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Planning of production and utility systems under unit performance degradation and alternative resource-constrained cleaning policies

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HIGHLIGHTS

- A model for the simultaneous planning of production and utility systems is presented.
- The performance degradation and recovery is modeled for the utility units.
- Alternative cleaning policies are modeled under limited cleaning resources.
- Fixed and variable operating, cleaning and power consumption costs are optimized.
- Industrial-inspired case studies show the benefits of the proposed approach.
- Reduction in utilities purchases and startup, cleaning and power consumption costs.

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ABSTRACT

A general optimization framework for the simultaneous operational planning of utility and production systems is presented with the main purpose of reducing the energy needs and material resources utilization of the overall system. The proposed mathematical model focuses mainly on the utility system and considers for the utility units: (i) unit commitment constraints, (ii) performance degradation and recovery, (iii) different types of cleaning tasks (online or offline, and fixed or flexible time-window), (iv) alternative options for cleaning tasks in terms of associated durations, cleaning resources requirements and costs, and (v) constrained availability of resources for cleaning operations. The optimization function includes the operating costs for utility and production systems, cleaning costs for utility systems, and energy consumption costs. Several case studies are presented in order to highlight the applicability and the significant benefits of the proposed approach. In particular, in comparison with the traditional sequential planning approach for production and utility systems, the proposed integrated approach can achieve considerable reductions in startup/shutdown and cleaning costs, and most importantly in utilities purchases, as it is shown in one of the case studies.

1. Introduction

In the highly dynamic and competitive global market with stringent environmental and safety regulations, it has grown the significance of systematic operational and maintenance planning for energy intensive process plants in order to maximize profit, improve plant reliability and enhance the efficient management of assets, resources and energy. Major industrial facilities consist of interconnected production and utility systems. The production system produces the desired final products from raw materials that can undergo different production processes, such as chemical reactions or separations. These processes require significant amounts of several types of utilities, such as electricity, steam, industrial gases and water. In general, most industrial process industries have built onsite utility systems that are directly connected via pipelines to the main production system so as to satisfy its demands for utilities.

Combined heat and power systems, boilers, gas and steam turbines, compressor stations and air separation systems are some typical examples of onsite utility systems. Combined heat and power systems, cogenerate electricity and heat usually from natural gas, are among the most important types of utility systems in process industry, because they generate efficiently the main utilities needed for the operation of major equipment of the production system. In another example, for a cryogenic air separation system, the atmospheric air is first compressed and then undergoes a

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Nomenclature

Indices/Sets

$e \in E$ utility types (utilities)
$i \in I$ utility units
$g \in G$ final products
$j \in J$ connecting lines
$l \in L$ inventory tanks for final product
$n \in N$ processing units
$q \in Q$ offline cleaning task options
$t \in T$ time periods
$z \in Z$ inventory tanks for utility types

Superscripts

es earliest
ls latest
max maximum
min minimum
off offline
on online
FP production system
UT utility system
+ inlet
− outlet

Subsets

E_i utility types that can be produced from utility unit i
G_n final products that can be produced from processing unit n
I_e utility units that can be produced utility type e
J_i connecting lines that are linked to utility unit i
J_n connecting lines that are linked to processing unit n
L_g inventory tanks that can store final product g
L_n inventory tanks for final products that are linked to processing unit n
N_e processing units that require utility type e
N_g processing units that can produce final product g
N_l processing units that are connected to final product inventory tank l
N_z processing units that are connected to utility inventory tank z
Q_i alternative offline cleaning task options for utility unit i
Z_e inventory tanks that can store utility type e
Z_n inventory tanks for utilities that are linked to processing unit n
CB_i^{off} utility units i that are subject to condition-based offline cleaning tasks
CB_i^{on} utility units i that are subject to condition-based online cleaning tasks
DM_i utility units i that are under in-progress offline cleaning at the beginning of the planning horizon (information carried over from previous planning horizon)
FM_i utility units i that are subject to flexible time-window offline cleaning
MR_i utility units i that are subject to maximum runtime constraints

Parameters

$\alpha_{(n,g,e)}$ coefficient for processing unit n that provides the variable needs for utility e for the production of a unit of product g
$\beta_{(n,g,e)}$ coefficient for processing unit n that provides the fixed needs for utility e for the production of product g
$\gamma_{(e,z,t)}$ bounds on the total flow of utility e to inventory tank z in time period t
γ_i^{on} minimum time between two consecutive online cleanings in utility unit i
δ_i performance degradation rate for utility unit i
$\varepsilon_{(e,z,t)}$ bounds on the total flow of utility e to inventory tank z in time period t
$\zeta_{(g,t)}$ demand for final product g at time period t
η_t^{max} limited amount of available resources for cleaning operations in time period t
$\vartheta_{(i,q)}^{off}$ resource requirements for offline cleaning task option q of utility unit i
ϑ_i^{on} resource requirements for online cleaning of utility unit i
$\kappa_{(n,g,t)}^{FP}$ bounds on the production level of final product g in processing unit n in time period t
$\kappa_{(i,t)}^{UT}$ bounds on the production level of utility unit i in time period t
$\hat{\kappa}_{(i,j,t)}^{UT}$ bounds on the production level of utility unit i that serves connecting line j in time period t
λ_n^{max} max number of products that a processing unit n can produce at the same time
μ_i a sufficient big number
$\nu_{(i,q)}$ duration of offline cleaning task option q that could take place in utility unit i
$\xi_{(g,l)}^{FP}$ bounds on the capacity of inventory tanks l that can store final product g
$\xi_{(e,z)}^{UT}$ bounds on the capacity of inventory tanks z that can store utility e
o_i maximum runtime for utility unit i
$\rho_{(i,e)}$ stoichiometry coefficient that relates the operating level of the utility unit i with the produced amount of each coproduced utility e
ρ_i^{rec} recovery factor of utility unit i after its online cleaning
τ_i starting time of offline cleaning task for utility unit i
υ_i^{max} extra power consumption limit for utility unit i (performance degradation)
ϕ associated cost coefficients for objective function terms related to utility unit i (i.e., utilities purchase prices, startup and shutdown costs, electricity price, extra power consumption cost, online and offline cleaning tasks costs)
χ associated cost coefficients for objective function terms related to processing unit n (i.e., variable and fixed operating cost and purchase price for products)
ψ_i minimum shutdown idle time for utility unit i
ω_i minimum runtime for utility unit i

Parameters (initial state of the overall system)

$\tilde{\beta}_{(g,l)}^{FP}$ initial inventory level of final product g at inventory tank l
$\tilde{\beta}_{(e,z)}^{UT}$ initial inventory level of utility e at inventory tank z
$\tilde{\gamma}_i^{on}$ initial state of utility unit $i \in CB_i^{on}$ with respect to its last online cleaning
$\tilde{\eta}_{(i,t)}$ time periods t for utility unit $i \in DM_i$ that there is a known cleaning resource requirement (in-progress offline cleaning task from previous planning horizon)
$\tilde{\rho}_i$ initial cumulative time of operation for utility unit i
$\tilde{\varphi}_{(i,j)}$ active connection between utility unit i and connecting line j just before the beginning of the planning horizon
$\tilde{\chi}_i$ operating status of utility unit i just before the start of the planning horizon
$\tilde{\psi}_i$ total number of time periods at the beginning of the planning horizon that utility unit i has been continuously not operating since its last shutdown