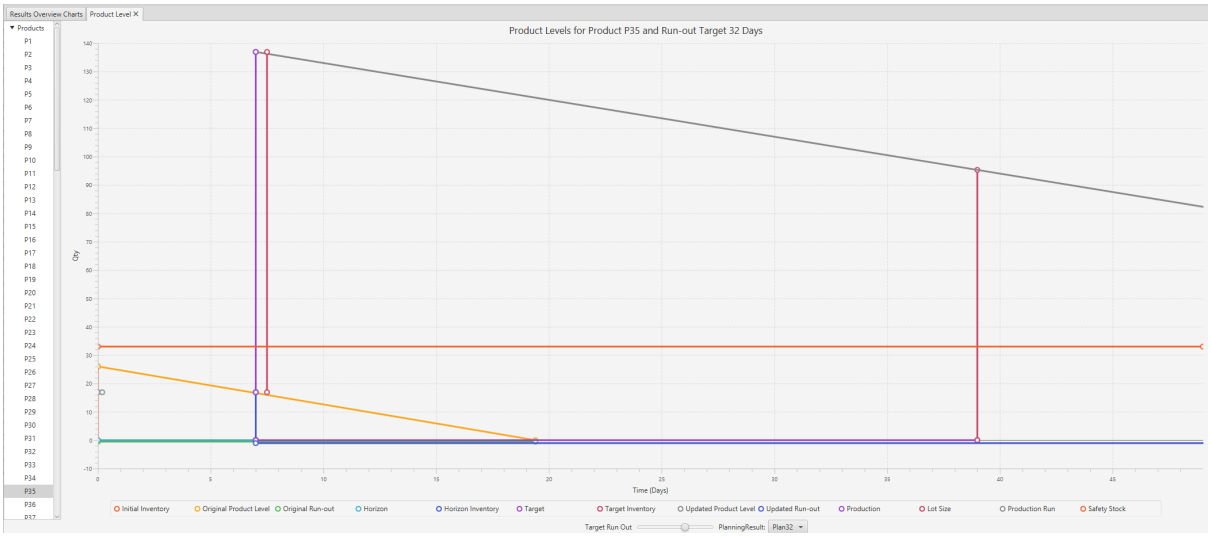

## Planner Results




## Product Level Chart for Product P3




## Product Level Chart for Product P35

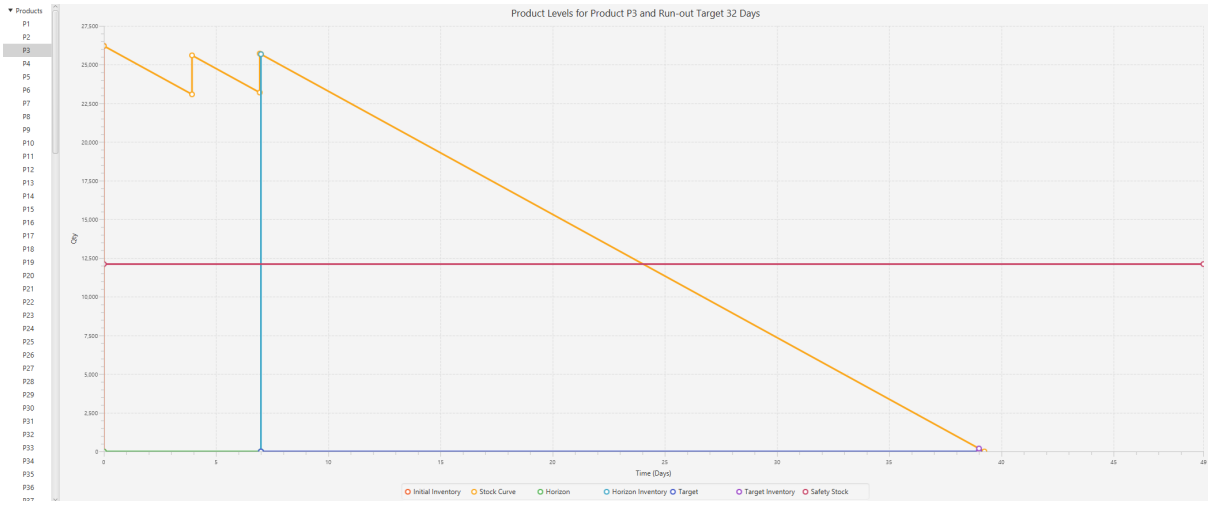



## Scheduled Production Runs

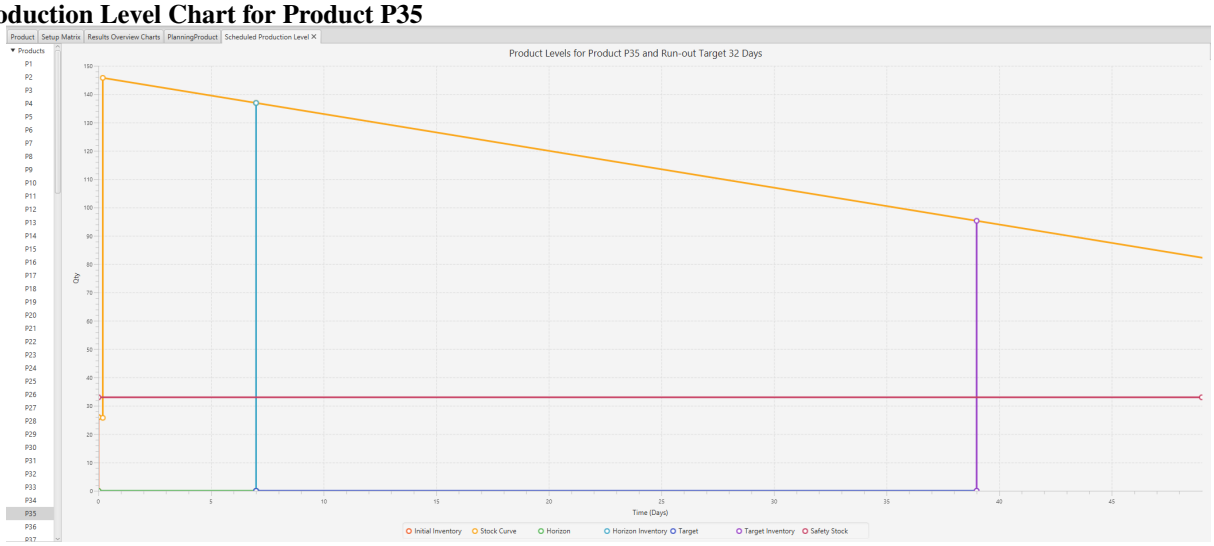
Product | Results Overview Charts | Product Level | Scheduled Production Level | ProductionRun

| 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 |

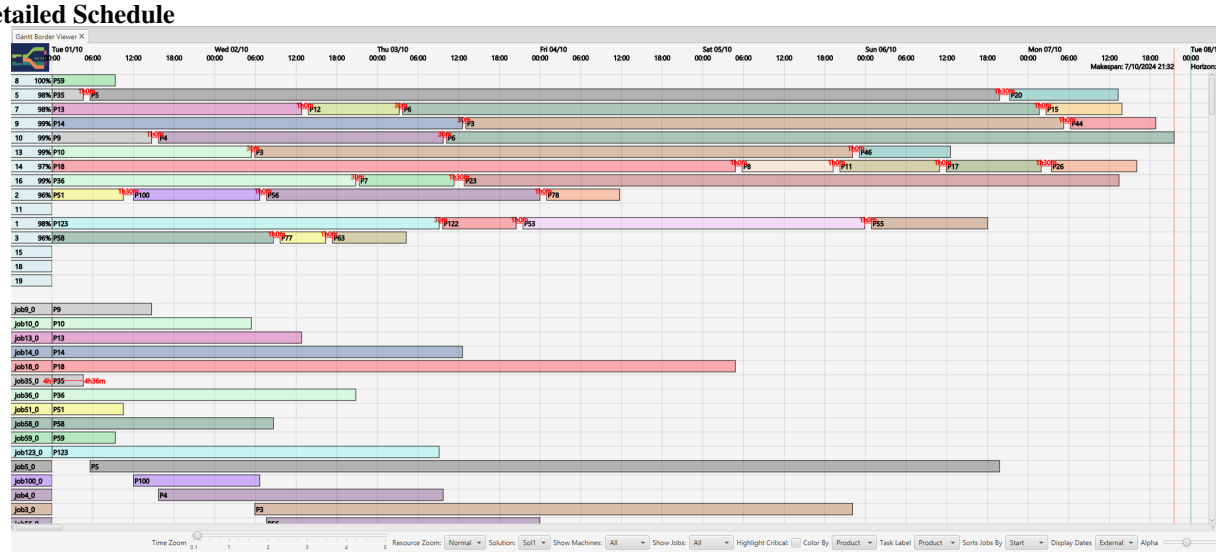
## Production Level Chart for Product P3



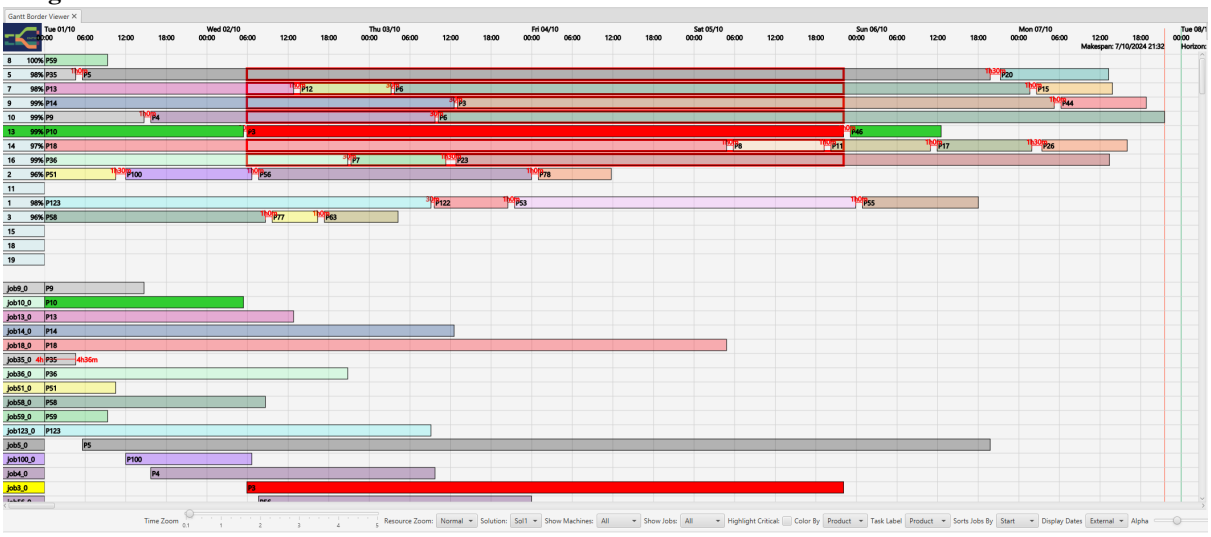

## Production Level Chart for Product P35




## 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**

-

# Part XI
# Factory Design Case Study

**Key Points**

-

**Problem Description**

**Feature Overview**

**Summary**

-

# Part XII
# Oven Scheduling Case Study

**Key Points**

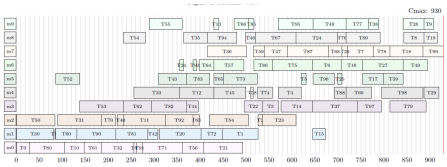
- Discusses two topics:
  - Solve a very specific industrial scheduling problem from the ASSISTANT EU project
  - Discuss the general issue of short-term scheduling vs. long-term objectives

**Research Challenge**

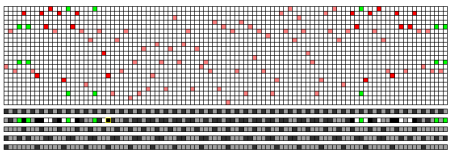
- Often the long-term business objectives are not visible in the operational decision problem
- We optimize a short-term objective without understanding the impact in the long term
- What choices should we make in short-term to improve overall result?
- Especially important when future data not yet visible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

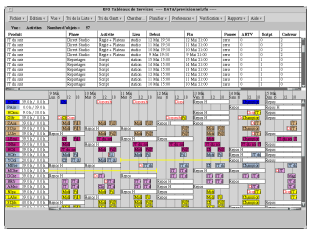


- Car Sequencing
- The best heuristics push difficult cars to the edge of schedule
- Because they are easier to schedule this way
- But: It makes it hard to schedule next day



**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

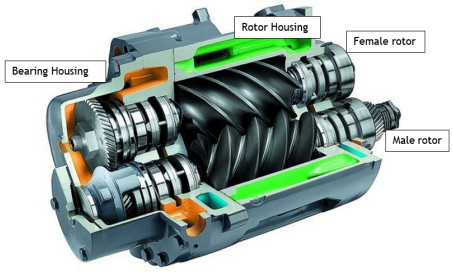
- Build daily delivery tours, optimizing cost
- Where are your trucks at 10PM?
- Also, avoid cherry-picking at start of week

**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

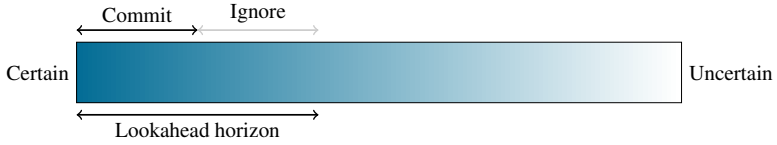
**Solution Approach: Constraint Programming**

- 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

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

**Resource Constraints**

We start from the basic decomposition of thedisjunctive 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 $i$

$$\forall_{i \in N} \forall_{j \in Q} : \quad z_{ij} = \sum_{i_1=1}^{i-1} b_{i_1 i j} + \sum_{i2=i+1}^{n} b_{i i_2 j}$$

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!**

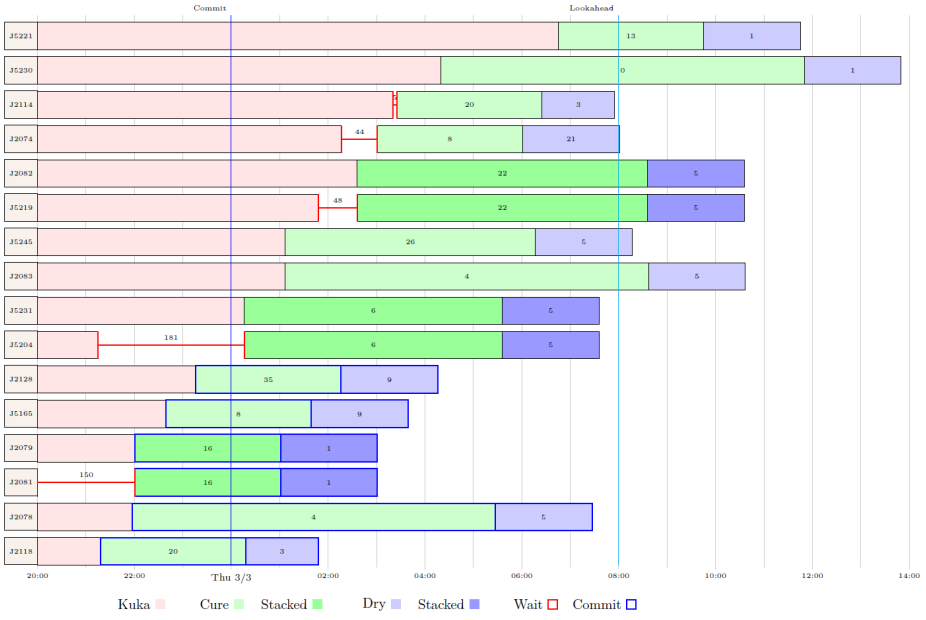
- Weakness of basic decomposition model was the reason to develop the scheduling constraints in the first place
- Does not scale well to thousands of tasks
- But model is well suited to some solvers
  - SAT based solvers, Chuffed, CP-SAT (OR-Tools)
  - MIP solvers
- This works (only) as long as problem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

**Compound Objective**

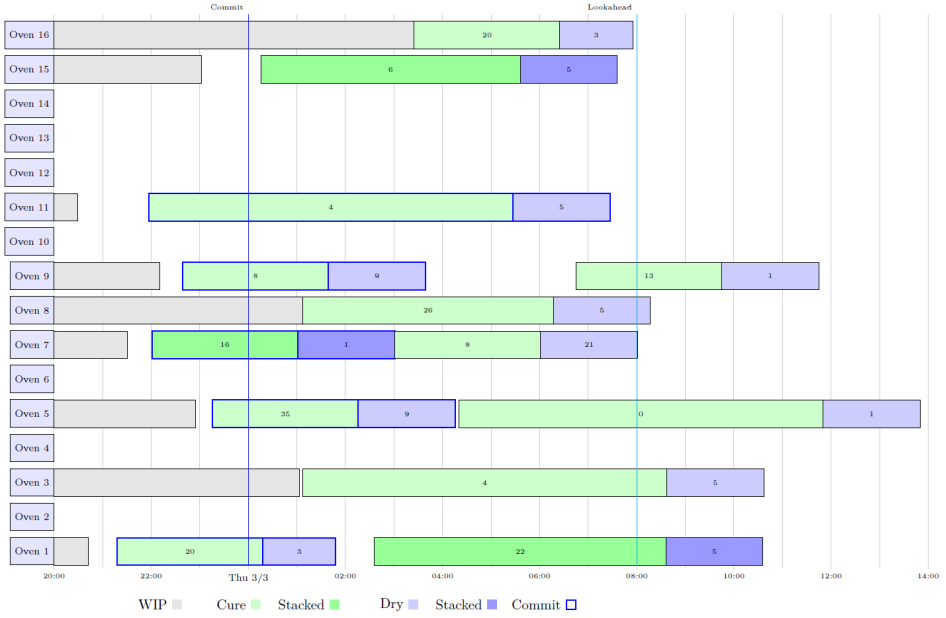
$$\min \alpha_1 \sum_{i \in N} c_i + \alpha_2 \text{nrOvens} + \alpha_3 \sum_{i \in N, j \in Q} z_{ij}$$

- 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**



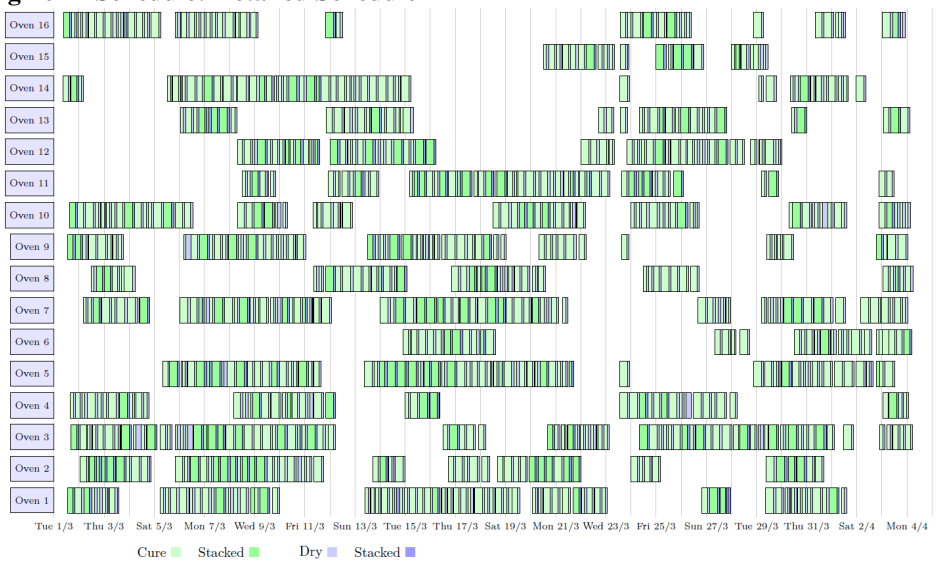
### Short Term Schedule: Resource View



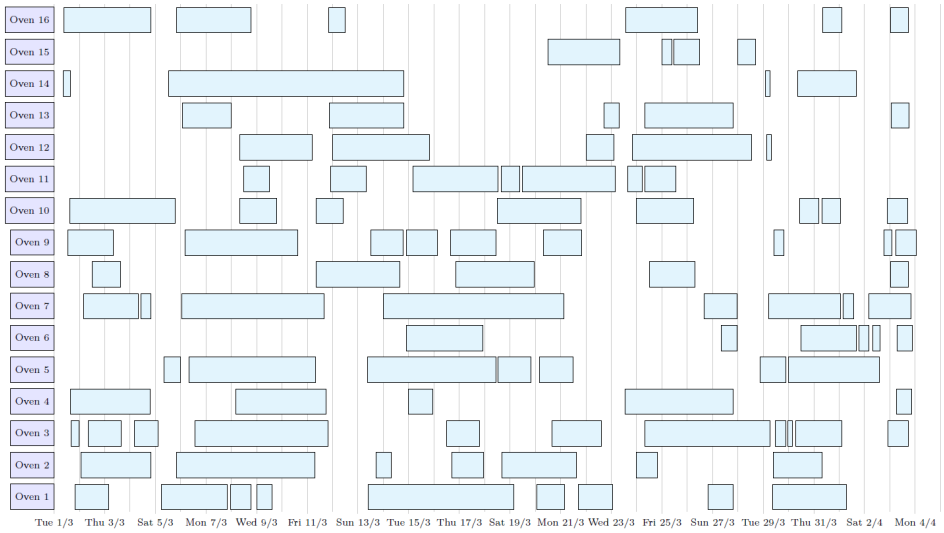

### Are the short-term solutions good?

- 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



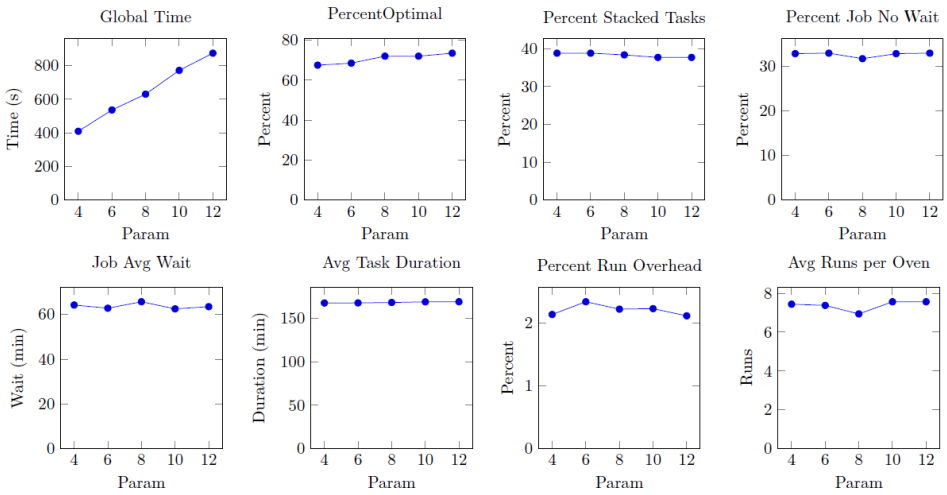

### Long Term Schedule: Abstracted Oven Runs



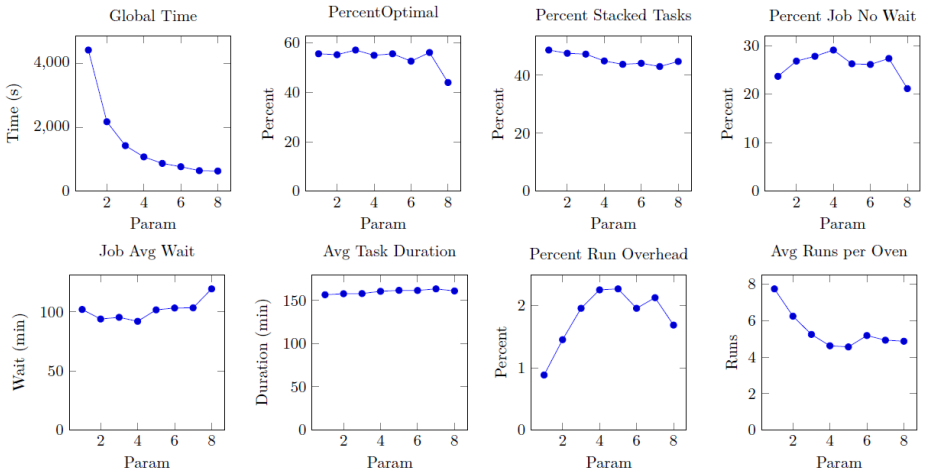

## Is that a good global schedule? KPIs

| 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 |

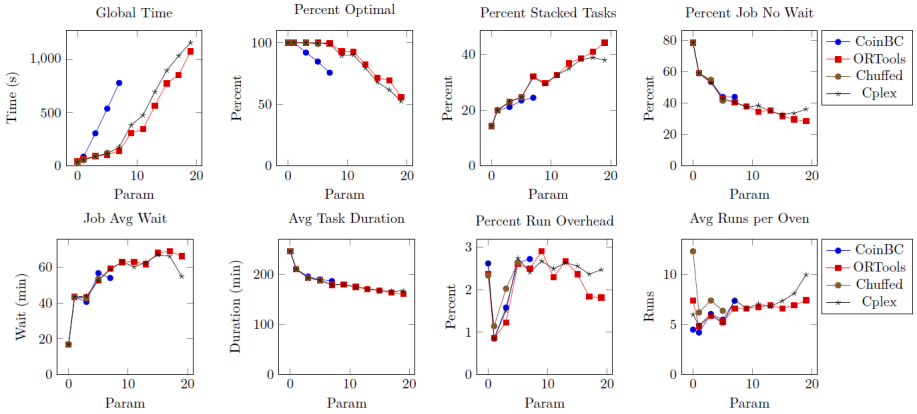
## Impact of Lookahead Parameter




## 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

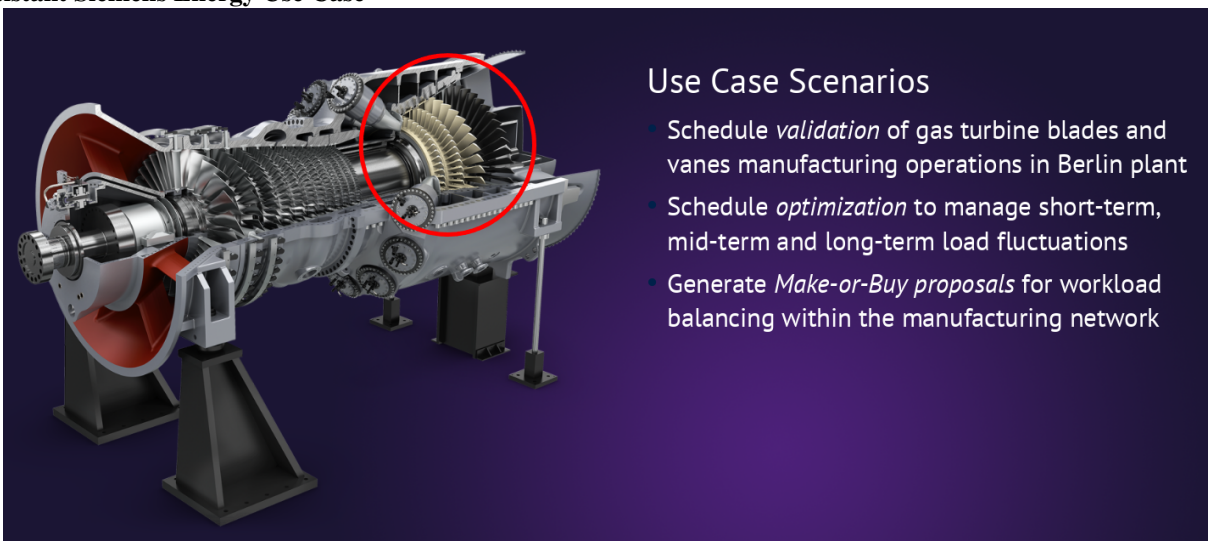
- But is the overall schedule close to the global optimum?
- In any case, industry partner was happy with solution and analysis

# Part XIII
# Blades and Vanes Production Case Study

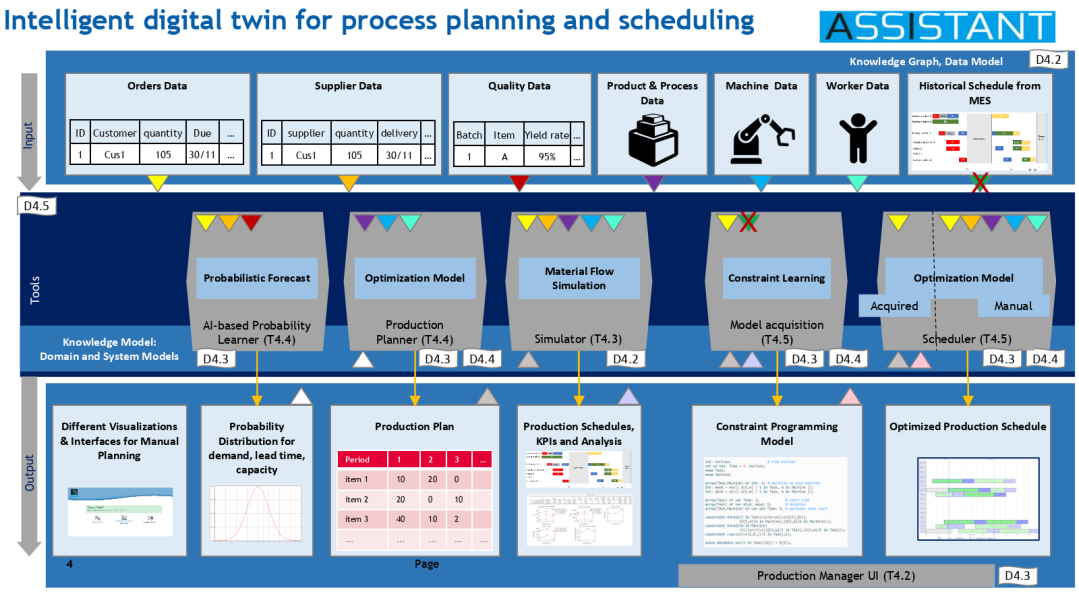
**Key Points**

- 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

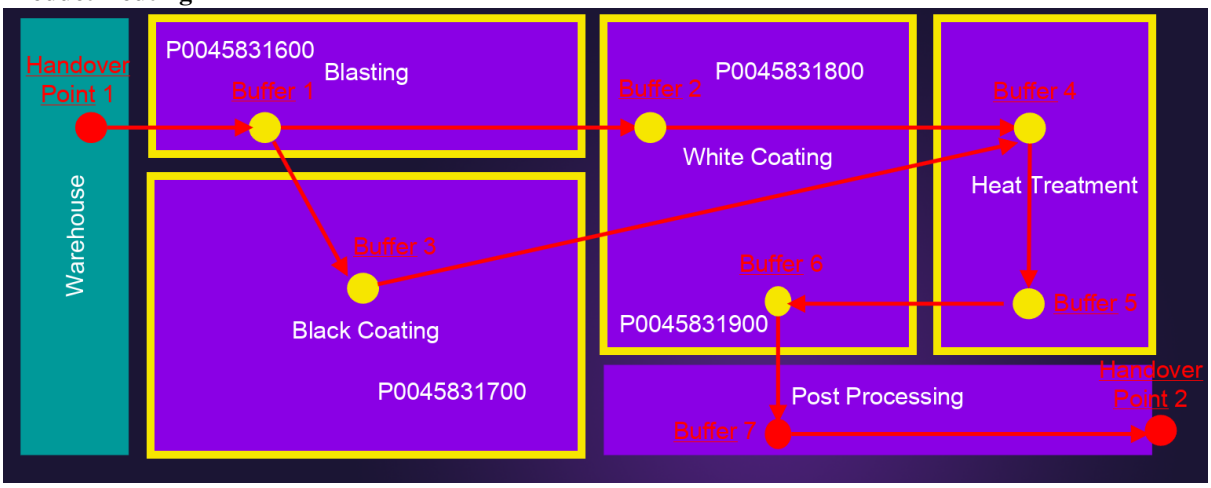
**Assistant Siemens Energy Use Case**




**ASSISTANT Project Overview**




**SE Product Routing**




**Test Datasets**

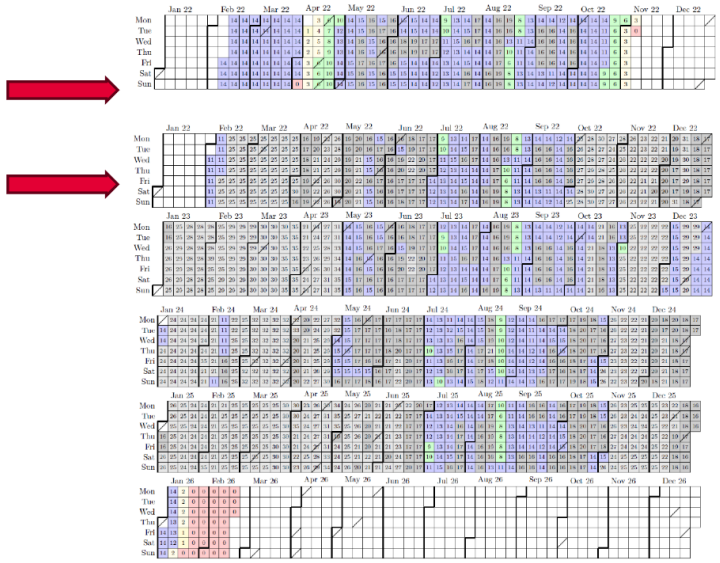
## Full Scale Datasets

Berlin06: 96 orders, 9 months horizon, previous review

Berlin07: 450 orders, 4 years horizon

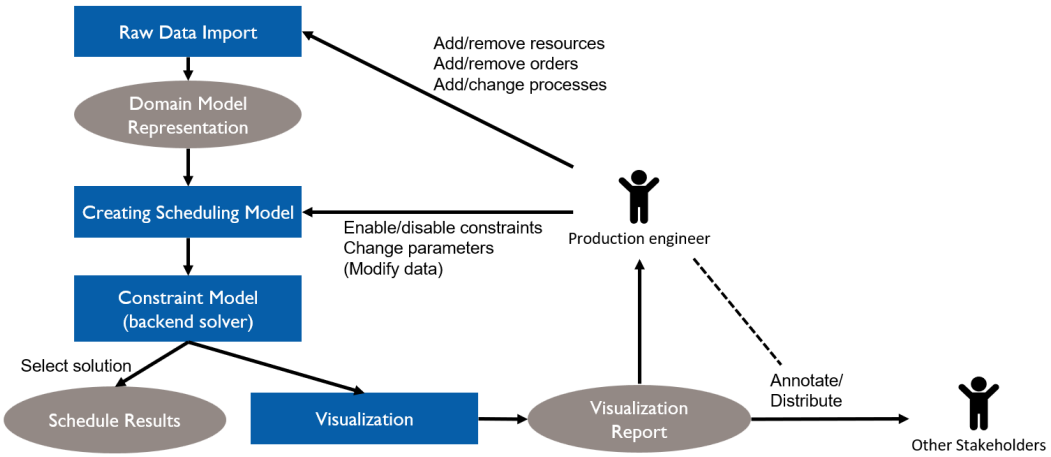
Berlin08: 559 orders, Christmas gap added

Berlin08a: 670 orders, filling gaps



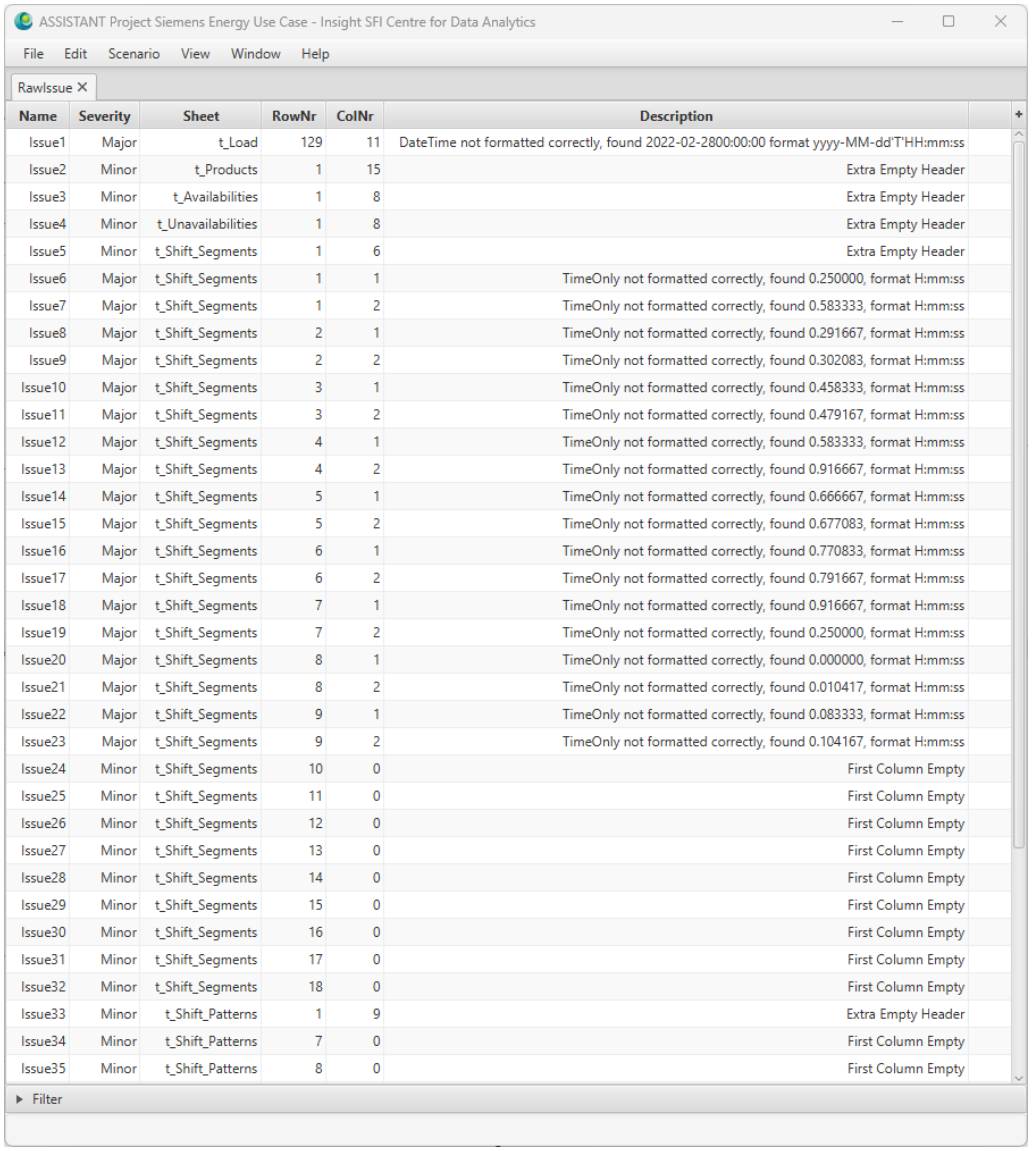
Value in cell indicates active orders
Yellow and red colors indicate low order volume

### Optimizer High Level Structure




### Raw Data - Manual Data Entry Causes Problems

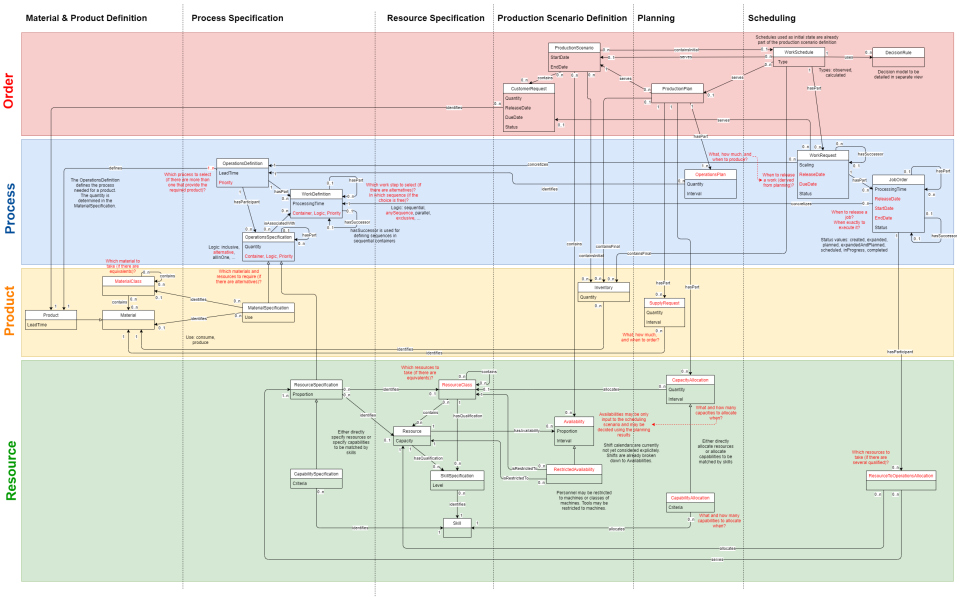
- Raw data come from spreadsheet
  - 20 tabs
- Excel is a particularly bad input data format
- Realistic, not real data
- Created by hand/automatically from existing test scenarios
- Series of files Berlin01 - Berlin05 were too inconsistent to run
- Berlin06 still contains some errors
- Optimizer explains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



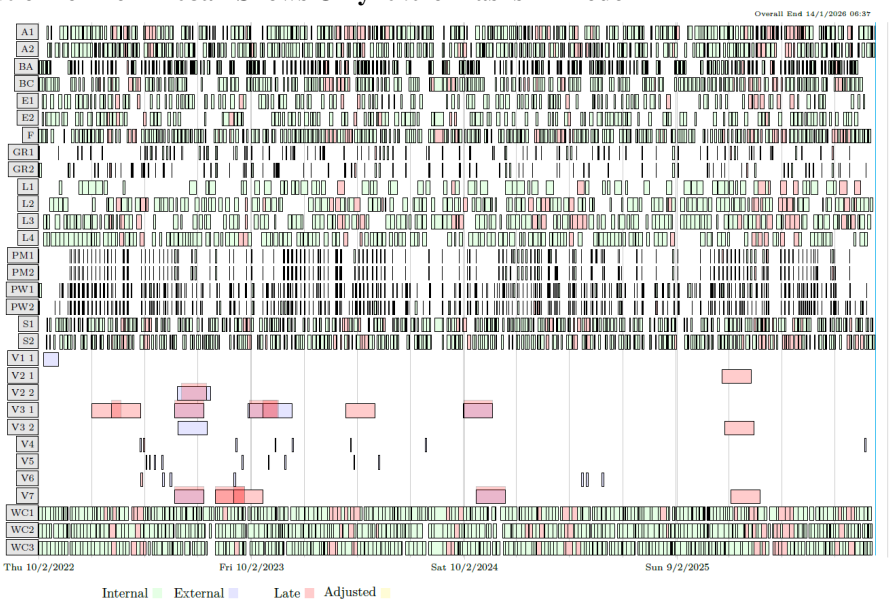

| Name | Severity | Sheet | RowNr | ColNr | Description |
|---|---|---|---|---|---|
| Issue1 | Major | t_Load | 129 | 11 | DateTime not formatted correctly, found 2022-02-2800:00:00 format yyyy-MM-dd'T'HH:mm:ss |
| Issue2 | Minor | t_Products | 1 | 15 | Extra Empty Header |
| Issue3 | Minor | t_Availabilities | 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 |



**Domain Model - Knowledge Graph**




## Solution for Berlin 08a - Shows Only20% of Tasks in Model



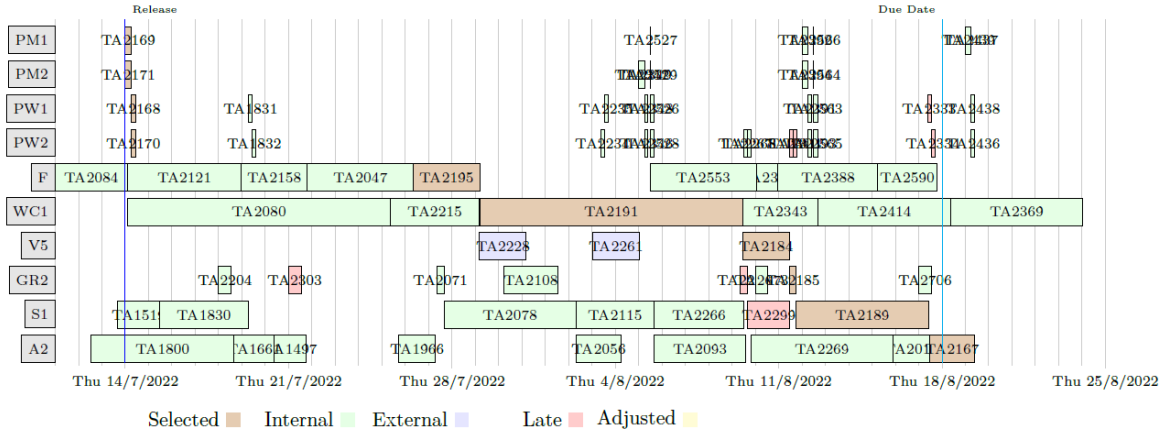

## Implementation

- 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`

## 38 CP and Scheduling Literature Survey

**A Survey of the Existing Literature**

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

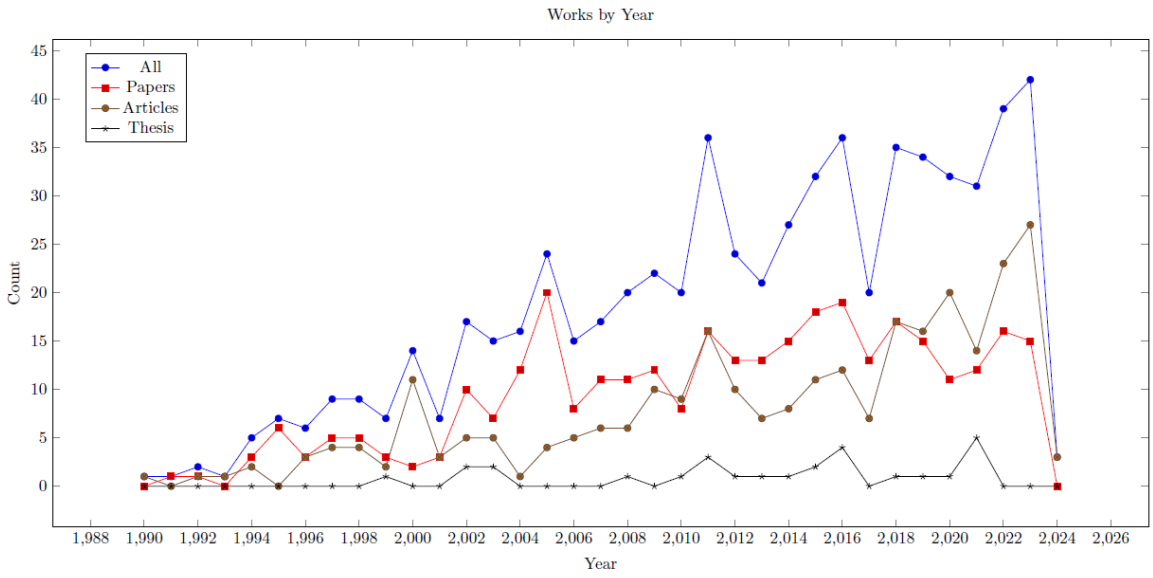
### 38.1 Methodology

**Methodology**

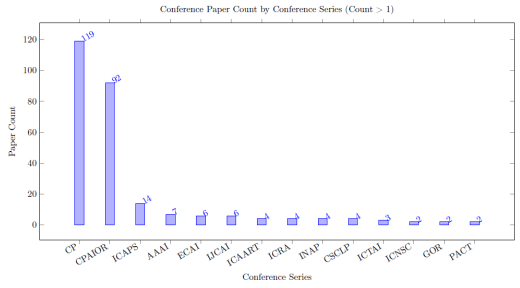
- Manually curated list of works, somewhat inclusive
- Starting with bibtex files
- Citation links through OpenCitations (open access)
- Content analysis on local copies of pdf files
- Closure of domain by analyzing missing cited and citing works
- Limited manual analysis of works (datasets, code)
-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

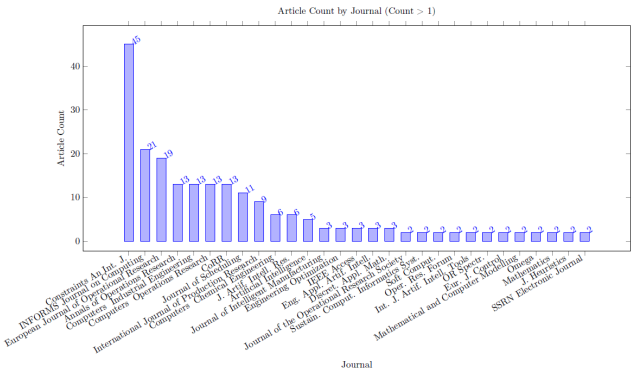
### 38.2 Analysis Results

**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. Talmre | 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 new 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, Jose M. Framinan | 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 Adelgren2023 | N. Adelgren, Christos T. Maravelias | On the utility of production scheduling formulations including record keeping variables | Yes | [7] | 2023 | Computers Industrial Engineering | 12 | 0 | 43 | 1245 | 1501 |
| AfsarVPG23 AfsarVPG23 | S. Afsar, Camino R. Vela, Juan José Palacios, I. González-Rodríguez | Mathematical models and benchmarking for the fuzzy job shop scheduling problem | Yes | [8] | 2023 | Computers Industrial Engineering | 14 | 0 | 50 | 1246 | 1502 |
| AkramNHHSA23 AkramNHRSA23 | Bilal Omar Akram, Nor Kamariah Noordin, F. Hashim, Mohd Fadlee A. Rasid, Mustafa Ismael Salman, Abdulrahman 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 |
| AlfieriGPS23 AlfieriGPS23 | A. Alfieri, M. Garraffa, E. Pastore, F. Salassa | Permutation flowshop problems minimizing core waiting time and core idle time | Yes | [15] | 2023 | Computers Industrial Engineering | 13 | 0 | 37 | 1249 | 1504 |
| Caballero23 Caballero23 | Jordi Coll Caballero | Scheduling through logic-based tools | Yes | [127] | 2023 | Constraints An Int. J. | 1 | 0 | 0 | 1287 | 1505 |
| CzerniachowskaWZ23 CzerniachowskaWZ23 | K. Czerniachowska, R. Wichniarek, K. Żywicki | 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 |
| FahimiQ23 FahimiQ23 | H. Fahimi, C. Quimper | Overload-Checking and Edge-Finding for Robust Cumulative Scheduling | No | [207] | 2023 | INFORMS Journal on Computing | null | 0 | 16 | No | 1507 |
| Fatemi-AnarakiTFV23 Fatemi-AnarakiTFV23 | S. Fatemi-Anaraki, R. Tavakkoli-Moghaddam, M. Foumani, B. Vahedi-Nouri | Scheduling of Multi-Robot Job Shop Systems in Dynamic Environments: Mixed-Integer Linear Programming and Constraint Programming Approaches | Yes | [212] | 2023 | Omega | 15 | 7 | 60 | 1312 | 1508 |
| GhasemiMH23 GhasemiMH23 | S. Ghasemi, R. Tavakkoli-Moghaddam, M. Hamid | Operating room scheduling by emphasising 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. Pinarbasi, 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 Yildiz, Özge Satir 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 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 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 | semiconductor railway, container terminal, satellite, robot, pipeline, aircraft, shipping line | 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 | time-tabling | 984 | 1514 |
| LammaMM97 [377] | 15 | job-shop, resource, scheduling, precedence, order, task, job, distributed, no-wait | | circuit, disjunctive | C++, Prolog | ECLiPSe, OPL, CHIP | railway | | real-life | | 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, benchmark, random instance | energetic reasoning, sweep, edge-finding | 1110 | 1640 |
| LiW08 [386] | 18 | precedence, activity, resource, completion-time, setup-time, 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, ECLiPSe, OPL, CHIP | | | real-world | | 1178 | 1708 |
| LiessM08 [388] | 12 | preempt, resource, scheduling, machine, job, activity, precedence, job-shop, task, make-span, order, cmax | 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 |
| LombardiM10a [402] | 30 | due-date, distributed, order, job, make-span, release-date, re-scheduling, task, completion-time, resource, activity, precedence, preempt, scheduling, machine | TCSP | cycle, 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AalianPG23 AalianPG23 [1] | Optimization of Short-Term Underground Mine Planning Using Constraint Programming | CP Opt | real-world | 1 | n | | n | | | ? | 1 | 325 |
| Bit-Monnot23 Bit-Monnot23 [96] | Enhancing Hybrid CP-SAT Search for Disjunctive Scheduling | ARIES CP Opt OR-Tools Mistral | real-world, github, benchmark | 1 | y | | y | - | JSSP OSSP | - | 2 | 371 |
| EfthymiouY23 EfthymiouY23 [194] | Predicting the Optimal Period for Cyclic Hoist Scheduling Problems | OR-Tools | benchmark, random instance, generated instance, real-life, industrial instance | 3 | n | | n | - | CHSP | - | 3 | 415 |
| JuvinHHL23 JuvinHHL23 [328] | An Efficient Constraint Programming Approach to Preemptive Job Shop Scheduling | CP Opt Mistral | supplementary material, github, benchmark | 6 | ref | | y | | PJSSP | endBeforeStart span noOverlap | 4 | 476 |
| JuvinHL23 JuvinHL23 [330] | 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 | 5 | 477 |
| KameugneFND23 KameugneFND23 [336] | Horizontally Elastic Edge Finder Rule for Cumulative Constraint Based on Slack and Density | ? | benchmark | 5 | BL PSPlib | | n | - | RCPSPs | cumulative | 6 | 480 |
| KimCMLLP23 KimCMLLP23 [345] | 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 Mehdizadeh-Somarin23 [430] | A Constraint Programming Model for a Reconfigurable Job Shop Scheduling Problem with Machine Availability | CP Opt | random instance | 0 | n | | n | - | JSSP RMS | alternative endBeforeStart noOverlap | 8 | 529 |
| PerezGSL23 PerezGSL23 [496] | A Constraint Programming Model for Scheduling the Unloading of Trains in Ports | custom | real-world, generated instance | 0 | n | | n | - | SUTP | table disjunctive | 9 | 553 |
| PovedaAA23 PovedaAA23 [506] | Partially Preemptive Multi Skill/Mode Resource-Constrained Project Scheduling with Generalized Precedence Relations and Calendars | CP Opt MiniZinc Chuffed | real-world, github, benchmark, industrial instance, real-life | 4 | y | | y | | PP-MS-MMRCPSP/max-cal | | 10 | 557 |
| SquillaciPR23 SquillaciPR23 [564] | Scheduling Complex Observation Requests for a Constellation of Satellites: Large Neighborhood Search Approaches | Cplex Studio | github, benchmark | 2 | y | | n | - | EOSP | ? | 11 | 584 |
| TardivoDFMP23 TardivoDFMP23 [575] | 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 TasselGS23 [576] | 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 WangB23 [629] | Dynamic All-Different and Maximal Cliques Constraints for Fixed Job Scheduling | FaCiLe | real-world, random instance | 0 | (y) | | n | 628 | FJS | - | 14 | 620 |
| YuraszeckMC23 YuraszeckMC23 [649] | 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] | GelbingerKKMMW21 [234] | FatemiAnarakiTFV23 [212], Mehdizadeh-Somarin23 [430], GurPAE23 [270], JuvinHL23a [331], OujanaAYB22 [487], Lemos21 [381] |
| ApplicationAreas | HVAC | LimHTB16 [390], LimBTBB15 [391], GrimesIOS14 [260] | | |
| ApplicationAreas | agriculture | | | AkramNHRSA23 [13], BenderWS21 [84], HamPK21 [275], Astrand21 [35], QinWSLS21 [511], AstrandOF21 [36], MejiaY20 [431] |
| ApplicationAreas | aircraft | PohlAK22 [502], WangB20 [628], TranDRFWOVB16 [596], Fahimi16 [205], BajestaniB13 [42], LombardiM12 [405], BajestaniB11 [41], FrankK05 [219], ArtiouchineB05 [34], Simonis99 [558] | WangB23 [629], GombolayWS18 [253], Ham18 [273], Simonis07 [559], SakkoutW00 [529], Simonis95a [556] | PrataAN23 [509], PovedaAA23 [506], Adelgren2023 [7], EtminaniesfahaniGNMS22 [202], ElciOH22 [195], ZarandiASC20 [654], HauderBRPA20 [283], abs-1902-09244 [282], Hooker19 [312], LaborieRSV18 [372], HookerH17 [314], TranAB16 [594], Lombardi10 [398], Laborie09 [370], KovacsB08 [355], KrogtLPH107 [608], MartinPY01 [427], SimonisCK00 [560], GrulianK98 [264], Darby-DowmanLMZ97 [163], Wallace96 [625], Simonis95 [557], SimonisC95 [561] |
| ApplicationAreas | automotive | | GuoZ23 [269], YuraszeckMPV22 [650], EmdeZD22 [199], Groleaz21 [261], LimtanyakulS12 [393], SunLYL10 [567], Lombardi10 [398], BarlattCG08 [52], SchildW00 [532] | PovedaAA23 [506], NaderiRR23 [460], CzerniachowskaWZ23 [159], NaderiBZ22 [457], NaderiBZ22a [456], AntuoriHHEN21 [22], HubnerGSV21 [318], AbreuAPNM21 [166], KoehlerBFFHPSSS21 [348], VikHT21 [623], BarzegaranZP20 [61], GelbingerMM19 [236], abs-1911-04766 [235], BonfiettiZLM16 [113], Siala15a [552], SchnellH15 [533], AlesioNBG14 [181], HarjunkoskiMBC14 [279], BeninlBGM06 [88], KovacsV06 [360], Wallace96 [625] |
| ApplicationAreas | cable tree | KoehlerBFFHPSSS21 [348] | | |
| ApplicationAreas | car manufacturing | | AntuoriHHEN21 [22] | BelldiceanuC94 [78] |
| ApplicationAreas | container terminal | QinDCS20 [512], SacramentoSP20 [526] | LaborieRSV18 [372] | abs-2312-13682 [497], PerezGSL23 [496], TouatBT22 [592], CauwelaertDS20 [142], WallaceY20 [627], ZarandiASC20 [654], FallahiAC20 [209], Hooker19 [312], CauwelaertDMS16 [140], Dejemeppe16 [172], DejemeppeCS15 [179], NovasH12 [479], CorreaLR07 [158], LimRX04 [389] |
| ApplicationAreas | crew-scheduling | ZarandiASC20 [654], PourDERB18 [505] | BourreauGGLT22 [118], Zahout21 [652], GombolayWS18 [253], Mason01 [429], Touralvane95 [593] | NaderiRR23 [460], WangB23 [629], Adelgren2023 [7], EtminaniesfahaniGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], ElciOH22 [195], Lemos21 [381], MokhtarzadehTNP20 [443], TangLWSK18 [574], HookerH17 [314], DoulabiRP16 [190], LipovetzkyBPS14 [394], HachemiGR11 [272], MilanoW09 [441], WuBB09 [643], MilanoW06 [440], BeldiceanuC02 [79], JainG01 [323], SimonisCK00 [560] |
| ApplicationAreas | dairies | | | Bartak02 [54], Bartak02a [53] |
| ApplicationAreas | dairy | EscobetPQPRA19 [201] | PrataAN23 [509], HarjunkoskiMBC14 [279] | Groleaz21 [261] |
| ApplicationAreas | datacenter | HermenierDL11 [300] | | Zahout21 [652], GalleguillosKSB19 [225], Madi-WambaLOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383] |
| ApplicationAreas | datacentre | | HurleyOS16 [319] | |
| ApplicationAreas | day-ahead market | | | |
| ApplicationAreas | deep space | | | HebrardALLCMR22 [285] |
| ApplicationAreas | drone | MontemanniD23a [446], MontemanniD23 [447], Ham18 [273] | | GuoZ23 [269], JuvinHL23a [331], Adelgren2023 [7], ShaikhK23 [547], EmdeZD22 [199], Astrand21 [35], Astrand0F21 [36], AntuoriHHEN21 [22], ZarandiASC20 [654], 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], RoshanaeiBAUB20 [521], TranPZLDB18 [597], TranVNB17 [599], TranVNB17a [600], CohenHB17 [154], BoothNB16 [114], KuB16 [365], TranAB16 [594], TranWDRFOVB16 [601], LuoVLBM16 [415], TranDRFWOVB16 [596], BajestaniB15 [43], KoschB14 [353], TerekhovTDB14 [581], LouieVNB14 [412], HeinzSB13 [294], HeinzKB13 [291], BajestaniB13 [42], TranTDB13 [598], HeinzB12 [290], TerekhovDOB12 [580], TranB12 [595], ZarandiB12 [213], KovacsB11 [356], BeckFW11 [66], HeckmanB11 [289], BajestaniB11 [41], WuBB09 [643], BidotVLB09 [94], CarchraeB09 [131], WatsonB08 [632], KovacsB08 [355], BeckW07 [73], Beck07 [64], KovacsB07 [354], Beck06 [63], CarchraeBF05 [132], WuBB05 [642], BeckW05 [72], BeckW04 [71], BeckR03 [70], BeckPS03 [69], BeckF00 [68], Beck99 [62], BeckF98 [67], BeckDF97 [65] |
| Michela Milano | 31 | 297 | BorghesiBLMB18 [115], BonfiettiZLM16 [113], BridiBLMB16 [120], BridiLBBM16 [121], LombardiBM15 [399], BartoliniBBLM14 [60], BonfiettiLM14 [111], BonfiettiLBM14 [109], BonfiettiLM13 [110], LombardiM13 [406], LombardiMB13 [407], LombardiM12 [405], BonfiettiLBM12 [108], LombardiM12a [404], BonfiettiM12 [112], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], Milano11 [438], LombardiM10 [403], LombardiM10a [402], LombardiMRB10 [408], LombardiM09 [401], RuggieroBBMA09 [525], MilanoW09 [441], BeniniLMR08 [89], BeniniBGM06 [88], MilanoW06 [440], MilanoORT02 [439], LammaMM97 [377], BrusoniCLMMT96 [123] |
| Andreas Schutt | 27 | 322 | YangSS19 [644], KreterSSZ18 [364], GoldwaserS18 [251], MusliuSS18 [455], KreterSS17 [363], YoungFS17 [646], GoldwaserS17 [250], SchuttS16 [543], SzerediS16 [570], KreterSS15 [362], EvenSH15 [203], EvenSH15a [204], SchuttFSW15 [542], ThiruvadyWGS14 [585], GuSSWC14 [266], SchuttFS13 [537], SchuttFS13a [536], GuSS13 [265], SchuttFSW13 [541], ChuGNSW13 [147], SchuttCSW12 [535], SchuttFSW11 [540], Schutt11 [534], SchuttW10 [544], abs-1009-0347 [539], SchuttFSW09 [538], SchuttWS05 [545] |
| Michele Lombardi | 25 | 194 | BorghesiBLMB18 [115], CauwelaertLS18 [141], BonfiettiZLM16 [113], BridiBLMB16 [120], BridiLBBM16 [121], LombardiBM15 [399], BartoliniBBLM14 [60], BonfiettiLM14 [111], BonfiettiLBM14 [109], BonfiettiLM13 [110], LombardiM13 [406], LombardiMB13 [407], LombardiM12 [405], BonfiettiLBM12 [108], LombardiM12a [404], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], LombardiM10 [403], LombardiM10a [402], LombardiI10 [398], LombardiMRB10 [408], LombardiM09 [401], BeniniLMR08 [89], HoeveGSL07 [609] |
| Peter J. Stuckey | 24 | 453 | YangSS19 [644], DemirovicS18 [177], KreterSSZ18 [364], MusliuSS18 [455], KreterSS17 [363], SchuttS16 [543], BlomPS16 [100], KreterSS15 [362], BurtLPS15 [124], SchuttFSW15 [542], BlomBPS14 [99], LipovetzkyBPS14 [394], GuSSWC14 [266], SchuttFS13 [537], SchuttFS13a [536], GuSS13 [265], SchuttFSW13 [541], SchuttCSW12 [535], GuSW12 [267], SchuttFSW11 [540], BandaSC11 [170], abs-1009-0347 [539], SchuttFSW09 [538], OhrimenkoSC09 [483] |
| John N. Hooker | 19 | 1316 | EfcfOH22 [195], Hooker19 [312], Hooker17 [311], HookerH17 [314], HechingH16 [288], CireCH16 [150], HarjunkoskiMBC14 [279], CireCH13 [149], CobanH11 [153], CobanH10 [152], Hooker10 [310], Hooker07 [309], Hooker06 [308], Hooker05 [306], Hooker05a [307], Hooker04 [305], HookerO03 [313], HookerY02 [315], Hooker00 [304] |
| Emmanuel Hebrard | 17 | 71 | JuvinHHL23 [328], HebrardALLCMR22 [285], AntuoriHHEN21 [22], ArtiguesHQT21 [32], GodetLHS20 [247], AntuoriHHEN20 [21], HebrardHJMPV16 [286], SimoninAHL15 [555], SialaAH15 [553], GrimesH15 [258], BessiereHMQW14 [93], SimoninAHL12 [554], BillautHL12 [95], GrimesH11 [257], GrimesH10 [256], GrimesHM09 [259], HebrardTW05 [287] |
| Pierre Lopez | 17 | 90 | JuvinHHL23 [328], JuvinHL23a [331], JuvinHL23 [330], HebrardALLCMR22 [285], JuvinHL22 [329], Polo-MejiaALB20 [503], NattafHKAL19 [466], NattafAL17 [463], NattafALR16 [464], SimoninAHL15 [555], NattafAL15 [462], SimoninAHL12 [554], BillautHL12 [95], LahimerLH11 [375], TrojetHL11 [602], LopezAKYG00 [410], TorresL00 [591] |
| Christian Artigues | 16 | 203 | PovedaAA23 [506], PohlAK22 [502], HebrardALLCMR22 [285], ArtiguesHQT21 [32], Polo-MejiaALB20 [503], NattafHKAL19 [466], NattafAL17 [463], NattafALR16 [464], SimoninAHL15 [555], NattafAL15 [462], SialaAH15 [553], SimoninAHL12 [554], NeronABCDD06 [481], DemasseyAM05 [176], ArtiguesBF04 [30], ArtiguesR00 [33] |
| Pierre Schaus | 15 | 79 | CauwelaertDS20 [142], ThomasKS20 [586], HoundjiSW19 [316], CappartTSR18 [130], CauwelaertLS18 [141], CappartS17 [129], CauwelaertDMS16 [140], DejemeppeCS15 [173], GayHLS15 [229], GayHS15 [230], GayHS15a [231], HoundjiSWD14 [317], GaySS14 [232], SchausHMCMD11 [531], SchausD08 [530] |
| Helmut Simonis | 15 | 154 | ArmstrongGOS22 [27], ArmstrongGOS21 [26], AntunesABD20 [20], AntunesABD18 [19], HurleyOS16 [319], GrimesIOS14 [260], IfrimOS12 [320], SimonisH11 [562], Simonis07 [559], SimonisCK00 [560], Simonis99 [558], SimonisC95 [561], Simonis95 [557], Simonis95a [556], DincbasSH90 [184] |
| Nicolas Beldiceanu | 13 | 274 | Madi-WambaLOBM17 [418], Madi-WambaB16 [417], LetortCB15 [385], LetortCB13 [384], LetortBC12 [383], ClercqPBJ11 [151], BeldiceanuCDPT11 [80], BeldiceanuCP08 [81], PoderB08 [500], BeldiceanuP07 [82], PoderBS04 [501], BeldiceanuC02 [79], Aggoun93 [9] |
| Luca Benini | 13 | 146 | BorghesiBLMB18 [115], BridiBLMB16 [120], BridiLBBM16 [121], BonfiettiLBM14 [109], LombardiMB13 [407], BonfiettiLBM12 [108], BonfiettiLBM11 [107], LombardiBMB11 [400], BeniniLMR11 [90], LombardiMRB10 [408], RuggieroBBMA09 [525], BeniniLMR08 [89], BeniniBGM06 [88] |
| Philippe Laborie | 12 | 513 | LunardiBLRV20 [413], LaborieRSV18 [372], Laborie18a [371], MelgarejoLS15 [11], VilimLS15 [621], Laborie09 [370], BidotVLB09 [94], BaptisteLPN06 [47], NeronABCDD06 [481], GodardLN05 [245], Laborie03 [369], FocacciLN00 [215] |
| Philippe Baptiste | 11 | 403 | BaptisteB18 [46], Baptiste09 [45], BaptisteLPN06 [47], NeronABCDD06 [481], ArtiouchineB05 [34], Baptiste02 [44], BaptistePN01 [50], BaptisteP00 [49], PapaB98 [492], BaptisteP97 [48], PapeB97 [491] |
| Roman Barták | 11 | 88 | SvancaraB22 [569], JelinekB16 [325], BartakV15 [59], Bartak14 [55], BartakS11 [57], BartakCS10 [56], BartakSR10 [58], VilimBC05 [620], VilimBC04 [619], Bartak02 [54], Bartak02a [53] |

## 38.3 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

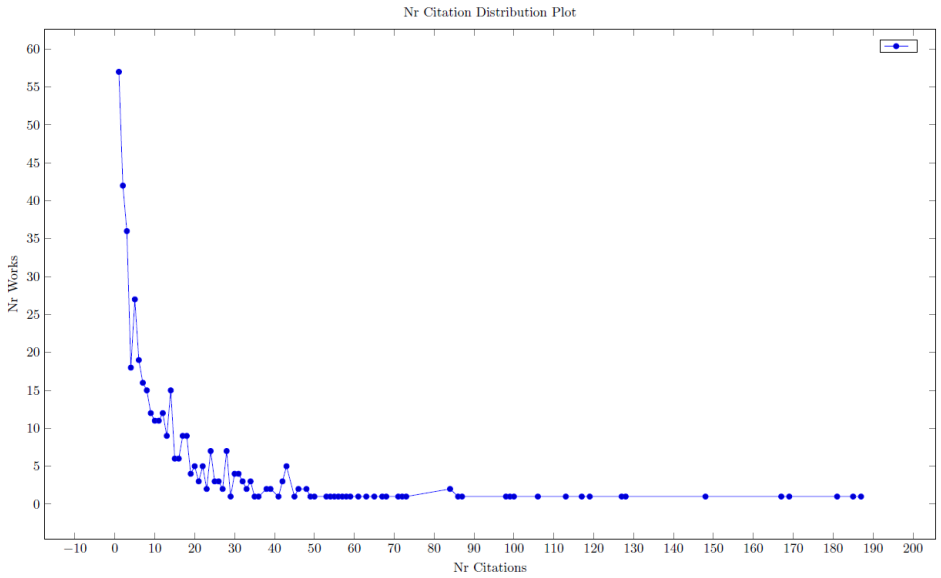
Table 9: Works from bibtex (Total 30)

| 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 | 45 | 490 | 150 | 1352 | 1753 |
| HarjunkoskiMBC14 HarjunkoskiMBC14 | I. Harjunkoski, Christos T. Maravelias, P. Bongers, Pedro M. Castro, S. Engell, Ignacio E. Grossmann, John N. Hooker, C. Méndez, G. Sand, J. Wassick | Scope for industrial applications of production scheduling models and solution methods | Yes | [279] | 2014 | Computers Chemical Engineering | 33 | 381 | 176 | 1335 | 1649 |
| BlazewiczDP96 BlazewiczDP96 | J. Błażewicz, W. Domschke, E. Pesch | The job shop scheduling problem: Conventional and new solution techniques | Yes | [125] | 1996 | European Journal of Operational Research | 33 | 344 | 127 | 1278 | 1762 |
| HookerO03 HookerO03 | John N. Hooker, G. Ottosson | Logic-based Benders decomposition | Yes | [313] | 2003 | Mathematical Programming | 28 | 317 | 0 | 1347 | 1729 |
| BaptistePN01 BaptistePN01 | P. Baptiste, Claude Le Pape, W. Nuijten | Constraint-Based Scheduling | No | [50] | 2001 | 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 | [323] | 2001 | INFORMS Journal on Computing | 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 | Mathematical and Computer Modelling | 17 | 187 | 11 | 1247 | 1767 |
| Hooker00 Hooker00 | John N. Hooker | Logic Based Methods for Optimization: Combining Optimization and Constraint Satisfaction | No | [304] | 2000 | Book | null | 185 | 0 | No | n/a |
| Hooker07 Hooker07 | John N. Hooker | Planning and Scheduling by Logic-Based Benders Decomposition | Yes | [309] | 2007 | Operations Research | 29 | 181 | 19 | 1345 | 1715 |
| HarjunkoskiG02 HarjunkoskiG02 | I. Harjunkoski, Ignacio E. Grossmann | Decomposition techniques for multistage scheduling problems using mixed-integer and constraint programming methods | Yes | [278] | 2002 | Computers Chemical Engineering | 20 | 169 | 11 | 1334 | 1733 |
| BeldiceanuC94 BeldiceanuC94 | N. Beldiceanu, E. Contejean | Introducing Global Constraints in CHIP | Yes | [78] | 1994 | Mathematical and Computer Modelling | 27 | 167 | 8 | 1271 | 1765 |
| LaborieRSV18 LaborieRSV18 | P. Laborie, J. Rogerie, P. Shaw, P. Vilím | IBM ILOG CP optimizer for scheduling - 20+ years of scheduling with constraints at IBM/ILOG | Yes | [372] | 2018 | Constraints An Int. J. | 41 | 148 | 35 | 1370 | 1610 |
| Laborie03 Laborie03 | P. Laborie | Algorithms for propagating resource constraints in AI planning and scheduling: Existing approaches and new results | Yes | [369] | 2003 | Artificial Intelligence | 38 | 128 | 10 | 1369 | 1731 |
| OhrimenkoSC09 OhrimenkoSC09 | O. Ohrimenko, Peter J. Stuckey, M. Codish | Propagation via lazy clause generation | Yes | [483] | 2009 | Constraints An Int. J. | 35 | 127 | 15 | 1417 | 1702 |
| KuB16 KuB16 | W. Ku, J. Christopher Beck | Mixed Integer Programming models for job shop scheduling: A computational analysis | Yes | [365] | 2016 | Computers Operations Research | 9 | 119 | 17 | 1367 | 1630 |
| Rodriguez07 Rodriguez07 | J. Rodriguez | A constraint programming model for real-time train scheduling at junctions | Yes | [520] | 2007 | Transportation Research Part B: Methodological | 15 | 117 | 6 | 1430 | 1716 |
| LiW08 LiW08 | H. Li, K. Womer | Scheduling projects with multi-skilled personnel by a hybrid MILP/CP benders decomposition algorithm | Yes | [386] | 2008 | Journal of Scheduling | 18 | 113 | 31 | 1374 | 1708 |
| CorreaLR07 CorreaLR07 | Ayoub Insa Corrêa, A. Langevin, L. Rousseau | Scheduling and routing of automated guided vehicles: A hybrid approach | Yes | [158] | 2007 | Computers Operations Research | 20 | 106 | 20 | 1296 | 1714 |
| MengZRZL20 MengZRZL20 | L. Meng, C. Zhang, Y. Ren, B. Zhang, C. Lv | Mixed-integer linear programming and constraint programming formulations for solving distributed flexible job shop scheduling problem | Yes | [435] | 2020 | Computers Industrial Engineering | 13 | 100 | 62 | 1393 | 1574 |
| BensanaLV99 BensanaLV99 | E. Bensana, M. Lemaître, G. Verfaillie | Earth Observation Satellite Management | Yes | [91] | 1999 | Constraints An Int. J. | 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




# 39 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