Concepts

Helmut Simonis

Constraint Based Production Scheduling

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Acknowledgments

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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

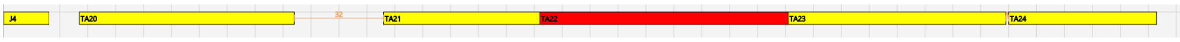
- Each *process* consists of one or more *process steps*
- A process step contains a duration formula to describe how long it lasts
- The order of *process steps* is defined by *process sequences*
- The resources needed are defined by *resource needs* (described later on)
- Tasks are created for each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

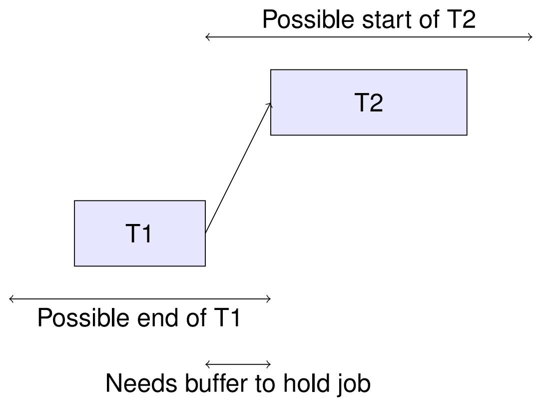


Annotations on Features

- ✓Currently available in scheduling tool
- (✓)Will be available shortly
- ✗Currently not available, may be added in future version

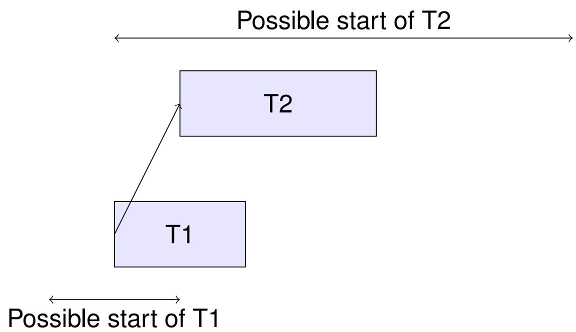
The Most Common Relation: EndBeforeStart ✓

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



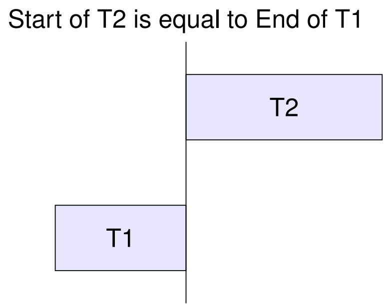
Less Common: StartBeforeStart ✓

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



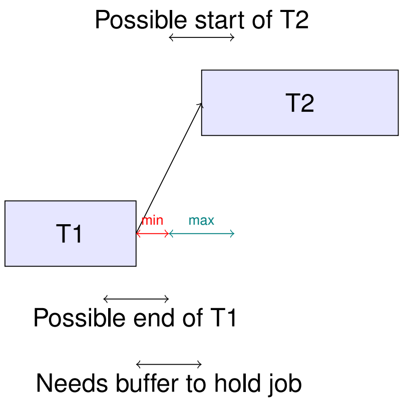
NoWait ✓

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



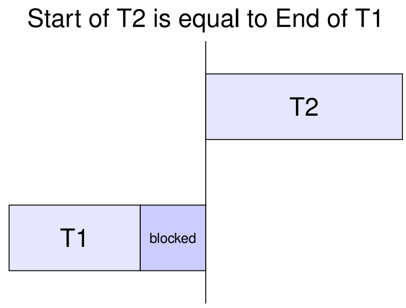
MaxWait (✓)

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



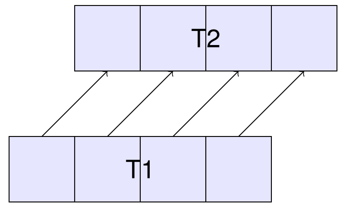
Blocking ✓

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



Special Case: Pipelining ✗

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



More General: Relations between Intervals ✗

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

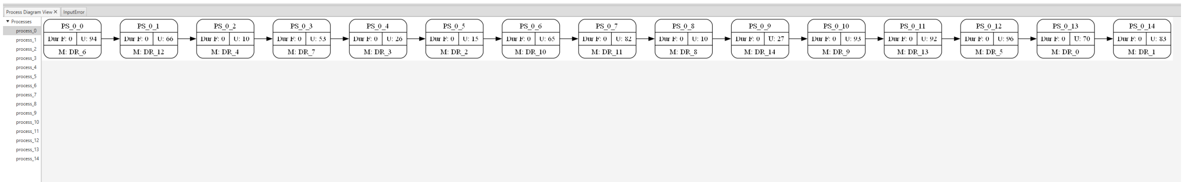
Relation	Illustration	Interpretation
$X < Y$ $Y > X$	X Y	X precedes Y Y is preceded by X
$X\,\mathbf{m}\,Y$ $Y\,\mathbf{mi}\,X$	X Y	X meets Y Y is met by X (*i* stands for *inverse*)
$X\,\mathbf{o}\,Y$ $Y\,\mathbf{oi}\,X$	X Y	X overlaps with Y Y is overlapped by X
$X\,\mathbf{s}\,Y$ $Y\,\mathbf{si}\,X$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

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

Start and End of Jobs ✓

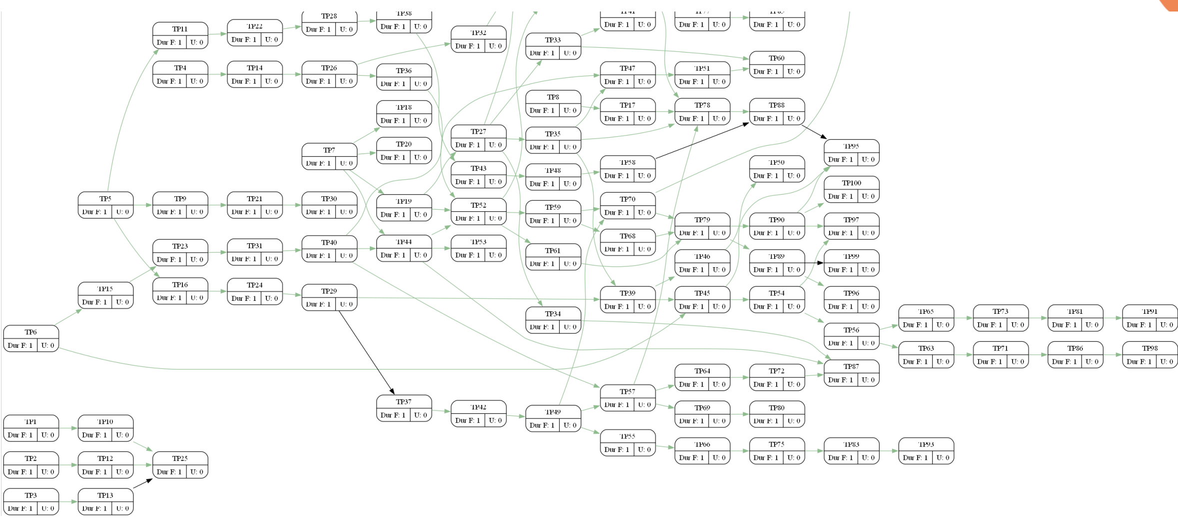
- The start of a job is equal to the start of the earliest task of the job
- The end of a job is equal to the latest end of any of its tasks
- Also called: the job *spans* its tasks
- Sometimes very simple
  - Start of job is start of first process step
  - End of job is end of last process step
  - 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

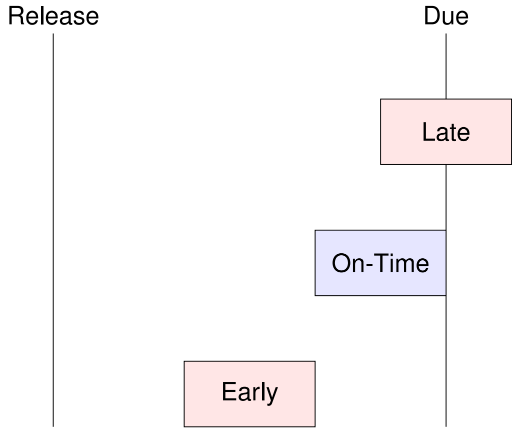
An Example of a More Complex Process



- 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

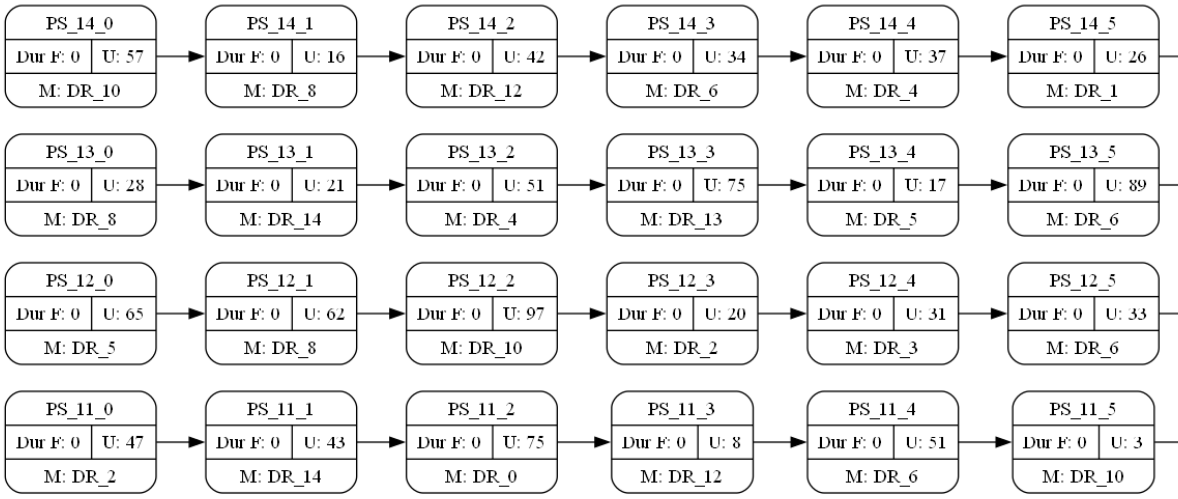
Problem Classification

- 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 ✓

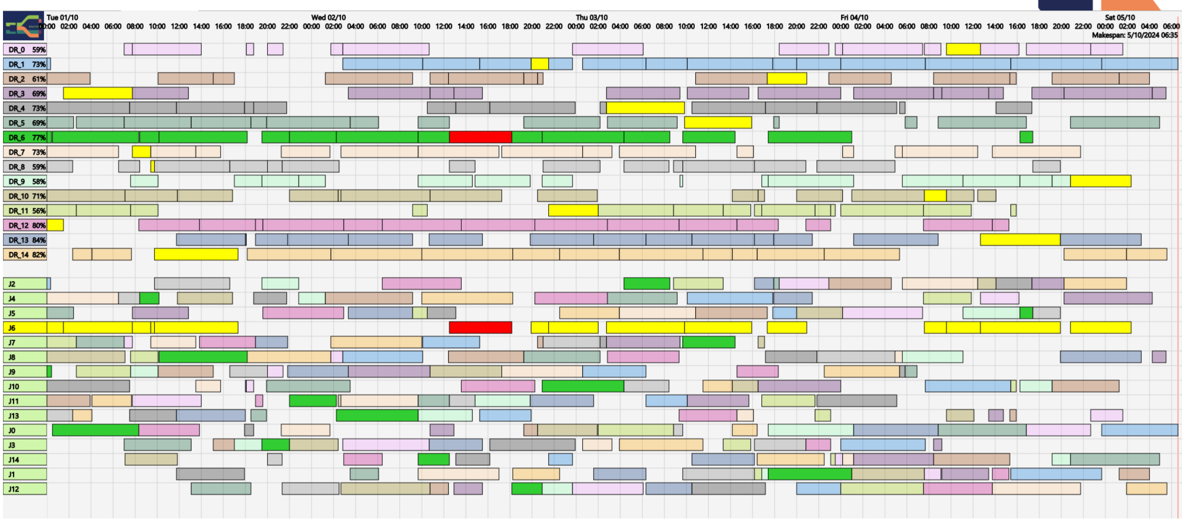
- Consists of a number of jobs and a number of machines
- Each job visits each machine, but possibly in a different order, depending on process
- Tasks of a job are linked as a precedence chain
- Objective is to minimize overall end, the *makespan*

Example Job-Shop Process



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

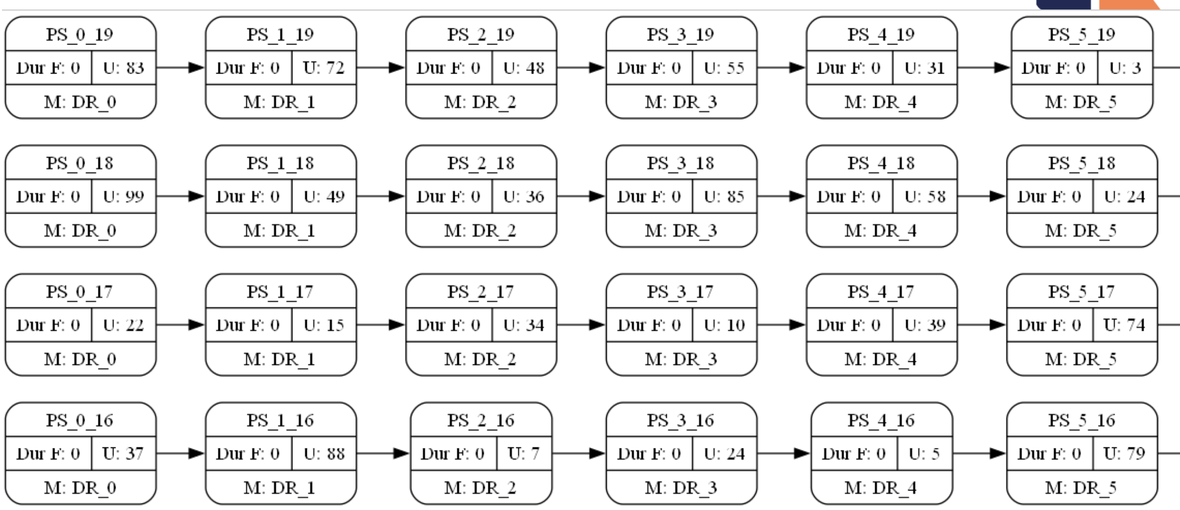
Example Job-Shop Solution



- One task is selected (in red), in both Machine and Job Gantt Chart
- Tasks are colored by machine, note coloring in jobs is different for each job

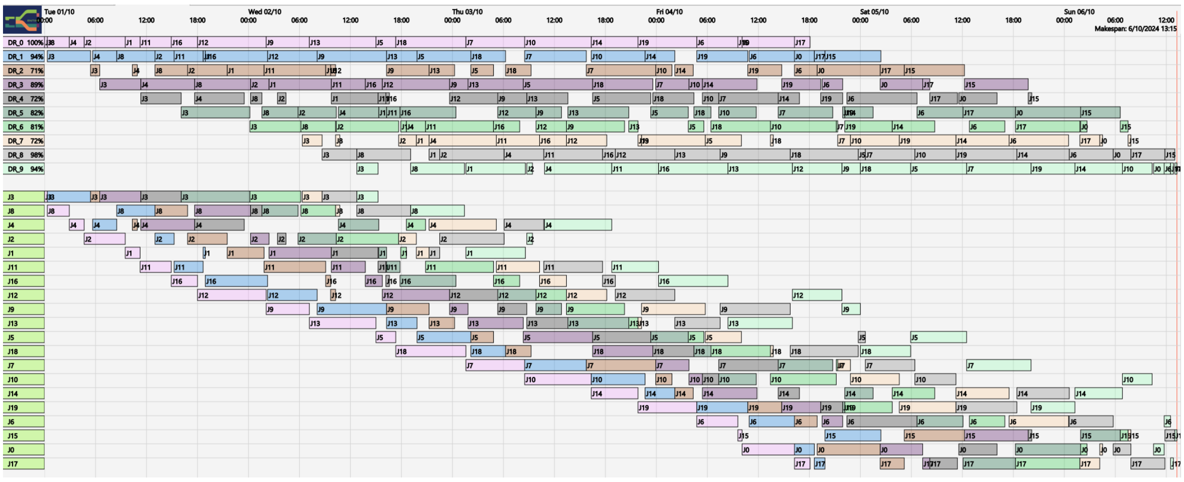
Flow-Shop ✓

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



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

Example Flow-Shop Solution



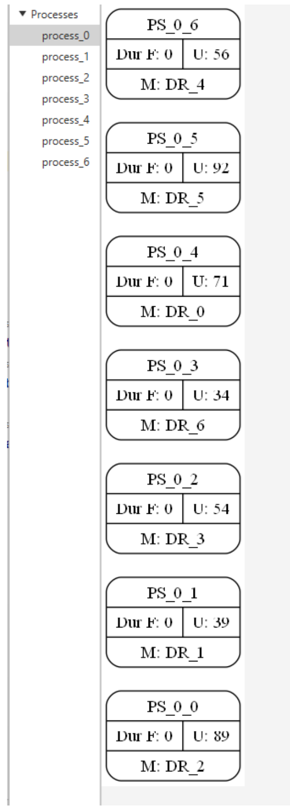
- Tasks are colored by machine, note the regular pattern in the Job Gantt Chart

Open-Shop ✓

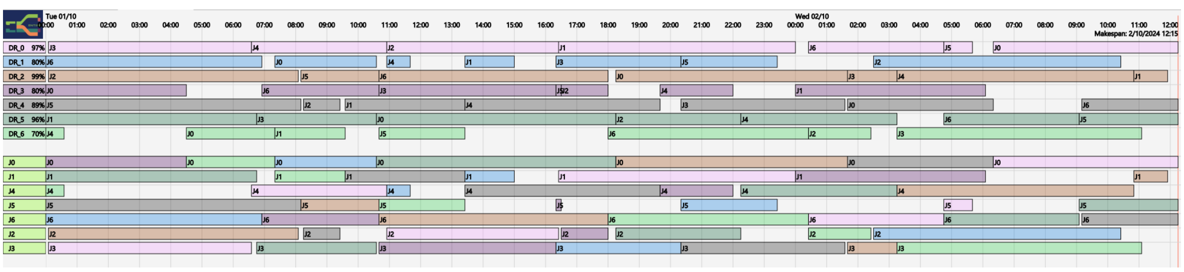
- Consists of a number of jobs and a number of machines
- Each jobs visits each machine, we have to choose the sequence individually for each order
- There are no temporal constraints between tasks, but tasks of the same job cannot overlap
- Objective is to minimize overall end, the *makespan*

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



Open-Shop Example Solution



- Example solution for 7x7 open shop example
- Order of tasks within jobs not constrained
- Note that machines are still idle in optimal solution

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

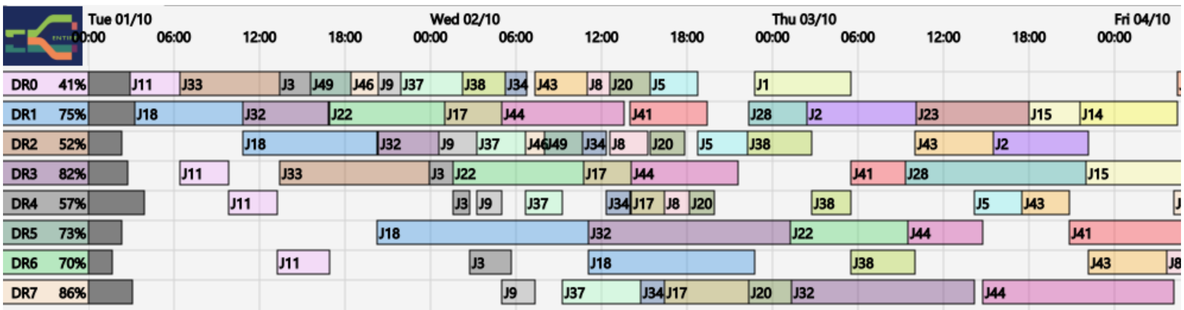
$\alpha/\beta/\gamma$ Notation

- The previous classes are good for algorithm 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

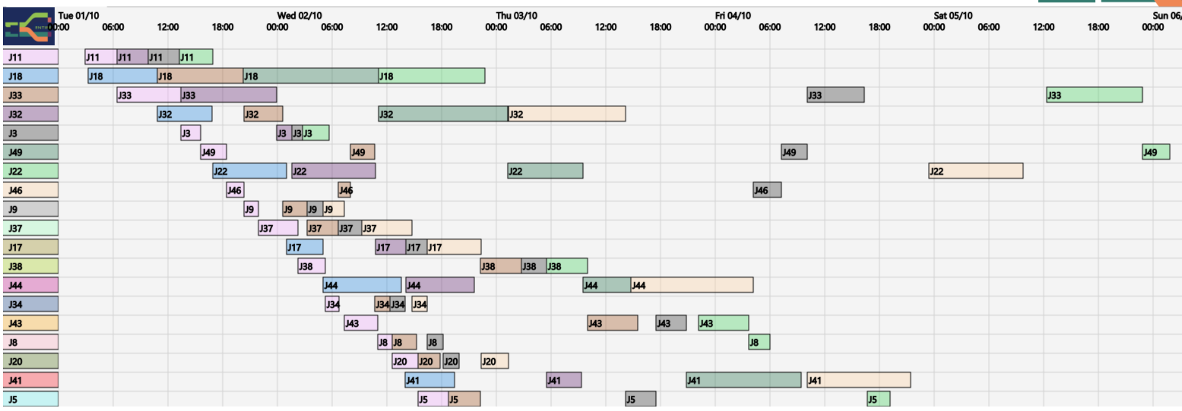
- Visualization is key to present and to understand results
- Many different ways to give an overview of schedule, and highlight problems
- Some diagrams types are used a lot, and are provided in our generic scheduling tool
- Customization is key

Machine Gantt Chart ✓



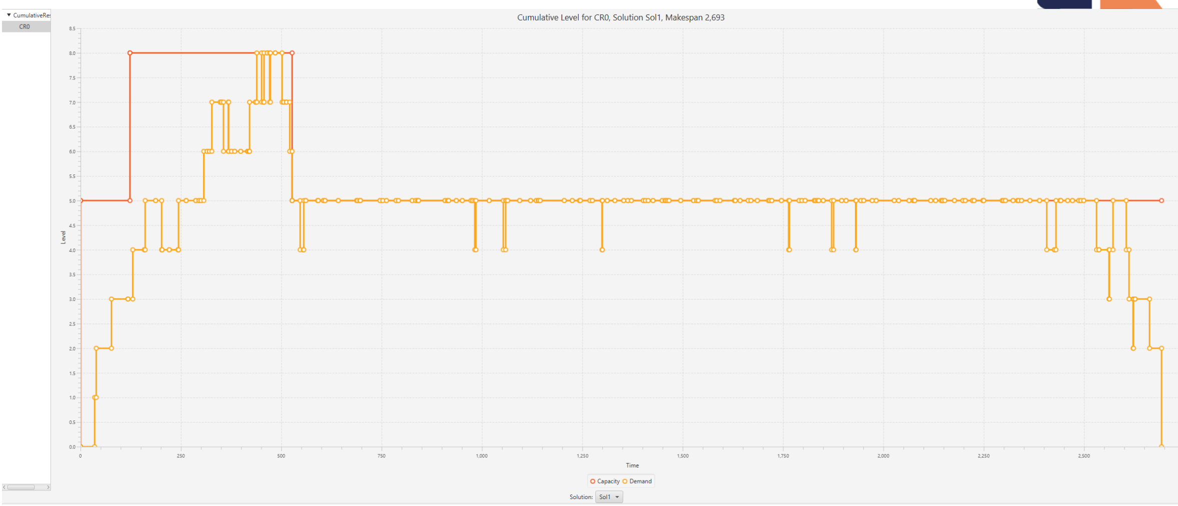
- Shows all tasks that are assigned to each machine
- Tasks should not overlap
- Also shows work in progress (WiP), down-times
- Optional display of setup and idle times

Job Gantt Chart ✓



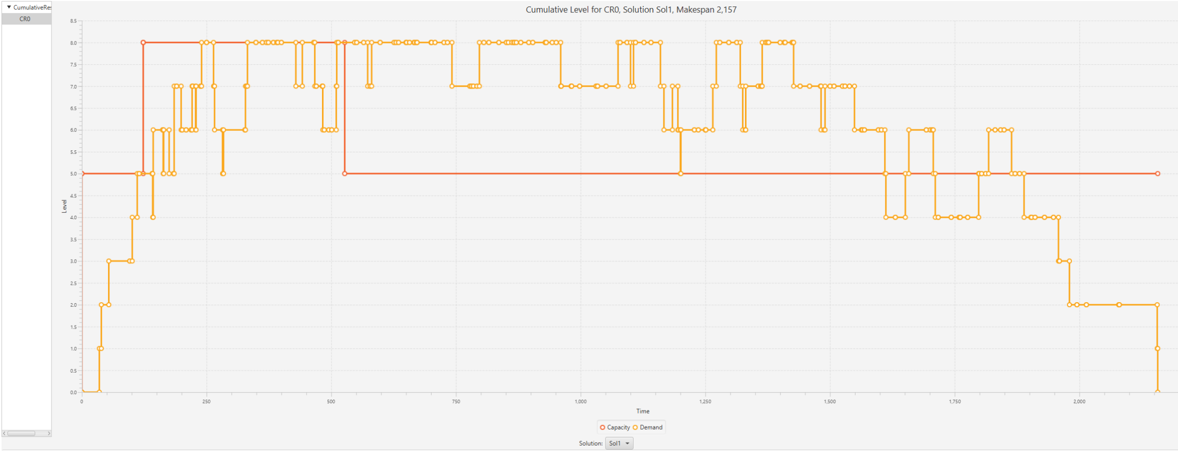
- Shows all tasks of a job in one line
- Only works for single chain of process steps
- Possible display of earliness, lateness
- Optional display of waiting and transport times

Cumulative Resource Chart ✓

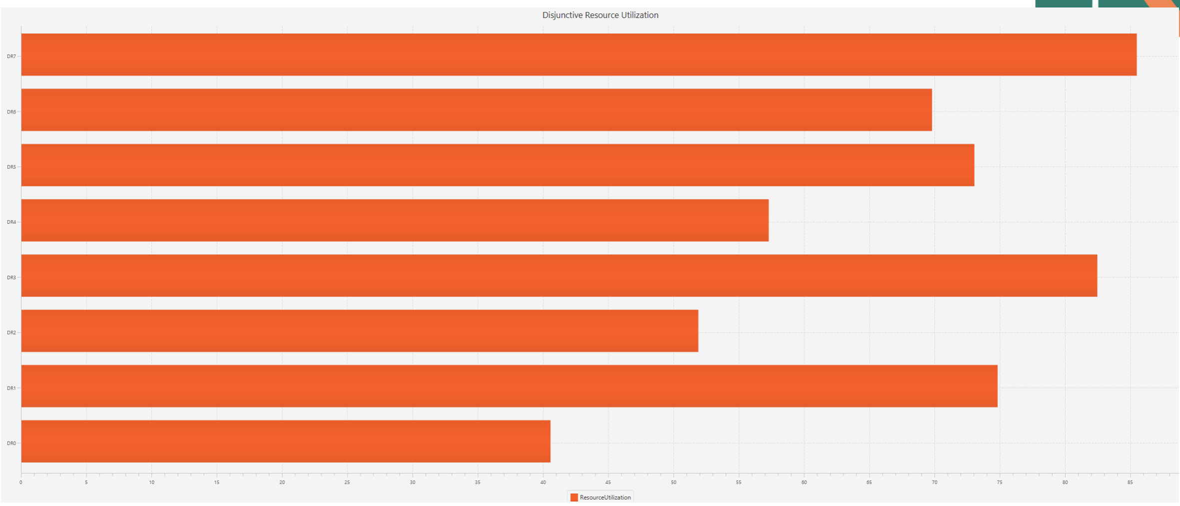


- Shows resource utilization of cumulative resource over time
- Utilization should be below capacity profile
- Unless we relax the cumulative resource constraint

Cumulative Resource Constraint Relaxed

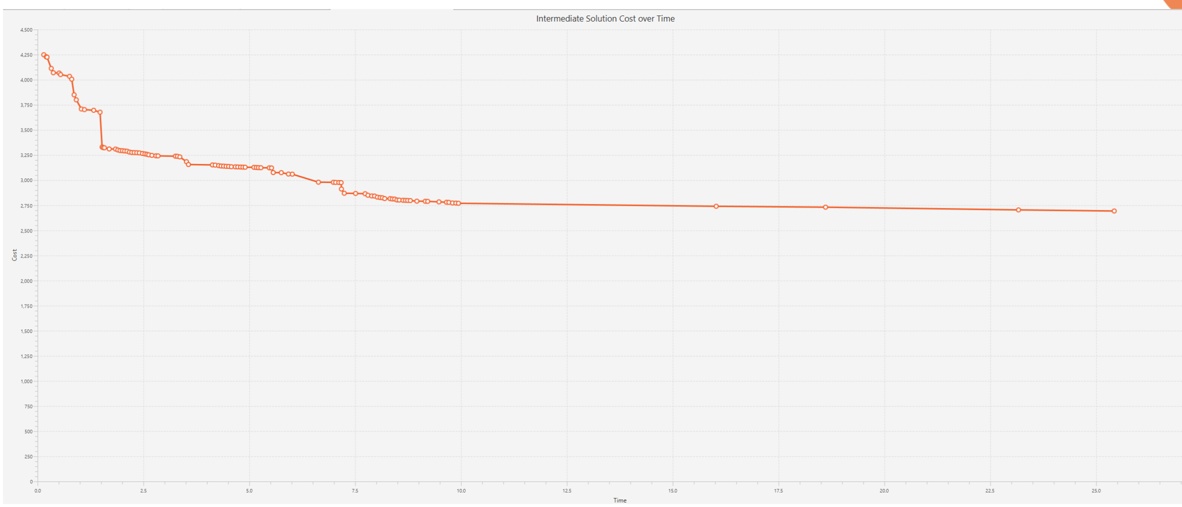


Resource Utilization ✓



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

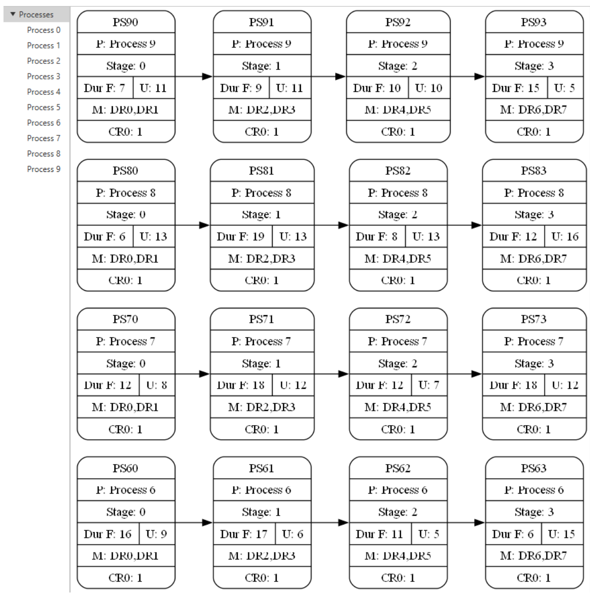
Intermediate Solutions ✓



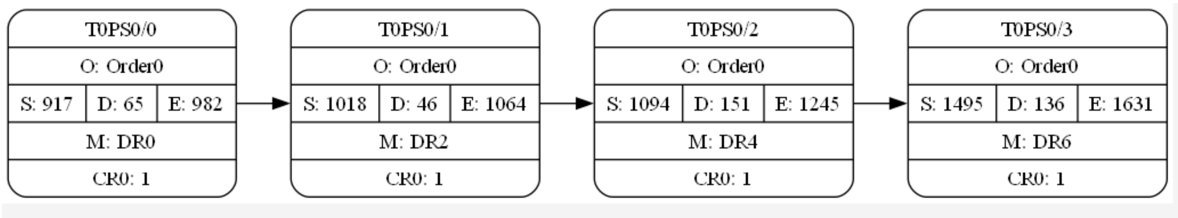
- Shows intermediate solutions found over time
- Useful to see if enough/too much time is allocated

Process Diagram ✓

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

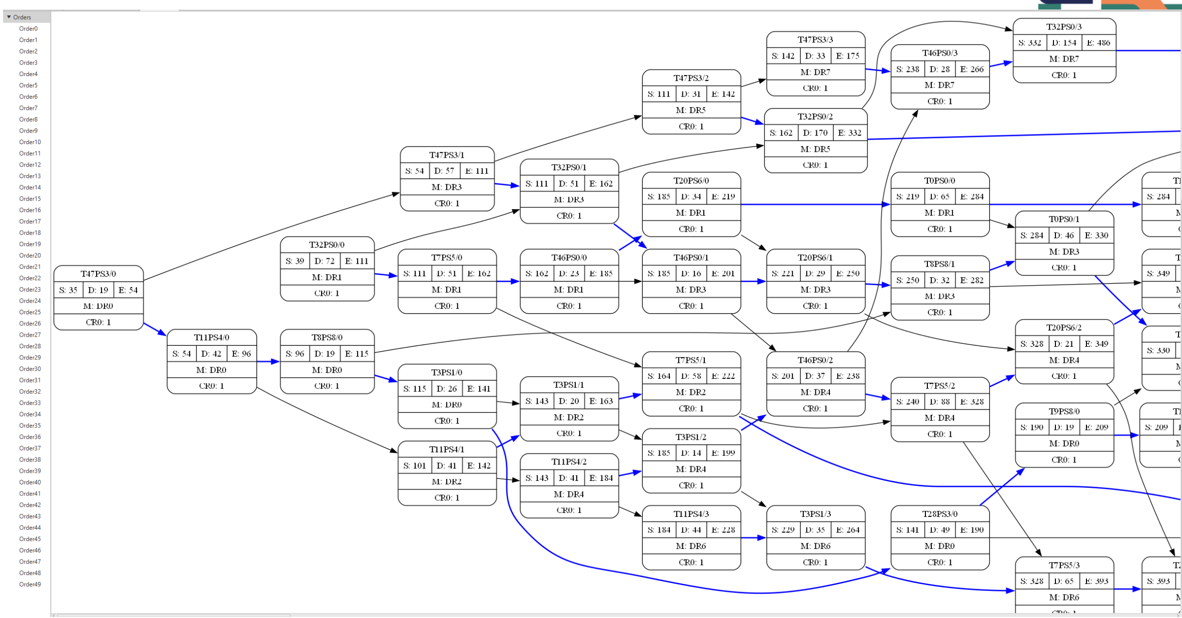


PERT Chart(Program Evaluation Review Technique) ✓



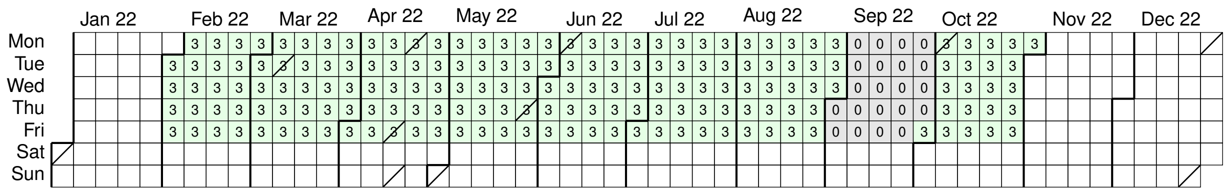
- Show details of job as a graph
- Useful if task graph is not a chain
- Often used in project management

PERT Charts become Confusing Quite Quickly



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

Calendars ✗



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

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