

Skills Development Program

Scheduling

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Constraint Based Production Scheduling



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Note



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

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



4 Co-Lead Universities 9 partner institutions	Built on 20 years of research in Data Analytics and AI
450+ Academics, Postdocs, PhDs, RAs	3400+ Scientific conference and journal papers
175+ Funded collaborations with industry partners	350+ Research Awards
16 Spin out companies 72 license agreements	135+ H2020 consortia, 500+ collaborations, 40+ countries
1,137+ school visits, 28,000 students	276 PhDs graduated

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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



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Slide 6



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

Developing a Generic Scheduling Tool



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

Introducing a Simple Scheduling Problem



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

Excerpt of JSON Description



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

```

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Orders Loaded



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

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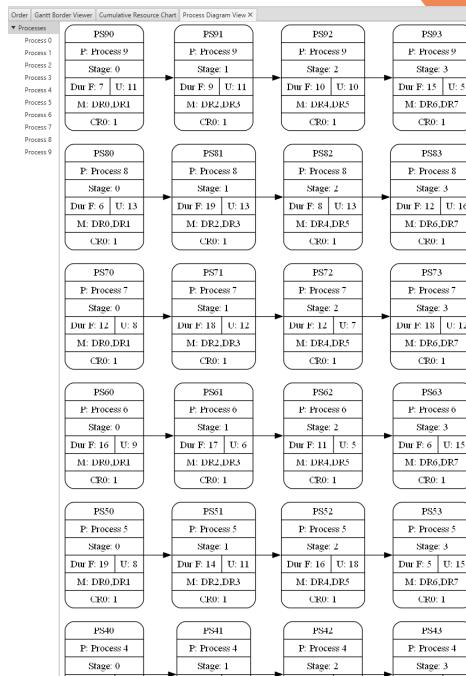
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Slide 13

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,...)

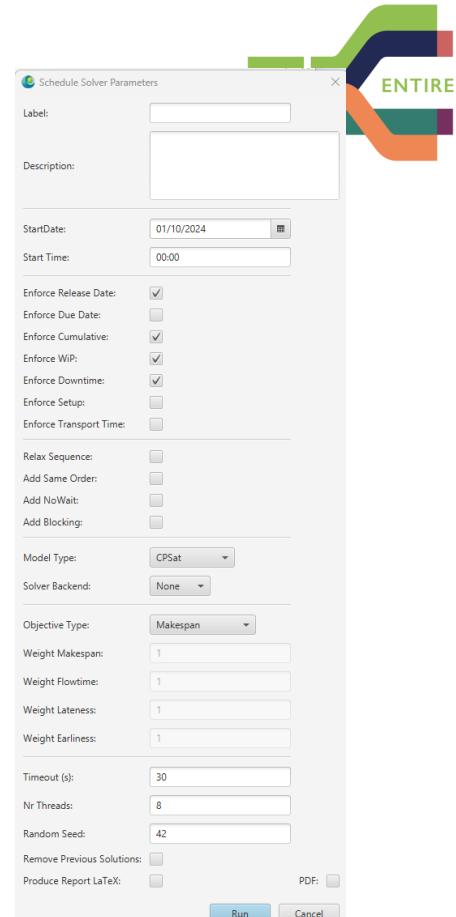


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Selecting Solver Options



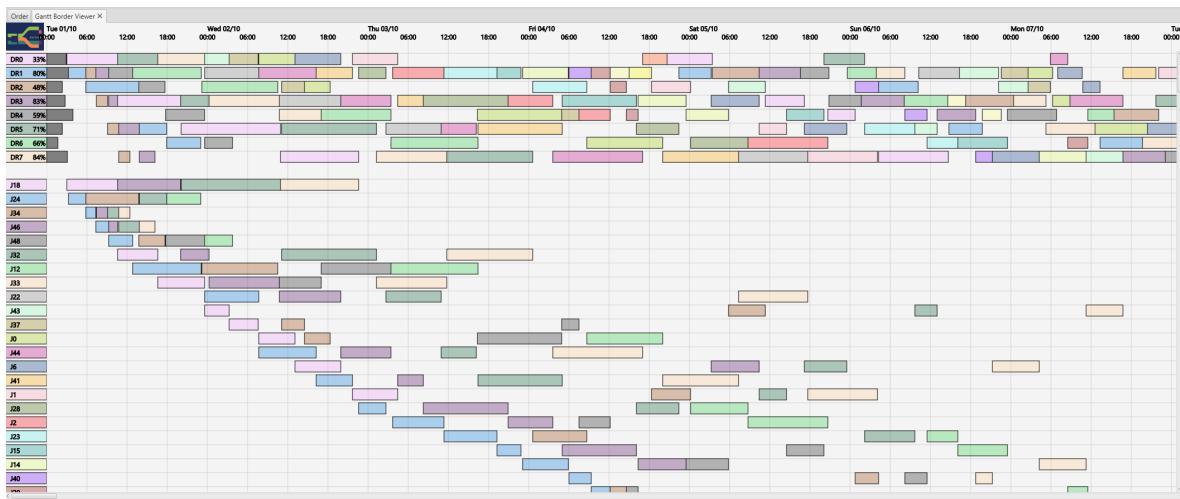
- Which constraints to enforce
 - Here: do not enforce due dates
- Additional constraints to try
- Why solver to run
 - Here: Use open-source CPSat solver
- Which objective to use
 - Here: Makespan, overall project end
- What resources to use
 - Allow 30 seconds
 - Use 8 parallel threads

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Schedule - Initial Gantt Chart

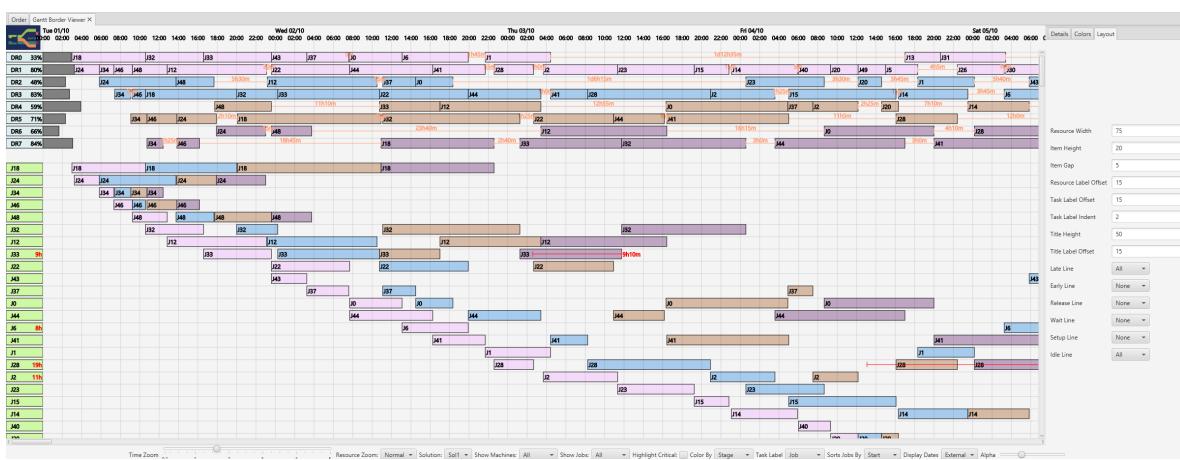


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Adapted Gantt Chart

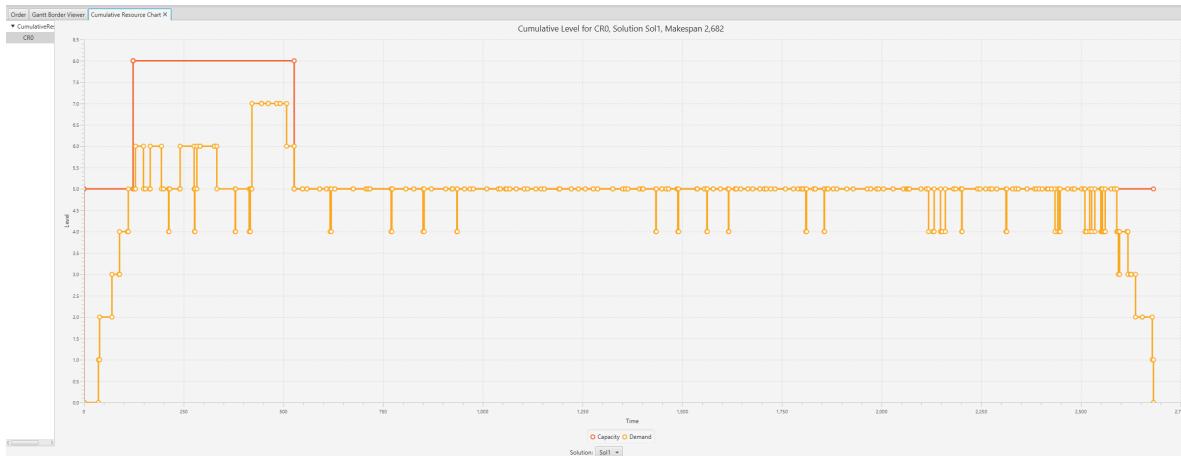


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Cumulative Resource Chart

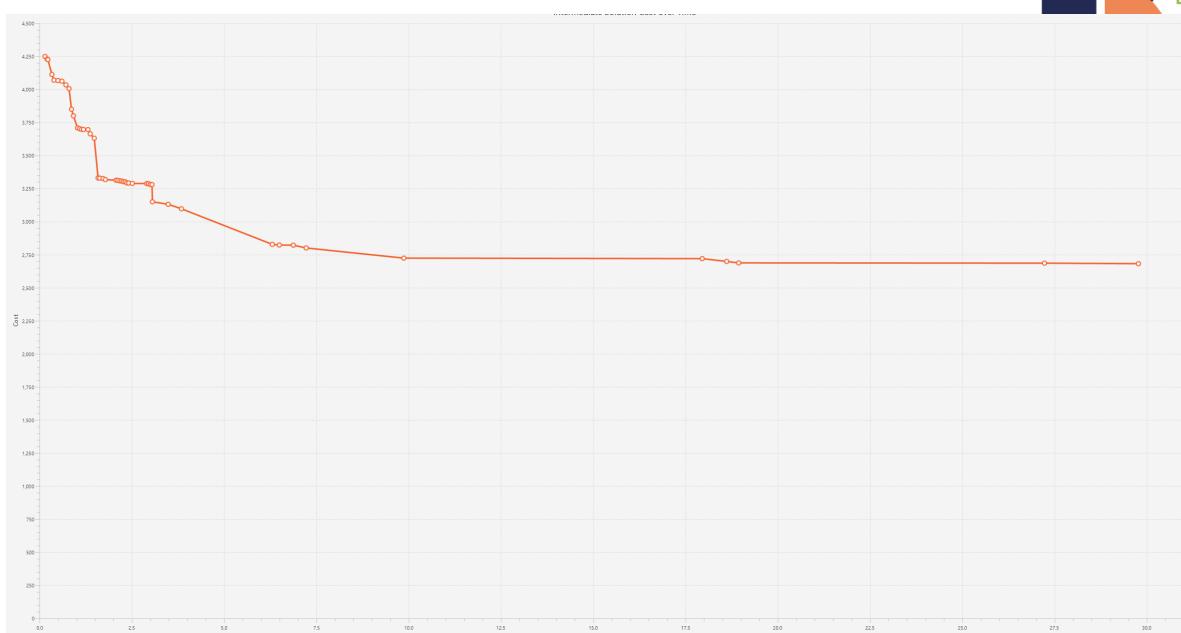


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Intermediate Solutions Found



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

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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/>

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Other Technologies



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

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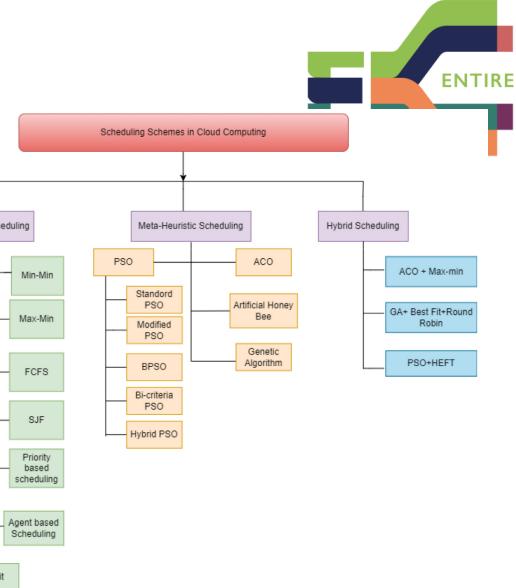
Heuristics

- 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

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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>

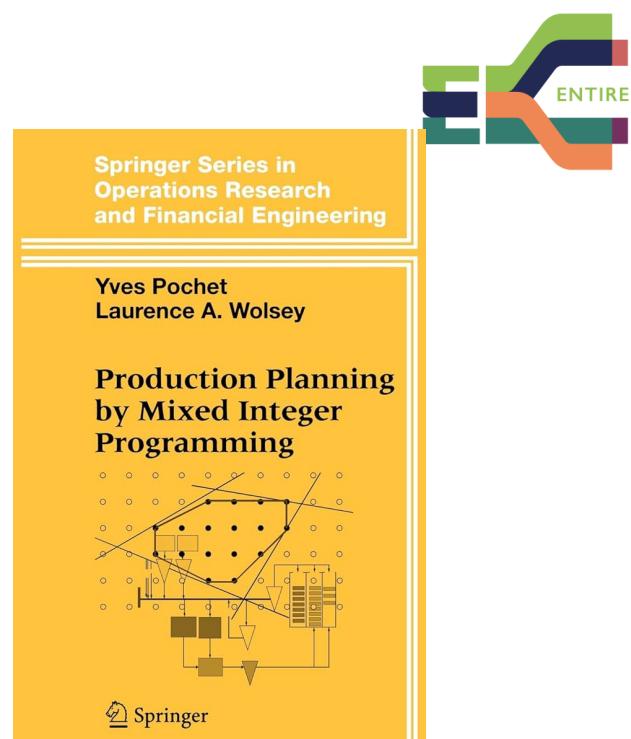
Integer Programming

- 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

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Slide 27

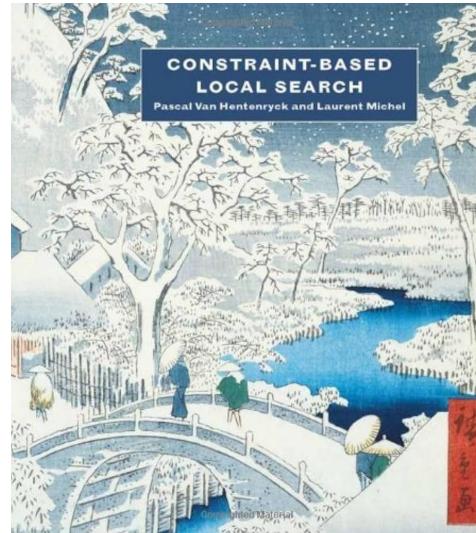


<https://link.springer.com/book/10.1007/0-387-33477-7>

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

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Slide 28

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	-

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Slide 30

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>

Summary



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



Part II

Concepts

Key Points



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

Most basic description of scheduling problem



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

Scheduling orders



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

Process Description



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

Where do the orders come from?



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

Temporal Relations



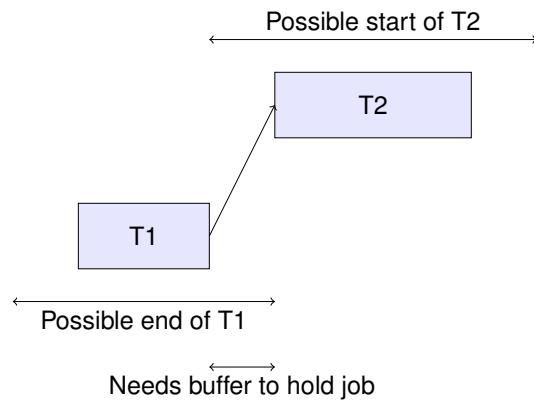
- Temporal constraints between tasks and/or jobs
- Defined by the manufacturing process
- In simple cases
 - A single sequence of process steps performed in that order
 - Each task must finish before the next one can start



The Most Common Relation: EndBeforeStart



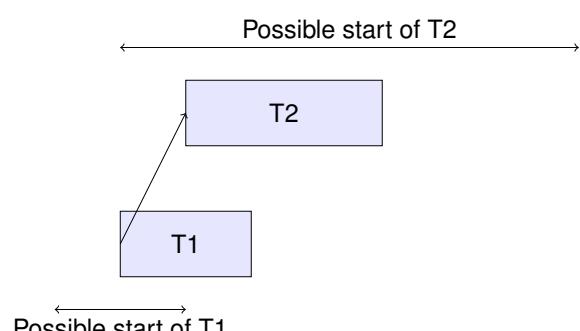
- States that one task (T1) must end before the next one (T2) can start
- Typical for manufacturing process based on the same item
- Addition: offset
 - Wait at least offset units between end and start
 - For example cooling, drying time outside a machine



Less Common: StartBeforeStart



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

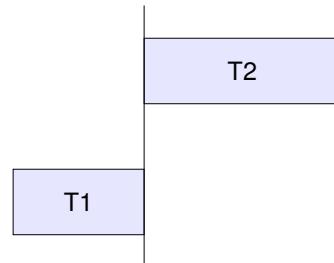


NoWait



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

Start of T2 is equal to End of T1

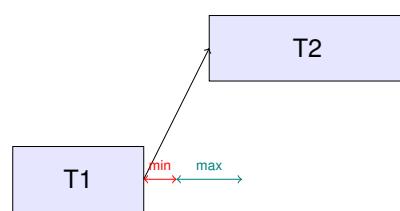


MaxWait



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

Possible start of T2



Possible end of T1

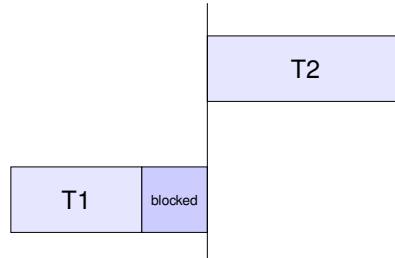
Needs buffer to hold job

Blocking



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

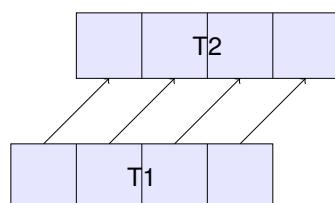
Start of T2 is equal to End of T1



Special Case: Pipelining



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



More General: Relations between Intervals



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

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

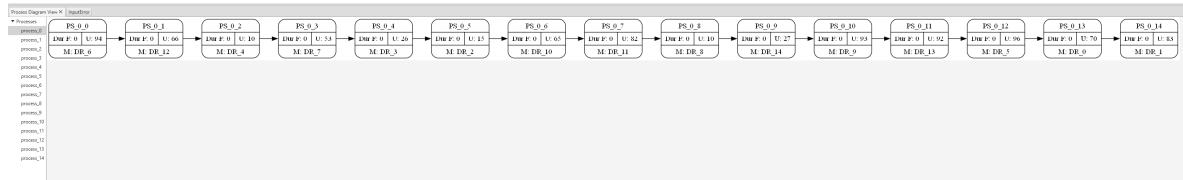
from Wikipedia: https://en.wikipedia.org/wiki/Allen%27s_interval_algebra

Start and End of Jobs



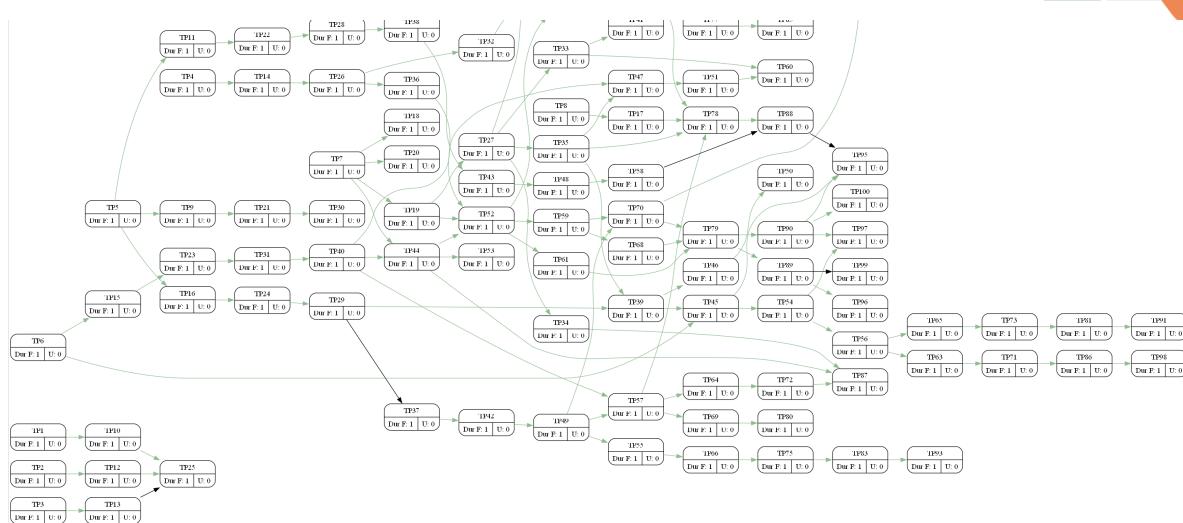
- The start of a job is equal to the start of the earliest task of the job
- The end of a job is equal to the latest end of any of its tasks
- Also called: the job *spans* its tasks
- Sometimes very simple
 - Start of job is start of first process step
 - End of job is end of last process step
 - But,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

An Example of a Simple Process



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

An Example of a More Complex Process

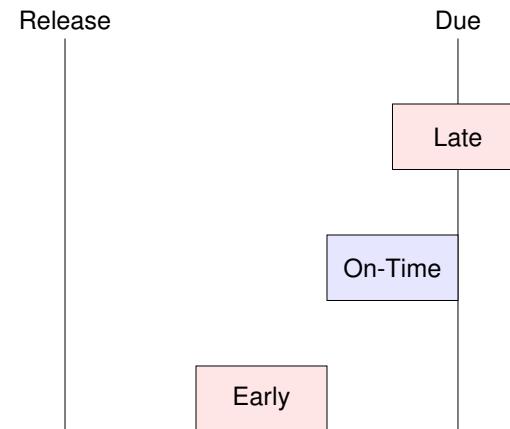


- There is no clear first or last process step

Jobs: Release and Due Dates



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



Relations between Jobs



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

More Complexity



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

Intermediate products



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

Raw materials



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

Bill of Materials (BoM), Bill of Processes



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

Problem Classification



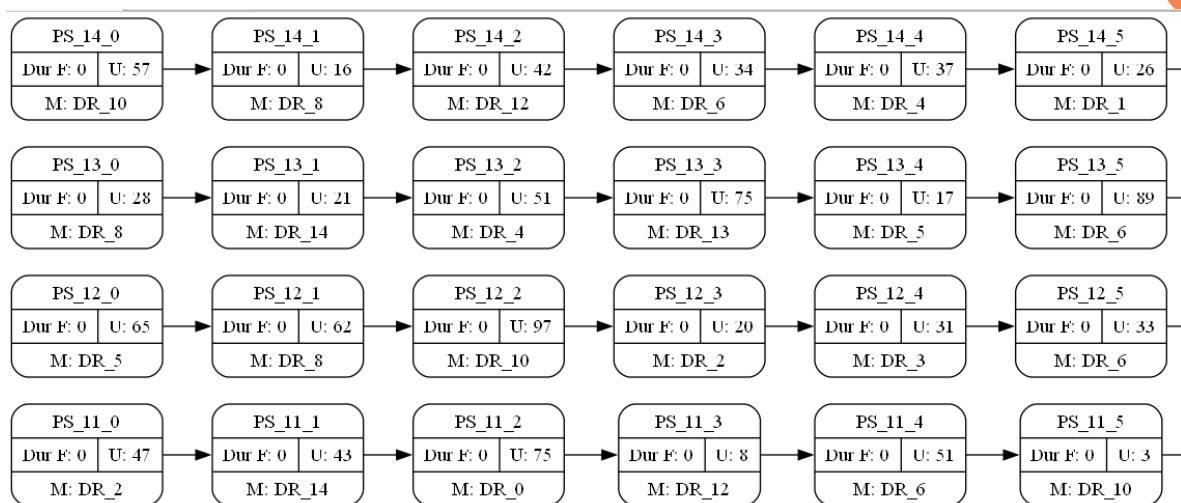
- Most real-world problems are messy, with many special conditions and exceptions
- Academic research prefers well-structured problems
- Scheduling research often focuses on well-structured problem types
 - Easier to understand
 - Possible to exploit structure
 - Easier to compare results
- A small number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

Job-Shop



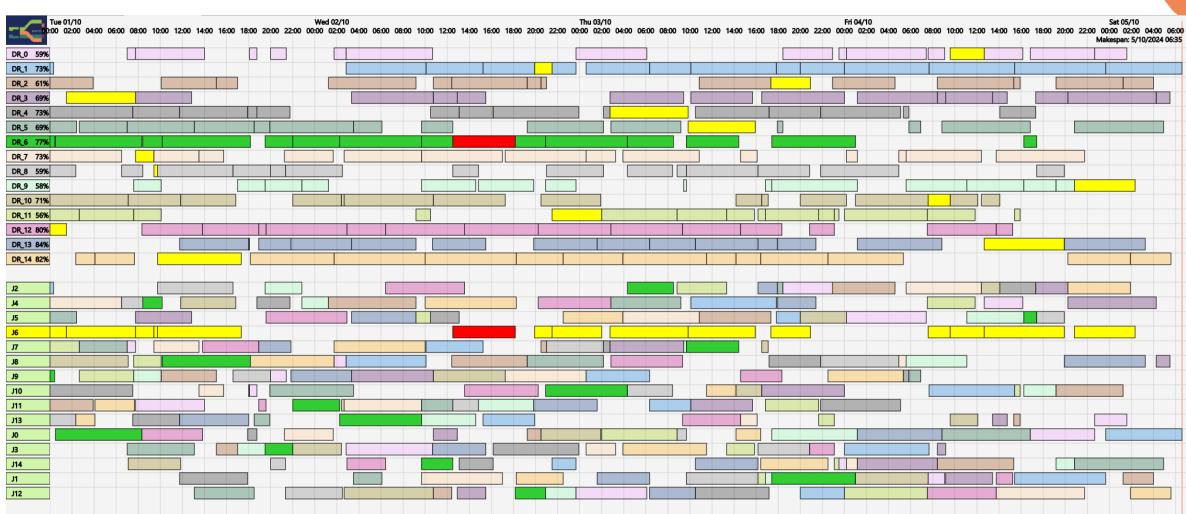
- Consists of a number of jobs and a number of machines
- Each job visits each machine, but possibly in a different order, depending on process
- Tasks of a job are linked as a precedence chain
- Objective is to minimize overall end, the *makespan*

Example Job-Shop Process



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

Example Job-Shop Solution



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

Flow-Shop

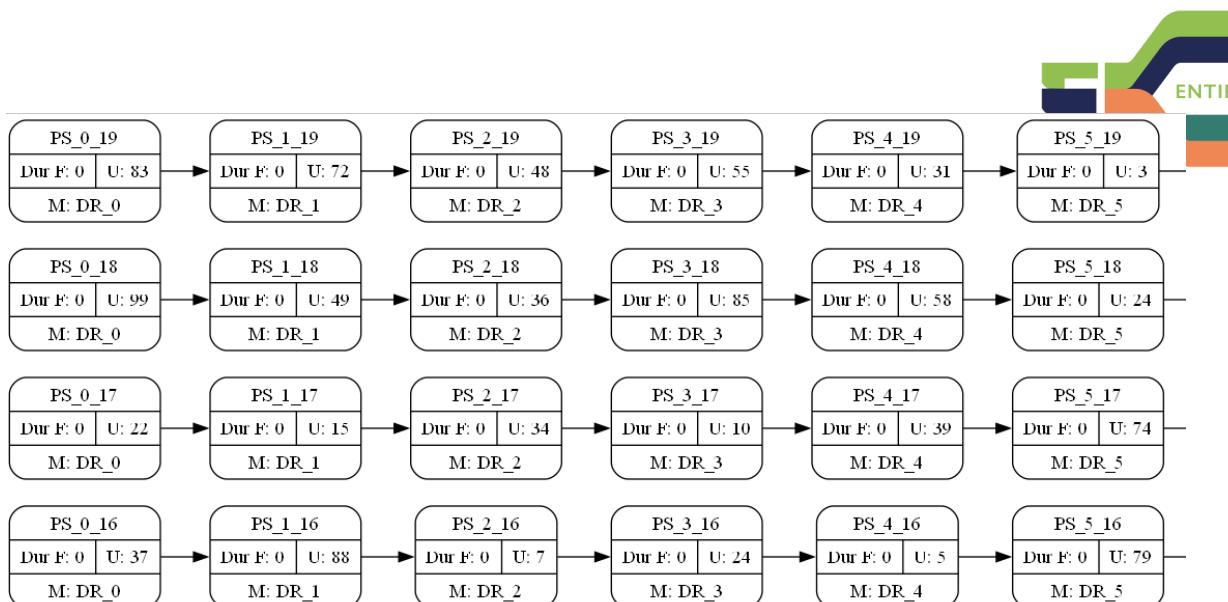


- Consists of a number of jobs and a number of machines
- Each job visits each machine, all jobs in the same order
- Tasks of a job are linked in a precedence chain
- Objective is to minimize overall end, the *makespan*

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Production Scheduling

Slide 66



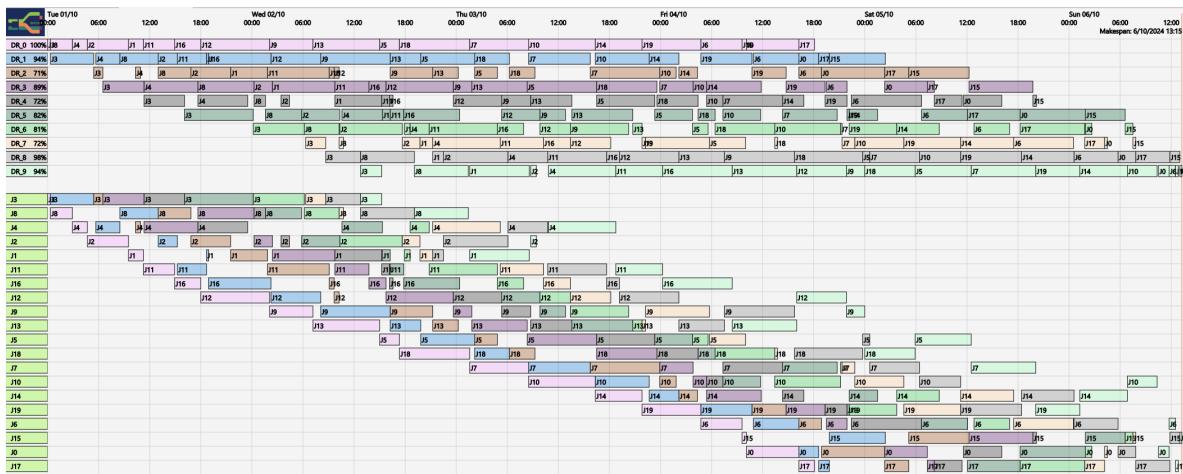
- Note that each process visits the machines in order DR_0, DR_1, ...

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Slide 67

Example Flow-Shop Solution



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

Open-Shop



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

Open Shop Example Process



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

▼ Processes	PS_0_6
process_0	Dur F: 0 U: 56
process_1	M: DR_4
process_2	
process_3	
process_4	
process_5	
process_6	

▼ Processes	PS_0_5
process_0	Dur F: 0 U: 92
process_1	M: DR_5
process_2	
process_3	
process_4	
process_5	
process_6	

▼ Processes	PS_0_4
process_0	Dur F: 0 U: 71
process_1	M: DR_0
process_2	
process_3	
process_4	
process_5	
process_6	

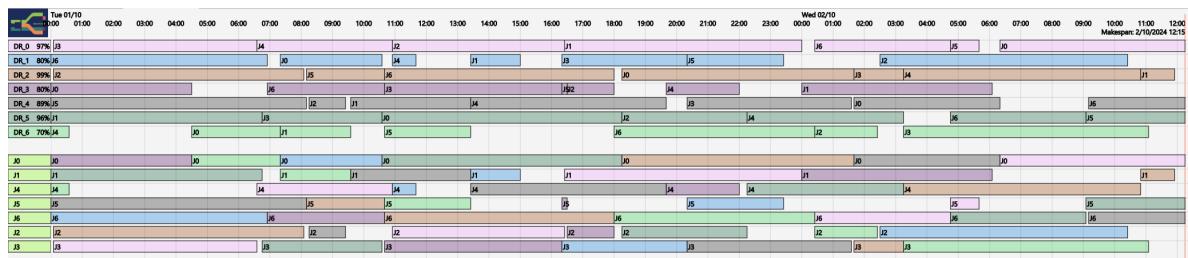
▼ Processes	PS_0_3
process_0	Dur F: 0 U: 34
process_1	M: DR_6
process_2	
process_3	
process_4	
process_5	
process_6	

▼ Processes	PS_0_2
process_0	Dur F: 0 U: 54
process_1	M: DR_3
process_2	
process_3	
process_4	
process_5	
process_6	

▼ Processes	PS_0_1
process_0	Dur F: 0 U: 39
process_1	M: DR_1
process_2	
process_3	
process_4	
process_5	
process_6	

▼ Processes	PS_0_0
process_0	Dur F: 0 U: 89
process_1	M: DR_2
process_2	
process_3	
process_4	
process_5	
process_6	

Open-Shop Example Solution



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

Resource Constrained Project Scheduling Problem (RCPSP)



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



$\alpha/\beta/\gamma$ Notation

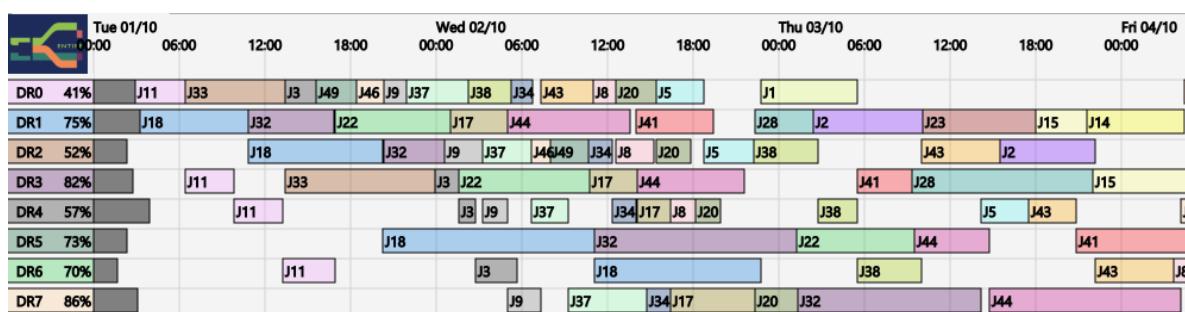
- The previous classes are good for research, but not very practical
- General scheme to describe problem type introduced in 1979
- Based on three parameters
 - α resource structure, stages
 - β temporal relations
 - γ objective
- $P2/r_j, \bar{d}_j/C_{\max}$: One stage, two identical parallel machines,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

Visualization



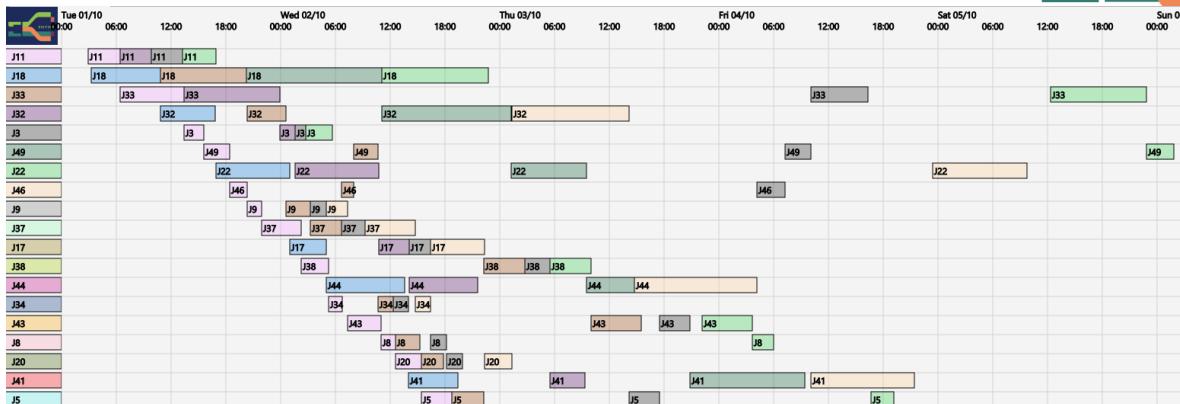
- Visualization is key to present and to understand results
- Many different ways to give an overview of schedule, and highlight problems
- Some diagrams types are used a lot, and are provided in our generic scheduling tool
- Customization is key

Machine Gantt Chart



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

Job Gantt Chart



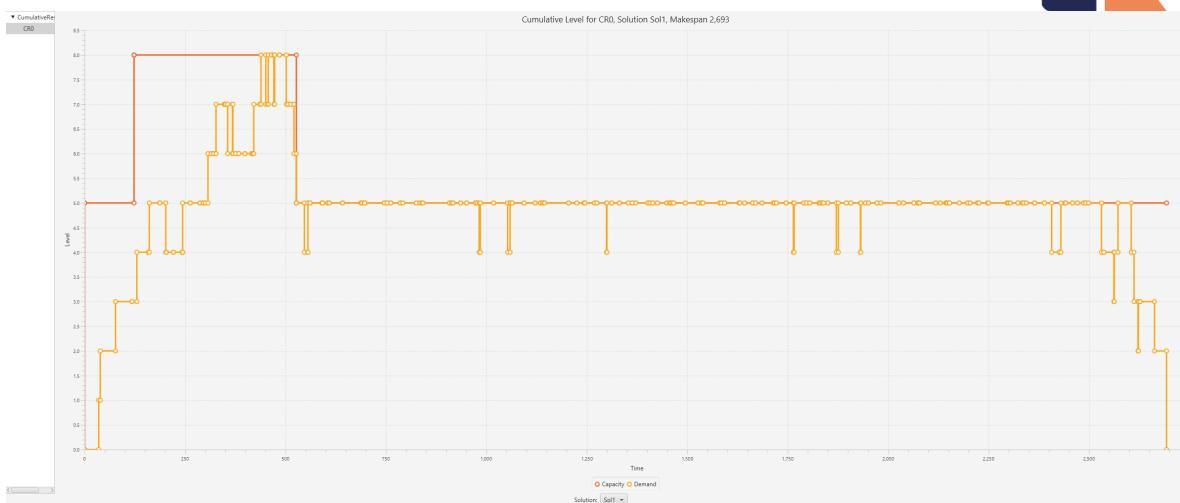
- Shows all tasks of a job in one line
- Only works for single chain of process steps
- Possible display of earliness, lateness
- Optional display of waiting and transport times

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Slide 77

Cumulative Resource Chart



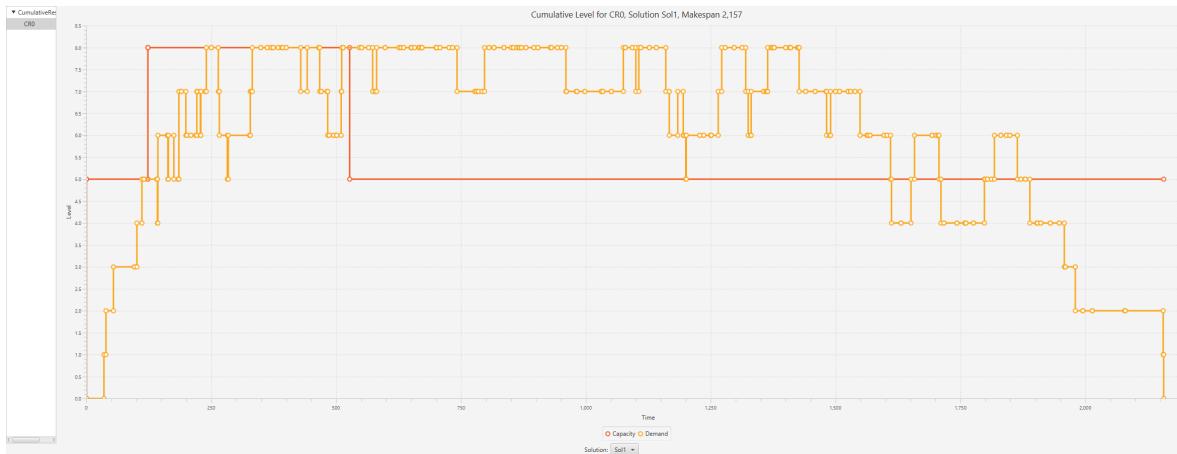
- Shows resource utilization of cumulative resource over time
- Utilization should be below capacity profile
- Unless we relax the cumulative resource constraint

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Slide 78

Cumulative Resource Constraint Relaxed

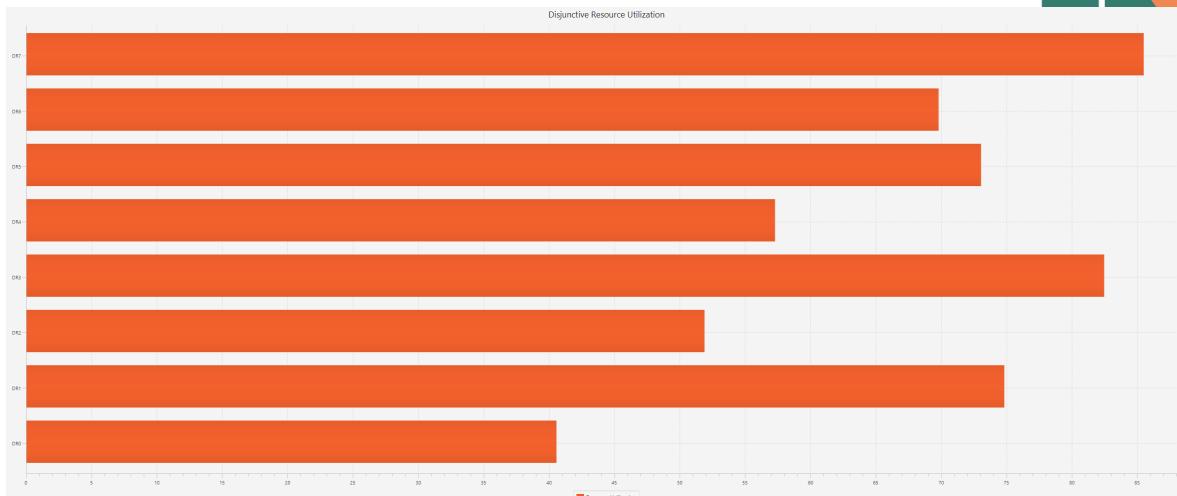


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Slide 79

Resource Utilization



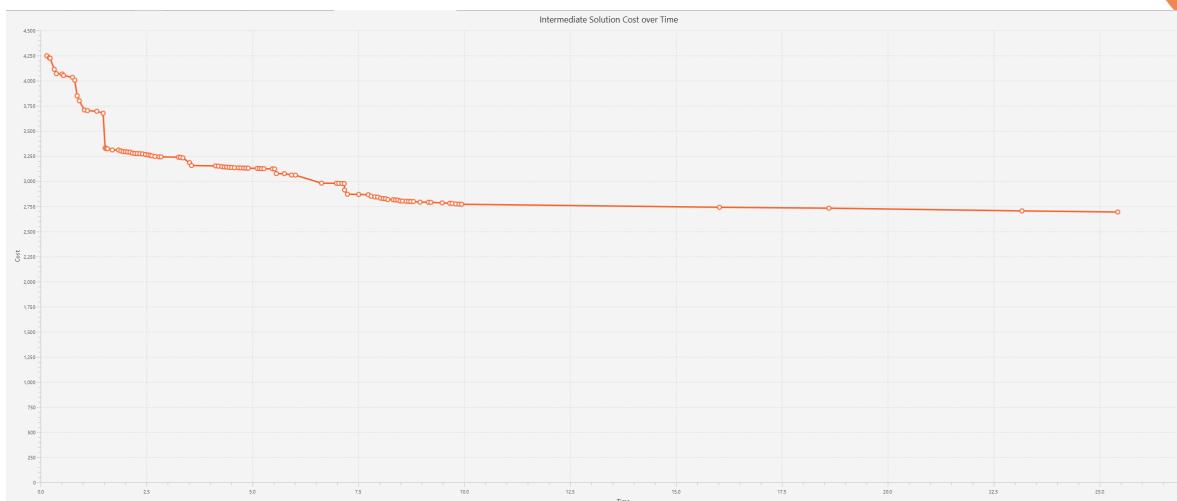
- Shows utilization of machines as percentage of active time
- Helpful to identify bottleneck machines
- Information also shown in Machine Gantt

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Slide 80

Intermediate Solutions



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

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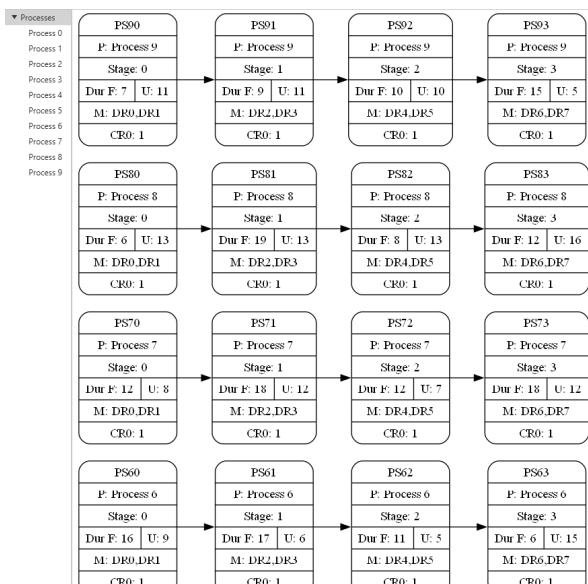
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Slide 81

Process Diagram



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

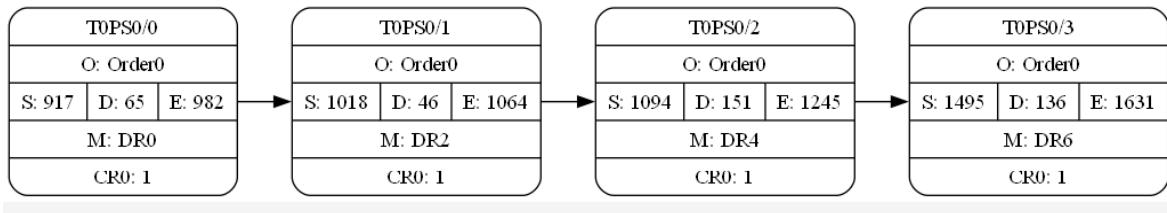


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Slide 82

PERT Chart(Program Evaluation Review Technique)



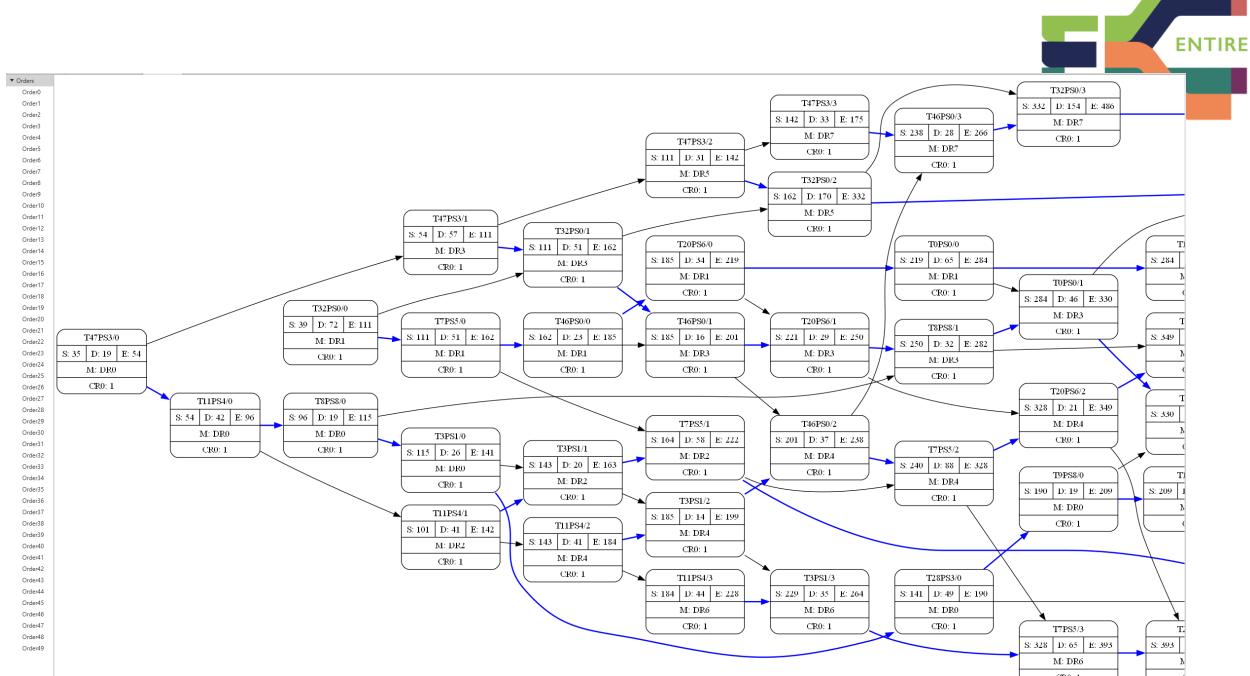
- Show details of job as a graph
 - Useful if task graph is not a chain
 - Often used in project management

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Slide 83

PERT Charts become Confusing Quite Quickly



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

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Slide 84

Summary



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



Part III

Machines and Resources

Key Points



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Slide 88

Summary



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Production Scheduling

Slide 95



Part IV

Experiments

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Production Scheduling

Slide 96



Key Points

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ENTIRE EDIH

Production Scheduling

Slide 97

Summary



-

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Production Scheduling

Slide 105



Part V

Objectives

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Production Scheduling

Slide 106

Key Points



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ENTIRE EDIH

Production Scheduling

Slide 107

Summary



-

ENTIRE EDIH

Production Scheduling

Slide 112



Part VI

Advanced Concepts

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Production Scheduling

Slide 113



Key Points

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Production Scheduling

Slide 114

Summary



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Production Scheduling

Slide 124



Part VII

Case Studies

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Production Scheduling

Slide 125

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

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Production Scheduling

Slide 130

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

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Production Scheduling

Slide 131

Product List (Sorted by Daily Sales)



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

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Production Scheduling

Slide 132

Product List (Sorted by Days Cover)



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

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Production Scheduling

Slide 133

Product List (Sorted by Safety Alert)

Product X														NTIRE	
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			
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			

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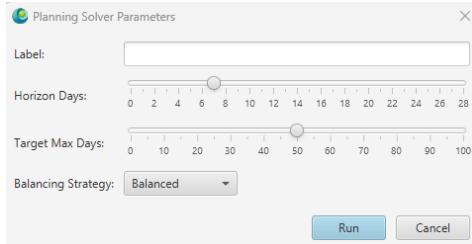
Slide 134

Setup Matrix



Row		pt1	pt2	pt3	pt4	pt5	pt6	pt7	pt8	pt9	pt10	pt11	pt12	pt13	pt14	pt15	pt16	pt17	pt18	pt19	pt20	pt21	pt22	pt23	pt24	pt25	pt26	pt27	pt28	pt29	pt30	pt31	pt32	pt33	pt34	pt35	pt36	pt37	pt38	pt39	pt40	pt41	pt42	pt43	pt44	pt45	pt46	pt47	pt48	pt49	pt50	pt51	pt52	pt53	pt54	pt55	pt56	pt57	pt58	pt59	pt60	pt61	pt62	pt63	pt64	pt65	pt66	pt67	pt68	pt69	pt70	pt71	pt72	pt73	pt74	pt75	pt76	pt77	pt78	pt79	pt80	pt81	pt82	pt83	pt84	pt85	pt86	pt87	pt88	pt89	pt90	pt91	pt92	pt93	pt94	pt95	pt96	pt97	pt98	pt99	pt100	pt101	pt102	pt103	pt104	pt105	pt106	pt107	pt108	pt109	pt110	pt111	pt112	pt113	pt114	pt115	pt116	pt117	pt118	pt119	pt120	pt121	pt122	pt123	pt124	pt125	pt126	pt127	pt128	pt129	pt130	pt131	pt132	pt133	pt134	pt135	pt136	pt137	pt138	pt139	pt140	pt141	pt142	pt143	pt144	pt145	pt146	pt147	pt148	pt149	pt150	pt151	pt152	pt153	pt154	pt155	pt156	pt157	pt158	pt159	pt160	pt161	pt162	pt163	pt164	pt165	pt166	pt167	pt168	pt169	pt170	pt171	pt172	pt173	pt174	pt175	pt176	pt177	pt178	pt179	pt180	pt181	pt182	pt183	pt184	pt185	pt186	pt187	pt188	pt189	pt190	pt191	pt192	pt193	pt194	pt195	pt196	pt197	pt198	pt199	pt200	pt201	pt202	pt203	pt204	pt205	pt206	pt207	pt208	pt209	pt210	pt211	pt212	pt213	pt214	pt215	pt216	pt217	pt218	pt219	pt220	pt221	pt222	pt223	pt224	pt225	pt226	pt227	pt228	pt229	pt230	pt231	pt232	pt233	pt234	pt235	pt236	pt237	pt238	pt239	pt240	pt241	pt242	pt243	pt244	pt245	pt246	pt247	pt248	pt249	pt250	pt251	pt252	pt253	pt254	pt255	pt256	pt257	pt258	pt259	pt260	pt261	pt262	pt263	pt264	pt265	pt266	pt267	pt268	pt269	pt270	pt271	pt272	pt273	pt274	pt275	pt276	pt277	pt278	pt279	pt280	pt281	pt282	pt283	pt284	pt285	pt286	pt287	pt288	pt289	pt290	pt291	pt292	pt293	pt294	pt295	pt296	pt297	pt298	pt299	pt300	pt301	pt302	pt303	pt304	pt305	pt306	pt307	pt308	pt309	pt310	pt311	pt312	pt313	pt314	pt315	pt316	pt317	pt318	pt319	pt320	pt321	pt322	pt323	pt324	pt325	pt326	pt327	pt328	pt329	pt330	pt331	pt332	pt333	pt334	pt335	pt336	pt337	pt338	pt339	pt340	pt341	pt342	pt343	pt344	pt345	pt346	pt347	pt348	pt349	pt350	pt351	pt352	pt353	pt354	pt355	pt356	pt357	pt358	pt359	pt360	pt361	pt362	pt363	pt364	pt365	pt366	pt367	pt368	pt369	pt370	pt371	pt372	pt373	pt374	pt375	pt376	pt377	pt378	pt379	pt380	pt381	pt382	pt383	pt384	pt385	pt386	pt387	pt388	pt389	pt390	pt391	pt392	pt393	pt394	pt395	pt396	pt397	pt398	pt399	pt400	pt401	pt402	pt403	pt404	pt405	pt406	pt407	pt408	pt409	pt410	pt411	pt412	pt413	pt414	pt415	pt416	pt417	pt418	pt419	pt420	pt421	pt422	pt423	pt424	pt425	pt426	pt427	pt428	pt429	pt430	pt431	pt432	pt433	pt434	pt435	pt436	pt437	pt438	pt439	pt440	pt441	pt442	pt443	pt444	pt445	pt446	pt447	pt448	pt449	pt450	pt451	pt452	pt453	pt454	pt455	pt456	pt457	pt458	pt459	pt460	pt461	pt462	pt463	pt464	pt465	pt466	pt467	pt468	pt469	pt470	pt471	pt472	pt473	pt474	pt475	pt476	pt477	pt478	pt479	pt480	pt481	pt482	pt483	pt484	pt485	pt486	pt487	pt488	pt489	pt490	pt491	pt492	pt493	pt494	pt495	pt496	pt497	pt498	pt499	pt500	pt501	pt502	pt503	pt504	pt505	pt506	pt507	pt508	pt509	pt510	pt511	pt512	pt513	pt514	pt515	pt516	pt517	pt518	pt519	pt520	pt521	pt522	pt523	pt524	pt525	pt526	pt527	pt528	pt529	pt530	pt531	pt532	pt533	pt534	pt535	pt536	pt537	pt538	pt539	pt540	pt541	pt542	pt543	pt544	pt545	pt546	pt547	pt548	pt549	pt550	pt551	pt552	pt553	pt554	pt555	pt556	pt557	pt558	pt559	pt560	pt561	pt562	pt563	pt564	pt565	pt566	pt567	pt568	pt569	pt570	pt571	pt572	pt573	pt574	pt575	pt576	pt577	pt578	pt579	pt580	pt581	pt582	pt583	pt584	pt585	pt586	pt587	pt588	pt589	pt590	pt591	pt592	pt593	pt594	pt595	pt596	pt597	pt598	pt599	pt600	pt601	pt602	pt603	pt604	pt605	pt606	pt607	pt608	pt609	pt610	pt611	pt612	pt613	pt614	pt615	pt616	pt617	pt618	pt619	pt620	pt621	pt622	pt623	pt624	pt625	pt626	pt627	pt628	pt629	pt630	pt631	pt632	pt633	pt634	pt635	pt636	pt637	pt638	pt639	pt640	pt641	pt642	pt643	pt644	pt645	pt646	pt647	pt648	pt649	pt650	pt651	pt652	pt653	pt654	pt655	pt656	pt657	pt658	pt659	pt660	pt661	pt662	pt663	pt664	pt665	pt666	pt667	pt668	pt669	pt670	pt671	pt672	pt673	pt674	pt675	pt676	pt677	pt678	pt679	pt680	pt681	pt682	pt683	pt684	pt685	pt686	pt687	pt688	pt689	pt690	pt691	pt692	pt693	pt694	pt695	pt696	pt697	pt698	pt699	pt700	pt701	pt702	pt703	pt704	pt705	pt706	pt707	pt708	pt709	pt710	pt711	pt712	pt713	pt714	pt715	pt716	pt717	pt718	pt719	pt720	pt721	pt722	pt723	pt724	pt725	pt726	pt727	pt728	pt729	pt730	pt731	pt732	pt733	pt734</

Running the Planning Solver

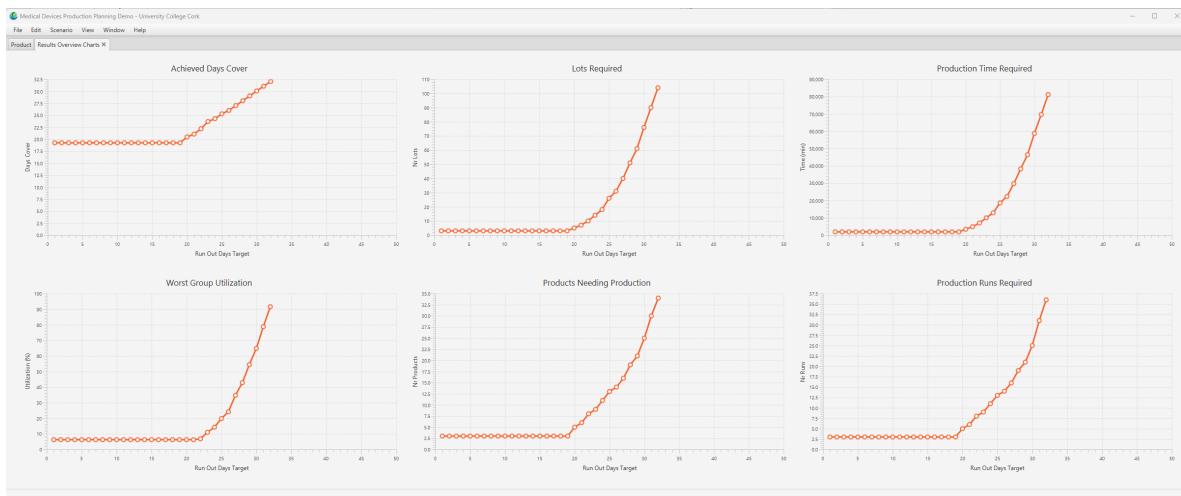


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Slide 136

Planner Results

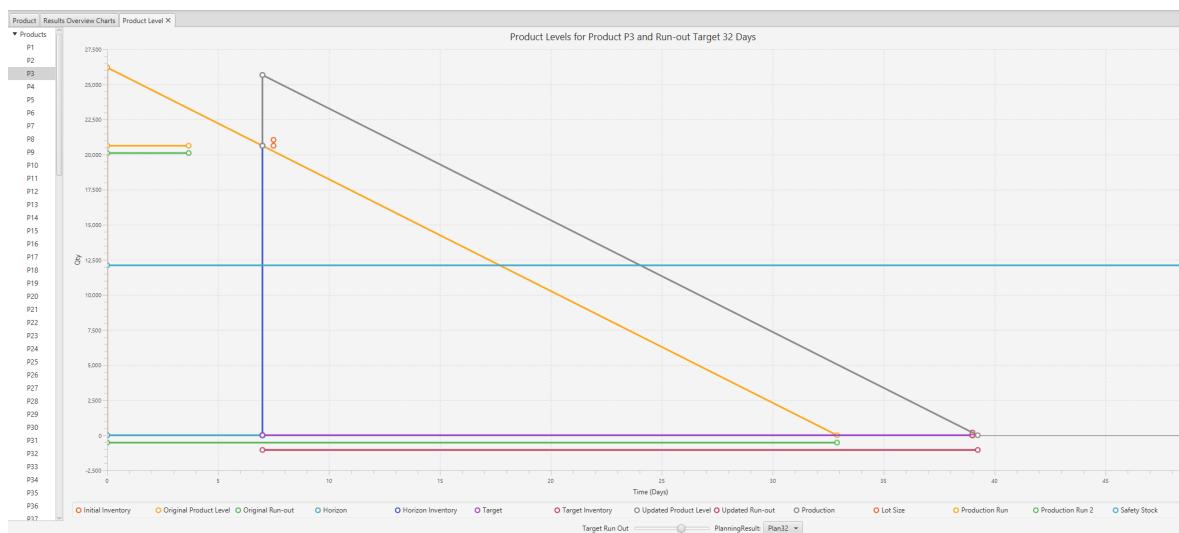


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Slide 137

Product Level Chart for Product P3

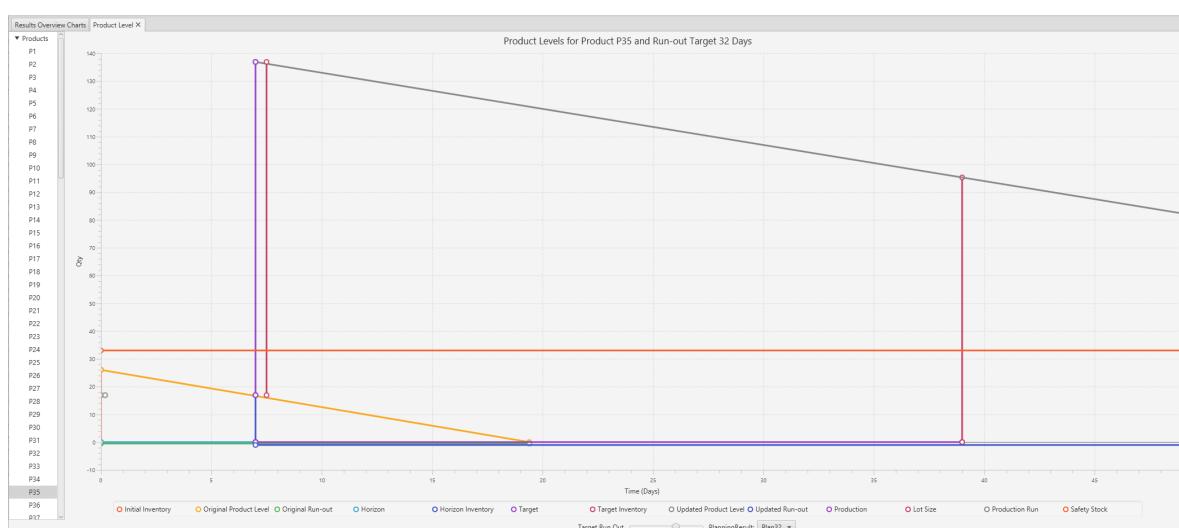


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Slide 138

Product Level Chart for Product P35



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Slide 139

Scheduled Production Runs



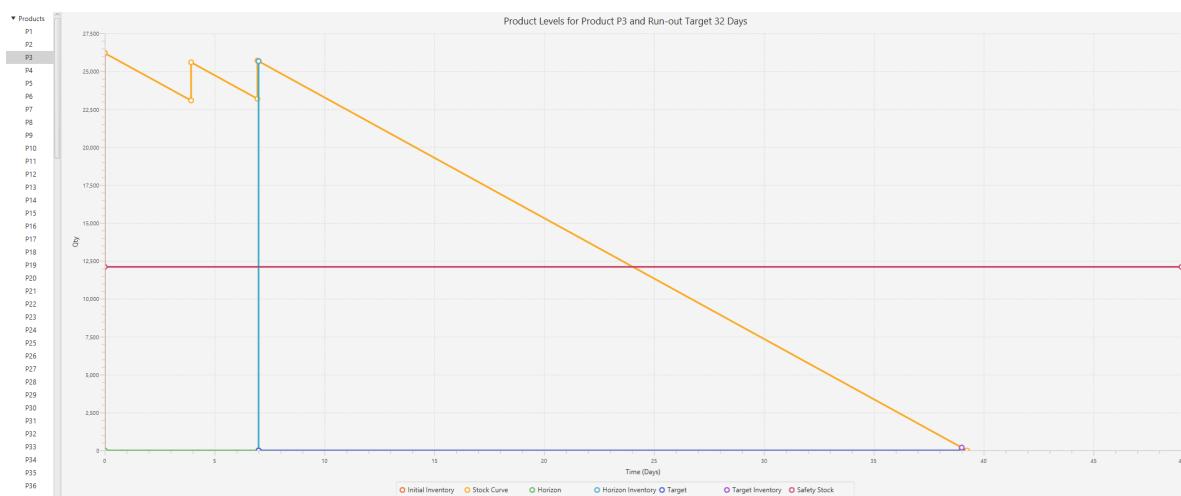
Product	Results Overview Charts	Product Level	Scheduled Production Level	ProductionRun X					
Name	Product	NrLots	Qty	Due	Start	End	Duration	StartDay	EndDay
job3_0	P3	6	2,520	10,080	366	5,658	5,292	0.25	3.93
job3_1	P3	6	2,520	10,080	4,712	10,004	5,292	3.27	6.95
job4_0	P4	3	1,260	10,080	0	2,520	2,520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

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Slide 140

Production Level Chart for Product P3

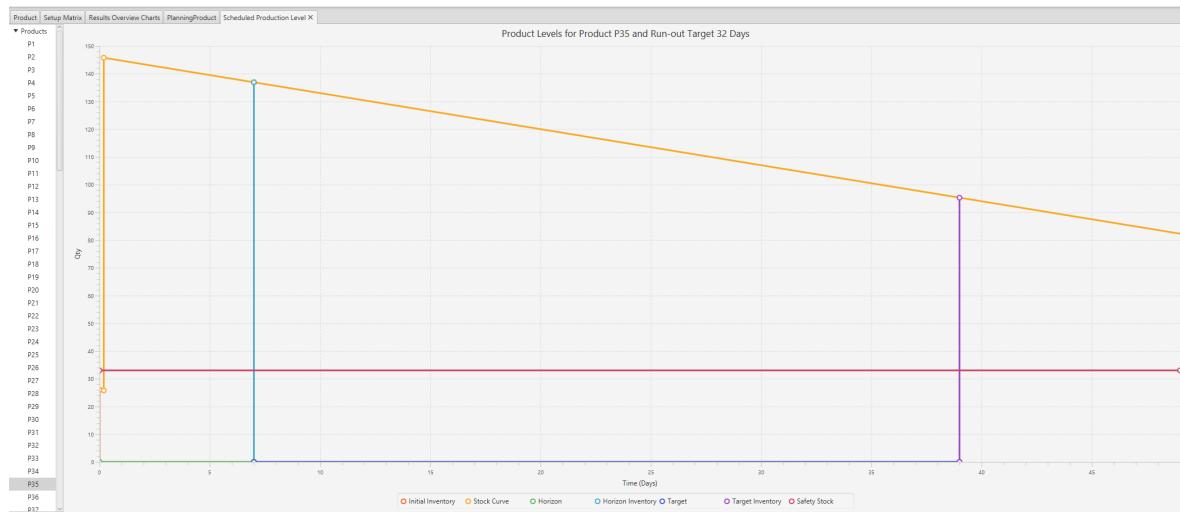


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Slide 141

Production Level Chart for Product P35

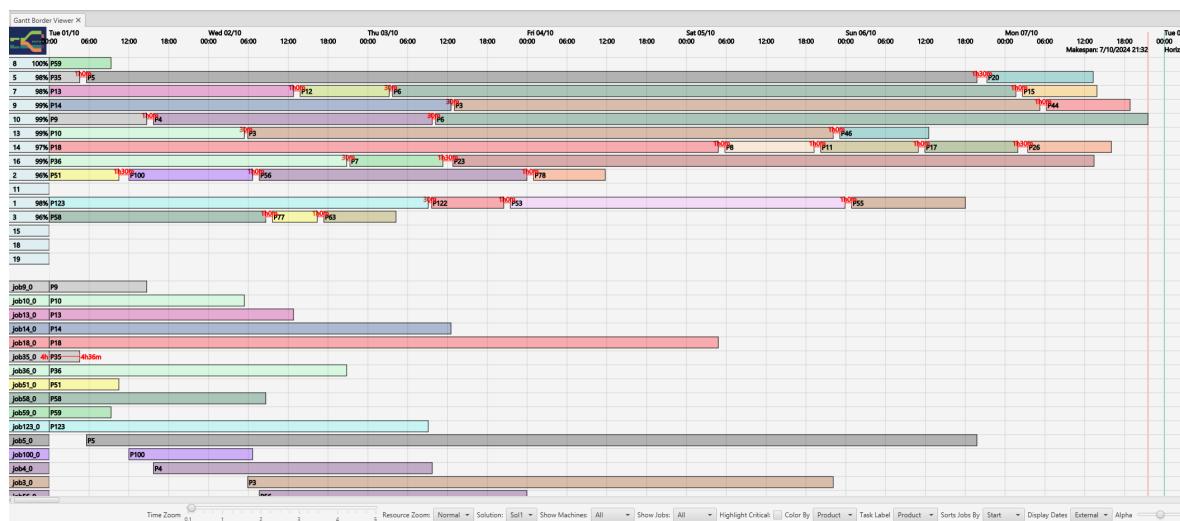


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Slide 142

Detailed Schedule

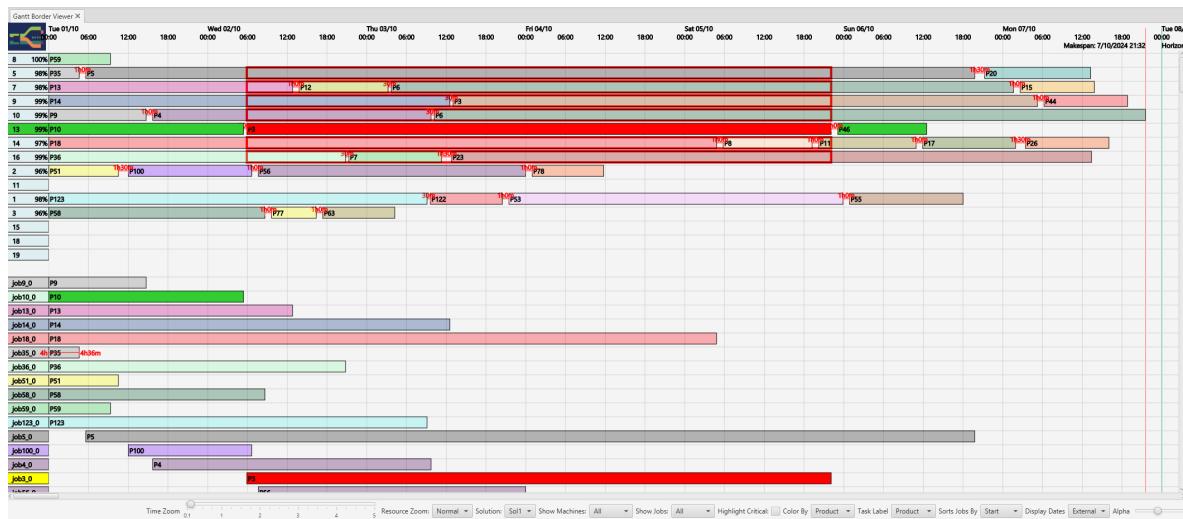


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Slide 143

Showing Alternative Machines in Gantt Chart



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Slide 144

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

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Production Scheduling

Slide 145



Part IX

Assembly Line Balancing Case Study

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Production Scheduling

Slide 146



Key Points

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Production Scheduling

Slide 147

Problem Description



ENTIRE EDIH

Production Scheduling

Slide 148

Feature Overview



ENTIRE EDIH

Production Scheduling

Slide 149

Summary



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Production Scheduling

Slide 150



Part X

Test Scheduling Case Study

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Production Scheduling

Slide 151

Key Points



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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



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Slide 154

Summary



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Production Scheduling

Slide 155



Part XI

Factory Design Case Study

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Production Scheduling

Slide 156



Key Points

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ENTIRE EDIH

Production Scheduling

Slide 157

Problem Description



ENTIRE EDIH

Production Scheduling

Slide 158

Feature Overview



ENTIRE EDIH

Production Scheduling

Slide 159

Summary



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Production Scheduling

Slide 160



Part XII

Oven Scheduling Case Study

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Production Scheduling

Slide 161

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



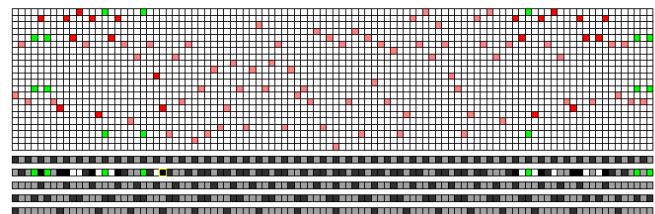
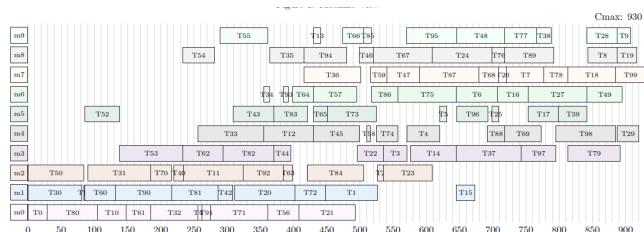
- Often the long-term business objectives are not visible in the operational decision problem
- We optimize a short-term objective without understanding the impact in the long term
- What choices should we make in short-term to improve overall result?
- Especially important when future data not yet visible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



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Production Scheduling

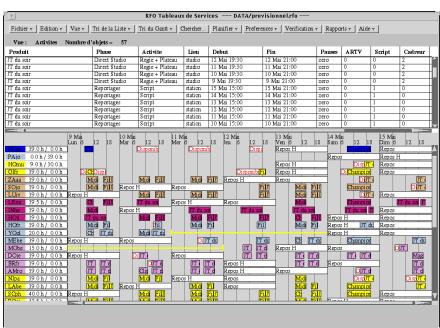
Slide 164

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



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Production Scheduling

Slide 165

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

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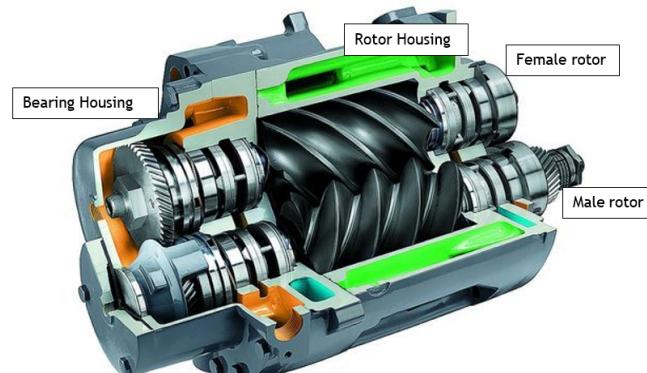
Production Scheduling

Slide 166

What does this look like in the real world?



Industrial Oven



Rotors in Compressor

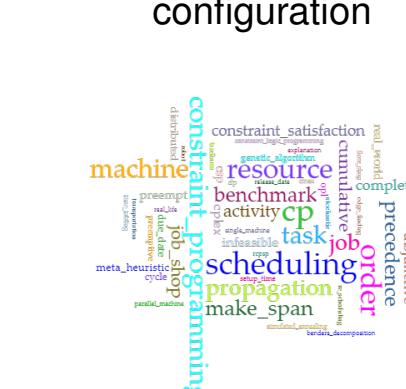
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Slide 167

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

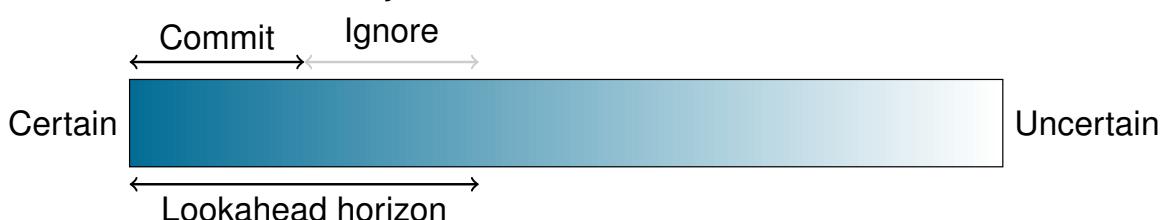
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Slide 168

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



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Production Scheduling

Slide 169

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

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

Resource Constraints



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

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

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

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

Limit stacking

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



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

Count how many jobs share stage j with job i

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

Limit how many tasks can be stacked together

$$\forall i \in N \forall j \in Q : \quad Z_{ij} < \text{maxStacked}$$

This should not work!



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

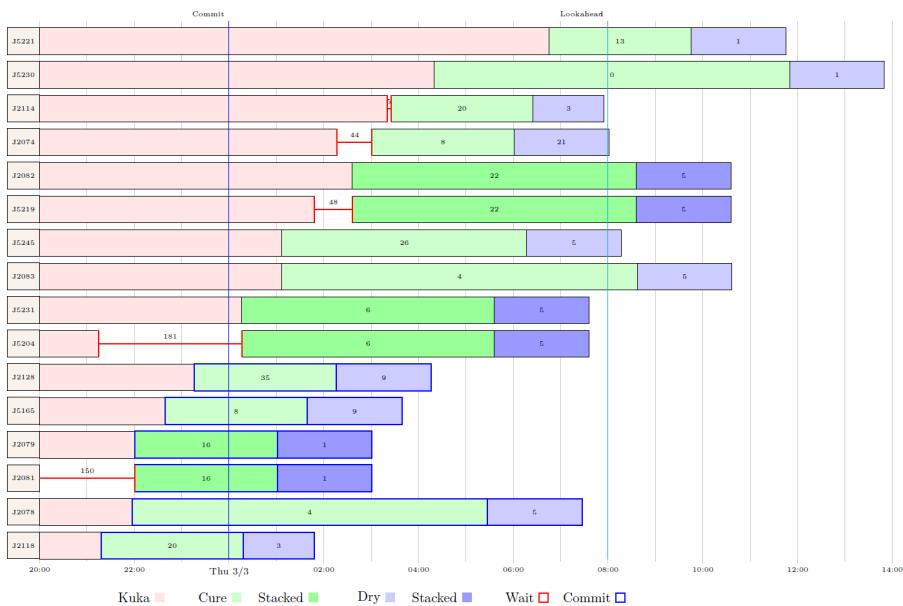
Compound Objective



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

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

Short-Term Schedule: Job View

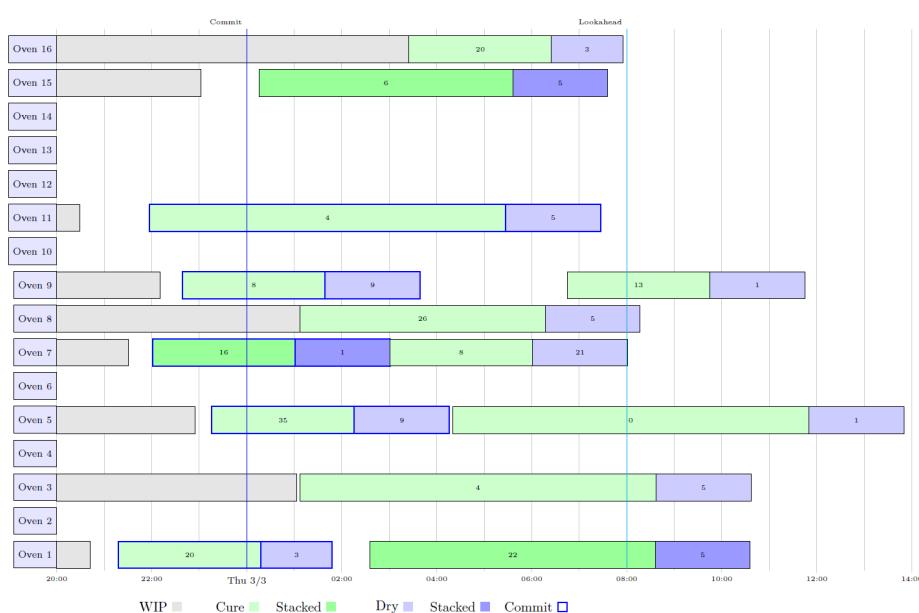


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Slide 176

Short Term Schedule: Resource View



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Slide 177

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?

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Production Scheduling

Slide 178

Long Term Schedule: Detailed Schedule

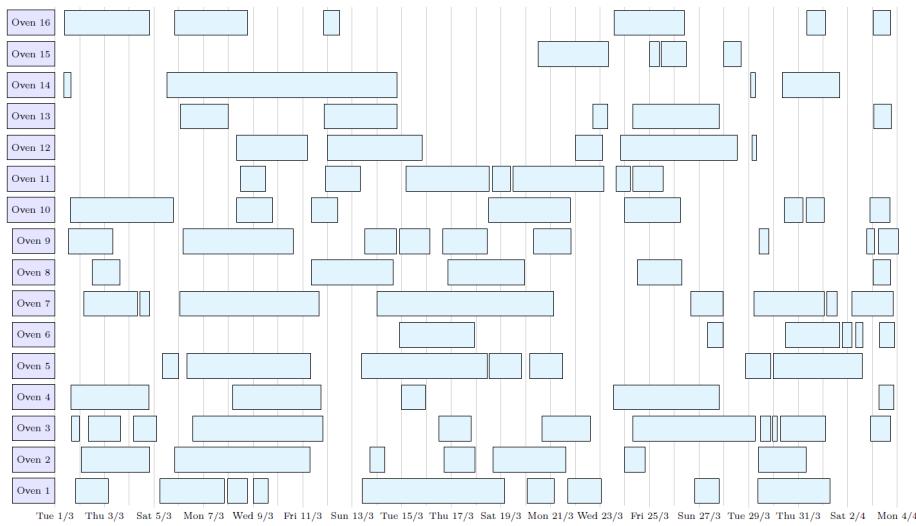


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Slide 179

Long Term Schedule: Abstracted Oven Runs



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Slide 180

Is that a good global schedule? KPIs



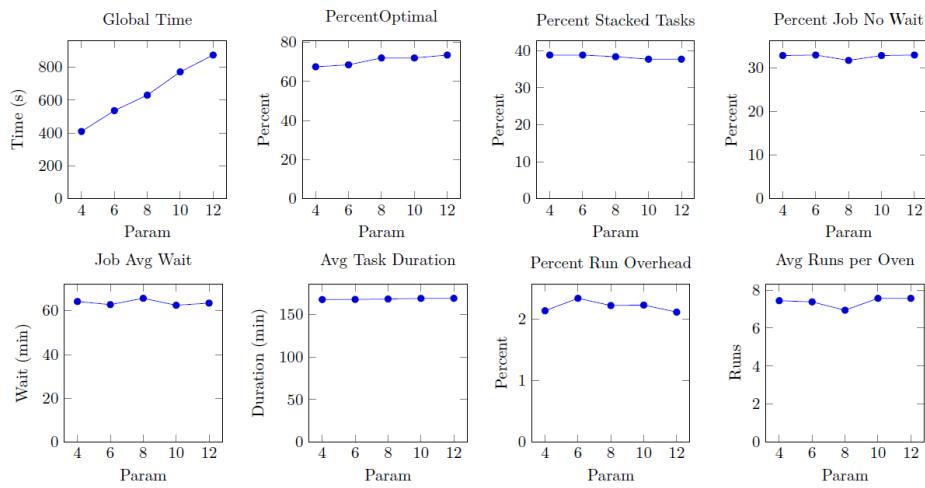
Name	Unit	Explanation
Global Time	Seconds	Total time for solving all sub problems
Nr Jobs	-	Total number of jobs scheduled
Nr Tasks	-	Total number of tasks scheduled
Percent Optimal	Percentage (0-100)	How many sub problems were solved to optimality
Percent Stacked Tasks	Percentage (0-100)	Percentage 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

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Production Scheduling

Slide 181

Impact of Lookahead Parameter

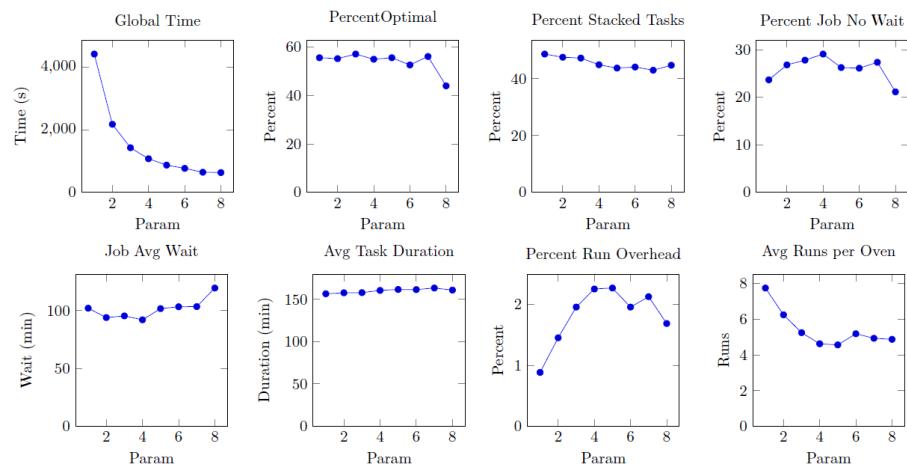


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Slide 182

Impact of CommitHorizon Parameter

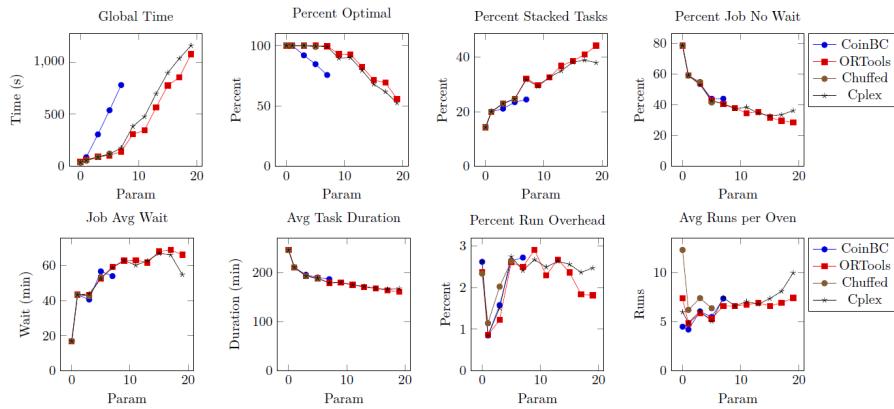


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Slide 183

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

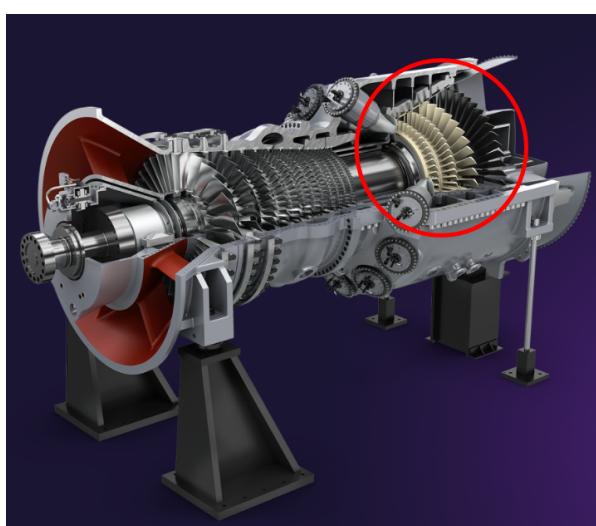
Blades and Vanes Production Case Study

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



A detailed 3D cutaway diagram of a gas turbine engine. A red circle highlights a specific area within the complex internal components, including multiple stages of blades and vanes.

Use Case Scenarios

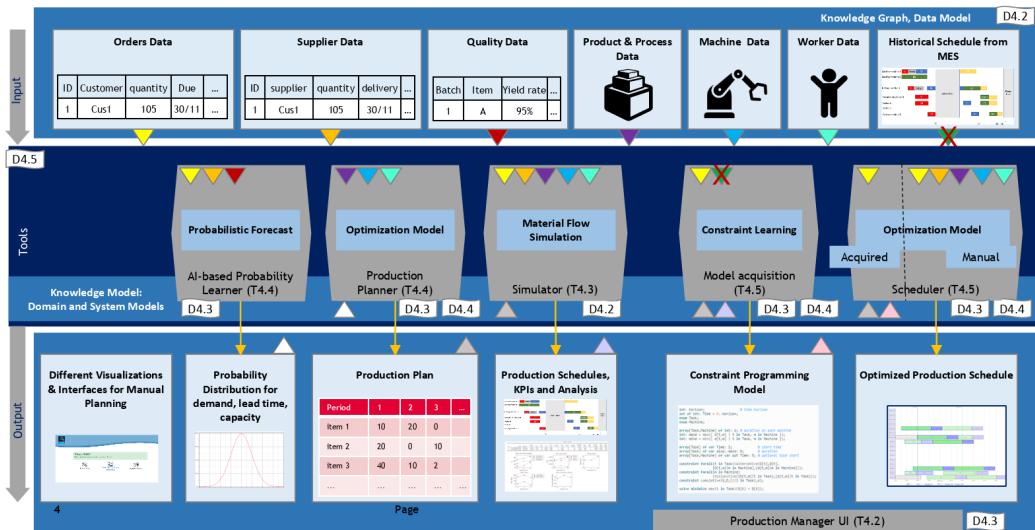
- Schedule *validation* of gas turbine blades and vanes manufacturing operations in Berlin plant
- Schedule *optimization* to manage short-term, mid-term and long-term load fluctuations
- Generate *Make-or-Buy proposals* for workload balancing within the manufacturing network

ASSISTANT Project Overview



Intelligent digital twin for process planning and scheduling

ASSISTANT



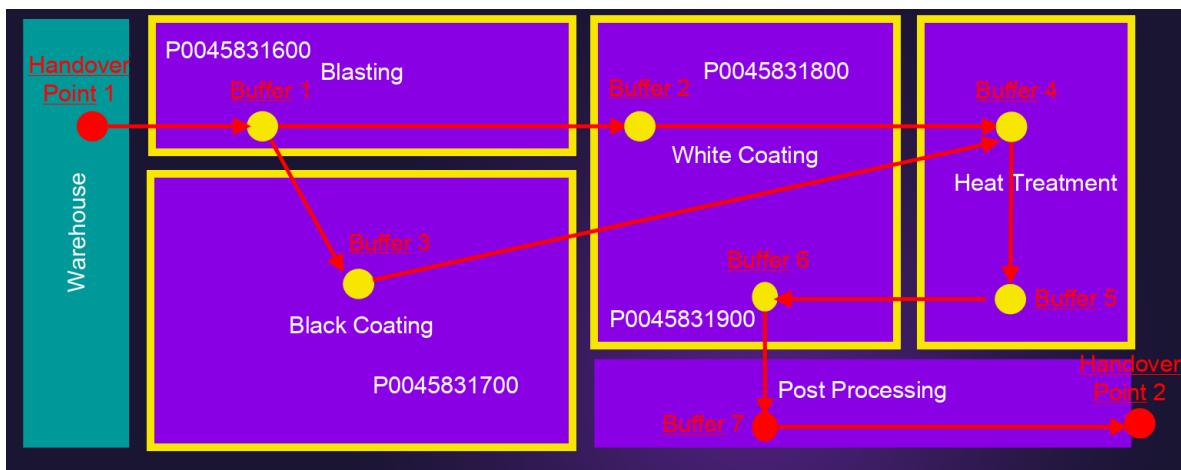
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Slide 190



SE Product Routing



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Slide 191

Test Datasets



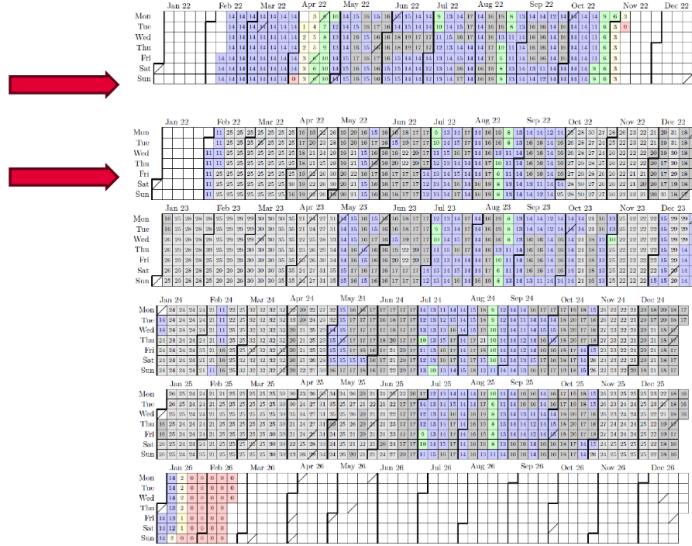
Full Scale Datasets

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

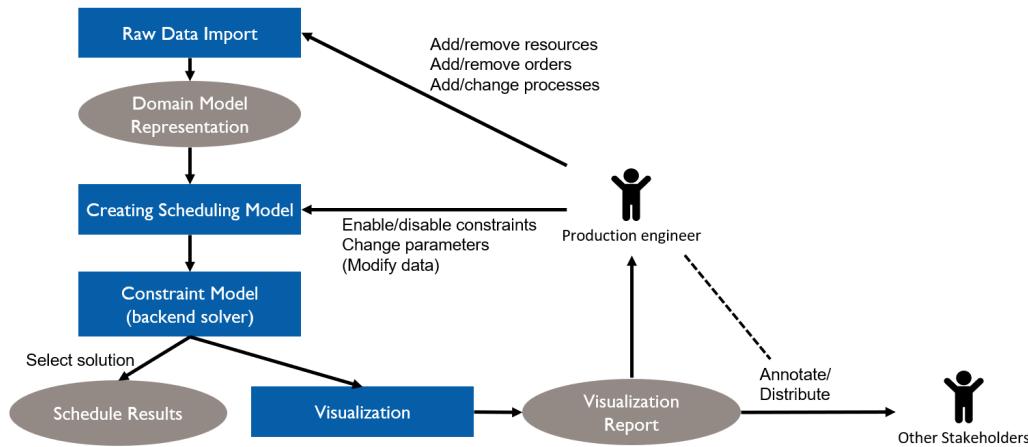
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Slide 192



Optimizer High Level Structure



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Slide 193

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

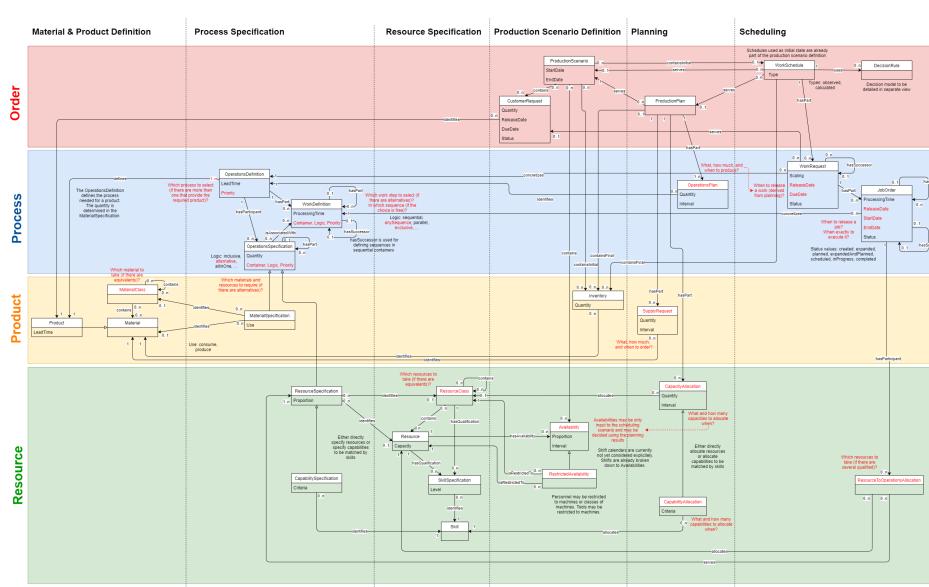
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Production Scheduling

Slide 194

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-ddTHH: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 1.0.0.0.0.0 format Hmmiss
Issue7	Major	t_Shift_Segments	1	2	TimeOnly not formatted correctly, found 1.0.0.0.0.0 format Hmmiss
Issue8	Major	t_Shift_Segments	2	1	TimeOnly not formatted correctly, found 1.2191667 format Hmmiss
Issue9	Major	t_Shift_Segments	2	2	TimeOnly not formatted correctly, found 1.2320383 format Hmmiss
Issue10	Major	t_Shift_Segments	3	1	TimeOnly not formatted correctly, found 1.4593333 format Hmmiss
Issue11	Major	t_Shift_Segments	3	2	TimeOnly not formatted correctly, found 1.4791667 format Hmmiss
Issue12	Major	t_Shift_Segments	4	1	TimeOnly not formatted correctly, found 1.5833333 format Hmmiss
Issue13	Major	t_Shift_Segments	4	2	TimeOnly not formatted correctly, found 1.9166667 format Hmmiss
Issue14	Major	t_Shift_Segments	5	1	TimeOnly not formatted correctly, found 1.9666667 format Hmmiss
Issue15	Major	t_Shift_Segments	5	2	TimeOnly not formatted correctly, found 1.677083 format Hmmiss
Issue16	Major	t_Shift_Segments	6	1	TimeOnly not formatted correctly, found 1.7708333 format Hmmiss
Issue17	Major	t_Shift_Segments	6	2	TimeOnly not formatted correctly, found 1.7916667 format Hmmiss
Issue18	Major	t_Shift_Segments	7	1	TimeOnly not formatted correctly, found 1.9166667 format Hmmiss
Issue19	Major	t_Shift_Segments	7	2	TimeOnly not formatted correctly, found 1.2500000 format Hmmiss
Issue20	Major	t_Shift_Segments	8	1	TimeOnly not formatted correctly, found 1.0000000 format Hmmiss
Issue21	Major	t_Shift_Segments	8	2	TimeOnly not formatted correctly, found 0.010417 format Hmmiss
Issue22	Major	t_Shift_Segments	9	1	TimeOnly not formatted correctly, found 1.0833333 format Hmmiss
Issue23	Major	t_Shift_Segments	9	2	TimeOnly not formatted correctly, found 0.104167 format Hmmiss
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

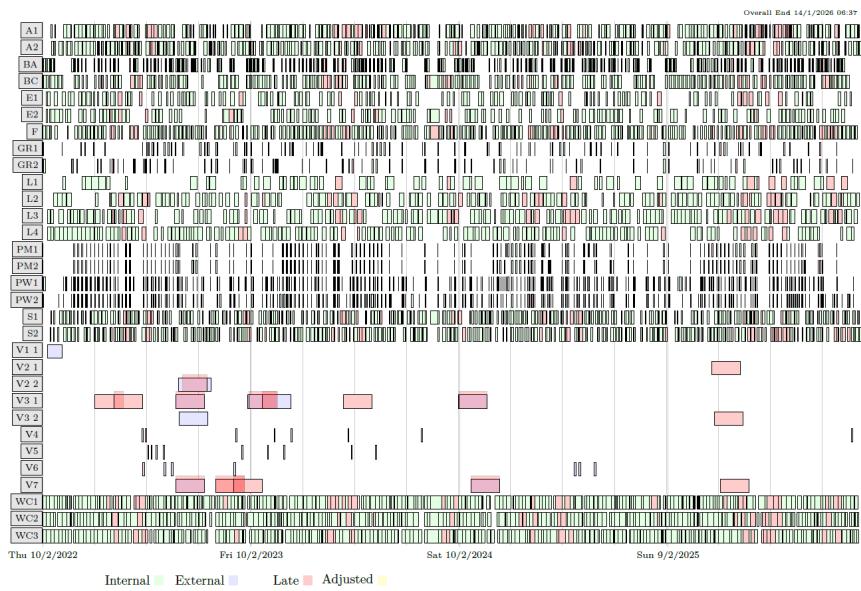


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Slide 195

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



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Slide 196

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

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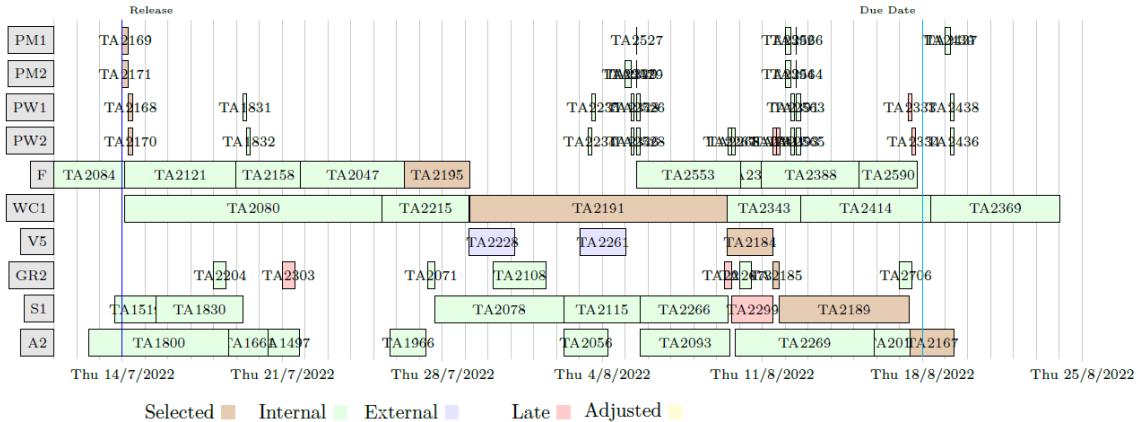
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Slide 197

Explaining Late Delivery



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



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Slide 198

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

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Slide 199

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

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Slide 200

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

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Slide 201



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>

A Survey of the Existing Literature



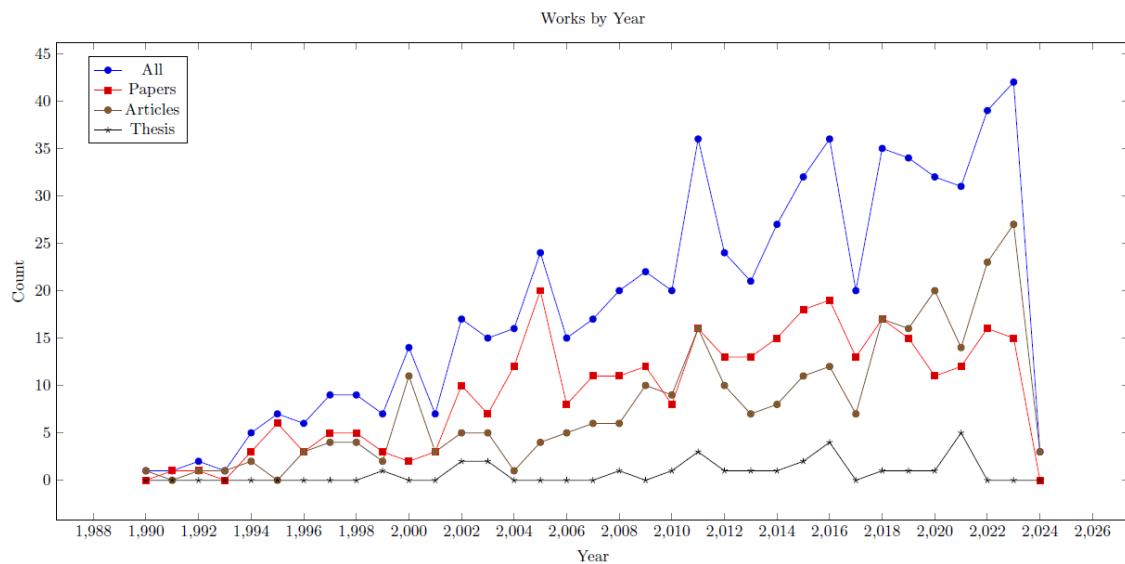
- Joint work with Cemallettin Ozturk, MTU
- What is out there
- Where to start
- Where to publish
- I'm interested in some specific topic, what is relevant

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/>

Overall Analysis (Based on 671 Works)

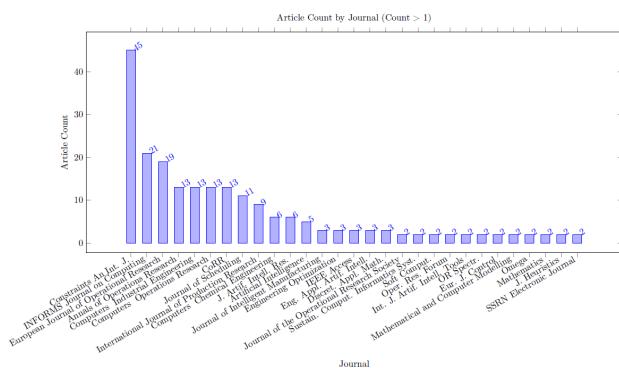
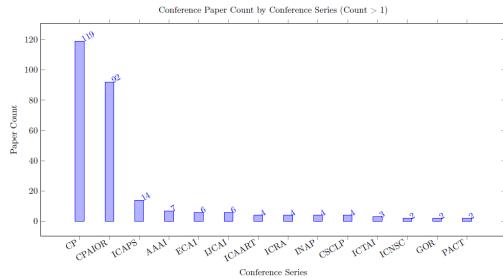


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Slide 207

Origin of Papers/Articles



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Slide 208

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. Tsaiure	Combining optimisation and simulation using logic-based Benders decomposition	Yes	[217]	2024	European Journal of Operational Research	15	0	26	1314	1490
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 Scido Nagano [Bruno A. Prata	A new two-stage constraint programming approach for a short 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	[9]	2023	Computers & Operations Research	12	0	46	1244	1500
Adelgren2023 Adelgren2023	N. Adelgren [Christos T. Maravillas	On the utility of prediction scheduling formulations for job shop keeping variables	Yes	[7]	2023	Computers & Industrial Engineering	12	0	43	1245	1501
AlsaifVP23 AlsaifVP23	S. Alsaif [Camino R. Vela [Juan José Palacios [Luis González-Rodríguez	Mathematical models and benchmarking for the fuzzy job shop scheduling problem	Yes	[8]	2023	Computers & Industrial Engineering	14	0	50	1246	1502
AkramNHSA23 AkramNHSA23	Bilal Omar Akrami [Nor Kamariah Noordin [F. Hashimi [Moh. Fadlee A. Rasid [Mustafa Ismael [Salman [Abdulrahman M. Abdullaheen	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. Garratia [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.	1	0	0	1287	1505
CzerniachowskaW223 CzerniachowskaW223	K. Czerniachowska [R. Wichniarek [K. Zywicki	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 [B. Torokhtei-Moghaddam [M. Foumani [S. Vahedi-Nouri	Scheduling of Multi-Robotic 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. Hamdi	Operating room scheduling by emphasizing human factors and dynamic decision-making styles: a constraint programming method	No	[242]	2023	International Journal of Systems Sciences: 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. Gur [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
IstikYA23 IstikYA23	Eyüp Ensar İstik [Seyda Topaloglu Yıldız [Özge Sattır Akpinar	Constraint programming models for the hybrid flow shop scheduling problem and its extensions	Yes	[321]	2023	Soft Comput.	28	0	127	1350	1512
JuvinalHL23a JuvinalHL23a	C. Juvinal [L. Housain [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.	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
LaborieO3 [369]	38	task, precedence, order, emax, 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, memory, transportation, manpower, due-time, setup-time, batch process, order, tardiness, flow-shop, job, make-span, re-scheduling, task, distributed	psplib, parallel machine, RCPSP	alternative constraint, cumulative, disjunctive, noOverlap, disjunction, span constraint, cycle, alwaysIn, endBeforeStart	C , Python, Gecode, C++, Java	CHIP, Ilog Solver, CPLEX, Ilog Scheduler, OPL, Choco Solver, CPO, Gurobi	semiconductor, railway, container terminal, satellite, robot, pipeline, aircraft, shipping line	chemical industry, petro-chemical 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	C++, OPL, CPLEX, OR-Tools, MiniZinc, Gurobi	Clflush, Cplex, OPL, CPLEX, OR-Tools, MiniZinc, Gurobi	semiconductor oven scheduling	electronics industry, steel industry, manufacturing industry	random instances, industrial partner, benchmark, instance generator, zenodo, real-life real-life	time-tabling	984	1514
LammaMM97 [377]	15	job-shop, resource, scheduling, precedence, order, task, job, distributed, job		disjunctive, circuit, disjunctive	C++, Prolog	ECLIPSe, OPL, CHIP	railway				1230	1760
LetortCB15 [385]	52	machine, make-span, job, precedence, resource, scheduling, task, order	psplib	cumulative, cycle, bin-packing	Java, Prolog	Choco Solver, CHIP, SICStus Prolog			generated instance, Roadef, benchmark, random instance	energetic reasoning, sweep, edge-finding	1110	1640
LiW08 [386]	18	precedence, activity, resource, completion-time, setup-times, make-span, scheduling, machine, preempt, job, job-shop, no preempt, job, re-scheduling, open-shop, due-date, task, order	RCPSP	disjunctive, cycle, bin-packing	OZ	Ilog Solver, OZ, CPLEX, ECLIPSe, OPL, CHIP			real-world		1178	1708
LiessM08 [388]	12	precedence, scheduling, machine, job, activity, precedence, job-shop, task, make-span, order, emax	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, Scheduler, Cplex	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	Optimization of Short-Term Underground Mine Planning Using Constraint Programming	CP Opt	real-world	1	n	n	n	-	?	-	1	325
AalianPG23 [1]	Enhancing Hybrid CP-SAT Search for Disjunctive Scheduling	ARIES	real-world	1	y	y	-	JSSP OSSP	-	-	2	371
Bit-Monnot23	Predicting the Optimal Period for Cyclic Hoist Scheduling Problems	CP Opt OR-Tools	github, bench-mark	3	n	n	-	CHSP	-	-	3	415
EfthymiouY23	An Efficient Constraint Programming Approach to Preemptive Job Shop Scheduling	CP Opt	benchmark, random instance, generated instance, real-life, industrial instance	6	ref	y	PJSSP	endBeforeStart span noOverlap	-	-	4	476
JuvinHHL23	Constraint Programming for the Robust Two-Machine Flow-Shop Scheduling Problem with Budgeted Uncertainty	CP Opt Cplex	real-world	0	ref	n	-	Perm FSSP	endBeforeStart noOverlap sameSequence cumulative	-	5	477
KamegneFND23	Horizontally Elastic Edge Finder Rule for Constraint Constraint Based on Slack and Density	?	benchmark	5	BL PSPlib	n	-	RCPSPs	-	-	6	480
KimCMLLP23	Iterated Greedy Constraint Programming for Scheduling Steelmaking Continuous Casting	Gurobi OR-Tools	real-world, benchmark, zenodo	0	y	n	-	SCC	alternative noOverlap	-	7	485
Mehdizadeh-Somarin23	A Constraint Programming Model for a Reconfigurable Job Shop Scheduling Problem with Multiple Resources	CP Opt	random instance	0	n	n	-	JSSP RMS	alternative endBeforeStart noOverlap	-	8	529
PerezGSL23	A Constraint Programming Model for Scheduling the Unloading of Trains in Ports	custom	real-world, generated instance	0	n	n	-	SUTP	noOverlap	-	9	553
PovedaAA23	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	Scheduling Complex Observation Requests for a Constellation of Satellites: Large Neighborhood Search Approaches	Cplex Studio	github, benchmark	2	y	n	-	EOSP	?	-	11	584
TardivoDFMP23	Constraint Propagation on GPU: A Case Study for the Cumulative Constraint	MiniCPP MiniZinc	bitbucket, github, benchmark, real-world	9	PSPLib BL Pack	y	-	RCPSp	cumulative	-	12	590
TasseGS23	An End-to-End Reinforcement Learning Approach for Job-Shop Scheduling Problems Based on Constraint Programming	custom Choco	industrial instance, real-world, supplementary material, github, benchmark	0	ref	y	-	JSSP	noOverlap	-	13	591
WangB23	Dynamic All-Different and Maximal Cliques Constraints for Fixed Job Scheduling	FaCILe	real-world, random instances	0	(y)	n	[628]	FJS	-	-	14	620
WangB23 [629]	A competitive constraint programming approach for the group shop scheduling problem	CP Opt	github, benchmark	0	ref	n	-	GSSP	noOverlap endBeforeStart	-	15	633

Extracted Features: Application Areas



Table 16: Works for Concepts of Type ApplicationAreas

Type	Keyword	High	Medium	Low
ApplicationAreas	COVID	[GuZ23] [269]	GeilingerKKMMW21 [234]	Fatemi-AnarakiTFV23 [212], Mehdizadeh-Somarin23 [430], GurPAE23 [270], JuvinHHL23a [331], OujanaAYB22 [487], Lemos21 [381]
ApplicationAreas	HVAC	[LimHTB16] [390], [LimBTBB15] [391], GrimesOS14 [260]	-	-
ApplicationAreas	agriculture	-	-	AkramNHRSA23 [13], BenderWS21 [84], HamPK21 [275], Astrand21 [53], QinWLSL21 [511], AstrandDF21 [36], Mejia201 [431]
ApplicationAreas	aircraft	[PolIAK22] [562], [WangB20] [528], [TranDHTWVOV17] [390], [Fahim16] [205], [BajestaniB13] [42], [LombardiM12] [493], [BajestaniB11] [41], [FrankK05] [210], [ArtionchimeB05] [34], [Simoni99] [558]	[WangB23] [629], [GombolayWS18] [253], [Ham15] [273], [Simoni87] [559], [SakkoutWoo] [329], [Simoni95] [556]	PrataA23 [509], PovedaAA23 [501], Adelgren2023 [7], KavvounisDimitrisGMS22 [202], EleO22 [196], ZarandiASC20 [654], [HaiderBRPA20] [283], abs-1902-09244 [282], Hooker19 [312], LaborieRSV18 [372], HookerH17 [314], TranAB16 [594], Lombardi10 [308], Laborie09 [370], KovacsB03 [355], KrogtLPHJ07 [668], MartinPY01 [427], SimonsK09 [569], GruijanK08 [264], Darby-DowlingM20 [561], Wallace09 [624], Simoni95 [557], PovedaAA23 [509], NaderiRR23 [460], CzerwinskiowaW23 [159], NaderiBZ22 [457], NaderiBZ22 [457], AntuoriHHEN21 [22], HubnerGSV21 [318], AbreuAPNM21 [166], KochierBFPHPS21 [348], VlkHT21 [623], BarzegaranP20 [61], GelbingerMM19 [236], abs-1911-04766 [235], BonattiZLM19 [113], Stalatz19 [652], SchmittH13 [333], [AkhsonBU13] [181], [HanjumoskIM14] [279], BennifGCM06 [881], KovacsO06 [369], Wallace09 [624]
ApplicationAreas	automotive	-	[GuoZ23] [269], [YuraszeckMPV22] [650], [EmdeZD22] [169], [Grotaek21] [261], [LimtanyakuS12] [303], [SunYL10] [567], [Lombardi10] [308], [BarlaitCG08] [52], [SchildWoo] [532]	BoldiceanuC94 [78], abs-2312-13682 [497], PerezGSL23 [499], TonatBT22 [592], CaueelaertDS22 [14], [Wallace20] [627], ZarandiASC20 [654], abs-1911-04766 [235], CaueelaertDMS16 [140], Denecker91 [172], [DeneckerCS15] [173], NovashH12 [476], CorreaLR07 [158], LimRG07 [850], NaderiR23 [460], WangB23 [629], Adelgren2023 [7], EtmianieshantGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], EleO22 [195], Lemos21 [381], MokhtarzadehTNP20 [443], TangLWSR18 [574], HookerH17 [314], [DorabiliRP16] [190], LipovetzkyBPS14 [394], HachmiO22 [22], MilanoW09 [441], [WdhB09] [623], MilanoW08 [440], BoldiceanuC02 [74], JainG01 [523], SimoniK09 [569]
ApplicationAreas	cable tree	[KochierBFHPSS21] [348]	-	BoldiceanuC94 [78], abs-2312-13682 [497], PerezGSL23 [499], TonatBT22 [592], CaueelaertDS22 [14], [Wallace20] [627], ZarandiASC20 [654], abs-1911-04766 [235], CaueelaertDMS16 [140], Denecker91 [172], [DeneckerCS15] [173], NovashH12 [476], CorreaLR07 [158], LimRG07 [850], NaderiR23 [460], WangB23 [629], Adelgren2023 [7], EtmianieshantGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], EleO22 [195], Lemos21 [381], MokhtarzadehTNP20 [443], TangLWSR18 [574], HookerH17 [314], [DorabiliRP16] [190], LipovetzkyBPS14 [394], HachmiO22 [22], MilanoW09 [441], [WdhB09] [623], MilanoW08 [440], BoldiceanuC02 [74], JainG01 [523], SimoniK09 [569]
ApplicationAreas	car manufacturing	[QinDCS20] [512]	[AntuoriHHEN21] [22]	BoldiceanuC94 [78], abs-2312-13682 [497], PerezGSL23 [499], TonatBT22 [592], CaueelaertDS22 [14], [Wallace20] [627], ZarandiASC20 [654], abs-1911-04766 [235], CaueelaertDMS16 [140], Denecker91 [172], [DeneckerCS15] [173], NovashH12 [476], CorreaLR07 [158], LimRG07 [850], NaderiR23 [460], WangB23 [629], Adelgren2023 [7], EtmianieshantGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], EleO22 [195], Lemos21 [381], MokhtarzadehTNP20 [443], TangLWSR18 [574], HookerH17 [314], [DorabiliRP16] [190], LipovetzkyBPS14 [394], HachmiO22 [22], MilanoW09 [441], [WdhB09] [623], MilanoW08 [440], BoldiceanuC02 [74], JainG01 [523], SimoniK09 [569]
ApplicationAreas	container terminal	[SacramentoSP20] [526]	[LaborieRSV18] [372]	BoldiceanuC94 [78], abs-2312-13682 [497], PerezGSL23 [499], TonatBT22 [592], CaueelaertDS22 [14], [Wallace20] [627], ZarandiASC20 [654], abs-1911-04766 [235], CaueelaertDMS16 [140], Denecker91 [172], [DeneckerCS15] [173], NovashH12 [476], CorreaLR07 [158], LimRG07 [850], NaderiR23 [460], WangB23 [629], Adelgren2023 [7], EtmianieshantGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], EleO22 [195], Lemos21 [381], MokhtarzadehTNP20 [443], TangLWSR18 [574], HookerH17 [314], [DorabiliRP16] [190], LipovetzkyBPS14 [394], HachmiO22 [22], MilanoW09 [441], [WdhB09] [623], MilanoW08 [440], BoldiceanuC02 [74], JainG01 [523], SimoniK09 [569]
ApplicationAreas	crew-scheduling	[ZarandiASC20] [654], [PourDERB18] [505]	[BourreauGG17] [22], [Zahout21] [652], [GombolayWS18] [253], [Mason01] [420], [Touralvane95] [593]	BoldiceanuC94 [78], abs-2312-13682 [497], PerezGSL23 [499], TonatBT22 [592], CaueelaertDS22 [14], [Wallace20] [627], ZarandiASC20 [654], abs-1911-04766 [235], CaueelaertDMS16 [140], Denecker91 [172], [DeneckerCS15] [173], NovashH12 [476], CorreaLR07 [158], LimRG07 [850], NaderiR23 [460], WangB23 [629], Adelgren2023 [7], EtmianieshantGNMS22 [202], NaderiBZ22a [456], NaderiBZ22 [457], HeinzNVH22 [295], EleO22 [195], Lemos21 [381], MokhtarzadehTNP20 [443], TangLWSR18 [574], HookerH17 [314], [DorabiliRP16] [190], LipovetzkyBPS14 [394], HachmiO22 [22], MilanoW09 [441], [WdhB09] [623], MilanoW08 [440], BoldiceanuC02 [74], JainG01 [523], SimoniK09 [569]
ApplicationAreas	dairies	-	-	Bartak02 [54], Bartak02a [53], Grotaek21 [261], Zahout21 [652], GalleguillosKS19 [225], Madl-WambalOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383]
ApplicationAreas	dairy	[EscobetPQPR19] [201]	[PrataAN23] [509], [HarjunkoskiMBC14] [279]	Bartak02 [54], Bartak02a [53], Grotaek21 [261], Zahout21 [652], GalleguillosKS19 [225], Madl-WambalOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383]
ApplicationAreas	datacenter	[HermenierDL11] [390]	-	Bartak02 [54], Bartak02a [53], Grotaek21 [261], Zahout21 [652], GalleguillosKS19 [225], Madl-WambalOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383]
ApplicationAreas	datacentre	-	[HurleyOS16] [319]	Bartak02 [54], Bartak02a [53], Grotaek21 [261], Zahout21 [652], GalleguillosKS19 [225], Madl-WambalOBM17 [418], Letort13 [382], IfrimOS12 [320], LetortBC12 [383]
ApplicationAreas	day-ahead market	-	-	HebrandALLCMR22 [285], GuoZ23 [269], JuvinHHL23a [331], Adelgren2023 [7], ShaikhK23 [547], EmdeZD22 [199], AstrandDF21 [36], AstrandDF21 [36], [AntuoriHHEN21] [22], ZarandiASC20 [654], Ham18 [274]
ApplicationAreas	deep space	[MontemannID23a] [446], [MontemannID23] [447], Ham18 [273]	-	HebrandALLCMR22 [285], GuoZ23 [269], JuvinHHL23a [331], Adelgren2023 [7], ShaikhK23 [547], EmdeZD22 [199], AstrandDF21 [36], AstrandDF21 [36], [AntuoriHHEN21] [22], ZarandiASC20 [654], Ham18 [274]
ApplicationAreas	drone	-	-	HebrandALLCMR22 [285], GuoZ23 [269], JuvinHHL23a [331], Adelgren2023 [7], ShaikhK23 [547], EmdeZD22 [199], AstrandDF21 [36], AstrandDF21 [36], [AntuoriHHEN21] [22], ZarandiASC20 [654], Ham18 [274]

Prolific Authors



Table 8: Co-Authors of Articles/Papers

ENTIRE EDIH

Production Scheduling

Slide 213

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)

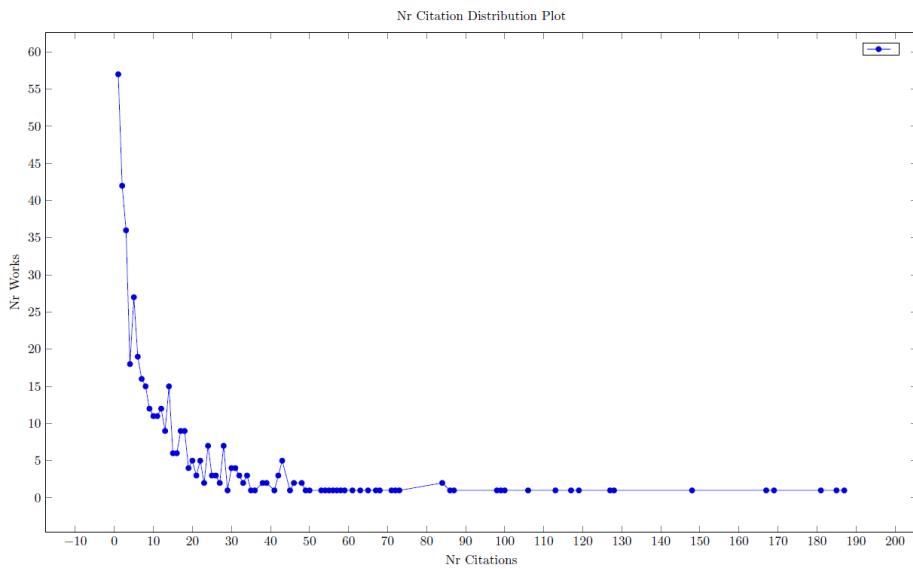
Key	Authors	Title	LC	Cite	Year	Conference /Journal	Pages	Nr Cites	Nr Refs	b	c
JainM99 [JainM99]	A. Jain, S. Meeran	Deterministic job-shop scheduling: Past, present and future	Yes	322	1999	European Journal of Operational Research	45	490	150	1352	1753
HarjunkoskiMBC14 [HarjunkoskiMBC14]	I. Harjunkoski, Christos T. Maravelias, P. Bongers, Pedro M. Castro, S. Engel, 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. Blazewicz, 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: Extending CHIP in order to solve complex scheduling and placement problems	Yes	323	2001	INFORMS Journal on Computing	19	279	23	1351	1738
AggounB93 [AggounB93]	A. Aggoun, N. Beldiceanu	Logic Based Methods for Optimization: Combining Optimization and Constraint Satisfaction	No	304	2000	Mathematical and Computer Modelling Book	null	185	0	No	n/a
Hooker00 [Hooker00]	John N. Hooker	Planning and Scheduling by Logic-Based Benders Decomposition	Yes	309	2007	Operations Research	29	181	19	1345	1715
Hooker07 [Hooker07]	John N. Hooker	Decomposition techniques for multistage scheduling problems using mixed-integer and constraint programming methods	Yes	278	2002	Computers Chemical Engineering	20	169	11	1334	1733
HarjunkoskiG02 [HarjunkoskiG02]	I. Harjunkoski, Ignacio E. Grossmann	Introducing Global Constraints in CHIP	Yes	78	1994	Mathematical and Computer Modelling	27	167	8	1271	1765
BeldiceanuC94 [BeldiceanuC94]	N. Beldiceanu, E. Contejean	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
LaborieRSV18 [LaborieRSV18]	P. Laborie, J. Rogerie, P. Shaw, P. Vilim	Algorithms for propagating resource constraints in AI planning and scheduling: Existing approaches and new results	Yes	369	2003	Artificial Intelligence	38	128	10	1369	1731
KuB16 [KuB16]	W. Ku, J. Christopher Beck	Propagation via lazy clause generation	Yes	483	2009	Constraints An Int. J.	35	127	15	1417	1702
OhrimenkoSC09 [OhrimenkoSC09]	O. Ohrimenko, Peter J. Stuckey, M. Codish	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. Werner	Scheduling projects with multi-skilled personnel by a hybrid MILP/CP approach: A decomposition algorithm	Yes	456	2008	Journal of Scheduling	18	113	31	1374	1708
CorreaLR07 [CorreaLR07]	Ayoub Insa Corréa, 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
MengZRLZ20 [MengZRLZ20]	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. Lemaitre, 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



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