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Giancarlo Dalle Ave

Energy- and Equipment-Condition-Aware Online Scheduling Methods for the Process Industries

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Abstract

Production scheduling is key to the profitability of an industrial production site. This work investigates various aspects of scheduling systems with an emphasis placed on industrial requirements; particularly focusing on some of the challenges associated with operating in an online industrial environment, taking into consideration cost-related concerns including both energy and maintenance costs. This work builds upon the generic Resource Task Network (RTN) scheduling framework (Pantelides, 1994) as it is readily adaptable to the ISA-95 industrial standard for production scheduling (ANSI/ISA-95.00.03-2005, 2005).

This work begins with a general discussion of online scheduling. First it is shown that faster rescheduling generally results in better closed-loop performance. This precipitates the needs for fast scheduling solution algorithms as the faster a schedule can be computed, the more flexibility one has regarding rescheduling. Next, end of horizon effects and scheduling nervousness are discussed qualitatively, and it is argued that scheduling models should be developed with these concerns in mind.

The next chapter focuses on addressing some of these online scheduling concerns for the RTN scheduling model. Firstly, an iterative combined heuristic/Mixed Integer Linear Programming (MILP) solution algorithm is proposed to solve RTN-based scheduling problems. The algorithm is initialized with a constructive heuristic solution. Information from this solution is used to limit the domain of the MILP such that the problem size is reduced while still allowing for better solutions to be found. This is performed iteratively until the algorithm has converged. Results show that the new algorithm can find good quality solutions orders of magnitude faster than a full-space RTN model directly solved using a MILP solver. Furthermore, the algorithm is suitable for online use as it provides a feasible solution at every iteration meaning that even in the presence of extremely stringent computation times a solution is still returned. Next the topic of scheduling nervousness is addressed in relation to the RTN model. A set of penalties are proposed to enforce scheduling stability between subsequent iterations of the schedule. An overlying algorithm is used to set the magnitude of the penalties. Results show that the approach can efficiently balance the trade-off between scheduling stability and optimality.

A couple of aspects that are becoming increasingly important for the profitability of the process industries are energy management, via Demand Side Management (DSM), and equipment condition and maintenance. A novel DSM formulation, built on top of the RTN, is proposed in this work that combines the problems of following a previously committed load, with purchasing decisions for future use. The formulation is shown to have two benefits, firstly additional flexibility is unlocked as production can be shifted around with updates to future purchasing decisions. Secondly, the formulation is more suitable for online use as it avoids the sharp drop in electricity consumption towards the end of the scheduling horizon as is characteristic of current state-of-the-art DSM formulations. Further, condition-based maintenance is incorporated into the RTN model by tracking the Remaining Useful Lifetime (RUL) of a process unit. When the RUL of a unit has been depleted a maintenance-action is needed to restore it. The RUL in this case can be tied to the intensity at which the corresponding equipment is operated at, creating a close coupling between batch timing and batch length, resource consumption, and need for maintenance. Revisiting the steelmaking application, it is shown that the formulation can effectively balance these trade-offs and is suitable for online scheduling use.

Zusammenfassung

Bessere Produktionsplanung ist der Schlüssel zu Profitabilitätssteigerungen in der Industrie. In der vorliegende Arbeit wird Produktionsplanung mit besonderem Fokus auf industrielle Anforderungen untersucht. Die Herausforderungen, welche in dieser Arbeit beleuchtet werden, sind die Anforderungen der Echtzeitproduktionsplanung sowie den Einfluss von Betriebskosten, zum Beispiel Energiekosten oder Instandhaltungskosten. Dabei wird auf das Resource Task Network (RTN) Konzept (Pantelides, 1994) aufgebaut, da so einfach auf den ISA-95 Standard für die industrielle Produktionsplanung aufgesetzt werden kann (ANSI/ISA-95.00.03-2005, 2005).

Zuerst wird ein iterativer heuristischer Ansatz zur Lösung von Planungsproblemen in der Domäne der linearen gemischt-ganzzahligen Programme (MILP) entwickelt. In den ersten Schritt wird eine heuristische Lösung genutzt, um den Definitionsbereich des MILP einzugrenzen und so den Suchraum zu verkleinern. Dieses heuristische Eingrenzen wird bis zur Konvergenz angewendet und die Ergebnisse zeigen, dass so eine gute Lösungen um Größenordnungen schneller als bei der Verwendung des vollen RTN Modells in Kombination mit einem MILP-Lösers gefunden werden können. Der Algorithmus eignet sich für die Anwendung in der Echtzeit-Planung, da in jeder Iteration selbst bei geringer Verfügbarkeit von Rechenzeit eine zulässige Lösung gefunden wird. Darüberhinaus wird die „Nervosität" der Lösungsstruktur durch die Einführung von Nebenbedingungen addressiert, welche eine gewisse Konstanz zwischen den Iteration erzwingen. Dabei bestimmt ein übergeordneter Algorithmus den Einfluss der durch die Nebenbedingungen eingeführten Strafen. Die Ergebnisse zeigen, dass das verwendete Konzept einen effektiven Kompromiss zwischen der Stabilität und der Optimalität der Planung erreicht.

Die Problemformulierung wird im Folgenden erweitert, um auf zukünftige Anforderungen in der Produktionsplanung einzugehen: Dynamische Laststeuerung auf Verbraucherseite (Demand-Side Management, DSM) sowie die Einbeziehung von zustandsbasierter Instandhaltung. Dazu wird eine Problemformulierung für DSM entwickelt, welche die Einhaltung vorher vereinbarter Verbrauchsmengen mit den Entscheidungen über die zukünftigen Verbrauchsmengen kombiniert, was folgende Vorteile liefert: Zum Einen wird zusätzliche Flexibilität geschaffen, da die Produktion unabhängig von zukünftigen Einkaufsentscheidungen angepasst werden kann. Zum Anderen ist die Struktur für die Echtzeit-Planung geeignet, da der Einfluss des Planungshorizontes verringert wird.

Um zustandsbasierte Instandhaltung zu berücksichtigen, wird eine nutzungsabhängige Restnutzungsdauer (RUL) je Produktionseinheit in die Planung mit einbezogen. Sobald die RUL einer Produktionseinheit zu Ende geht, ist eine Instandhaltungsmaßnahme notwendig. Die RUL hängt von der Intensität der Nutzung der Ausrüstung ab, wodurch eine Abhängigkeit zwischen der Planung der Startzeiten der Batches, der Batchlänge, dem Ressourcenverbauch, und den Instandhaltungsmaßnahmen entsteht wird. Anhand einer Fallstudie aus der Stahlproduktion wird exemplarisch erörtert, dass die vorgeschlagene Struktur einen günstigen Kompromiss zwischen diesen Aspekten erreicht. Somit können sowohl die Problemformulierung mit dynamischer Laststeuerung und zustandsbasierter Instandhaltung als auch Problemlösungsverfahren einen Beitrag zu mehr Produktivität liefern.

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List of Acronyms

DSM	Demand Side Management
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
ERP	Enterprise Resource Planning
MES	Manufacturing Execution System
DCS	Distributed Control System
EWO	Enterprise Wide Optimization
PSE	Process Systems Engineering
STN	State-Task Network
UOPSS	Unit-Operation-Port-State-Superstructure
P&ID	Piping and Instrumentation Diagram
PFD	Process Flow Diagram
RTN	Resource-Task Network
TOU	Time-of-Use
RUL	Remaining Useful Lifetime
EAF	Electric Arc Furnace
AOD	Argon Oxygen Decarburizer
LF	Ladle Furnace
CC	Continuous Caster
LHD	Load, Haul, Dump Machine
DES	Discrete Event Simulation
SCT	Sum of Completion Times
ASAP	As Soon as Possible
EET	Earliest End Time
RTO	Real Time Optimization

Nomenclature

Index/Set/Subset

	Base RTN
$r \in R$	Resources
$i \in I$	Tasks
$u \in U$	Processing units
$u \in U_k$	Processing units at stage k
$t \in T$	Set of RTN time points
	Iterative Neighbourhood Algorithm Related
$i_u \in I_u$	Tasks i processed on each of the parallel machines at stage k
$i \in I_{changeover}$	Set of changeover tasks
$\eta \in H$	Set of iterative algorithm neighbourhoods
$t \in \eta$	Set of time points belonging to a neighbourhood
$i \in I_\eta$	Set of tasks i that can can start in neighbourhood η
	Scheduling Nervousness Related
$j \in J$	Set of versions of the online agenda
$i \in I^{resched}$	Set of tasks to be rescheduled
$i \in I^u$	Set of tasks scheduled to take place on machine u
	DSM and Non-uniform Time Grid Related
$r \in R^{IL}$	Resources for steel heats at the inlet location of a stage
$r \in R^{OL}$	Resources for steel heats at the outlet location of a stage
$i \in I_{h,u}$	Processing task for heat h that can be processed by unit u
$i \in I_{g,u}$	Processing task for heat group g that can be processed by unit u
$i \in I_{h,u,u'}$	Transfer task for heat h occurring between units u and u'
$h \in H$	Steel heats
$g \in G$	Steel heat groups
$k \in K$	Processing stages
$t \in T_{detail}$	Set of RTN time points in the detailed portion of the non-uniform grid

$t \in T_{agg}$	Set of RTN time points in the aggregate portion of the non-uniform grid
θ	Relative time to start of task
$t \in T_{hr}$	Set of hours in the time horizon
$t \in T_{peak}$	Set of times over which the peak is calculated
$t \in T_{intra}$	Set of times over which electricity is sold
$t \in T_{day1}$	Set of time slots that belong to the first day
	Equipment Degradation Related
$m \in M$	Set of equipment operating modes
$r \in R_{RUL}$	Set of equipment RUL resources
$i \in I_M$	Set of tasks with multiple operating modes
$i \in I_{maint}$	Set of maintenance tasks

Parameters

	Base RTN
$\tau_{i,t}$	Duration of task i in time slots
$\|H\|$	Length of the Scheduling Horizon
δ	Time grid discretization for the uniform-grid cases
$\mu_{r,i,t,\theta}$	Extend of discrete interaction of r with i
	Iterative Neighbourhood Algorithm Related
W	Neighborhood size (number of jobs to look ahead/behind)
st_i	Start time of the ith job defined by the previous iteration solution
$st_{m,i-W}$	Start time of the Wth predecessor to task i on Machine m
$st_{m,i+W}$	Start time of the Wth successor to task i on Machine m
st_i^{early}	Earliest start time of task i based on its neighborhood definition
st_η	Start time of neighbourhood η
RD_i	Release date of task i
DD_i	Due date of task i
	Scheduling Nervousness Related
ST_i^{j-1}	Start time of task i in the current in-progress agenda ($j-1$)
	DSM and Non-uniform Time Grid Related
$\delta_{T_{detail}}$	Time grid discretization for the detailed model

$\delta_{T_{agg}}$	Time grid discretization for the aggregate model
δ_{intra}	Length of interval size for which it is possible to trade on the intraday market
$maxtrf_{u,u'}$	Maximum transfer time between units u and u'
$mintrf_{u,u'}$	Minimum transfer time between units u and u'
$power_{h,u}$	Power consumption of heat h in unit u
T_{sell}	Time until trading on the intraday market begins
y^{BL}	Amount of electricity load from a baseload contract
ξ_{toDate}	Largest peak achieved in this current billing period
y_t^{CL}	Total amount of current day committed electricity load
y_t^{TOU}	Amount of electricity load from a TOU contract
y_t^{BL}	Amount of electricity load from a baseload contract
c_{pf}^{DA}	Penalty free tolerance on load tracking
C_t^{DA}	Cost of electricity at time t from the day-ahead market
C_t^{TOU}	Cost of electricity at time t from the TOU contract
C_t^{BL}	Cost of electricity at time t from the baseload contract
C_t^{+}	Cost of positive electricity deviations from day-ahead commitment at time t
C_t^{-}	Cost of electricity deviations from TOU contract at time t
C_t^{-}	Cost of electricity deviations from baseload contract at time t
C_t^{TOU}	Cost of negative electricity deviations from day-ahead commitment at time t
C_t^{DABuy}	Cost of buying additional electricity on the intraday market at time t
C_t^{DASell}	Revenue from selling electricity on the intraday market from the day-ahead contract at time t
$C_t^{TOUSell}$	Revenue from selling electricity on the intraday market from the TOU contract at time t
C_t^{BLSell}	Revenue from selling electricity on the intraday market from the baseload contract at time t
	Equipment Degradation Related
$threshold$	Maximum RUL at which at maintenance action can be performed
C^{maint}	Cost of a maintenance action (€)

RUL_{new}	RUL of a new unit

Variables

	Base RTN
$N_{i,t}$	Binary - execution of task i at time slot t
$R_{r,t}$	Amount of r available at t
$\Pi_{r^{el},t}$	Electricity consumption at t
	Iterative Algorithm Related
S_i	Due date slack for task i
	Scheduling Nervousness Related
$S_i^{backwards}$	Slack variable incurred from moving task i backwards in time relative to its start time in an earlier scheduling iteration
$S_i^{forwards}$	Slack variable incurred from moving task i forwards in time relative to its start time in an earlier scheduling iteration
$S_i^{equipment}$	Slack variable incurred from changing the machine assignment of a task i relative to its assignment in an earlier scheduling iteration
$S_i^{regionChange}$	Slack variable incurred from moving task i forward to the short-term zone from later zones
	DSM and Non-uniform Time Grid Related
$\Pi_{r^{el},t}^{TOU}$	Electricity consumption from the TOU contract at t
$\Pi_{r^{el},t}^{BL}$	Electricity consumption from the BL contract at t
σ_t	Free variable - total amount of electricity load bought or sold on the intraday market
σ_t^+	Amount of electricity bought on the intraday market
σ_t^{DA}	Amount of electricity sold from the day-ahead contract on the intraday market
σ_t^{TOU}	Amount of electricity sold from the TOU contract on the intraday market
σ_t^{BL}	Amount of electricity sold from the base load contract on the intraday market
y_t^{PL}	Total amount of load to be purchased at time t on the second day of the scheduling horizon

y_t^{DA}	Total amount of electricity the comes from the day-ahead market
Δ_t	Total deviations from all the contract.
$\Delta_t^+, \Delta_t^{DA}$	Positive and negative deviations from the day-ahead committed load respectively
Δ_t^{TOU}	Negative deviations from the TOU load
Δ_t^{BL}	Negative deviations from the base load
ξ	Maximum electricity peak
ξ_{detail}	Maximum electricity peak in the detailed portion of the model
ξ_{agg}	Maximum electricity peak in the aggregate portion of the model
ω_t	Free variable - penalty free zone from the day-ahead contract
	Equipment Degradation Related
ner	Number of maintenance tasks required