Computers and Chemical Engineering 99 (2017) 325–339

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Optimization of multipurpose process plant operations: A multi-time-scale maintenance and production scheduling approach

Matteo Biondi [a,b], Guido Sand [a,c], Iiro Harjunkoski [a,*]

[a] ABB Corporate Research Germany, Wallstadter Str. 59, 68526 Ladenburg, Germany
[b] Chair of Production Management, University of Mannheim, 68131 Mannheim, Germany
[c] University of Applied Science Pforzheim, Tiefenbronner Str. 65, 75175 Pforzheim, Germany

ARTICLE INFO

Article history:
Received 4 July 2016
Received in revised form 8 November 2016
Accepted 4 January 2017
Available online 16 January 2017

Keywords:
Plant operations
Maintenance
Scheduling
Optimization
Performance degradation

ABSTRACT

Scheduling of production and maintenance plays a fundamental role in the effective operation of process plants. Frequently the two decision processes are independently addressed, overlooking the tight relation existing between the way the plant is operated to produce the required goods and the appearance of maintenance requirements. The presence of degradation phenomena affecting the performance of plant units and limiting the operational choices makes the integration of the two decision processes even more important. In this paper an industrial framework for the integration of maintenance and production scheduling of process plants is presented as well as some considerations on how the presence of plant unit degradation impacts on the scheduling problem. The proposed approach ties industrial key-components such as asset management and production scheduling closer together and represents therefore a contribution to the smart manufacturing revolution. The integrated maintenance and production scheduling problem is formulated as a mixed integer linear program (MILP) and tested on a generic process plant described as a State Task Network (STN).

1. Introduction

The scheduling of production and maintenance is a critical decision process for the profitable management of any process plant. While the first ensures reaching the production targets to satisfy customer demands, the second makes sure that plant assets are available and in the condition to perform the required tasks when needed by the production. The two decision processes are highly interdependent since they share a clear common denominator: the assets of the plant, which are used/consumed by production tasks and restored by maintenance activities.

Asset management is the engineering practice that deals with the optimization of plant assets usage with the ultimate objective of reducing production costs. In real industrial plants, it is responsibility of the asset management system (NAMUR, 2009) to:

- manage the assets over the whole life cycle, in particular regarding their reliability and efficiency
- optimize utilization and cost-effective maintenance of the assets
- generate and provide information regarding the development and prognosis of the "asset health" to support decision making of the enterprise and production management.

Fig. 1 shows a screenshot of the summary page of an asset management system from a real industrial plant. Assets are here represented grouped by classes to have a better overview of the overall system health. As mandated by the NAMUR recommendation, other critical information to effectively manage the overall plant are also summarized, for example the indication of the assets health (in terms of risk of failure) with a trend over the last time periods to support the prognosis of the remaining asset life. The information contained in the asset management system is of vital importance to support the maintenance team to effectively plan repair, cleaning and maintenance actions.

One of the most striking aspects appearing from the asset management system described above is the lack of connection with the actual process conditions, i.e. with information on the kind of products that are being processed or will be processed in the plant in the near future, which ultimately determines the asset wear-out rates. This kind of information is managed by another key system for the plant operations, the planning and scheduling, which vice versa has typically no interconnection with the asset management system.

* Corresponding author.
E-mail address: iiro.harjunkoski@de.abb.com (I. Harjunkoski).

http://dx.doi.org/10.1016/j.compchemeng.2017.01.007
0098-1354/

Nomenclature

Indices

i	Task
j	Unit
k	Operation mode
t	Time interval
t_s	Scheduling time interval
t_p	Planning time interval
n	Natural number

Sets

I	Production tasks
I_j	Tasks that can be performed on unit j
I_s	Tasks fed by state s
$\bar{I}_s$	Tasks producing output material in state s
J	Plant units
J_i	Units that can perform task i
K_j	Operation modes of unit j
S	Initial, intermediate and final states
T	Time intervals
T_s	Scheduling time intervals
T_p	Planning time intervals

Parameters

p_{ijk}	Production time of task i on unit j in mode k
τ_j	Duration of a maintenance task on unit j
V_{ij}^{min}	Lower bound on batch size of task i on unit j
V_{ij}^{max}	Upper bound on batch size of task i on unit j
ρ_{is}	Proportion of input of task i from state s
$\bar{\rho}_{is}$	Proportion of output of task i from state s
d_{st}	Demand of product in state s at the end of time t
C_s	Maximum storage capacity for product in state s
R_j^{max}	Maximum life of unit j
D_{ijk}	Wear on unit j caused by the processing of task i in mode k
H	Length of each planning horizon time interval
$c_s^{storage}$	Storage cost for one unit of material in state s
m_k	Threshold on the percentage of remaining useful life of a unit to use mode k

Binary variables

W_{ijkt}	=1 if unit j starts processing task i in mode k at the beginning of time interval $t \in T_s$
M_{jt}	=1 if a maintenance task start on unit j at the beginning of time interval $t \in T$
$Mode_{jkt}$	=1 if unit j operates in mode k within planning time interval $t \in T_p$
Q_{ijktn}	Binary for the 2-based representation of integers $t \in T_p$

Integer variables

N_{ijkt}	Number of copies of task i produced by unit j in mode k within the time interval $t \in T_p$

Continuous variables

B_{ijkt}	Amount of material which starts undergoing task i on unit j in mode k at time $t \in T_s$
S_{st}	Amount of material stored in state s, at the beginning of time period $t \in T$
S_s^{fin}	Inventory level of state s at the end of the scheduling horizon
R_{jt}	Residual life of unit j at the end of time interval $t \in T$
F_{jt}	Residual life restoration on unit j due to a maintenance task starting at time $t \in T$
A_{ijt}	Total amount of material undergoing task i in unit j within time interval $t \in T_p$
O_{ijktn}	Auxiliary variable for linearization of bilinear terms $t \in T_p$

Using asset health information to generate an optimal production plan is a viable solution to better integrate the two systems and to increase the overall performance (e.g. in terms of costs) of plant operations.

The objective of this paper is twofold: first, to propose a joint scheduling approach for the production and maintenance of process plants that explicitly keeps track of the assets life cycle. Fig. 2 shows a workflow of the integrated decision process. The scheduling system includes a simple model of the asset wear that can be based on the concept of residual useful life (RUL) or of probability of failure (p^{fail}). In the following, we will focus on a deterministic formulation of the integrated maintenance and production scheduling problem and therefore consider the residual useful life as a unique indicator of the asset health. The asset monitoring system is responsible of providing two types of information to the scheduling system: on the one hand, an estimation of the parameters describing the wear caused by the production on the asset. On the other hand, if an extraordinary condition of the asset is detected, it is responsible of updating the current RUL in the asset wear model of the scheduling system. Assets health information, along with the production orders, is managed by the scheduling system that takes care of the sequencing and timing of production tasks on the plant and triggers a maintenance action on the assets whenever this is required. Furthermore, the system can select an optimal production or operation mode to influence the equipment wear in an optimal manner. The typically slow dynamics of the asset wear-out process (and therefore the low frequency of maintenance requirements) poses significant challenges to the integrated maintenance and production approach. For this reason, in Section 4 a multi-time scale framework is introduced to account for the short term decisions (e.g. maintenance and production scheduling) as well as for the medium-long term ones (e.g. maintenance and production planning).

The second objective of the paper is to investigate the effects of asset aging on the integrated maintenance and production model presented before. If the aging has influence on the asset performance, the scheduling model should take that into account to generate the optimal schedule and eventually anticipate a maintenance action on an asset, if this improves its performance. In Section 0, two ways to account for performance degradation due to asset aging are introduced and the influence on the integrated maintenance and production approach is modeled and tested.

With these characteristics included in the models, the presented approaches show not only elements of novelty from the scientific point of view, but also an important step forward from an industrial perspective. As a matter of fact, the methods make an effective use of units' health information to generate a feasible plan for production and maintenance. They represent therefore a significant interconnection between the domains of asset management and production planning, two critical components for the management of operations of process plant that are still frequently considered independently in practical applications.

Before entering into the modeling details, Section 2 summarizes the integrated maintenance and production approaches found in literature that inspired this work. In Section 3, the modeling framework for the scheduling approach as well as the key elements to