Machines and Resources

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Constraint Based Production Scheduling

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Key Points

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

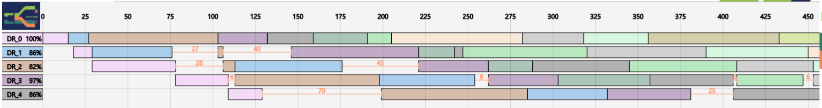
Outline

- Disjunctive Resources
  - Preemption
- Cumulative Resources
- Manpower
- Machine Choice
- Work in Progress and Planned Downtimes
- Calendars
- Summary

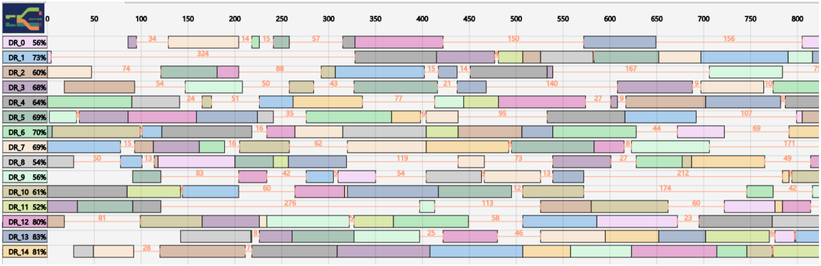
Disjunctive Resource ✓

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

Disjunctive Machines Examples



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



- Job-Shop example, a lot of idle time

Preemption ✗

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

How to Deal with Preemption in Scheduling

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

Outline

Disjunctive Resources

Cumulative Resources

- Demand and Capacity
- Variants

Manpower

Machine Choice

Work in Progress and Planned Downtimes

Calendars

Summary

Cumulative Resources ✓

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

Specifying Cumulative Resources

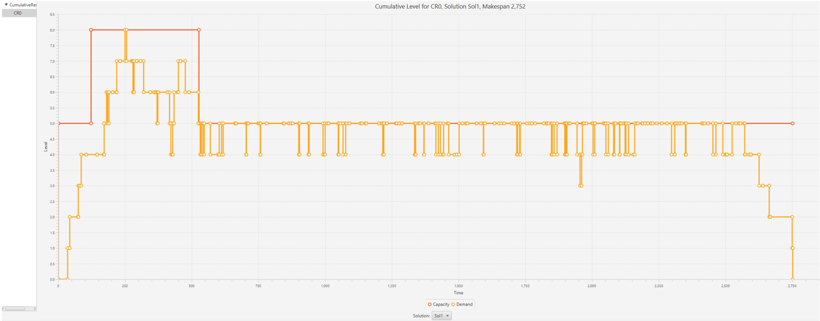
- Describing a cumulative resource
  - The resource itself
  - The capacity profile over time
  - The demands per processStep
- Each task may or may not need a specific cumulative resource
- The assumed total amount of work needed is constant
- We can calculate resource utilization by comparing demand to capacity

name	*CR0*

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

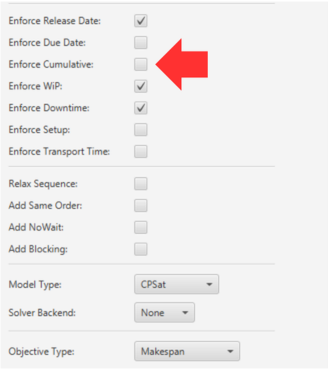
cumulativeResource	*CR0*
name	*CN0/0/CR0*
processStep	*PS0/0*
demand	1

Cumulative Resource Profile

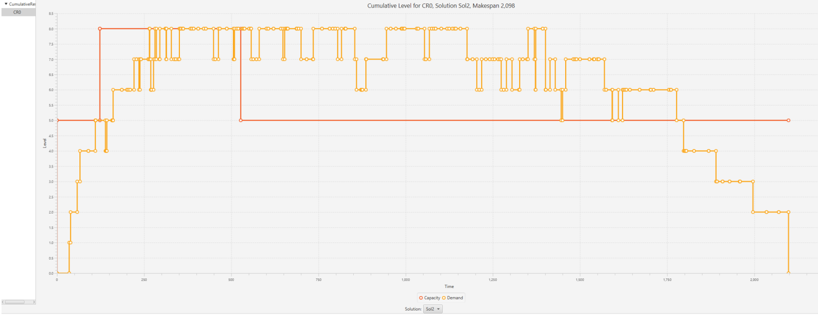


What is the Impact of the Cumulative?

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



Cumulative Profile When Constraint is Disabled



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

Variant: Resource Limit as Objective ✗

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

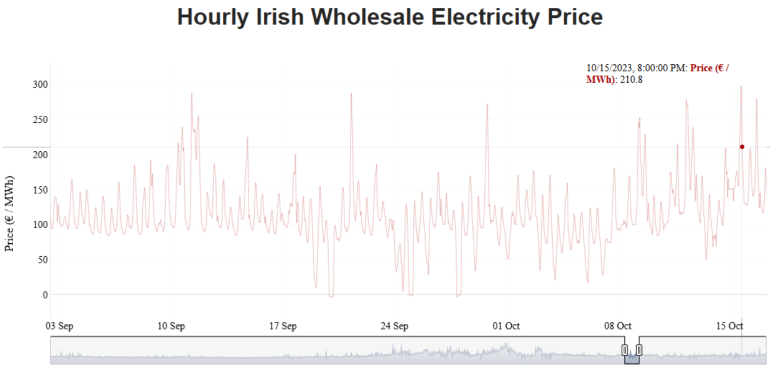
Variant: Trading Time for Capacity ✗

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

Variation: Time Variable Resource Cost ✗

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

Example: Electricity Price in Ireland



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

Variant: Soft/Hard Limits ✗

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

Variant: Lower Utilization Limit ✗

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

Outline

Disjunctive Resources

Cumulative Resources

Manpower

- Nested Skill Levels
- Assigned Operators
- Fractional Manpower Needs

Machine Choice

Work in Progress and Planned Downtimes

Calendars

Summary

Manpower Constraints ✓

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

Skills ✗

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

Alternative: Assigned Operators ✗

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

Fractional Manpower Needs ✗

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

Outline

Disjunctive Resources

Cumulative Resources

Manpower

Machine Choice

- Identical Machines
- Machine Dependent Speed
- Machine Preferences

Work in Progress and Planned Downtimes

Calendars

Summary

Choosing which machine to use

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

Identical Machines ✓

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

Machine Dependent Speed (✓)

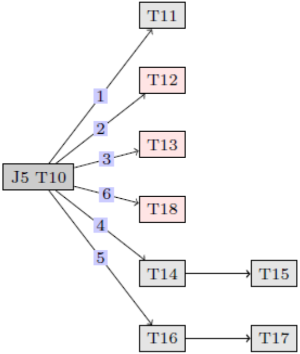
- Duration of the task depends on machine on which it is run
- Two common scenarios
    1. Some machines are faster than others (new generation)
    2. Different processes are faster/slower on some machines
- Express task duration as part of ResourceNeed
- Prefer faster machines, but balance machine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

Machine Preference (✓)

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

Example from Siemens Energy Case Study

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



Outline

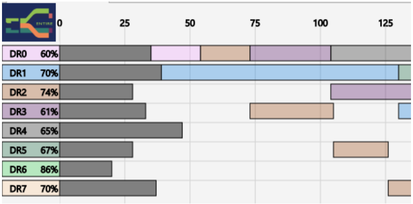
Work in Progress ✓

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

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

Work in Progress ✓

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



Planned Downtimes ✓

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

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

Variant: Scheduled Downtime ✗

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

Unplanned Downtime ✗

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

Outline

- Disjunctive Resources
- Cumulative Resources
- Manpower
- Machine Choice
- Work in Progress and Planned Downtimes
- Calendars
  - Factory Wide Calendars
  - Calendar Dependent Duration
  - Task/Break Interaction
- Summary

Calendars

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

Important Questions

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

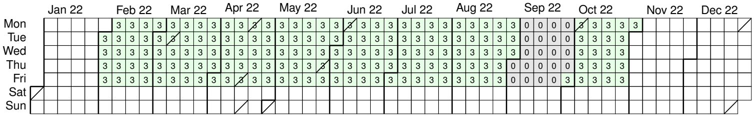
Single, Factory-wide Calendar

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

Shift Pattern Definition

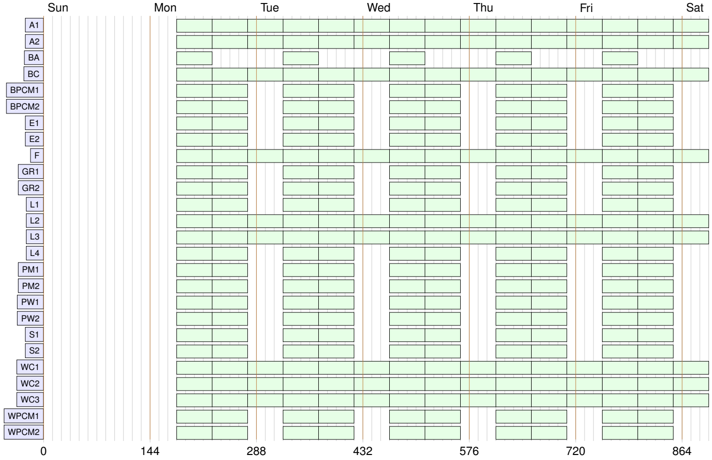
Name	Shift Model	Percentage	Start Date	End Date	Start Time	End Time	Mon	Tue	Wed	Thu	Fri	Sat	Sun
AV12	Shift 15 1	0.80	01/02/2022	01/11/2022	06:00	14:00	x	x	x	x	x		
AV13	Shift 15 2	0.80	01/02/2022	01/11/2022	14:00	22:00	x	x	x	x	x		
AV14	Shift 15 3	0.80	01/02/2022	01/11/2022	22:00	06:00	x	x	x	x	x		
UV4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

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



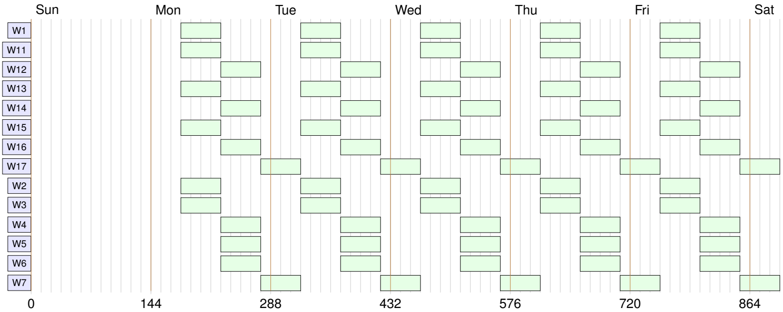
- Resulting shift calendar

Weekly Machine Dependent Calendar



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

ShiftPattern for Workers



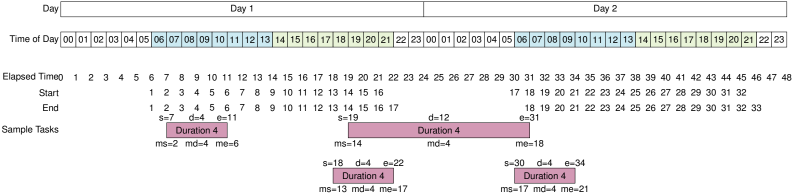
- Note different resource levels for morning, afternoon and night shift

Calendar Dependent Duration ✗

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

Tasks Stretching over Shutdown ✗

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



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

Outline

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- Cumulative Resources
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Summary

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