

Oven Scheduling Case Study

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Constraint Based Production Scheduling

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Key Points



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

Research Challenge



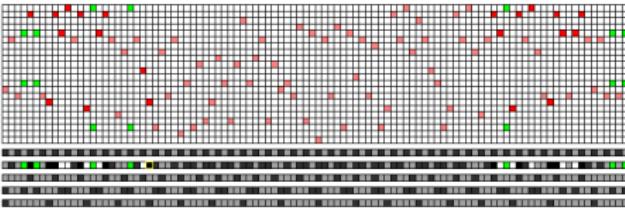
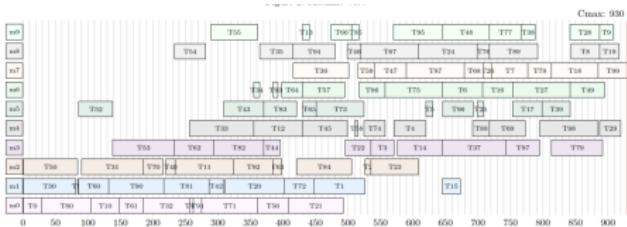
- Often the long-term business objectives are not visible in the operational decision problem
- We optimize a short-term objective without understanding the impact in the long term
- What choices should we make in short-term to improve overall result?
- Especially important when future data not yet visible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

Examples



- Production Scheduling
- Nearly all scheduling benchmarks use c_{max} (makespan) as objective
- Why?
- Do we want to close factory as rapidly as possible?

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



Examples



- Personnel Rostering
- Satisfy working rules and demands for period
- But: rules apply on a rolling horizon
- Easy to over-constrain problem for next period

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

| EDIH Planification de Services — ENTIREplanning | | | | | | | | | | | | | | | |
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Problem Studied Here

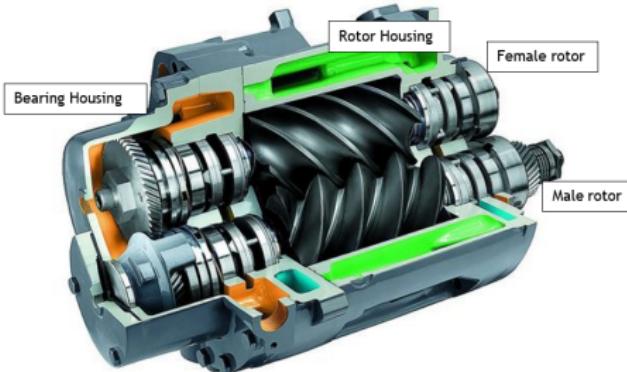


- Example from the ASSISTANT EU project (ended last year)
- Oven schedule for one of the industrial partners
- Schedule tasks on a set of ovens
- Tasks can share oven only if they are compatible
- Conflicting objectives
 - Energy use of ovens very significant, reduce when ovens are used
 - Waiting for an oven affects quality of product
- Jobs only visible when previous process step starts
- Currently scheduled by hand, industry partner expressed strong need for change

What does this look like in the real world?



Industrial Oven



Rotors in Compressor

Solution Approach: Constraint Programming



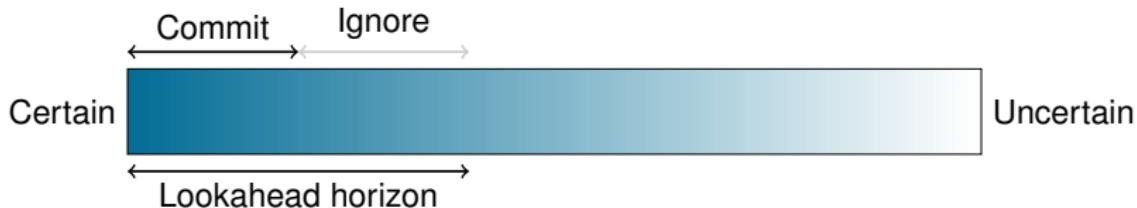
- Declarative modelling approach for combinatorial problems
 - Problem expressed in terms of variables and constraints
- Global constraints
 - Combines expressive modelling abstractions and powerful reasoning
 - Examples: disjunctive, cumulative, global_cardinality
- Compositional: Add constraints as required
- Main application areas
 - Scheduling, rostering, transportation
 - Also: test generation, verification, configuration



Overall Decomposition (Standard)



- We can only see that far into future
- We do not want to take decisions now that we might regret later
- We have to make some decisions now otherwise we never do anything
- *Rolling horizon* decomposition
 - We schedule up to *lookahead horizon* units into the future
 - We commit to implement resulting schedule only to up *commitHorizon*
 - We reschedule when we receive new information, or we reach the end of commitment
 - We solve each short-term sub problem based on short-term objectives



Short-Term Schedule Modelling



- Challenge: There is no global constraint to express the oven resource constraint
- We are not able to invest a lot of time/resources to develop such a constraint
- Two choices:
 - Two traditional models with variables linking them (Lackner et al, Constraints 2023)
 - Direct model expressing conditions as disjunctions of basic constraints

The Standard Pieces



- Jobs N consisting of multiple stages Q , tasks for each stage of each job, running on machines M
- Release dates r_i of jobs given by up-stream schedule
- WiP w_k on certain machines resulting from earlier schedule
- Machine m_{ij} and start variables s_{ij} for each task
- Precedence constraints between tasks of each jobs, with total waiting time c_i when waiting for resource
- Total number of ovens used in schedule $nrOvens$ by *nvalue* constraint

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

Resource Constraints



We start from the basic decomposition of 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



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

Count how many jobs share stage j with job i

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

Limit how many tasks can be stacked together

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

This should not work!



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

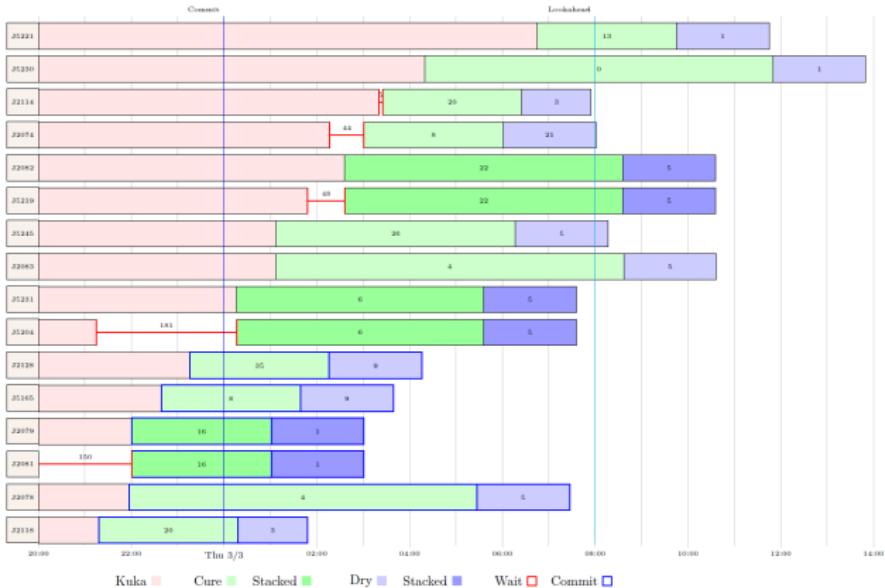
Compound Objective



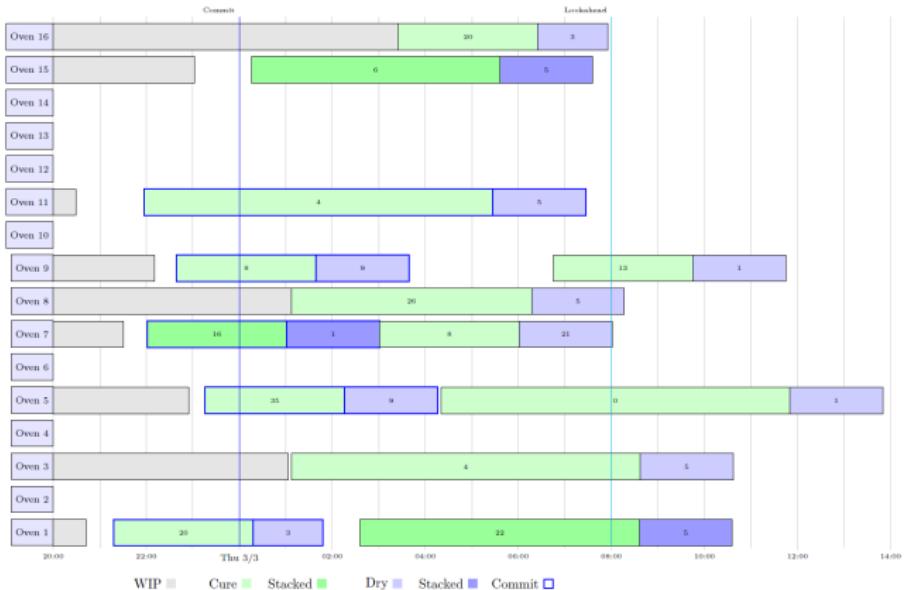
$$\min \alpha_1 \sum_{i \in N} c_i + \alpha_2 \text{nrOvens} + \alpha_3 \sum_{i \in N, j \in Q} z_{ij}$$

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

Short-Term Schedule: Job View



Short Term Schedule: Resource View



Are the short-term solutions good?

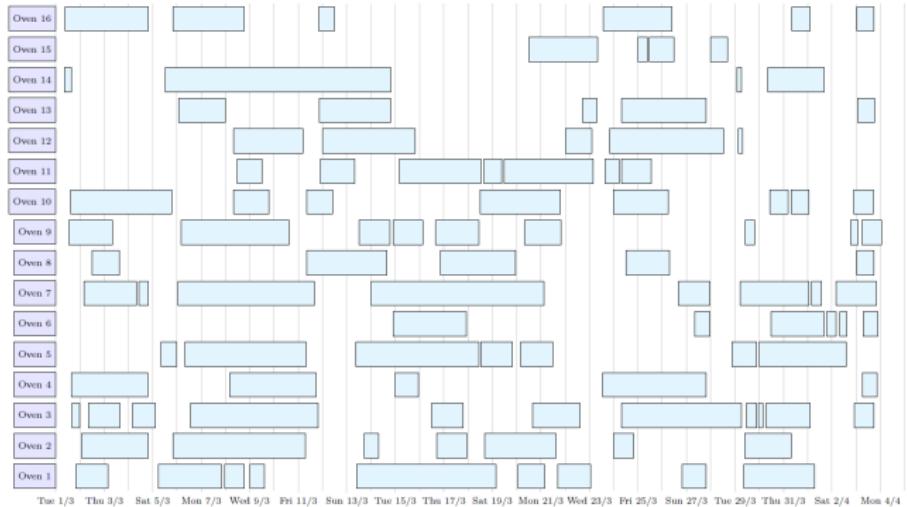


- We solve many problems to optimality, depending on solver
- Optimality gap is small, increasing search time helps a bit
- But are we optimizing the best possible objective?

Long Term Schedule: Detailed Schedule



Long Term Schedule: Abstracted Oven Runs

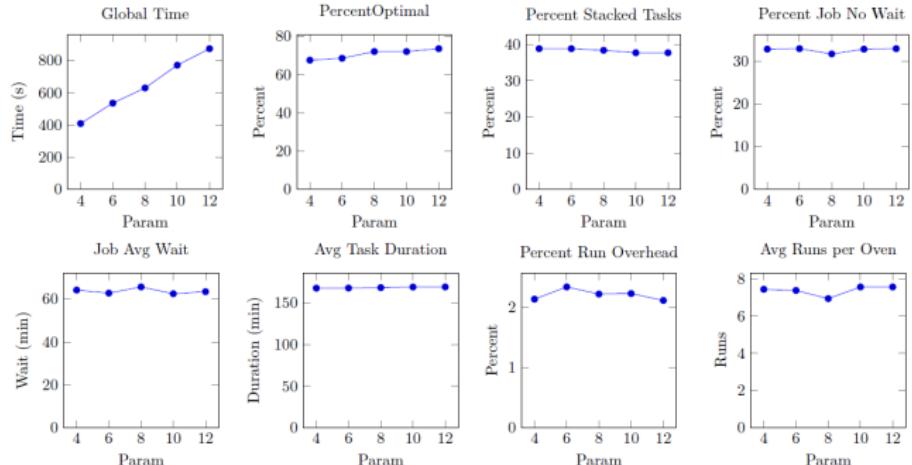


Is that a good global schedule? KPIs

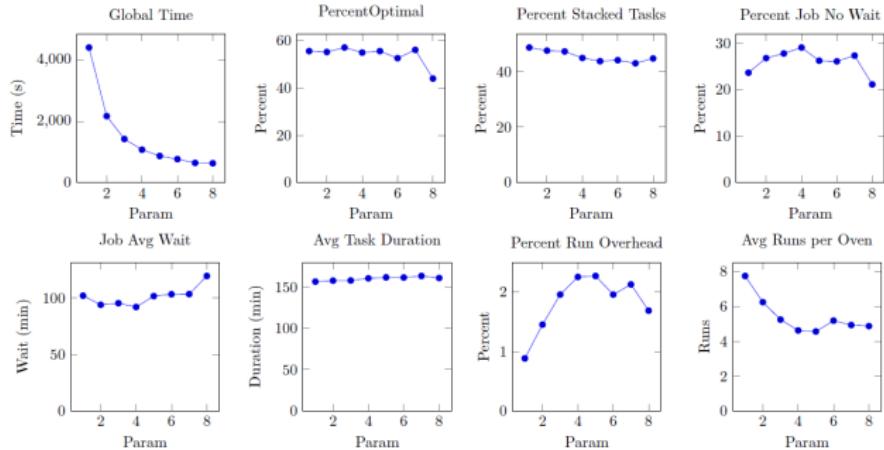


| Name | Unit | Explanation |
|------------------------|--------------------|---|
| Global Time | Seconds | Total time for solving all sub problems |
| Nr Jobs | - | Total number of jobs scheduled |
| Nr Tasks | - | Total number of tasks scheduled |
| Percent Optimal | Percentage (0-100) | How many sub problems were solved to optimality |
| Percent Stacked Tasks | Percentage (0-100) | Percentage of all tasks scheduled that were stacked |
| Percent Jobs No Wait | Percentage (0-100) | Percentage of jobs that were scheduled without any waiting time |
| Job Average Wait | Minutes | Average wait time over all jobs |
| Job Maximal Wait | Minutes | Largest waiting time for any job scheduled |
| Ovens Used | - | Total number of ovens used during period |
| Avg Task Duration | Minutes | Average tasks duration (influenced by stacking) |
| Oven Runs | - | Number of oven runs over total horizon |
| Run Overhead Percent | Percentage (0-100) | Overhead during oven runs when machine is idle |
| Avg Runs per Oven Used | - | Average number of oven runs per oven used |

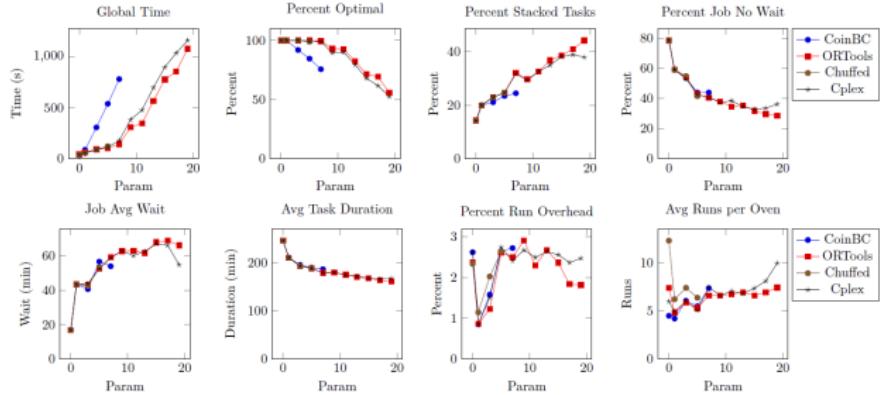
Impact of Lookahead Parameter



Impact of CommitHorizon Parameter



Comparing Different Solvers



Is the global solution really good?



- We schedule with limited information
- Hindsight is 20/20, we cannot expect best possible solution from partial information
- Process Challenge: Can we improve data visibility?
- Demand is variable over time, no steady-state solution
- Modelling Challenge: Can we define a short-term objective that produces better long-term solutions?
- Algorithm Challenge: Can we solve the global problem to optimality?
 - Assumes "a priori" visibility of data
 - This would provide a lower bound
 - But we need optimality to use as bound

Summary



- Discussed a non-standard oven scheduling problem from industry
- Models with decomposition of resource constraints
- Good/very good short-term solutions
- But is the overall schedule close to the global optimum?
- In any case, industry partner was happy with solution and analysis