Scope for industrial applications of production scheduling models and solution methods

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\textbf{Abstract}

This paper gives a review on existing scheduling methodologies developed for process industries. Above all, the aim of the paper is to focus on the industrial aspects of scheduling and discuss the main characteristics, including strengths and weaknesses of the presented approaches. It is claimed that optimization tools of today can effectively support the plant level production. However there is still clear potential for improvements, especially in transferring academic results into industry. For instance, usability, interfacing and integration are some aspects discussed in the paper. After the introduction and problem classification, the paper discusses some lessons learned from industry, provides an overview of models and methods and concludes with general guidelines and examples on the modeling and solution of industrial problems.
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- Iiro Harjunkoski, ABB Corporate Research (DE)
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- Ignacio E. Grossmann, Carnegie Mellon University (US)
- John Hooker, Carnegie Mellon University (US)
- Carlos Méndez, INTEC (AR)
- Guido Sand, ABB Corporate Research (DE)
- John Wassick, The Dow Chemical Company (US)
Motivation

- Bridge the gap between theory and practice in the scheduling area by providing
  - for academic researchers some insights into the industrial aspects of solving real scheduling problems at hand and deploying theoretical models
  - for industrial practitioners an overview and tutorial to some of the available solution methods and their main characteristics and limitations
- Target not to exhaust the article with equations but refer to other scientific papers and classify methods highlighting their main idea (strengths, limitations)
Content

- Classification of scheduling problems
- Summary of industrial requirements for scheduling
- Review of existing scheduling optimization models and methods, including heuristics, metaheuristics and constraint programming
- Lessons learned and success stories on real industrial scheduling implementations
- General guidelines and examples on the modeling and solution of industrial problems
- Future challenges for industry in the area of planning and scheduling
Where is scheduling “located”
Traditional system hierarchy (Automation pyramid)
Production Management @ Industry

Functionalities

ERP
(mainly supporting business functions, strategy and targets)

Production cost

Equipment health & condition

Product quality

Energy efficiency

Inventory, safety, ...

Control
(execution layer, data collection, short-term decisions)
Where is Scheduling Located?
Part of a Complex SW & HW System

Source: ARC (2010)
Planning and Scheduling – the Big Picture
Planning and Scheduling – how academics like to think
Planning and Scheduling – industrial view

World

User Interfaces

System

Integration
Classification of scheduling problems
Main scheduling decisions

- Production facility data; e.g. processing unit and storage vessel capacities, availability of utilities, manpower
- Detailed production recipes; e.g. processing times/rates, utility and material requirements, mixing rules
- Equipment unit suitability to carry out specific tasks
- Production costs; e.g. raw materials, utilities, cleaning
- Production targets or orders with due dates
Classification of scheduling problems
Various aspects

- **Market environment**
  - Commodity/specialty products, make-to-order or –stock

- **Planning functions**
  - Procurement, distribution, push / pull driven production

- **Production facility**
  - Batch / continuous process
Requirements for scheduling
When integrated to an industrial SW-environment

- Solution must be **robust, scalable** and stable. In case optimization fails, a feasible schedule must be reported.
- Every schedule is a **re-schedule**. In case of sudden disturbances, generate new adjusted solution efficiently.
- Solution must be **maintainable**, both updating models and keeping up with major software updates in the plant.
- Easy integration and connection to other applications, e.g. ERP-software or tools that calculate and predict total costs.
- Cost to implement solution should ensure a good **ROI** – affected by related software license and development costs.
Review of existing scheduling optimization models

Modeling of time

- One of the most important decisions in scheduling is how to represent the time.

**Precedence (through sequencing variables)**

A

**Discrete-time grid**

B

**Continuous-time with multiple grids**

D

**Continuous-time with single grid**

C
Review of existing scheduling optimization models

- **Sequential processes** contains successive production stages and requires modeling of stages, units and routing.
- **Network** representation relies on the modeling of materials, tasks, units and utilities.
  - Most typical ones STN and RTN.

**State-Task Network (STN)**

**Resource-Task Network (RTN)**

*Task-unit mapping*
- Make B in U1
- Make D in U2
- Make E in U1 or U2
Select a modeling approach
Example procedure

Gather Info
Plant topology & Production recipe

Describe Process as STN/RTN

Network

Production Environment

Mathematical Model
Key Aspect: Time Representation

Continuous-time Models

STN/RTN-based Models

Discrete-time
Single uniform grid

Discrete-time
Multiple nonuniform grids

Continuous-time
Unit-specific grids

Continuous-time
Single time grid

Precedence

Multiple time grids
Basic RTN-model explained graphically

Indices
- \( r \) - resources
- \( i \) - tasks
- \( t \) - time points

Variables
- \( R_{r,t} \) - excess resource
- \( N_{i,t} \) - assignment (binary)
- \( \xi_{i,t} \) - extent

Variables or parameters
- \( R^0_r \) - initial availability

Structural parameters

<table>
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<th>related to</th>
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<td>( N_{i,t} )</td>
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<td>( \pi_{r,t} )</td>
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Other parameters
- \( \pi_{r,t} \) - external interaction

Assumption for illustrative purposes: Instance of a task lasts a single slot
Review of existing scheduling optimization models

- **Discrete-time models**
  - Most typically STN or RTN

- **Continuous-time models**
  - Precedence-based
  - Time-grids (single or multiple)
  - RTN / STN

- **Constraint programming models**

- **Nonlinear** scheduling models
Scheduling methods
Do you need optimization in first place?

Excel Spreadsheets

Low (<50%) utilization
- Single-stage production
- Single product
- Dedicated resources
- Long (=1 week) production runs
- Large capacity margin for future growth
- "Guesstimated" inventory, storage & delivery

High (> 70%) utilization
- Multi-stage production
- Complex product mix
- Shared resources
- Short (=1 shift) production runs
- De-bottlenecking existing site OR rationalization of many plants into only one
- Controlled inventory, storage & delivery

We want to be here
- Minimize capital
- Increase flexibility

Modeling & Optimization / Multi-Stage Scheduling
## Scheduling methods

A number of methods are discussed in short overviews:

- **MILP / MINLP**
- **Constraint programming**
- **Heuristics / metaheuristics**
- **Hybrid methods**
- **Rescheduling**

### Environment

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<tr>
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<th>Network</th>
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<td>J&lt;sub&gt;k&lt;/sub&gt;</td>
<td>= 1</td>
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<tr>
<td>k &gt; 1,</td>
<td>J&lt;sub&gt;k&lt;/sub&gt;</td>
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### Decisions

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### Methods

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<tr>
<td>Hybrid</td>
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<tr>
<td>Processing characteristics and constraints</td>
<td></td>
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</tr>
<tr>
<td>-------------------------------------------</td>
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| Changeover times | Changeover costs | Storage restrictions | Intermediate due dates | Variable batch sizes | Variable processing times | Holding & utility costs | Time-varying utility costs | ...

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<td>Continuous</td>
<td>Unit-specific</td>
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</table>

| Network | Time-grid-based | Discrete | Common | □ □ □ □ □ | □ □ □ | □ □ |
|---------|-----------------|-----------|--------|--------------|
| | Specific | □ □ □ □ □ | □ □ □ | □ □ |
| | Continuous | Common | □ □ □ □ □ | □ □ |
| | Unit-specific | □ □ □ □ □ | □ □ | □ □ |
Success stories on real industrial scheduling implementations

A number of successful examples
- Example from the dairy industry (Unilever)  
  - Scheduling optimization in the petrochemical industry
- Defining KPIs for estimating benefits not trivial
- Many companies unwilling to reveal benefits
  
- Scheduling in an integrated chemical complex (The Dow Chemical Company)
- Medium-term scheduling of large-scale chemical plants (ATOFINA Chemicals, BASF)
Lessons learned
Some general comments

- An **optimal schedule** and production plan can only bring true benefits when the **production** is **aligned** to it.
- Often only **partially following** an optimized schedule is not sufficient and may even lead to **worse** solutions than before.
- It is crucial that the planning system is able to **capture** the major **decisions** in a **correct** way and the user **expectations and needs** are fully **aligned** with the system and its user interfaces.
Lessons learned
Elements of successful implementation

- Assume the scheduler will adjust the schedule. Do not try to model all scheduling contingencies!
- Focus on the needs of the scheduler, who must feel that his job is enhanced and simplified with the advanced scheduling technology. The scheduling model or algorithm is only a part of the solution.
Lessons learned
Elements of successful implementation

- Quick proof-of-concept study: Expected value, ability to solve the problem, availability of data, how to integrate the advanced solution

- Stakeholder alignment critical: Production scheduler, his management, and the aligned groups need to all agree on the need and value of the solution

- A generic modeling approach is preferred: Easy to instantiate new model elements, add scheduling heuristics in the model, separate data from underlying equations or algorithm (fully parameterized model)

- Assume the scheduler will adjust the schedule. Do not try to model all scheduling contingencies!

- Focus on the needs of the scheduler, who must feel that his job is enhanced and simplified with the advanced scheduling technology. The scheduling model or algorithm is only a part of the solution
General guidelines on the modeling and solution of industrial problems

- A true production management system comprises scheduling as a natural part of a well-orchestrated environment, which raises many challenges on how to interface and compromise between various – potentially competing – optimization functions.

- Industry provides enough real-life problems to the research community and helps evaluating the results in order to guideline the research to look for the right KPIs.

- Academia values the importance of practical applicability of methods as to ensure fast solution of large and complicated problems, not necessarily to optimality.

- Various research fields and communities join in projects to merge methodologies where certain strengths can lend themselves to collaborative solutions.

- How to efficiently bring the various disciplines together to raise the state-of-the-art to the next level is a key question.
Emerging and future challenges for industry

- How to deal with **energy** (energy efficient, flexible, agile and adaptable)
- **Electricity pricing** / immediate impact on scheduling and potential new opportunities
- **Raw-material** pricing and availability
- **Regulations** on emissions (e.g. CO₂, NOₓ, SO₂) novel component
- **Globalization** – increased the transportation costs and **multi-site** planning
- How to efficiently use ever **increasing data** and knowledge
- Rapid **market changes** calls for more flexible processes and the design of which may need to be adapted **on-the-fly**
- How to measure “goodness” of a solution and represent costs and benefits in a generic way (KPIs)
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