SCHEDULING CEMENT PLANTS WITH ENERGY CONSTRAINTS

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A FEW THINGS ABOUT INETI
INETI - A PORTUGUESE RESEARCH LAB

- Largest national institution of R&D dedicated to companies
  - Ministry of Economics & Innovation
- Currently undergoing major restructuring (LNEG)
  - Focus of energy related issues
- Key indicators
  - Budget = M€45
  - 800 employees
DMS - PROCESS MODELING AND SIMULATION

- Two main research areas
  + Optimization
    - Planning/scheduling flexible production facilities
    - Design & planning supply chains
  + Innovation
    - Corporate strategies for technology market

- Small department
  + 18 staff (8 researchers)
  + Strong cooperation with Universities (degree-granting institutions)
    - 7 guest researchers
    - 4 PhD students

- Key performance indicators (2002-2007)
  + Scientific publications
    - 1 book & 9 book chapters
    - 7 theses (4 PhD)
    - 27 journal & 66 conference papers
  + Advanced training
    - 8 PhD + 10 MSc
    - 17 R&D trainees (grant-holders)
Cement producers currently under pressure to produce at lowest possible cost
+ Must look at best operating practices and optimize

Grinding process particularly complex
+ Requires high level control for stability and optimal performance

Scheduling plays an important part
+ Currently done with heuristic rules
  ✗ Focus on feasibility
+ Due to inherent complexity, choices are far from optimal
- **Scheduling decisions**
  - When and where to produce a certain grade
  - How much to keep in storage

- **Objectives**
  - Meet customer demands in time
  - Incorporate energy constraints (pricing and availability)
Contracts agreed between electricity supplier and cement plants (planning level)

- Energy cost [$/kWh]
  - Varies significantly during the day
  - From weekdays to weekends
- Maximum power consumption [MW]
  - Harsh cost penalties if levels are exceeded
  - Underproduction costs the same

Scheduling tools that can cope with such constraints can have a large impact on energy bill
WHAT TYPE OF MODEL DO WE NEED?

- Must be able to handle shared resources
  - General multipurpose models
- Rely on generic entities
  - Resources
  - Tasks
- Convert real entities into virtual ones
  - Generate Resource-Task Network (RTN)
- Process representation
Focus on continuous-time

- ABB’s Expert Optimizer can address scheduling by solving a control problem (discrete-time)
  - Leading software for cement plant control

Main challenge

- Account for discrete events that occur at known points in time
  - Multiple due dates for each product
  - Change in electricity
    * Availability
    * Cost
- Use as few event points as possible
  - To reduce total computational effort
CONTINUOUS-TIME FORMULATION

- Important property of continuous tasks
  - Can be divided as many times as required (same rate)

- One task on each time interval

- If tasks span more than one energy level
  - Tasks will be split (as more time intervals are added)
WHY NOT DISCRETE-TIME?

Arguments in favor
+ Discrete-events handled much more naturally
  ✗ Provided that the time grid is sufficiently fine
    ★ For accurate consideration of problem data
      ✗ Time intervals of 1 hour length (δ)
  ✗ No additional modeling effort
    ★ Same process representation (RTN)
    ✗ Fewer and simpler constraints

Minor limitation
+ Can lead to suboptimal solutions
**DISCRETE-TIME FORMULATION**

- Simple and elegant
  - Few constraints
    - Resource balances
      - \( R_{r,t} = R_{r,t}^0 + R_{r,t-1}^{\text{end}} |_{t=1} + R_{r,t-1} |_{r \in R^{CT}} + R_{r,t-1} |_{r \in (R^{CT} \cup R^{TP})} + \sum_{i \in I} (\mu_{r,i} N_{i,t} |_{t \neq |T|} + \nu_{r,i} \xi_{i,t} + \bar{\mu}_{r,i} N_{i,t-1}) + \sum_{i \in I^{CT}} (\bar{\nu}_{r,i} \xi_{i,t} + \bar{\mu}_{r,i} N_{i,t-1}) + \Pi_{i \in I}^{\text{in}} |_{r \in R^{CT} \land |t| \neq |T|} - \Pi_{i \in I}^{\text{out}} |_{r \in R^{FP} \land |t| \neq |T|} \forall r \in R, t \in T \)
      - \( R_{r,t}^{\text{end}} = R_{r,t} + \sum_{i \in I^{CT}} (\bar{\nu}_{r,i} \xi_{i,t} + \bar{\mu}_{r,i} N_{i,t-1}) \forall r \in R^{CT}, t \in T, t \neq |T| \)
    - Capacity constraints
      - \( \xi_{i,t} + \xi_{i,t}^* \leq (U |_{i \in I^c} + \delta \cdot \rho_{i}^{\text{max}} |_{i \in I^c}) \cdot N_{i,t} \quad \forall i \in I^c \cup I^e, t \in T, t \neq |T| \)
  - Objective function (minimize total electricity cost)
    - \( \min \sum_{i \in I^c} \sum_{r \in R^{CT}} \sum_{t \in T \land |t| \neq |T|} c_{e,t} \cdot (\mu_{r,i}) \cdot \frac{\xi_{i,t}}{\rho_{i}^{\text{max}}} \)
- Complexity at the level of RTN structural parameters generation
  - \( \mu_{r,i}, \bar{\mu}_{r,i}, \nu_{r,i}, \bar{\nu}_{r,i}, \lambda_{r,i} \)
MAIN RESULTS

- Continuous-time model can effectively model all features
  - Major breakthrough
  - Not efficient computationally
    - Limited to toy problems

- Discrete-time very good approach
  - Effectively solve problems of industrial relevance
    - Fast to nearly optimal solutions (0.8% gap in 5 CPU minutes)
  - Has potential to be incorporated into decision-making tool used by industry
    - After post-processing procedure eliminates superfluous information
      - Caused by high solution degeneracy

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Very tight discrete-time formulation (DT)
  + Integrality gap=0 in some cases
  DT grid uses much more event points $|T|$
  Solution for CT highly dependent on $|T|$

| Problem | $(|P|, |M|, |S|)$ | Model | $|T|$ | binary variables | single variables | constraints | RMIP (€) | MIP (€) | CPU s | nodes |
|---------|----------------|-------|------|-----------------|-----------------|------------|----------|--------|-------|-------|
| EX5     | (3,2,2)        | DT    | 169  | 2016            | 10784           | 6739       | 26738    | 26780  | 3600a | 133242 |
|         |                | CT    | 9    | 528             | 1089            | 562        | 25625    | 27222  | 7.18  | 3989  |
|         |                | CT    | 10   | 594             | 1221            | 629        | 25625    | 27008  | 369   | 138426 |
|         |                | CT    | 11   | 660             | 1353            | 696        | 25625    | 26911  | 4131  | 1295540 |
| EX6     | (3,2,3)        | DT    | 169  | 2520            | 13986           | 8423       | 43250    | 43259  | 3600b | 85900 |
| EX7     | (3,3,4)        | DT    | 169  | 3528            | 18365           | 10780      | 68282    | 68282  | 18.4  | 671   |
| EX8     | (3,3,5)        | DT    | 169  | 4032            | 21567           | 12464      | 101139   | 104622 | 3600c | 41252 |
| EX9     | (4,3,4)        | DT    | 169  | 4704            | 23923           | 13810      | 87817    | 87868  | 3600d | 24400 |
| EX10    | (5,3,4)        | DT    | 169  | 5880            | 29481           | 16840      | 86505    | 86581  | 3600e | 7500  |
POTENTIAL COST SAVINGS

- May be very substantial (≥20%)
  - When compared to scheduling based on feasibility

- Preliminary results function of a variety of factors
  - Electricity pricing policy
  - How far mills are operating below maximum capacity
  - How good are the heuristic rules in use at the plant

- Enough to motivate further research

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<td>Capacity (%)</td>
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