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

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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.

Keywords: energy planning; production planning; performance degradation; cleaning; optimization; utility system; combined heat and power.

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 cryogenic process before being separated into its principal components (nitrogen and oxygen) that constitute some of the key industrial gases used broadly in process industries.

For instance, nitrogen may be used for inerting process vessels for cleaning purposes and pipeline purging, while oxygen could be used for the oxidation of chemicals compounds [1].

The interaction of the production system with utility systems in process industry is illustrated in Figure 1. Utility raw materials can be any type of fuel or other resource, such as natural gas or atmospheric air. These raw materials then undergo a conversion process in utility units and they generate the desired set of utilities. Compressors, boilers, turbines, combustion chambers and combined heat and power systems are some representative examples of utility units. Depending on the type of utilities, different types of conversion processes may take place in a utility unit, such as reaction, combustion or compression. The generated utilities are then supplied to the production system for its own operation and production of the final products. Excessive amounts of utilities can be stored in buffer tanks (e.g., hot water), be recycled so as to undergo the same process (e.g., steam), or in some cases be released to the environment (e.g., exhaust heat). It is important to notice that the demands for utilities are determined by the needs of the production system, as a result of the production planning problem.

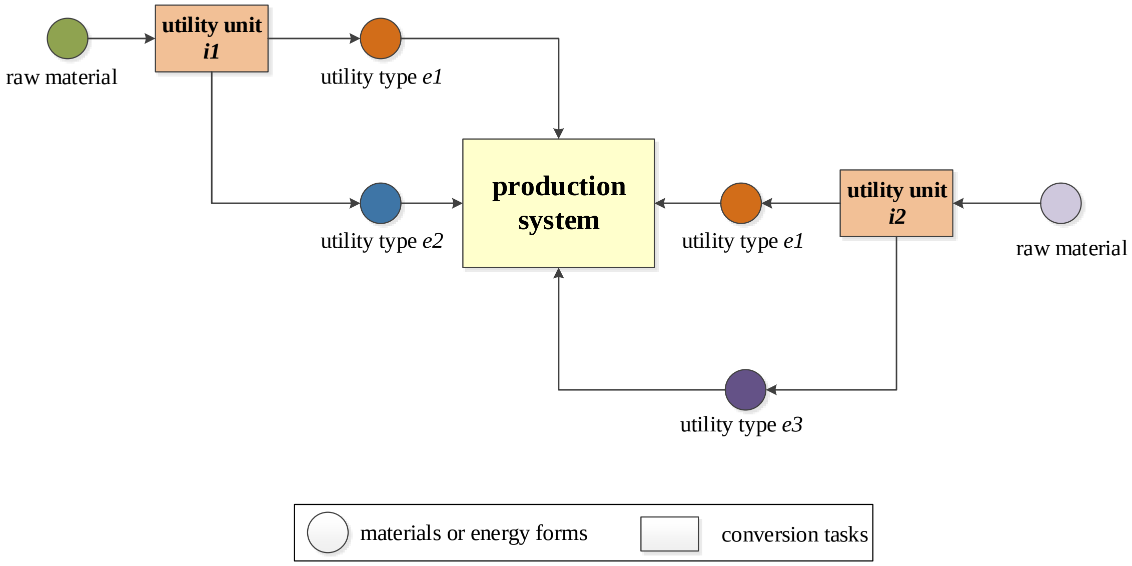


Figure 1. A representative layout of the interaction of production and utility systems.

In the open literature, the primary interest of production planning is usually in advanced equipment, such as chemical reactors, distillation systems, heat exchanger networks and compressor networks. An overview of operational planning and scheduling in process industries can be found in Kallrath [2]. Generally speaking, apart from safety the performance of a process plant is measured by the desired product quality, minimum operating cost and reduced environmental impact. Modern process plants are highly integrated and involve a set of complex operating equipment units that require maintenance (e.g., cleaning or parts replacement) based on specialized maintenance monitoring techniques in order to perform its required function in a timely manner to avoid equipment damage and the inefficient use of it. Effective maintenance policies can sustain the operational level, reduce operating and fixed costs and restrain the equipment unit and the overall system from entering hazardous states [3].

It is clear from the above discussion that a holistic systematic approach is needed for the optimization of the interconnected utility and production systems under maintenance considerations in process industries. For this reason, in this work a system-wide optimization framework is developed for the simultaneous operational and cleaning planning of production and utility systems considering maintenance aspects in terms of cleaning operation, in order to obtained solutions with enhanced energy savings and total cost reductions.

The paper is laid out as follows. Section 2 provides a brief literature review on the planning of production and utility systems and on cleaning operations. In Section 3, the problem statement of the subject study under question is formally defined. The proposed optimization framework is then presented in Section 4, followed by the description and the discussion of the results of all case studies in Sections 5 to 7. Finally, some concluding remarks with ongoing research directions are provided in Section 8.

2. Literature Review

2.1 Planning of production and utility systems.

Most process industries, and especially the most energy intensive, have installed onsite a utility system for meeting the utility requirements of the principal production system. A sequential approach is typically used for the planning of utility and production systems, as is explained below. First, the planning of the production system is performed considering simply upper bounds on the availability of utilities. Once the production plan is derived, the utility needs of the production are known. This information is then used for obtaining the operational planning of the utility system. This sequential approach provides suboptimal solutions (mainly in terms of energy efficiency and costs) because the two interconnected systems are not optimized at the same time. For this reason, this work focuses on the simultaneous planning of utility and production systems. A brief literature review on the subject follows.

Most previous studies have addressed either the planning of production systems [4–7] or the planning of utility systems independently [8–10]. There are few works that dealt with the simultaneous planning of utility and production systems. For example, Agha et al. [11] presented a Resource-Task Network based mathematical model for the simultaneous planning of a manufacturing and a combined heat and power plant. The results of their case studies demonstrated clearly that this integrated approach reduces significantly the energy costs and the emissions of greenhouse gases compared to the traditional sequential approach. In another study, Zhang et al. [12] developed a mixed integer nonlinear programming model that includes the heat integration of the process plant, the optimization of the utility system and coupling equations for the site-scale steam integration. Zhao et al. [13] presented mathematical models for the simultaneous planning of a refinery and its onsite utility system. The results of all the above works showed that the integrated planning of utility and production systems could result in significant energy savings, emissions and overall costs reductions.

2.2 Planning of cleaning operations.

The cleaning of specific equipment that are characterized by performance degradation (e.g., due to fouling), such as compressors and heat exchangers, is one of the major maintenance actions in process industry [14–16]. The purpose of these cleaning operations is to recover the performance (efficiency) of equipment and that way decrease their energy consumption or increase the energy savings over the operation of the equipment. There are two main cleaning strategies to deal with equipment performance degradation, namely online and offline cleaning. Online cleaning tasks take place without interrupting the operating status of the equipment and recover partially the performance of the equipment. An example of online cleaning task is the injection of a cleaning solution in the equipment while it is still under operation. Offline cleaning tasks can be performed only when the equipment is closed and it is generally assumed that they can recover the full performance of the equipment. The duration of offline cleaning tasks can be considerably higher than that of online tasks, because during offline cleaning other supplementary maintenance tasks, such as mechanical and electrical inspections, take place. The interested reader could be referred to the works of Pattanayak et al. [17] and Tian et al. [18] for a more detailed discussion on the cleaning of equipment.

A few studies studied different types of cleaning tasks, resource allocation, cleaning duration and costs. For example, Nguyen et al. [19] studied the trade-off between the number of workers, cleaning cost and economic losses. They show that for limited available cleaning resources, the cleaning tasks did not perform on time and economic loss occurred. While for excessive available cleaning resources, the maintenance tasks can be done on time but the total cleaning cost may become unnecessary high. Kopanos et al. [20] presented an optimization framework for the planning of a network of compressors considering limitations on the number of compressors that could be under maintenance simultaneously. Do et al. [21] studied a multi-component system with limited maintenance team and they showed that the minimum number of available resources can be obtained by minimizing the maintenance cost. Most of the works on the planning of cleaning tasks did not consider resources limits for the cleaning operations.

To the best of our knowledge, this is the first work that addresses the simultaneous operational and cleaning planning of production and utility systems considering unit performance degradation and recovery, unit commitment constraints and cleaning resources aspects (i.e., selection of alternative cleaning options, maximum availability of cleaning resources).

3. Problem Statement

The simultaneous planning of production and utility systems constitutes the subject of this study. In particular, the principal focus of this work is on the detailed operational and cleaning planning of the utility system considering traditional and alternative condition-based cleaning operations. Performance degradation and recovery are considered for the utility units that are subject to condition-based cleaning. Alternative options for cleaning tasks with respect to the duration, resource requirements and costs are also studied. The resulting problem is formally defined in terms of the following items:

- A given planning horizon divided into a number of equally-length time periods $t \in T$.
- A set of utility types $e \in E$ that are produced from a number of utility units $i \in I_e$ with given maximum (minimum) operating levels $\kappa_{(i,t)}^{UT,max}$ ($\kappa_{(i,t)}^{UT,min}$). For every utility unit $i \in I$, the minimum (maximum) runtime after its startup ω_i (o_i), the minimum idle time after its shutdown (ψ_i) and the costs for startup (ϕ_i^S) and shutdown (ϕ_i^F) are defined.
- A set of final products $g \in G$ with known demand profiles $\zeta_{(g,t)}$ that can be produced from a number of processing units $n \in N_g$ and maximum (minimum) production levels $\hat{\kappa}_{(n,g,t)}^{FP,max}$ ($\hat{\kappa}_{(n,g,t)}^{FP,min}$). For every processing unit $n \in N$ and final product $g \in G_n$, fixed and variable requirements for utilities are given ($\beta_{(n,g,e)}$ and $\alpha_{(n,g,e)}$, respectively). Fixed and variable operating costs for the processing units are also considered ($\chi_{(n,g)}^{FP,var}$ and $\chi_{(n,g)}^{FP,fix}$, respectively). Each processing unit is linked to a set of inventory tanks for final product ($n \in N_l$) and to a set of inventory tanks for utilities ($n \in N_e$).
- A set of utility-dedicated inventory tanks $z \in Z_e$ that are connected to processing units $n \in N_z$. These inventory tanks usually have a given maximum (minimum) inlet total flow $\varepsilon_{(e,z,t)}^{max}$($\varepsilon_{(e,z,t)}^{min}$) and maximum (minimum) storage capacities $\xi_{(e,z)}^{UT,max}$($\xi_{(e,z)}^{UT,min}$).

- A set of product-dedicated inventory tanks $l \in L_g$ with maximum (minimum) storage capacities $\xi_{(g,l)}^{FP,max}$ ($\xi_{(g,l)}^{FP,min}$).
- A number of cleaning policies for the utility units are considered. More specifically, a utility unit could be subject to: (i) flexible time-window offline cleaning ($i \in FM_i$) with given earliest (τ_i^{es}) and latest (τ_i^{ls}) starting times, (ii) in-progress offline cleaning carried over from the previous planning horizon ($i \in DM_i$), or (iii) condition-based cleaning ($i \in CB_i$) with known degradation rates (ρ_i) for the utility units. Furthermore, two types of condition-based cleaning tasks are considered, namely: online cleaning tasks (CB_i^{on}) with given recovery factors (ρ_i^{rec}), and offline cleaning tasks (CB_i^{off}).
- A set of alternative cleaning tasks options $q \in Q$. For each utility unit $i \in (CB_i^{off} \cup FM_i)$, there is a set of alternative cleaning tasks options Q_i that are characterized by different durations ($\nu_{(i,q)}$), cleaning resource requirements ($\vartheta_{(i,q)}^{off}$), and costs ($\phi_{(i,q)}^{off}$).
- Given purchase prices (or penalty costs) for acquiring utilities or final products from external sources, $\phi_{(e,n,t)}^{UT,ex}$ and $\chi_{(g,t)}^{FP,ex}$ respectively.
- A given time-varying electricity price profile $\bar{\phi}_t^{pw}$.

Some additional considerations of the problem under study follow. All parameters are assumed to be deterministic. Also, the demands for the final products should be fully satisfied. And, the inventory tanks for utilities could be connected to multiple processing units. In addition, there is a limited amount of available resources for cleaning tasks per time period.

For every time period, the key decisions to be made by the optimization model are:

- The operating status and the production level of final products for all processing units.
- The inventory levels for final products and utilities at each inventory tank.
- The utility requirements of the processing units.
- The operating status for each utility unit (i.e., startup, in operation, shutdown, under cleaning).
- The production level for the utility systems.
- The selection of the types and the timings for the cleaning tasks to be performed in the utility units.

And all the above with the objective to minimize the total cost of the overall system, which encompasses:

- fixed and variable operating costs for processing units,
- startup and shutdown costs for utility units,
- power consumption costs for utility units,
- total cleaning costs for utility units, and
- costs for acquiring utilities or final products from external sources.

4. Optimization Framework

A linear mixed integer programming model is presented for the operational and cleaning planning of utility system and the operational planning of the production system of a process plant. The main part of the presentation of the optimization framework is divided into the following parts: (i) the utility system, (ii) the production system, and (iii) the objective function.

4.1 The Utility System

4.1.1 Constraints related to startup and shutdown actions.

In order to model the main operational aspects of the utility units, the following binary variables are first introduced:

$$X_{(i,t)} = \begin{cases} 1 & \text{if utility unit } i \text{ is operating during time period } t, \\ 0 & \text{otherwise.} \end{cases}$$

$$S_{(i,t)} = \begin{cases} 1 & \text{if utility unit } i \text{ starts up at the beginning of time period } t, \\ 0 & \text{otherwise.} \end{cases}$$

$$F_{(i,t)} = \begin{cases} 1 & \text{if utility unit } i \text{ shuts downs at the beginning of time period } t, \\ 0 & \text{otherwise.} \end{cases}$$

Constraints (1) and (2) model startup and shutdown actions through the operating status of the utility unit.

$$\begin{aligned} S_{(i,t)} - F_{(i,t)} &= X_{(i,t)} - \tilde{\chi}_i \qquad \forall i \in I, t \in T : t = 1 \\ S_{(i,t)} - F_{(i,t)} &= X_{(i,t)} - X_{(i,t-1)} \qquad \forall i \in I, t \in T : t > 1 \end{aligned} \tag{1}$$

$$S_{(i,t)} + F_{(i,t)} \leq 1 \qquad \forall i \in I, t \in T \tag{2}$$

For instance, according to constraints (1), if a utility unit has not been operating in the previous time period but operates in the current time period, then a startup takes place (i.e., $S_{(i,t)} = 1$ and $F_{(i,t)} = 0$). Parameter $\tilde{\chi}_i$ denotes the operating status of utility unit i just before the start of the planning horizon. If the utility unit i has been operating just before the start of the planning horizon, then $\tilde{\chi}_i = 1$, otherwise it is zero. Constraints (2) excludes the simultaneous realization of a startup and a shutdown action. If startup and shutdown costs are included in the objective function, constraints (2) could be excluded from the optimization model, since their corresponding values will tend to zero.

Constraints (3) model the minimum runtime (ω_i) for a utility unit after its startup. These constraints ensure that if a utility unit startups at a given time period t, it will operate for at least ω_i time periods.

$$\begin{aligned} X_{(i,t)} &\geq \sum_{t'=\max\{1,t-\omega_i+1\}}^{t} S_{(i,t')} \qquad \forall i, t \in T : \omega_i > 1 \\ X_{(i,t)} &= 1 \qquad \forall i \in I, t = 1, \ldots, (\omega_i - \tilde{\omega}_i) : 0 < \tilde{\omega}_i < \omega_i \end{aligned} \tag{3}$$

Parameter $\tilde{\omega}_i$ describes the initial state of each utility unit with respect to its minimum runtime. More specifically, this parameter corresponds to the total number of time periods at the beginning of the planning horizon that utility unit i has been continuously operating since its last startup. For example, if $\omega_i = 4$ and $\tilde{\omega}_i = 2$, the second part of constraints (3) gives $X_{(i,1)} = X_{(i,2)} = 1$.

Similarly, constraints (4) model the minimum shutdown time (ψ_i) for a utility unit after its shutdown. These constraints ensure that if a utility unit shuts down at a given time period t, it will not operate for at least ψ_i time periods.

$$
\begin{aligned}
&1 - X_{(i,t)} \geq \sum_{t'=\max\{1, t-\psi_i+1\}}^{t} F_{(i,t')} && \forall i, t \in T : \psi_i > 1 \\
&X_{(i,t)} = 0 && \forall i \in I, t = 1, ..., (\psi_i - \tilde{\psi}_i) : 0 < \tilde{\psi}_i < \psi_i
\end{aligned} \tag{4}
$$

Parameter $\tilde{\psi}_i$ describes the initial state of each utility unit with respect to its minimum shutdown time, and corresponds to the 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.

Obviously, constraints (3) and (4) are needed only if the durations of the minimum runtime and minimum shutdown time are greater than a single time period, respectively.

In addition, there may be a maximum duration of a continuous operation of a utility unit ($i \in MR_i$), called here a maximum runtime (o_i). Usually this reflects in a way the performance deterioration of a unit during its operation and is used to prevent major mechanical damages and reduce the energy-inefficient use of the unit; when no more sophisticated methods for the performance degradation are considered. The maximum runtime for a utility unit is given by:

$$
\begin{aligned}
&\sum_{t'=\max\{1, t-o_i\}}^{t} X_{(i,t')} \leq o_i && \forall i \in MR_i, t \in T \\
&\sum_{t'=\max\{1, t-(o_i-\tilde{\omega}_i)\}}^{t} X_{(i,t')} \leq (o_i - \tilde{\omega}_i) && \forall i \in MR_i, t = (o_i - \tilde{\omega}_i + 1) : \tilde{\omega} > 1
\end{aligned} \tag{5}
$$

Similar constraints can be formulated for the maximum idle time of a utility system, if needed. Here, the maximum idle time is defined as the maximum duration that a utility system remains switched off after its last shutdown.

4.1.2 Constraints related to cleaning actions.

Alternative types of cleaning operations for the utility units are considered in this study. More specifically, the utility units could be subject to:

- In-progress offline cleaning, carried over from the previous planning horizon ($i \in DM_i$).
- Flexible time-window offline cleaning tasks ($i \in FM_i$).
- Condition-based cleaning tasks ($i \in CB_i$), where a performance degradation and recovery model is used. There are two types of condition-based cleaning tasks: online cleaning tasks (CB_i^{on}) and offline cleaning tasks (CB_i^{off}). Both condition-based cleaning task types could be available for a unit, or just one of them (e.g., a unit could undergo offline cleaning but no online cleaning).

For a utility unit i that could undergo condition-based offline cleaning (CB_i^{off}) or flexible time-window offline cleaning (FM_i), alternative options of cleaning tasks ($q \in Q_i$) are also considered and modeled. These options differ in the: duration, cost, and cleaning resources requirements.

In order to model the aforementioned cleaning tasks of the utility system, the following binary variables are first defined:

$$V_{(i,t)} = \begin{cases} 1 \text{ if an online cleaning task for } i \in CB_i^{on} \text{ takes place in time period } t, \\ 0 \text{ otherwise.} \end{cases}$$

$$W_{(i,t)} = \begin{cases} 1 \text{ if an offline cleaning task for } i \in (CB_i^{off} \cup FM_i) \text{ begins at the start of time period } t, \\ 0 \text{ otherwise.} \end{cases}$$

$$H_{(i,q,t)} = \begin{cases} 1 \text{ if a cleaning task option } q \text{ for } i \in (CB_i^{off} \cup FM_i) \text{ begins at the start of time period } t, \\ 0 \text{ otherwise.} \end{cases}$$

For the sake of clarity, an illustrative example of the major optimization variables is displayed in Figure 2.

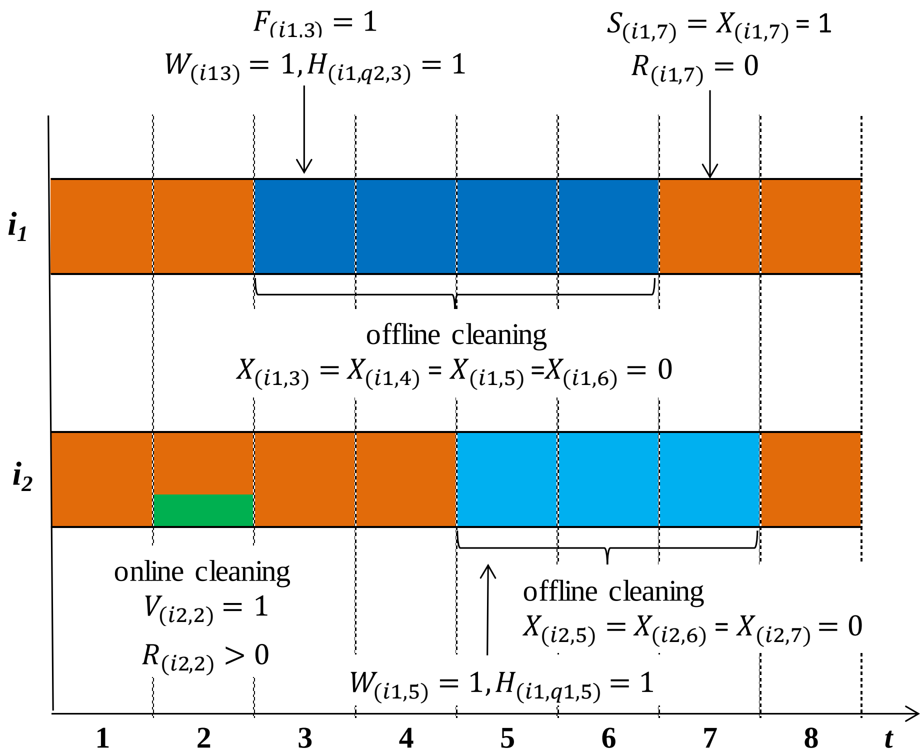


Figure 2. Illustrative example for the main optimization variables.

4.1.2.1 In-progress offline cleaning tasks carried over from the previous planning horizon.

At the beginning of the planning horizon of interest, there may be some in-progress unfinished offline cleaning tasks carried over from the previous planning horizon (i.e., started but not completed in the previous planning horizon). For the current planning horizon, these are predetermined cleaning tasks with known completion times and resource requirements per time period. Constraints (6) model this type of cleaning tasks by keeping closed the units $i \in DM_i$ for the all these time periods that there is a known cleaning resource requirement ($\tilde{\eta}_{(i,t)}$).

$$X_{(i,t)} = 0 \quad \forall i \in DM_i, t \in T : \tilde{\eta}_{(i,t)} > 0 \tag{6}$$

4.1.2.2 Flexible time-window offline cleaning tasks.

For utility units that are not subject to a condition-based cleaning policy, a flexible time-window offline cleaning policy ($i \in FM_i$) is usually employed. In general, these types of cleaning tasks have known durations and they should start within a given time-window $t = [\tau_i^{es}, \tau_i^{ls}]$. Constraints (7) ensure that the flexible time-window cleaning task for each utility unit $i \in FM_i$ starts within its corresponding time-window.

$$\sum_{q \in Q_i} \sum_{t=\tau_i^{es}}^{\tau_i^{ls}} H_{(i,q,t)} = 1 \quad \forall i \in FM_i \tag{7}$$

Notice that fixed offline cleaning tasks can also be modeled through the above constraints simply by setting equal the earliest and starting times (i.e., $\tau_i^{es} = \tau_i^{ls}$).

4.1.2.3 Extra power consumption for utility units (deviation from clean condition).

In this study, the condition-based cleaning of a utility unit is modeled through the extra power consumption of the unit ($U_{(i,t)}$) due to the deviation from its full performance (i.e., when the unit is completely clean). There can be an extra power consumption only in periods that the utility unit is under operation and this extra power consumption cannot exceed an associated upper limit (υ_i^{max}), as given below:

$$U_{(i,t)} \leq \upsilon_i^{\max} X_{(i,t)} \qquad \forall i \in CB_i, \forall t \in T \tag{8}$$

It is considered that the condition of a utility unit, which here is expressed by the extra power consumption, is related to its cumulative time of operation (R_i) from its fully clean condition and the corresponding degradation rate (δ_i) according to the following set of constraints:

$$\begin{aligned} U_{(i,t)} &\geq \delta_i R_{(i,t)} - \upsilon_i^{\max}(1 - X_{(i,t)}) \qquad \forall i \in CB_i, \forall t \in T \\ U_{(i,t)} &\leq \delta_i R_{(i,t)} + \upsilon_i^{\max}(1 - X_{(i,t)}) \qquad \forall i \in CB_i, \forall t \in T \end{aligned} \tag{9}$$

According to these constraints, if a utility unit is operating (i.e., $X_{(i,t)} = 1$), its extra power consumption is equal to $\delta_i R_{(i,t)}$, otherwise it becomes zero from constraints (8).

4.1.2.4 Performance degradation and recovery model for units under condition-based cleaning.

The performance degradation and recovery of the utility units is expressed through their cumulative time of operation. It is assumed here that a utility unit can retrieve its full performance after the occurrence of a condition-based offline cleaning task. This is expressed by a zero cumulative time of operation, as given by:

$$R_{(i,t)} \leq \mu_i (1 - W_{(i,t)}) \qquad \forall i \in CB_i^{off}, \forall t \in T \tag{10}$$

Parameter μ_i is a sufficient big number.

The evolution of the cumulative time of operation for any utility unit that is subject to condition-based offline or online cleaning is given by constraints (11) and (12), respectively.

$$\begin{aligned} R_{(i,t)} &\geq (\tilde{\rho}_i + X_{(i,t)}) - \mu_i (W_{(i,t)} + V_{(i,t)}) \qquad \forall i \in CB_i, \forall t \in T : t = 1 \\ R_{(i,t)} &\geq (R_{(i,t-1)} + X_{(i,t)}) - \mu_i (W_{(i,t)} + V_{(i,t)}) \qquad \forall i \in CB_i, \forall t \in T : t > 1 \end{aligned} \tag{11}$$

$$\begin{aligned} R_{(i,t)} &\geq (\tilde{\rho}_i + 1)(1 - \rho_i^{rec}) - \mu_i (1 - V_{(i,t)}) \qquad \forall i \in CB_i^{on}, \forall t \in T : t = 1 \\ R_{(i,t)} &\geq (R_{(i,t-1)} + 1)(1 - \rho_i^{rec}) - \mu_i (1 - V_{(i,t)}) \qquad \forall i \in CB_i^{on}, \forall t \in T : t > 1 \end{aligned} \tag{12}$$

Observe that the proposed modeling approach allows a utility to be able to be subject to both offline and online condition-based cleaning tasks, if needed.

4.1.2.5 Condition-based online cleaning tasks.

Some additional constraints for the condition-based online cleaning of utility units are included here. The duration of an online cleaning task is equal to a single time period. Constraints (13) ensure that online cleaning could take place in a utility unit at a given time period only if the unit is under operation.

$$V_{(i,t)} \leq X_{(i,t)} \qquad \forall i \in CB_i^{on}, \forall t \in T \tag{13}$$

In addition, there is usually a limitation on the frequency that online cleaning can take place in a utility unit in order to avoid potential damage or other negative effects on the performance on the unit. Constraints (14) ensure that the necessary minimum time between two consecutive online cleaning tasks (γ_i^{on}) on a utility unit is satisfied.

$$\begin{aligned} &\sum_{t'=\max\{1,t-\gamma_i^{on}+1\}}^{t} V_{(i,t')} \leq 1 && \forall i \in CB_i^{on}, \forall t \in T \\ &V_{(i,t)} = 0 && \forall i \in CB_i^{on}, t \leq (\gamma_i^{on} - \tilde{\gamma}_i^{on}) : \tilde{\gamma}_i^{on} < \gamma_i^{on} \end{aligned} \tag{14}$$

Parameter $\tilde{\gamma}_i^{on}$ provides the initial state of any utility unit $i \in CB_i^{on}$ with respect to its last online cleaning. This parameter represents the total number of time periods that have passed since the last online cleaning of a utility unit at the beginning of the current planning horizon.

4.1.2.6 Operational constraints for offline cleaning tasks.

Constraints (15) ensure that if an offline cleaning task takes place on a utility unit, that unit remains closed (i.e., $X_{(i,t)} = 0$) for the whole duration of the selected offline cleaning task option. And, constraints (16) relate the two operating binary variables for offline cleaning tasks.

$$X_{(i,t)} + \sum_{t'=\max\{\tau_i^{es},t-v_{(i,q)}+1\}}^{\min\{\tau_i^{ls},t\}} H_{(i,q,t')} \leq 1 \quad \forall i \in (FM_i \cup CB_i^{off}), q \in Q_i, \tau_i^{es} \leq t \leq (\tau_i^{ls} + v_{(i,q)} - 1) \tag{15}$$

$$W_{(i,t)} = \sum_{q \in Q_i} H_{(i,q,t)} \quad \forall i \in (FM_i \cup CB_i^{off}), t \in T : \tau_i^{es} \leq t \leq \tau_i^{ls} \tag{16}$$

For the condition-based offline cleaning tasks, earliest and latest starting times should be set equal to the first and the last period of the planning horizon, respectively.

4.1.2.7 Resource constraints for cleaning tasks.

In every time period, there is a limited amount of available resources for cleaning operations (η_i^{max}) shared by all types of cleaning tasks considered in this study.

$$\begin{aligned} &\sum_{i \in CB_i^{on}} \vartheta_i^{on} V_{(i,t)} + \sum_{i \in CB_i^{off}} \sum_{q \in Q_i} \sum_{t'=t-v_{(i,q)}+1}^{t} \vartheta_{(i,q)}^{off} H_{(i,q,t')} + \sum_{i \in FM_i} \sum_{q \in Q_i} \sum_{t'=\max\{\tau_i^{es},t-v_{(i,q)}+1\}}^{\min\{\tau_i^{ls},t\}} \vartheta_{(i,q)}^{off} H_{(i,q,t')} \\ &\leq \eta_t^{\max} - \sum_{i \in DM_i} \tilde{\eta}_{(i,t)} \quad \forall t \in T \end{aligned} \tag{17}$$

Parameters ϑ_i^{on} and $\vartheta_{(i,q)}^{off}$ correspond to the resource requirements for online cleaning and different offline cleaning task options, for every utility unit. Parameter $\nu_{(i,q)}$ denotes the duration of each offline cleaning task option.

4.1.3 Production of utilities.

The operating production level of any utility unit ($\tilde{Q}_{(i,t)}$) should be between its corresponding lower and upper bounds ($\kappa_{(i,t)}^{UT,min}$ and $\kappa_{(i,t)}^{UT,max}$) when the utility units operates, as given by:

$$\kappa_{(i,t)}^{UT,min} X_{(i,t)} \leq \bar{Q}_{(i,t)} \leq \kappa_{(i,t)}^{UT,max} X_{(i,t)} \quad \forall i \in I, t \in T \tag{18}$$

A utility unit may produce at the same time more than one utility types (e.g., a combined heat and power unit). Then, constraints (19) specify the amount of any utility e produced by each utility unit $i \in I_e$ per time period.

$$Q_{(i,e,t)}^{UT} = \rho_{(i,e)} \bar{Q}_{(i,t)} \quad \forall i \in I, e \in E_i, t \in T \tag{19}$$

Parameter $\rho_{(i,e)}$ stands for the stoichiometry coefficient that relates the operating level of the utility unit with the produced amount of each utility type that is coproduced by the utility system (e.g., heat to power ratio of a combined heat and power unit).

4.1.4 Inventories for utilities.

To continue with, the utility system contains a number of utility-dedicated inventory tanks. These inventory tanks can receive utilities ($B_{(e,z,t)}^{UT,+}$) from the utility units that are connected with, according to:

$$B_{(e,z,t)}^{UT,+} = \sum_{i \in I_e} Q_{(i,e,t)}^{UT} \quad \forall e \in E, z \in Z_e, t \in T \tag{20}$$

Also, there are usually lower and upper bounds on the flows of utilities to inventory tanks:

$$\varepsilon_{(e,z,t)}^{min} \leq B_{(e,z,t)}^{UT,+} \leq \varepsilon_{(e,z,t)}^{max} \quad \forall e \in E, z \in Z_e, t \in T \tag{21}$$

The utility balances in the utility-dedicated inventory tanks are given by:

$$\begin{aligned} B_{(e,z,t)}^{UT} &= \tilde{\beta}_{(e,z)}^{UT} + B_{(e,z,t)}^{UT,+} - \sum_{n \in (N_e \cap N_z)} B_{(e,z,n,t)}^{UT,-} \quad && \forall e \in E, z \in Z_e, t \in T : t = 1 \\ B_{(e,z,t)}^{UT} &= B_{(e,z,t-1)}^{UT} + B_{(e,z,t)}^{UT,+} - \sum_{n \in (N_e \cap N_z)} B_{(e,z,n,t)}^{UT,-} \quad && \forall e \in E, z \in Z_e, t \in T : t > 1 \end{aligned} \tag{22}$$

Parameter $\tilde{\beta}_{(e,z)}^{UT}$ provides the initial inventory for each utility inventory tank, variable $B_{(e,z,n,t)}^{UT,-}$ gives the amount of utility type e that leaves its inventory tank so as to satisfy the corresponding demand for utility of the connected processing units at each time period. Minimum and maximum inventory levels for these inventory tanks are also set:

$$\xi_{(e,z)}^{UT,min} \leq B_{(e,z,t)}^{UT} \leq \xi_{(e,z)}^{UT,max} \quad \forall e \in E, z \in Z_e, t \in T \tag{23}$$

4.1.5 Demands for utilities – The link between the utility and the production system.

Constraints (24) constitute the linking constraints between the utility and the production system. More specifically, the utilities demands of each processing unit consist of: (i) fixed utilities requirements depending on the operational status of the processing unit, and (ii) variable utilities needs depending on the production level of the processing unit.

$$NS^{UT}_{(e,n,t)} + \sum_{z\in(Z_e\cap Z_n)} B^{UT,-}_{(e,z,n,t)} = \sum_{g\in G_n}(\alpha_{(n,g,e)}Q^{FP}_{(n,g,t)} + \beta_{(n,g,e)}K_{(n,g,t)}) \quad \forall e\in E, n\in N_e, t\in T \tag{24}$$

Notice that variables $NS^{UT}_{(e,n,t)}$ give the amount of unsatisfied demand for each utility type per time period from the internal utility system. The acquisition of utilities from external sources is allowed here but it is highly undesirable and for this reason a very high purchase or penalty cost is typically introduced.

4.2 The Production System

4.2.1 Constraints related to the operational status and production level of the processing units.

The production system consists of a number of processing units that can produce the final products. The operation of the processing units along with the product-to-unit allocation are modeled through the following binary variables:

$$K_{(n,g,t)} = \begin{cases} 1 & \text{if final product } g \text{ is produced in processing unit } n \text{ during time period } t, \\ 0 & \text{otherwise.} \end{cases}$$

There are two main constraints for the processing units. More specifically, for every time period, there is a limited number of products (λ_n^{max}) that a processing unit could produce, according to:

$$\sum_{g\in G_n} K_{(n,g,t)} \le \lambda_n^{max} \quad \forall n\in N, \forall t\in T \tag{25}$$

Additionally, the produced amount of a final product should be within the lower and upper production level bounds ($\kappa^{FP,min}_{(n,g,t)}$ and $\kappa^{FP,max}_{(n,g,t)}$) of each operating processing unit, as given by:

$$\kappa^{FP,min}_{(n,g,t)} K_{(n,g,t)} \le Q^{FP}_{(n,g,t)} \le \kappa^{FP,max}_{(n,g,t)} K_{(n,g,t)} \quad \forall g\in G, n\in N_g, t\in T \tag{26}$$

4.2.2 Inventories for final products.

In this study, final product dedicated inventory tanks are considered. These inventory tanks can receive final products ($B^{FP,+}_{(g,l,t)}$) from the processing units that are connected with, according to:

$$B^{FP,+}_{(g,l,t)} = \sum_{n\in(N_g\cap N_l)} Q^{FP}_{(n,g,t)} \quad \forall g\in G, l\in L_g, t\in T \tag{27}$$

Hence, the material balances in the product-dedicated inventory tanks are given by:

$$\begin{aligned} B^{FP}_{(g,l,t)} &= \tilde{\beta}^{FP}_{(g,l)} + B^{FP,+}_{(g,l,t)} - B^{FP,-}_{(g,l,t)} && \forall g\in G, l\in L_g, t\in T : t=1 \\ B^{FP}_{(g,l,t)} &= B^{FP,+}_{(g,l,t-1)} + B^{FP,+}_{(g,l,t)} - B^{FP,-}_{(g,l,t)} && \forall g\in G, l\in L_g, t\in T : t>1 \end{aligned} \tag{28}$$

Parameter $\tilde{\beta}^{FP}_{(g,l)}$ represents the initial inventory level for each inventory tank, variable $B^{FP,-}_{(g,l,t)}$ provides the amount of final product g that leaves its inventory tank in order to satisfy the corresponding product demand at each time period. Minimum and maximum inventory levels for each inventory tank are defined as shown below:

$$\xi^{FP,min}_{(g,l)} \le B^{FP}_{(g,l,t)} \le \xi^{FP,max}_{(g,l)} \quad \forall g\in G, l\in L_g, t\in T \tag{29}$$

4.2.3 Demands for final products.

For every time period, the demands for final products ($\zeta_{(g,t)}$) are given and should be satisfied completely, according to the following equation:

$$NS_{(g,t)}^{FP} + \sum_{l \in L_g} B_{(g,l,t)}^{FP,-} = \zeta_{(g,t)} \quad \forall g \in G, t \in T \tag{30}$$

Variables $NS_{(g,t)}^{FP}$ give the amount of unsatisfied demand for every final product per time period from the internal production system. The purchases of final products is highly undesirable and for this reason a very high purchase or penalty cost is typically used in the objective function. In the case that final products purchases are not allowed, $NS_{(g,t)}^{FP}$ represent the lost sales of final products.

4.3 Objective Function

The optimization goal is to minimize the total cost of the production and the utility system. The total cost involves: (i) fixed and variable operating costs for processing units, (ii) cost for purchasing final products and utilities from external sources, (iii) startup and shutdown costs for utility units, (iv) total power consumption costs for utility units, and (v) cleaning costs for online and offline cleaning tasks for utility units. The objective function is shown below:

$$\min \left[\begin{array}{l} \sum_{t \in T} \sum_{n \in N} \sum_{g \in G} (\chi_{(n,g)}^{FP,var} Q_{(n,g,t)}^{FP} + \chi_{(n,g)}^{FP,fix} K_{(n,g,t)}) \\ + \sum_{t \in T} (\sum_{g \in G} \chi_{(g,t)}^{FP,ex} NS_{(g,t)}^{FP} + \sum_{e \in E} \sum_{n \in N_e} \phi_{(e,n,t)}^{UT,ex} NS_{(e,n,t)}^{UT}) \\ + \sum_{t \in T} \sum_{i \in I} (\phi_i^S S_{(i,t)} + \phi_i^F F_{(i,t)}) + \sum_{t \in T} \sum_{i \in I} (\bar{\phi}_t^{pw} \bar{Q}_{(i,t)} + \phi_t^{pw} U_{(i,t)}) \\ + \sum_{t \in T} (\sum_{i \in CB_i^{on}} \phi_i^{on} V_{(i,t)} + \sum_{i \in (CB_i^{off} \cup FM_i)} \sum_{q \in Q_i} \phi_{(i,q)}^{off} H_{(i,q,t)}) \end{array} \right] \tag{31}$$

In the above expression, all small-letter symbols multiplied by the optimization variables correspond to cost coefficients. A description of them is provided in the Nomenclature.

4.4 Special Case: No Storage of Utilities

In fact, some types of utilities cannot be stored usually due to several factors, such as their unstable nature, lack of good storage technology, and high storage energy needs. An example of such a type of utility is compressed air, whose storage is usually avoided due to high storage energy needs. Generally speaking, the absence of storage tanks for utilities in practice often results in a different layout for the utility system, where the utility units are connected directly to the processing units via connecting lines (e.g., pipelines). A representative layout of such utility systems can be seen in Figure 3 of the first case study considered in the paper. From the operational point of view, in this case the selection of which utility unit is connected to which connecting line (and thus to which processing unit) is an additional decision to be made for every time period. Typically, multiple utility units may serve a connecting line and utility property constraints should be considered for the utility units that serve the same connecting lines. For instance, in the case of a network of compressors, which is displayed in Figure 3, the outlet pressures (i.e., the property here) of the compressors that serve the same connecting lines at any given time period must be the same. The presentation of the necessary set of constraints for this type of utility systems follows.

4.4.1 Constraints related to the assignment of utility units to connecting lines.

In order to model the active connection among utility units and connecting lines (j), the following binary variables are introduced:

$$Y_{(i,j,t)} = \begin{cases} 1 & \text{if utility unit } i \text{ serves connecting line } j \text{ during time period } t, \\ 0 & \text{otherwise.} \end{cases}$$

When a utility is under operation, it can serve at most one connecting line at a time, as stated by:

$$\sum_{j \in J_i} Y_{(i,j,t)} = X_{(i,t)} \quad \forall i \in I, t \in T \tag{32}$$

As already mentioned, property constraints should be considered for the utility units that serve the same connecting line. The type of the property of interest and the related constraints depend on the utility system. For this reason, it is difficult to provide a general constraint that would describe any such utility system. However, in most of the cases the utility property is defined for the connecting lines and it could be expressed as a function of: (i) the total amount that the line receives, and (ii) a fixed term related to the active utility units connections. In general, constraints similar to those proposed by Kopanos et al. [20]) could be used (kindly refer to constraints (7) to (10) in Kopanos et al. [20]). Actually, these constraints have been used in Case Study 1.

4.4.2 Constraints related to assignment changes of utility units to connecting lines.

In practice is significant to avoid unnecessary assignment changes of utility units to connecting lines, since this would add unnecessary complexity in the plan implementation [20]. In order to model this, the following binary variables are introduced:

$$D_{(i,t)} = \begin{cases} 1 & \text{if utility unit } i \text{ changes connecting line at the beginning of time period } t, \\ 0 & \text{otherwise.} \end{cases}$$

Then, the utility unit to connecting line assignments can be modeled according to:

$$\begin{aligned} D_{(i,t)} &= Y_{(i,j,t)} - \tilde{\varphi}_{(i,j)} - S_{(i,t)} && \forall i \in I, t \in T : t = 1 \\ D_{(i,t)} &= Y_{(i,j,t)} - Y_{(i,j,t-1)} - S_{(i,t)} && \forall i \in I, t \in T : t > 1 \end{aligned} \tag{33}$$

Parameter $\tilde{\varphi}_{(i,j)}$ represents the initial state of the active connection between utility units and connecting lines just before the beginning of the current planning horizon. A detailed explanation of these constraints along with an illustrative example can be found in Kopanos et al. [20].

Finally, cost coefficients should be defined for these assignment changes and an associated cost term (i.e., total cost/penalty for assignment changes among utility units and connecting lines) must be added in the objective function of the problem.

4.4.3 Production of utility.

The production level ($\hat{Q}^{UT}_{(i,j,e,t)}$) of utility unit i that serves connecting line $j \in J_i$ must be between the corresponding lower and upper bounds ($\hat{\kappa}^{UT,min}_{(i,j,t)}$ and $\hat{\kappa}^{UT,max}_{(i,j,t)}$), as given by:

$$\hat{\kappa}^{UT,min}_{(i,j,t)} Y_{(i,j,t)} \le \hat{Q}^{UT}_{(i,j,e,t)} \le \hat{\kappa}^{UT,max}_{(i,j,t)} Y_{(i,j,t)} \quad \forall i \in I, j \in J_i, e \in E_i, t \in T \tag{34}$$

In this special case of utility system, a utility unit produces a single type of utility. A typical example of such a utility system is a compressor.

4.4.4 Demand for utility.

In this special case, constraints (24) are replaced by constraints (35). Now, these constraints are the linking constraints between the utility and the production systems.

$$NS^{UT}_{(e,n,t)} + \sum_{i \in I_e} \sum_{j \in (J_n \cap J_i)} \hat{Q}^{UT}_{(i,j,e,t)} = \sum_{g \in G_n} (\alpha_{(n,g,e)} Q^{FP}_{(n,g,t)} + \beta_{(n,g,e)} K_{(n,g,t)}) \quad \forall e \in E, n \in N_e, t \in T \qquad (35)$$

4.5 Remarks

The optimization frameworks presented in this section have been formulated in such a way that considers the complete set of parameters that define the initial state of the overall system. For this reason, the proposed approach can be readily used in a rolling horizon framework to deal with uncertainty aspects of the problem.

Finally, notice that one could solve the planning problem of just the utility system by replacing the right hand side of the constraints (24) or (35) by parameters that represent the given demands for utilities per processing unit and time period.

5. Case Study 1: Planning of a Utility System - An Industrial Network of Compressors.

This case study is a modified version of the industrial compressors network of the air separation plant of BASF SE studied by Kopanos et al. [20]. Compressed air is the only utility and product of interest here. The purpose of this example is to demonstrate the applicability of the proposed optimization framework in an industrial scenario where condition-based online and offline cleaning tasks for the utility units and operational tasks for the utility and production systems are considered and optimized simultaneously. In addition, different options for offline cleaning tasks are considered, thus increasing the complexity of the resulting decision-making optimization problem. A simplified version of the layout of the network of compressors of this example is displayed in Figure 3.

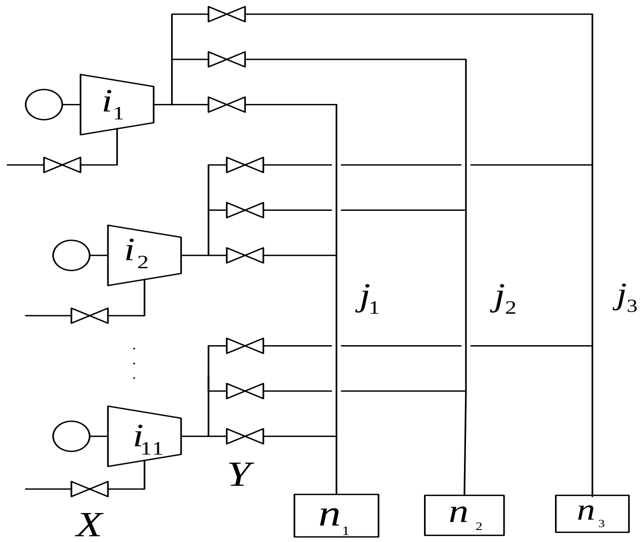


Figure 3. Case Study 1: Layout of the network of compressors.

5.1 Description of Case Study 1.

This case study considers a network of compressors that consists of eleven compressors connected in parallel that supply compressed air to three processing units ($n1$, $n2$, $n3$) through three headers ($j1$, $j2$, $j3$). There are five small compressors ($i1$, $i2$, $i3$, $i4$, $i5$) and six large compressors ($i6$, $i7$, $i8$, $i9$, $i10$, $i11$). Compressed air cannot be stored here. A compressor can be connected to at most one header per time period. Compressors could be connected to any header, but each header serves with compressed air a dedicated processing unit. More specifically, header $j1$ could supply compressed air to processing unit $n1$, header $j2$ is connected to processing unit $n2$, and header $j3$ serves processing unit $n3$. Minimum and maximum levels of outlet mass flow rates and pressure ratios of compressors, can be found in Kopanos et al. [20]. A total planning horizon of 30 days, divided in day time periods (i.e., 30 time periods), is considered. Table 1 provides the main operational parameters for this case study. The values for minimum and maximum runtime, minimum shutdown time and minimum time between two successive online cleanings are selected to reflect the typical status of the process industry. A condition-based approach is used, therefore there is no need for introducing earliest and latest starting times for cleaning tasks. Cost related data for the operational and the cleaning tasks can be found in Table 2. Penalty costs for changing headers, startup and shutdown cost for compressors and online cleaning costs are taken from the historical data of the compressors network by Kopanos et al. [20]. All parameters that describe the initial state of the overall system under consideration can be found in Table 3.

Table 1. Case Study 1: Main parameters.

Symbol	Value	Unit	Description
t	1	day	Duration of each time period.
T	30	days	Total number of periods (planning horizon).
ω_i	6	days	Minimum runtime for compressors.
ψ_i	3	days	Minimum shutdown time for compressors.
o_i	20	days	Maximum runtime for small compressors.
o_i	30	days	Maximum runtime for large compressors.
γ_i^{on}	8	days	Minimum time between two online cleanings.
ϑ_i^{on}	1	resource unit	Necessary cleaning resources for online cleaning.
$\eta_t^{\max}$	6	resource units	Available cleaning resources per time period.
ρ_i^{rec}	0.2	-	Recovery factor after online cleaning.

Table 2. Case Study 1: Costs for operational and cleaning tasks.

Symbol	Value	Unit	Description
-	750	m.u./change	Penalty term for changing header.
ϕ_i^S	4,900	m.u./startup	Cost of startup for small compressors.
ϕ_i^S	9,800	m.u./startup	Cost of startup for large compressors.
ϕ_i^F	2,500	m.u./shutdown	Cost of shutdown for small compressors.
ϕ_i^F	5,000	m.u./shutdown	Cost of shutdown for large compressors.

ϕ_i^{on}	61.75	m.u./ cleaning	Cost of online cleaning for small compressors.
ϕ_i^{on}	122.85	m.u./ cleaning	Cost of online cleaning for large compressors.
$\phi_{(i,q1)}^{off}$	213.75	m.u./cleaning	Cost of offline cleaning task $q1$ for small compressors.
$\phi_{(i,q1)}^{off}$	708.75	m.u./cleaning	Cost of offline cleaning task $q1$ for large compressors.
$\phi_{(i,q2)}^{off}$	142.50	m.u./cleaning	Cost of offline cleaning task $q2$ for small compressors.
$\phi_{(i,q2)}^{off}$	472.50	m.u./cleaning	Cost of offline cleaning task $q2$ for large compressors.
$\phi_{(i,q3)}^{off}$	106.88	m.u./cleaning	Cost of offline cleaning task $q3$ for small compressors.
$\phi_{(i,q3)}^{off}$	354.38	m.u./cleaning	Cost of offline cleaning task $q3$ for large compressors.

Table 3. Case Study 1: Initial state of the network of compressors.

	$i1$	$i2$	$i3$	$i4$	$i5$	$i6$	$i7$	$i8$	$i9$	$i10$	$i11$
$\tilde{\varphi}_{(i,j)} = 1$	-	$j3$	-	-	$j1$	-	$j1$	$j2$	$j3$	-	-
$\tilde{\rho}_i$	4	6	0	0	6	5	7	6	3	4	0
$\tilde{\omega}_i$	0	0	0	0	0	0	0	0	3	0	0
$\tilde{\psi}_i$	0	0	0	0	0	0	0	0	0	0	0

Figure 4 displays the normalized daily demand for compressed air for each processing unit; having as a reference the highest demand observed throughout the planning horizon. Demand is assumed to be deterministic. In addition, Figure 5 shows the electricity price profile over the planning horizon.

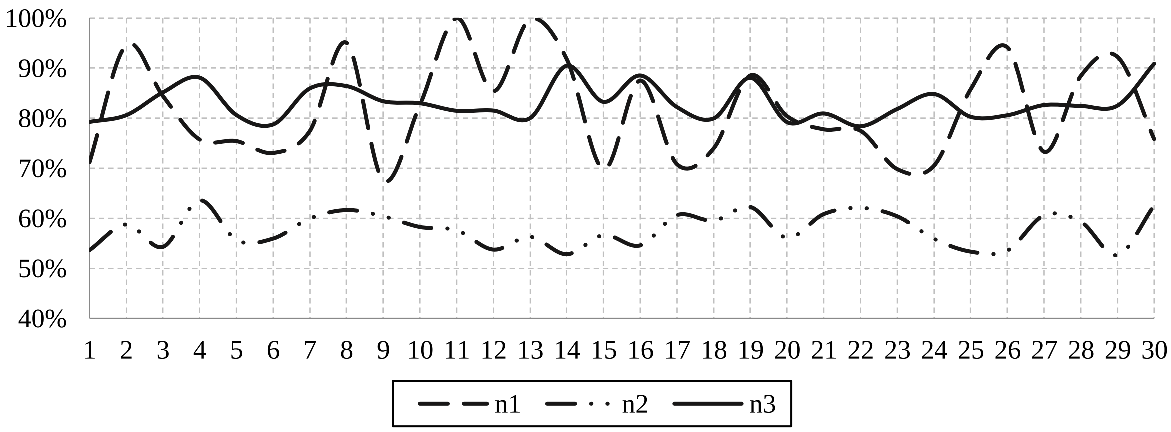


Figure 4. Case Study 1: Normalized daily demand for compressed air per processing unit.

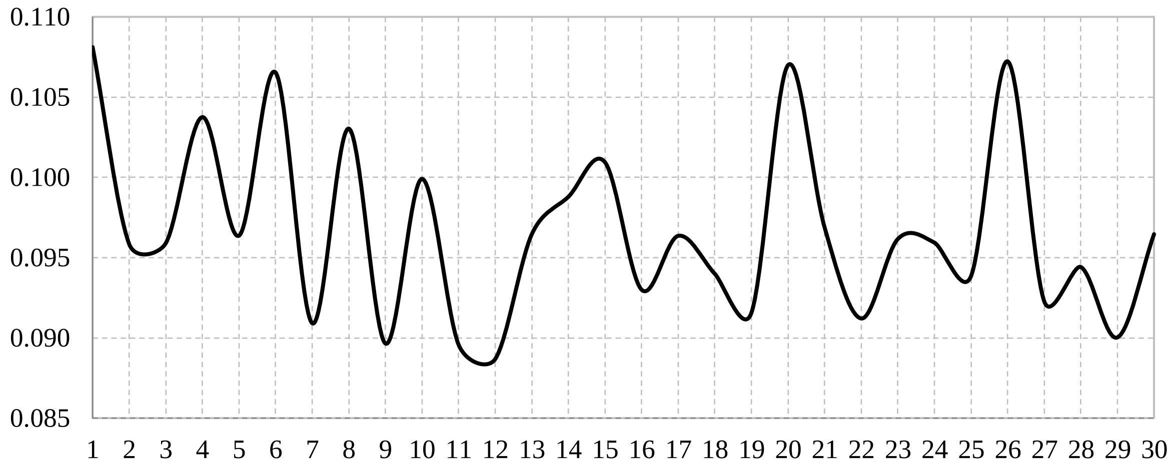


Figure 5. Case Study 1: Electricity price per time period.

5.2 Results of Case Study 1

The resulting optimization problem has been modeled using the general algebraic modeling language GAMS and solved by CPLEX 12 in an Intel(R) core(TM) i7 under standard configurations and a zero optimality gap. The optimal solution was found in about half an hour.

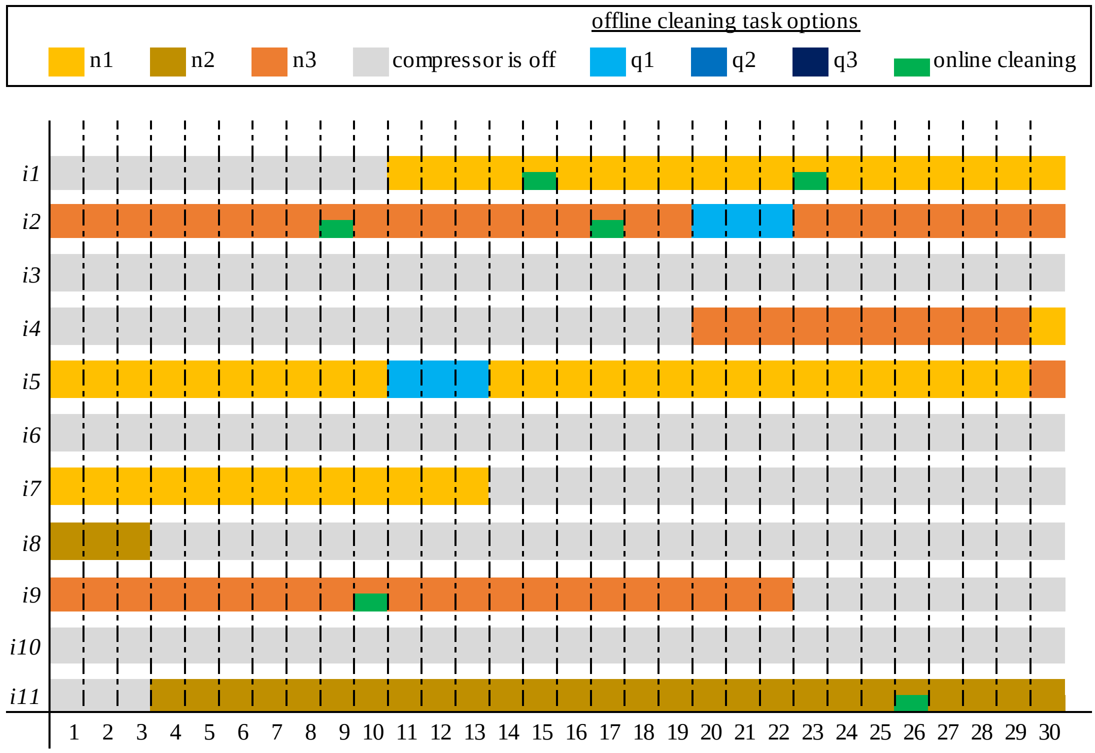


Figure 6. Case Study 1: Optimal operational and cleaning plan for the utility system.

Figure 6 presents the optimal plan for the operational and cleaning tasks for the network of compressors (i.e., the utility system). More specifically, this Gantt chart shows for each compressor: (i) its active header connection at each time period, (ii) the selected offline cleaning tasks options and their corresponding timing, and (iii) the online cleaning plan over the 30-day planning horizon. Compressors startups, shutdowns and header changes can be seen in this Gant chart as well. According to Figure 6, compressors $i3$ and $i10$ remain shutdown throughout the total planning horizon. According to the historical data and the operators' experience, this is basically due to the fact that these compressors are less-efficient compared to the other compressors. In addition, it is observed that exactly five compressors are operating at each time period in order to satisfy the total demand for compressed air. More specifically, three large compressors and two small compressors operate simultaneously from the beginning of the planning horizon until day 13, two large compressors and three small compressors operate at the same time from day 14 to day 22, and one large compressors and four small compressors operate simultaneously from day 23 to the end of the planning horizon. This decrease in the number of operating large compressors throughout the planning horizon is partially due to the decrease of the total demand for compressed air after day 14, as shown in Figure 4. The higher number of operating large compressors during the first half of the planning horizon is also due to the initial state of the system where three large compressors were under operation at the end of the previous planning horizon (see Table 3).

According to Table 3, compressors $i2$, $i5$, $i7$, $i8$ and $i9$ have been operating just before the beginning of the current planning horizon. As it can be seen in Figure 6, compressors $i2$ and $i5$ operate (except of a three-day offline cleaning break each) throughout the planning horizon, however compressors $i7$, $i8$ and $i9$ shutdown in day 14, day 3 and day 22 (and do not start again until the end of the planning horizon), respectively. Since the initial state of these three large compressors are quite similar, their observed shutdown sequence reveals their energy consumption performance. In other word, the more energy-inefficient compressors shutdown before the others (i.e., $i8$ shuts down first, followed by $i7$ and $i9$ is the last to shut down). Once compressor $i8$ shuts down, clean compressor $i11$ starts up and operates until the end of the planning horizon in order to meet the demand for compressed air in processing unit $n2$. As expected, the initial state of the system influences the optimal solution.

To continue with, it is observed in Figure 6 that compressors $i4$ and $i5$ interchange headers in day 30. In that day, there is a significant increase in the demand for compressed air in processing unit $n3$ and an important decrease in the demand for compressed air in processing unit $n1$ (see Figure 4). These demand fluctuations in tandem with the output mass flow rates and the performance of these compressors in day 30 might have triggered this interchange of headers.

According to the optimal plan of cleaning tasks displayed in Figure 6, there are six online and two offline cleaning tasks. More specifically, there are two online cleaning tasks for small compressors $i1$ and $i2$, and one online cleaning task for large compressors $i9$ and $i11$. Offline cleaning tasks are observed for small compressors $i5$ and $i2$ in day 11 and 20, respectively. In both cases the offline cleaning tasks option $q1$ has been selected. This cleaning task option has the highest cleaning cost but the shortest duration in comparison with the other cleaning task options. Therefore, it seems that the optimal solution tends to maximize the total number of operating periods for compressors $i5$ and $i2$ which might be an evidence of their higher energy-efficiency per compressed air unit produced in comparison the other compressors. The compressor with the most cleaning tasks is compressor $i2$ that undergoes two online and one offline cleaning tasks in order to restore its performance and increase its total operating period.

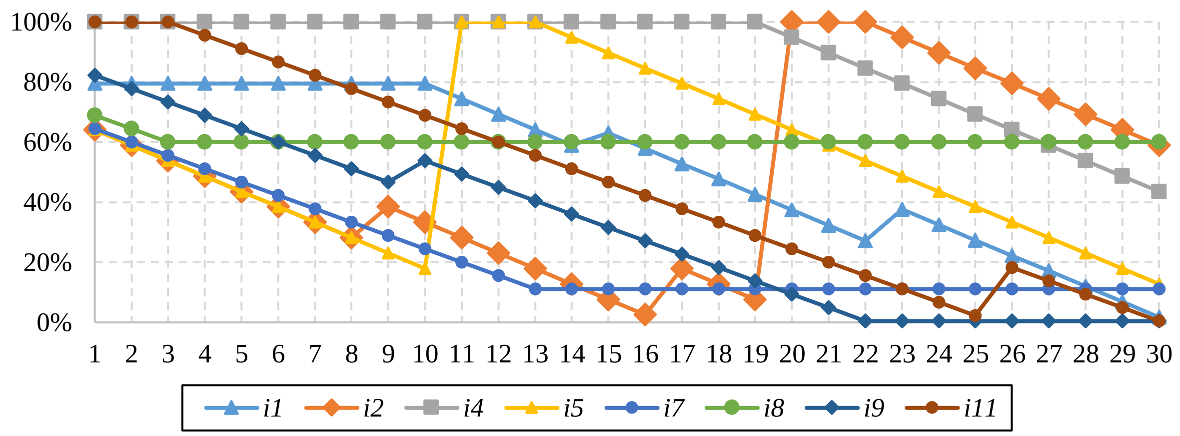


Figure 7. Case Study 1: Performance level profiles for compressors per time period.

Figure 7 illustrates the profiles of the performance level for all operating compressors within the overall planning horizon. The performance level of a compressor can be calculated as the deviation from maximum performance level of the compressor (i.e., 100%) minus the fraction of the current cumulative operating time and the maximum cumulative operating time.

All online and offline cleaning tasks can be seen in Figure 7 as an increase in the performance level of the corresponding compressor. For instance, observe the full recovery of the performance of compressors $i5$ and $i2$ in day 11 and 20 where their associated offline cleaning tasks start. Online cleaning tasks recover a much smaller part of the compressors performance. Also, notice that because the performance recovery has been modeled as a proportional function of the cumulative operating time, the lower the performance level of the compressor (i.e., higher cumulative operating time), the higher the performance recovery after an online cleaning task. For instance, as it can be clearly seen in Figure 7, the performance recovery of compressor $i1$ in day 23 is considerably higher than that in day 15.

In general, it is observed that most cleaning tasks take place in compressors performance levels lower that 50% and especially below 20%. For example, compressor $i5$ reaches a performance level below 20% in day 10 and this incites an offline cleaning task to start in the next day. A similar trend is observed for compressor $i2$. Before day 16, there are two online cleaning tasks to partially restore the performance level of compressor $i2$. In day 16, compressor $i2$ is at a critical low performance level and the option of performing an additional online cleaning tasks in next day has been chosen against the option to shut it down. This online cleaning task partially restores the performance level of this compressor and allows it to operate for three additional time periods before undergoing an offline cleaning task in day 20 so as to restore its full performance. The performance level of compressor $i2$ is very low in day 19 and there are only two available option for the next period: (i) to shut it down, or (ii) perform an offline cleaning task. Notice that there is not available the option of an online cleaning task because the minimum time between two consecutive online cleaning tasks in the same compressor is eight days, but there was an online cleaning took place in day 17.

Some compressors, such as compressor $i7$ and $i8$, shutdown when their performance levels reach a certain level and remain idle throughout the remaining planning horizon. At this point, it should be emphasized that having in hand the compressors performance levels profiles, the decision-maker may decide to perform offline cleaning operations to compressors $i7$ and $i8$ so as to restore their full performance level, in case they need to operate them in the next planning horizon. Offline cleaning tasks could be performed on the idle compressors $i3$ and $i10$ as well.

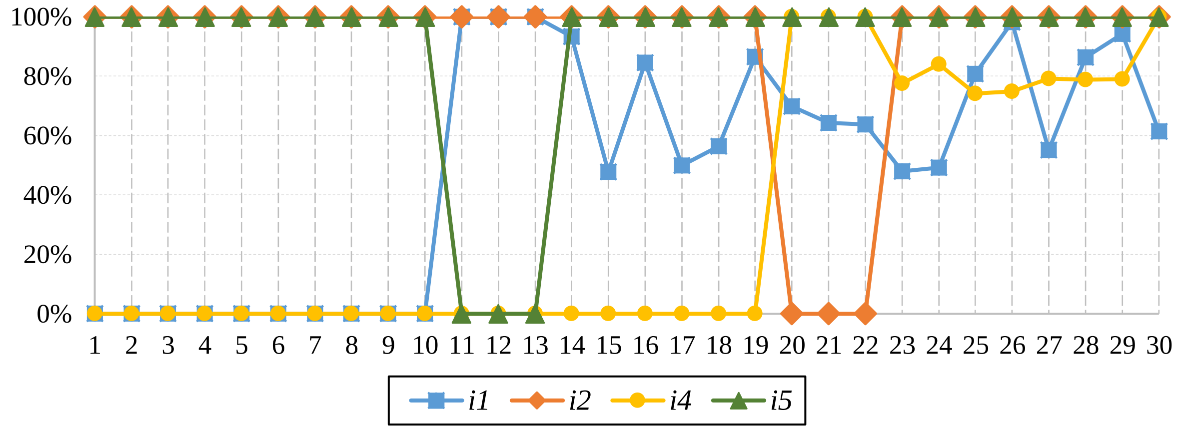


Figure 8. Case Study 1: Normalized outlet mass flow rate load for small compressors.

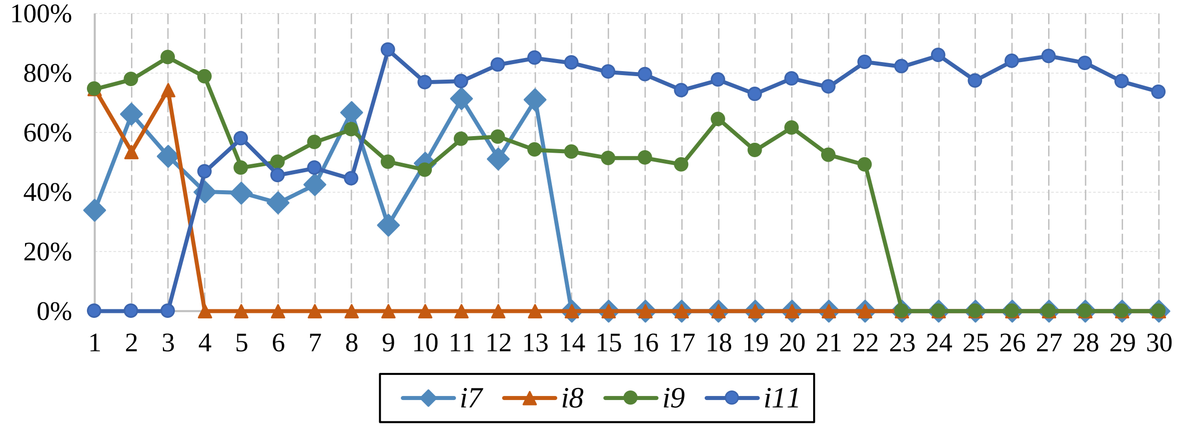


Figure 9. Case Study 1: Normalized outlet mass flow rate load for large compressors.

The normalized outlet mass flow rate profiles for each small and large compressor, with respect to its corresponding maximum mass flow rate, are displayed in Figures 8 and 9, respectively. Compressors that remain shutdown throughout the overall planning horizon are not included in this figures. It is observed that small compressors tend to operate in maximum load while large compressors operate in a broader range and they basically cover the demand fluctuations. Especially, compressors $i2$ and $i5$ operate at their maximum load in all their operating time periods, since they are among the most energy-efficient compressors when operating at maximum load. Meanwhile, compressors $i1$ and $i4$ are less energy-inefficient in a broader operational area and some fluctuations on their mass flow rates are observed. Figure 9 shows that none of the large compressors reaches its maximum load. On average, compressor $i11$ operate in higher loads than the remaining large compressors.

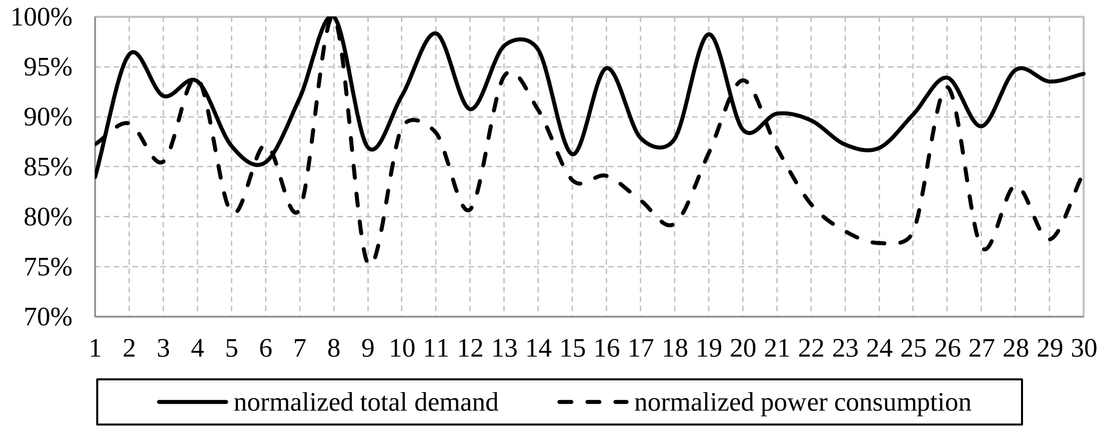


Figure 10. Case Study 1: Normalized total demand for compressed air and total power consumption profiles.

Figure 10 displays the profiles of the normalized total demand for compressed air of the production system and the normalized power consumption of the utility system (i.e., compressors network) throughout the overall planning horizon. These profiles have been normalized with respect to their corresponding highest values observed. In general, the normalized total power consumption of the utility system is higher in time periods with high normalized total demand for compressed air. The purpose of this figure is to highlight that these profiles show a quite similar pattern trend, which it was actually expected and it is mainly due to the absence of inventory options.

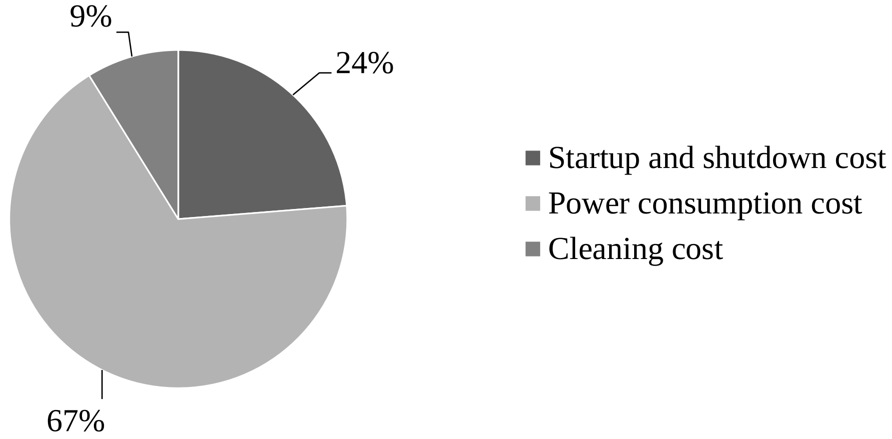


Figure 11. Case Study 1: Total percentage of operational and cleaning cost for the compressors network.

Figure 11 shows the breakdown of the major cost terms considered during the optimization. Namely, these cost terms associated to the network of compressors account for: (i) the startup and shutdown operations, (ii) the power consumption, and (iii) the online and offline cleaning tasks. As expected, power consumption costs contribute most to the total cost. The cleaning cost is the lowest cost term, despite of the fact that the most expensive offline cleaning task options have been selected. Overall, the total number of cleaning tasks is moderate. Also, more online than offline cleaning tasks are chosen, and partially this is due to their associated lower cost. The high power consumption cost is mainly due to the total high demand for compressed air.

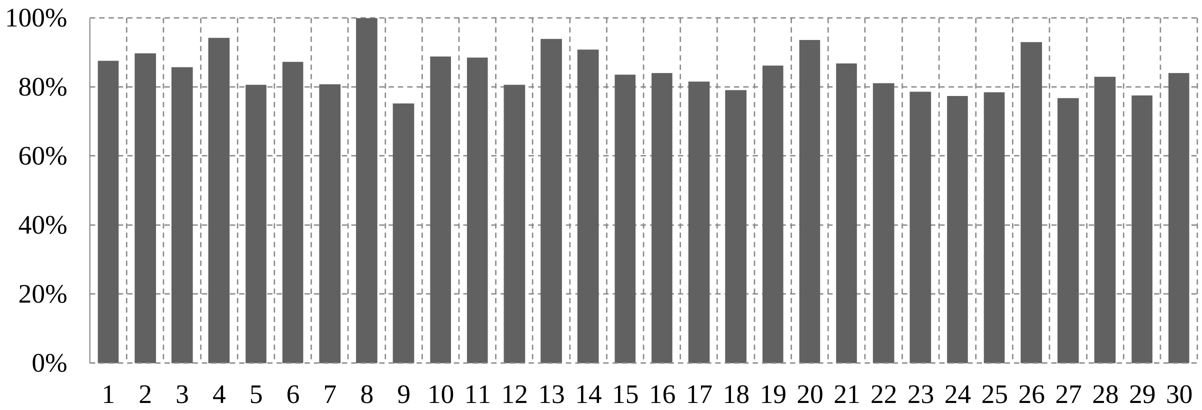


Figure 12. Case Study 1: Normalized total ideal power consumption cost profile.

Figure 12 displays the normalized total ideal power consumption profile throughout the 30-day planning horizon; having as a reference the maximum ideal total power consumption reported. It can be seen a significant ideal total power consumption reduction from day 8 to day 9, which is due to the fact that the peak of the total demand for compressed air is in day 8, followed by a rough drop in day 9 (see Figure 10) resulting in lower total outlet mass flow load. Similar observations can be made for day 26 and day 27.

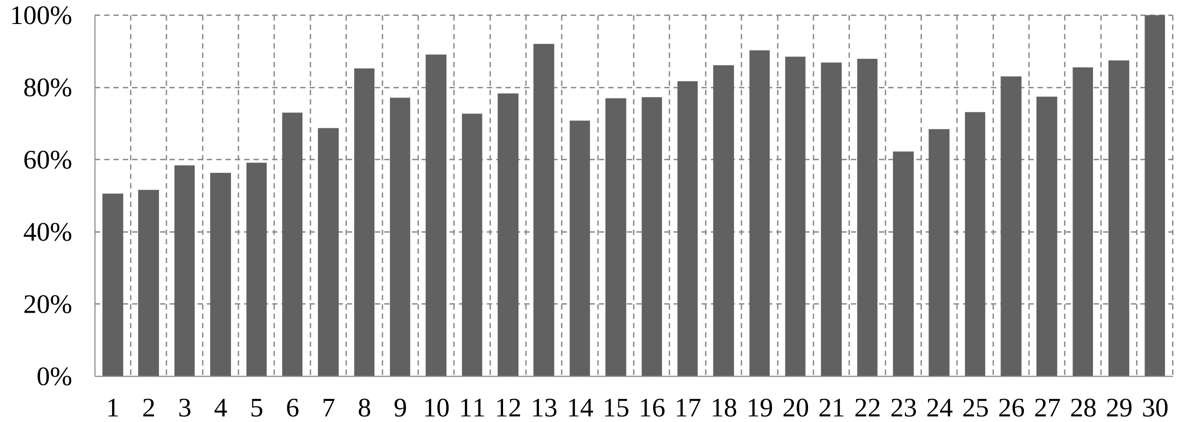


Figure 13. Case Study 1: Normalized total extra power consumption cost profile.

Figure 13 shows the normalized total extra power consumption cost profile. This extra power consumption is a result of the deviation of the performance of the compressors from their full performance (ideal). In day 23, there is a low total extra power due to: (i) the low total demand for compressed air, (ii) the full performance recovery of compressor $i2$, and (iii) the partial performance recovery of compressor $i1$. The peak of the total extra power consumption cost is observed in the last time period, and this result is mainly due to the absence of terminal constraints for the performance level of the compressors at the end of the planning horizon.

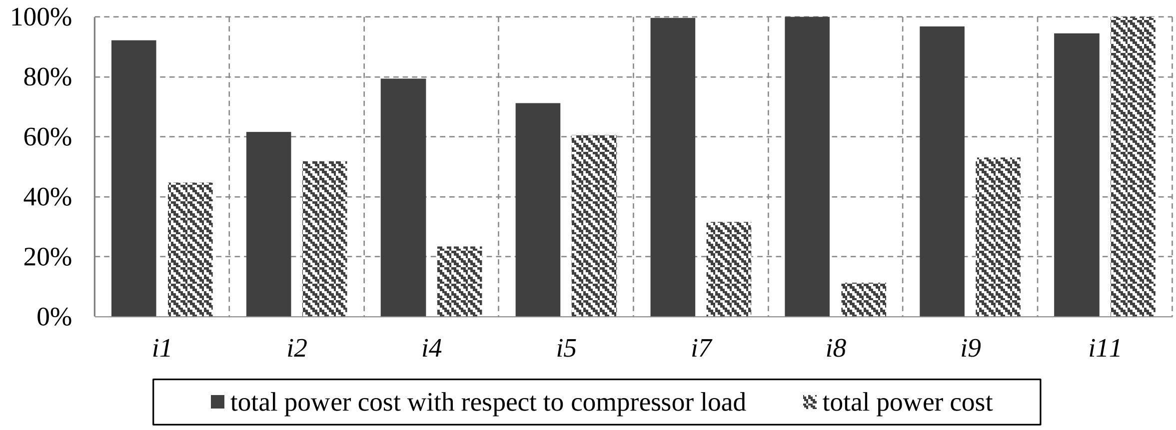


Figure 14. Case Study 1: Analysis of total power consumption cost with respect to compressor load and total power consumption cost

Figure 14 presents an analysis of: (i) the total power cost and for all compressors, and (ii) the power cost per unit of compressed air generated. In this case study, small compressors are more energy-efficient than large compressors, since they feature lower power cost per unit of compressed air generated. In other words, small compressor generate more compressed air for the same amount of power consumed compared to the large compressors. In particular, compressor $i2$ followed by compressor $i5$ are the most energy-efficient. Recall that these small compressors operate at their maximum load in all their operating time periods (see Figure 8), and this fact favors them to be more energy-efficient according to the historical data and previous operation experience of the plant. Also, one can observe that small compressor $i1$, which is characterized with more outlet mass flow load fluctuations away from its maximum load than any other small compressor, is the most energy-inefficient small compressor. Therefore, the results have validated that more fluctuations and especially in operational regions farther than the maximum outlet mass flow load result in less energy-efficient use of the small compressors. Compressor $i11$ is the most energy-efficient large compressor. This is because it operates at higher loads than any other large compressor for more time periods (see Figure 9). According to Figure 14, compressor $i8$ is the least-efficient operating compressor, and this actually explains the fact that it operates just for three periods.

6. Case Study 2: Simultaneous Planning of Utility and Production System (Single-Utility Single-Product Case).

This case study focuses on the interaction between the utility and the production system of a production facility. The utility and the final product can be stored in dedicated storage tanks. Flexible time-window offline cleaning tasks are considered here. There are different options for these cleaning tasks. In contrast to the previous case study, the demand for utility is an optimization variable here that is driven by the given demand for the final product. Figure 15 depicts the layout of the production facility that consists of a utility and a production system.

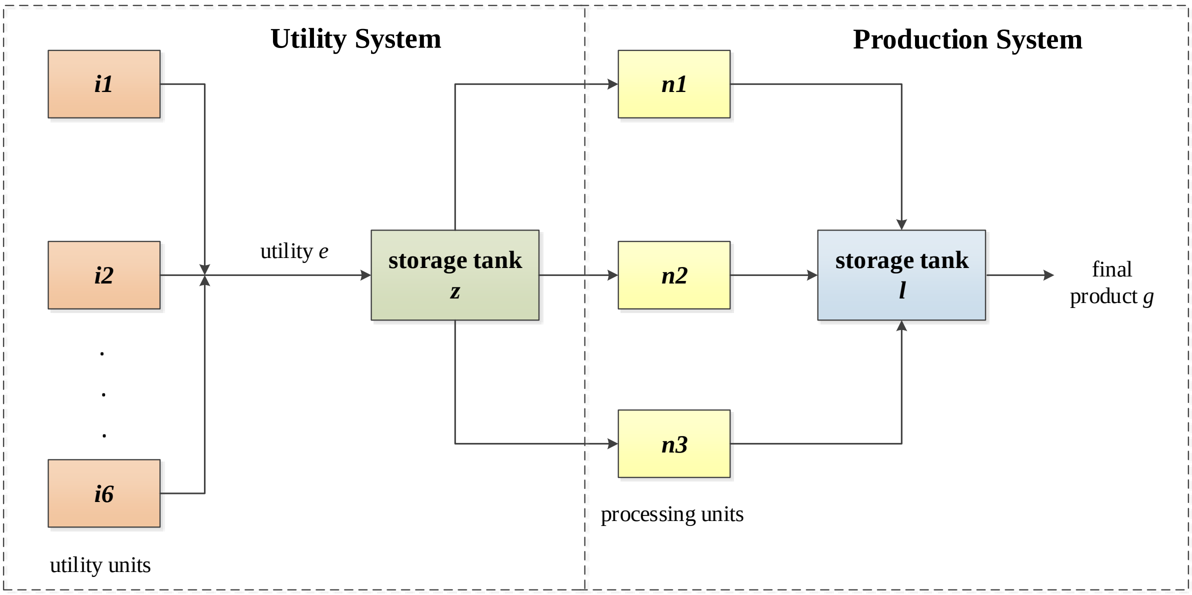


Figure 15. Case Study 2: Layout of the production plant: utility and production system.

6.1 Description of Case study 2

This illustrative example considers six utility units ($i1$, $i2$, $i3$, $i4$, $i5$, $i6$) that generate a utility type e which can be stored in a storage tank z. The interaction of the utility and production system takes place through the supply of the utility to the production system. Three types of processing units ($n1$, $n2$, $n3$) are considered which need utility type e in order to produce the final product g. The final product can be stored in a storage tank l. Small utility units ($i1$ and $i2$) have a lower and upper bound generation level equal to 10 and 45, respectively. Large utility units ($i3$, $i4$, $i5$ and $i6$) have a lower and upper bound generation level equal to 15 and 60, respectively. Table 4 gives the main operational parameters for this case study.

Table 4. Case Study 2: Main parameters.

Symbol	Value	Unit	Description
t	1	day	Duration of each time period.
T	30	days	Total number of periods (planning horizon).
ω_i	6	days	Minimum runtime for utility units.
ψ_i	3	days	Minimum shutdown time of utility units.
$\alpha_{(n1,g,e)}$	0.9	-	coefficient for processing unit $n1$
$\alpha_{(n2,g,e)}$	0.8	-	coefficient for processing unit $n2$
$\alpha_{(n3,g,e)}$	0.75	-	coefficient for processing unit $n3$
$\beta_{(n1,g,e)}$	10	-	coefficient for the load of processing unit $n1$
$\beta_{(n2,g,e)}$	14	-	coefficient for the load of processing unit $n2$
$\beta_{(n3,g,e)}$	17	-	coefficient for the load of processing unit $n3$
o_i	20	days	Maximum runtime of utility units ($i1$, $i2$, $i3$, $i6$).
o_i	30	days	Maximum runtime of utility unit $i4$.

o_i	22	days	Maximum runtime of utility unit $i5$.
τ_i^{es}	9	days	Earliest cleaning startup time for utility units ($i1$-$i4$).
τ_i^{ls}	13	days	Latest cleaning startup for utility units ($i1$-$i4$).
$\eta_t^{\max}$	12	resource units	Available cleaning resources per time period.
$\zeta_{(g,t)}$	125 to 425	kg/day	Demand for final product (range).
$\kappa_{(n1,g,t)}^{FP,min}$	50	kg/day	Minimum production level for processing unit $n1$.
$\kappa_{(n2,g,t)}^{FP,min}$	60	kg/day	Minimum production level for processing unit $n2$.
$\kappa_{(n3,g,t)}^{FP,min}$	20	kg/day	Minimum production level for processing unit $n3$.
$\kappa_{(n1,g,t)}^{FP,max}$	175	kg/day	Maximum production level for processing unit $n1$.
$\kappa_{(n2,g,t)}^{FP,max}$	125	kg/day	Maximum production level for processing unit $n2$.
$\kappa_{(n3,g,t)}^{FP,max}$	100	kg/day	Maximum production level for processing unit $n3$.
$\xi_{(e,z)}^{UT,min}$	0	kg/day	Minimum inventory level for utility.
$\xi_{(e,z)}^{UT,max}$	50	kg/day	Maximum inventory level for utility.
$\xi_{(g,l)}^{FP,min}$	0	kg/day	Minimum inventory level for final product.
$\xi_{(g,l)}^{FP,max}$	150	kg/day	Maximum inventory level for final product.

Utility units $i1$, $i2$, $i3$ and $i4$ should undergo a flexible time-window offline cleaning, according to the information given in Table 5. This example considers three alternative flexible time-window offline cleaning tasks options ($q1$, $q2$, $q3$) that are characterized by different durations, cleaning resources requirements and associated costs, as provided in Table 5. No condition-based cleaning is considered in this case study. Table 6 shows the operational costs for utility and production system.

Table 5. Case Study 2: Alternative flexible time-window offline cleaning task options.

Symbol	Unit	$q1$	$q2$	$q3$
$v_{(i,q)}$	days	3	4	5
$\vartheta_{(i,q)}^{off}$	resource units	6	4	3
$\phi_{(i,q)}^{off}$ (small utility unit)	m.u./cleaning	2,137.5	1425.0	1,068.8
$\phi_{(i,q)}^{off}$ (large utility unit)	m.u./cleaning	7,087.5	4725.0	3,543.8

Table 6. Case Study 2: Costs for operational tasks in utility and production systems.

Symbol	Value	Unit	Description
ϕ_i^S	4,900	m.u./startup	Cost of startup for small utility units.
ϕ_i^S	6,800	m.u./startup	Cost of startup for large utility units.
ϕ_i^F	2,500	m.u./shutdown	Cost of shutdown for small utility units
ϕ_i^F	2,700	m.u./shutdown	Cost of shutdown for large utility units.

$\phi^{UT,ex}_{(e,n,t)}$	4,000	m.u./kg	Cost for purchasing utility.
$\chi^{FP,ex}_{(g,t)}$	4,000	m.u./kg	Cost for purchasing final product.
$\chi^{FP,var}_{(n1,g)}$	1.2	m.u./kg	Variable operating cost for processing unit $n1$.
$\chi^{FP,var}_{(n2,g)}$	1.5	m.u./kg	Variable operating cost for processing unit $n2$.
$\chi^{FP,var}_{(n3,g)}$	1.4	m.u./kg	Variable operating cost for processing unit $n3$.
$\chi^{FP,fix}_{(n1,g)}$	50	m.u.	Fixed operating cost for processing unit $n1$.
$\chi^{FP,fix}_{(n2,g)}$	40	m.u.	Fixed operating cost for processing unit $n2$.
$\chi^{FP,fix}_{(n3,g)}$	80	m.u.	Fixed operating cost for processing unit $n3$.

Table 7. Case Study 2: Initial state of utility and production system.

	$i1$	$i2$	$i3$	$i4$	$i5$	$i6$
$\tilde{\omega}_i$	0	0	0	10	0	0
$\tilde{\psi}_i$	0	0	0	0	29	30
$\tilde{\beta}^{UT}_{(e,z)}$	10	Initial inventory for utility.				
$\tilde{\beta}^{FP}_{(g,l)}$	50	Initial inventory for final product.				

The parameters that define the initial state of the utility and production systems are given in Table 7. In addition, Figure 16 shows the normalized demand for the final product, having as a reference the peak demand value. In contrast to the previous case study, the daily utility requirements are not given but they are a result of the optimization. The electricity price profile is the same as in the previous case study, as given in Figure 5.

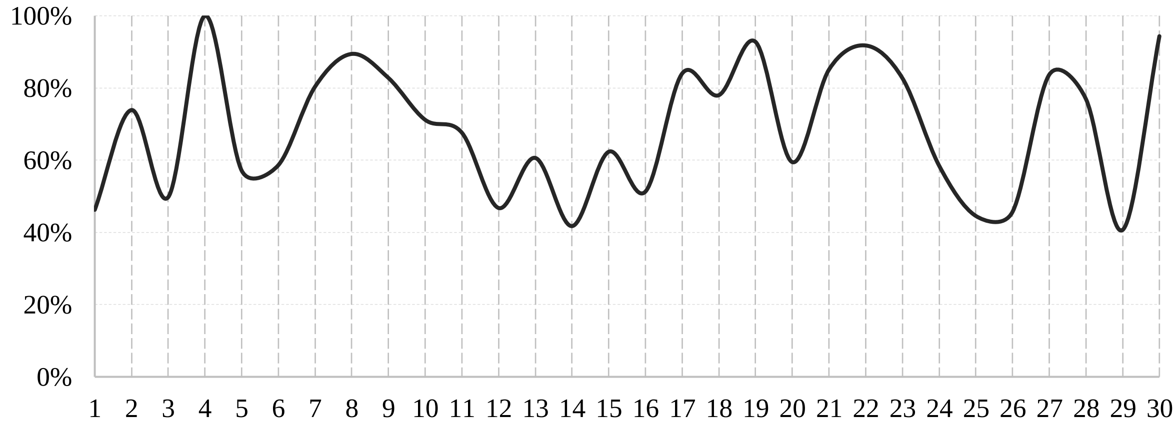


Figure 16. Case Study 2: Normalized daily final product demand profile.

6.2 Results of Case Study 2

The resulting optimization problem has been solved using GAMS/CPLEX 12 in an Intel(R) core(TM) i7 under standard configurations and a zero optimality gap, and the optimal solution has been reached in few seconds.

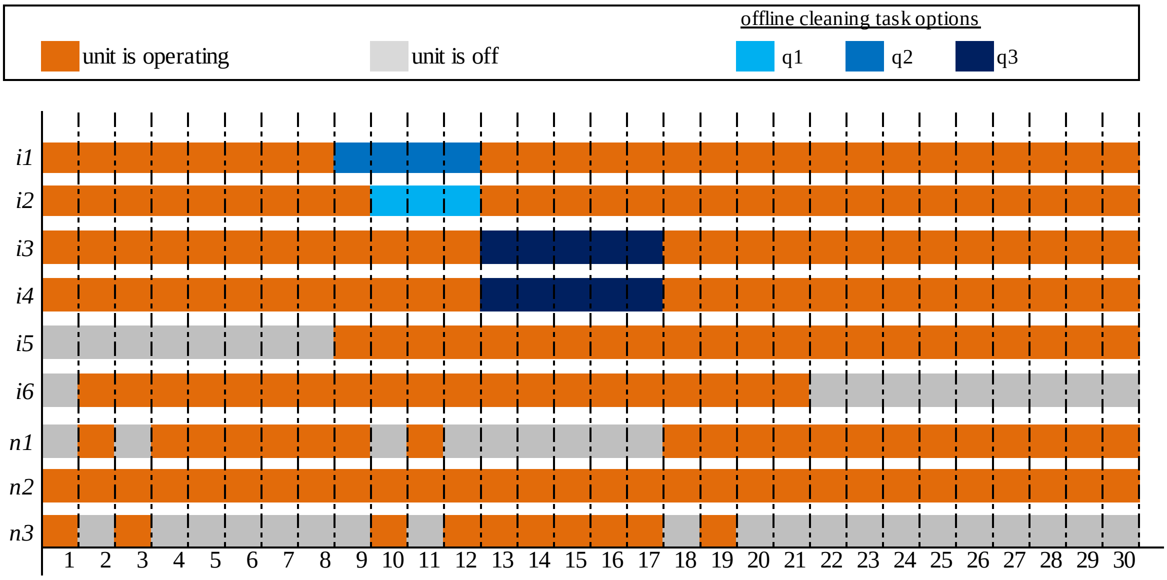


Figure 17. Case study 2: Optimal operational and cleaning plan for the utility system.

Figure 17 displays the optimal plan for the operational and cleaning tasks for the utility system. More specifically, this Gantt chart shows for each utility unit: (i) its operational status at each time period, (ii) the selected offline cleaning tasks options and their corresponding timing, and (iii) the operational status of processing units.

From Figure 17, all cleaning tasks options are selected on the flexible time-window from the earliest starting time τ_i^{es}= 9 until the latest starting time τ_i^{ls}=13. On the earliest starting time on day 9, only utility unit $i1$ with option $q2$ is cleaning. Then on the following day, utility unit $i2$ is under cleaning which selects option $q1$. Meanwhile, two utility units $i3$ and $i4$ are under cleaning both with option $q3$ on the latest starting time on day 13. The optimal clean schedule suggests that, small utility units ($i1$ and $i2$) choose short period of cleaning tasks with slightly expensive costs. On the other hand, large utility units ($i3$ and $i4$) select the longest cleaning duration with less cleaning cost.

The initial condition before the beginning of optimal scheduling horizon according to Table 7 has some influences on the result of optimal schedule. Utility unit $i4$ continue to operate with total runtime is 22 days before cleaning ($\widetilde{\omega}_{i4}$=12 days) which is less than maximum runtime, o_{i4} of 30 days (refer to Table 4). The utility units $i5$ and $i6$ remain offline mode at the beginning of optimum scheduling horizon. The utility unit $i5$ starts up in day 9 and continue operating until reaches its maximum runtime, o_{i5} of 22 days which is exactly on day 30. Meanwhile, utility unit $i6$ operates in day 2 until day 21 because it has reaches maximum runtime, o_{i6} of 20 days (refer Table 4).

Figure 17 also shows the operational status of processing units ($n1$, $n2$ and $n3$). Processing unit $n2$ operates on 30 days optimum scheduling horizon because the operating cost for processing unit $n2$ is the cheapest compared to other processing units, as shown in Table 6. In most time periods, it is observed that when processing unit $n1$ operates, processing unit $n3$ remains idle, and vice versa.

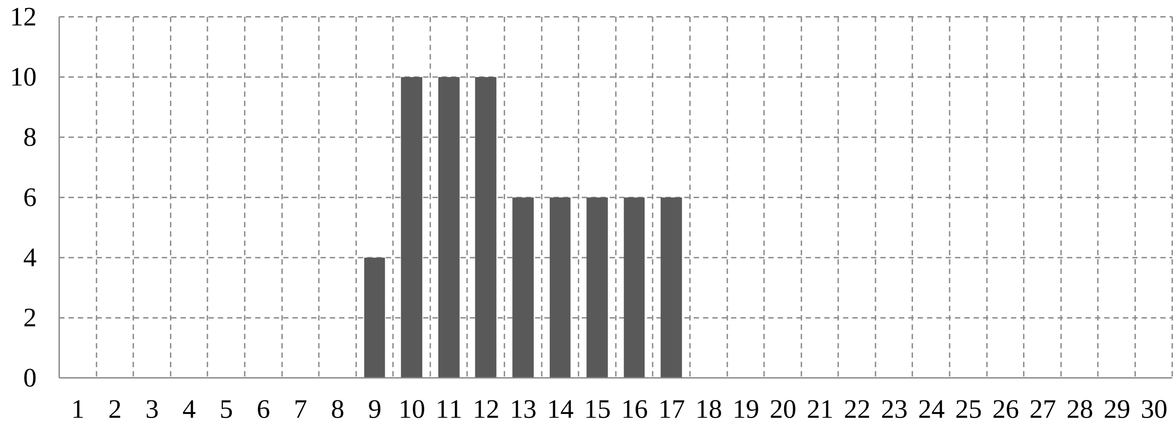


Figure 18. Case Study 2: Total cleaning resources utilization profile.

Figure 18 illustrates the total cleaning resources utilization profile. The maximum number of total cleaning resources is in day 10, 11 and 12 because two cleaning options $q1$ and $q2$ with cleaning resources ($\vartheta^{off}_{(i,q1)} = 6$) and ($\vartheta^{off}_{(i,q2)} = 4$) are selected according to Figure 17. The earliest cleaning time is performed in day 9 and the latest cleaning time is performed in day 17.

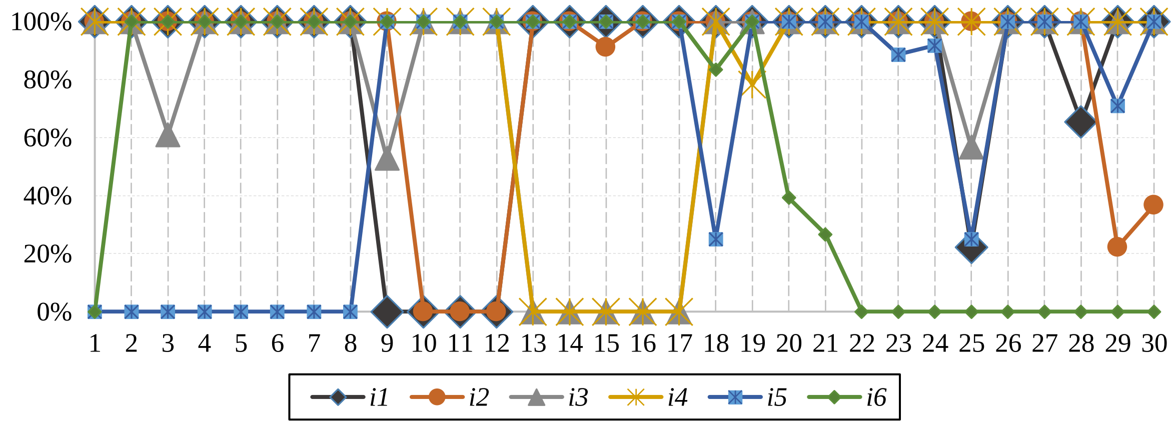


Figure 19. Case Study 2: Normalized generation level profiles for utility units.

Figure 19 shows normalized generation level profiles for utility units. The profile varies according to the needs for utility demand and supply. Utility units $i1$, $i2$, $i3$ and $i4$ operate throughout the planning horizon except during offline cleaning periods. Utility units $i5$ and $i6$ operate at their maximum runtime, which is 22 and 20 days, respectively. It is also observed that, at certain time period, the utility units operate at minimum capacity when utility demand is sufficiently supplied by other utility units. This is due to the relatively high shutdown costs compared to power consumption costs, for this reason the optimal solution prefers to continue operating these utility units at minimum capacity and avoids shutting them down. For instance, in day 25, three utility units ($i1$, $i3$, and $i5$) operate at their minimum capacities while utility units $i2$ and $i4$ operate at their maximum capacity. The total amount of utility supplied by utility units $i2$ and $i4$ are actually sufficient for that period. However, due to high shutdown cost for the other utility units, they continue operating at their minimum capacities.

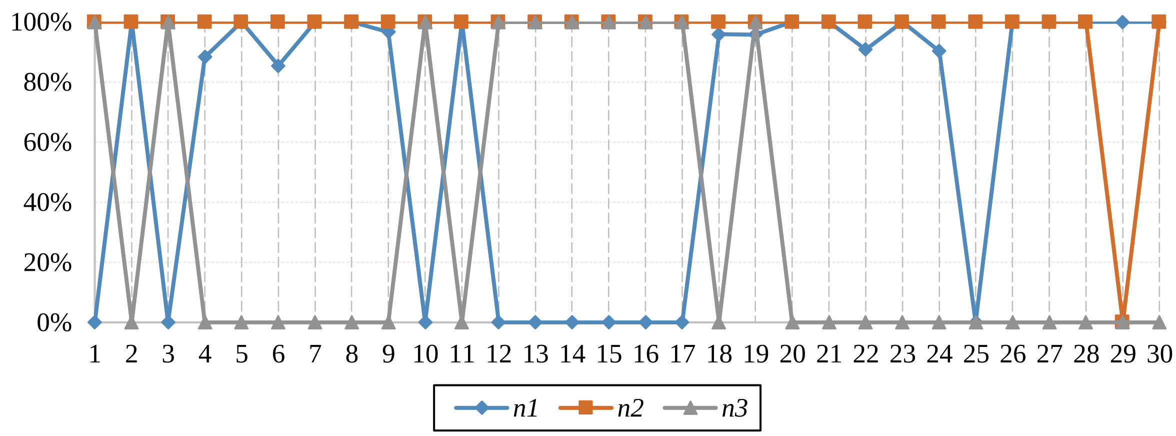


Figure 20. Case Study 2: Normalized production level profiles for processing units.

According to Figure 20, the production levels for processing unit $n2$ and $n3$ are at maximum processing capacity throughout the time horizon. Meanwhile, processing unit $n1$ varies according to final product demand. The processing unit $n1$ and $n3$ interchange their operational status except on day 19 where all processing units are operating at their maximum capacity. This is due to high final product demand on that day.

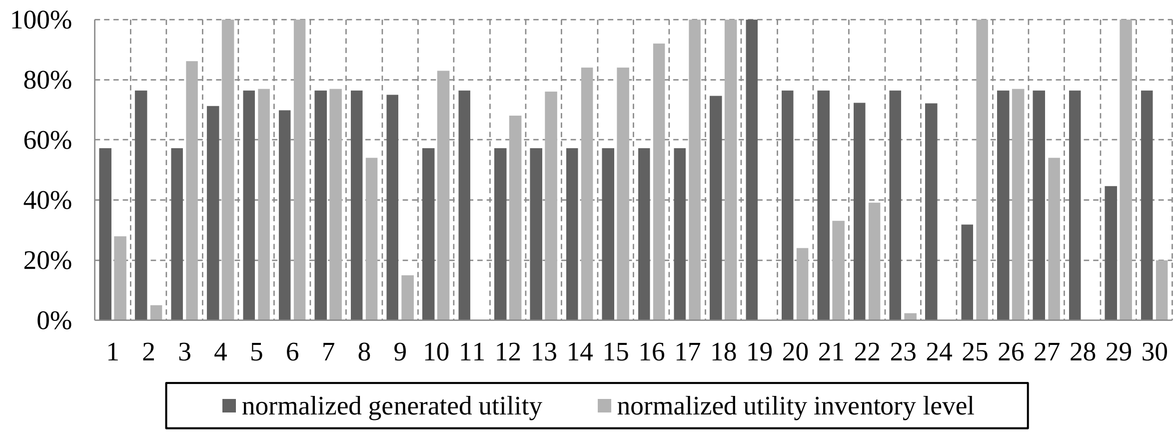


Figure 21. Case Study 2: Normalized total generated utility and utility inventory profiles.

Figure 21 displays the normalized profiles for: (i) total utility generated by the utility system, and (ii) the inventory of the utility. In days 11, 19, 24, and 28, there is no utility inventory level. The reason of low or none utility inventory level are due to the high amount of utility requirements from the processing units in order to satisfy the demand for final product. For example, the normalized utility inventory level in day 23 is only about 1% which is related to low inventory level from previous period but high utility generated. Other observation is that, the generated utility remains almost at the same level from day 12 to 17. This is due to the fact that, some of the utility units are offline for cleaning tasks (see Figure 17) and the remaining online utility units are operating at almost maximum capacities on those days (see Figure 19).

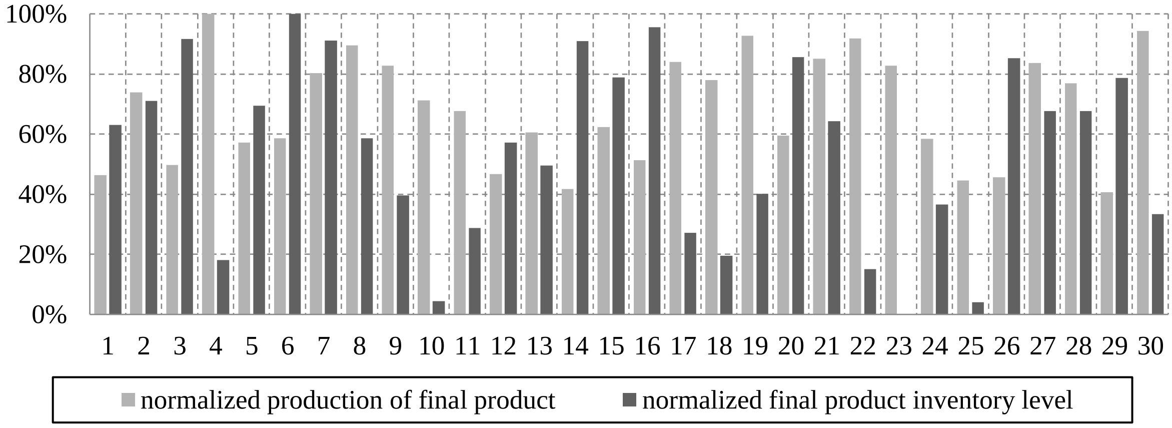


Figure 22. Case Study 2: Normalized total final product production and final product inventory profiles.

Figure 22 illustrates normalized mass flow rate profiles of (i) final product supplied to meet demand and, (ii) final product inventory level. The profile of final product supplied represents the actual final product demand profile (refer to Figure 16). This trend is expected because no final product is purchased from external source throughout the time period. The final product demand is sufficiently fulfil by the processing units. The trends for both profiles suggest that if the final product demand is high, the inventory level in storage tank should be lower for example in day 4, 10, 18 and 25. On the other hand, if the final product demand is low, the inventory level is significantly high as observed in day 6, 14, 15, 16 and 20 respectively.

The comparison of the trend for generated utility profile (Figure 21) and generated final product profile (Figure 22) shows the same trends for both profiles. For instances, when the production of final product is high then the generated utility is high as well and vice versa. For example, the production of final product increases from day 3 to day 4 and generated utility is also increases on the same days. Similar trends are observed from day 6 to 7 and day 18 to 19 as well.

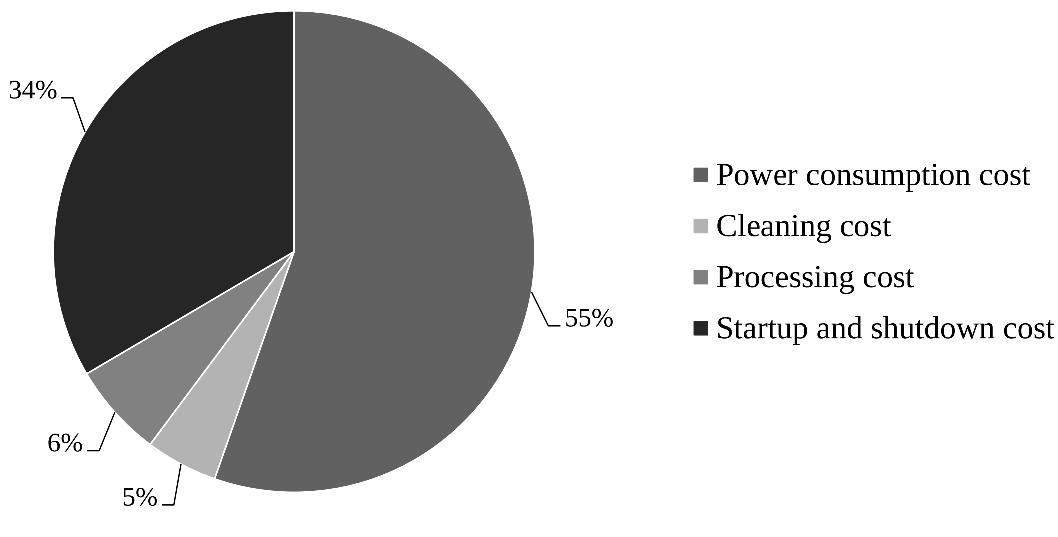


Figure 23.Case Study 2: Total percentage of operational and cleaning costs.

Figure 23 shows the breakdown of the total costs for the utility and the production systems. The types of cost for this case study are divided into: (i) the startup and shutdown operations, (ii) the power consumption, (iii) the offline cleaning tasks, and (iv) the operation of production system. As expected, 55% of total cost is due to the power consumption from the utility units due to high final product demand. The second highest cost is startup and shutdown costs which about 34%. The processing cost and cleaning cost are relatively small which about 6% and 5% respectively. Overall, the operational costs which consist of power consumption, startup and shutdown and processing units costs are the major contributors of total costs.

7. Case Study 3: Simultaneous Planning of Utility and Production System (Multiple-Utility Multiple-Product Case).

In this case study, we extend further the previous single-utility single-product case study by considering two utility types e and two final products g. Condition-based online and offline cleaning tasks for the utility units are considered. And, the operational tasks for the processing units and the operational and cleaning tasks for the utility system are optimized simultaneously.

7.1 Description of Case Study 3.

Case study 3 considers five utility units ($i1$, $i2$, $i3$, $i4$, $i5$) that supplies two utility types ($e1$, $e2$) which can be stored in their associated storage tanks ($z1$, $z2$). The utility types are consumed by the processing units ($n1$, $n2$, $n3$) to produce two types of final products ($g1$, $g2$) that can be stored in their dedicated storage tanks ($l1$, $l2$).

Utility unit ($i1$) have a lower and upper bound generation level equal to 10 and 40, respectively. Utility units ($i2$ and $i3$) have a lower and upper bound generation level equal to 15 and 60, respectively. Meanwhile, utility units ($i4$ and $i5$) have a lower and upper bound generation level equal to 15 and 40, respectively. Condition-based cleaning tasks for both offline and online cleaning are considered for this case study. Three alternative condition-based offline cleaning tasks options ($q1$, $q2$, $q3$) as mentioned in Table 5 in the previous case study are used. Utility unit ($i1$) is considered as small utility unit and utility units ($i2$, $i3$, $i4$ and $i5$) are regarded as large utility units. This assumption is based on their lower and upper bound generation level. Table 8 and 9 show the main parameters for this case study. Table 10 demonstrates the operational costs for the utility and the production system.

Table 8. Case Study 3: Main parameters.

Symbol	Value	Unit	Description
t	1	day	Duration of each time period.
T	30	days	Total number of periods (planning horizon).
ω_i	6	days	Minimum runtime for utility units.
ψ_i	3	days	Minimum shutdown time of utility units.
o_i	19	days	Maximum runtime of utility units $i1$ and $i3$.
o_i	22	days	Maximum runtime of utility unit $i2$.
o_i	21	days	Maximum runtime of utility unit $i4$.
o_i	20	days	Maximum runtime of utility unit $i5$.

$\eta_t^{\max}$	12	resource units	Available cleaning resources per time period.
$\zeta_{(g1,t)}$	40 to 100	kg/day	Demand for final product $g1$ (range).
$\zeta_{(g2,t)}$	50 to 120	kg/day	Demand for final product $g2$ (range).
$\kappa_{(n,g,t)}^{FP,min}$	0	kg/day	Minimum production level for processing units.
$\kappa_{(n1,g1,t)}^{FP,max}$	85	kg/day	Maximum production level for processing unit $n1$ that produces final product $g1$.
$\kappa_{(n1,g2,t)}^{FP,max}$	65	kg/day	Maximum production level for processing unit $n1$ that produces final product $g2$.
$\kappa_{(n2,g1,t)}^{FP,max}$	65	kg/day	Maximum production level for processing unit $n2$ that produces final product $g1$.
$\kappa_{(n2,g2,t)}^{FP,max}$	50	kg/day	Maximum production level for processing unit $n2$ that produces final product $g2$.
$\kappa_{(n3,g1,t)}^{FP,max}$	50	kg/day	Maximum production level for processing unit $n3$ that produces final product $g1$.
$\kappa_{(n3,g2,t)}^{FP,max}$	85	kg/day	Maximum production level for processing unit $n3$ that produces final product $g2$.
$\xi_{(e,z)}^{UT,min}$	0	kg/day	Minimum inventory level for both utilities.
$\xi_{(e1,z1)}^{UT,max}$	80	kg/day	Maximum inventory level for utility type $e1$.
$\xi_{(e2,z2)}^{UT,max}$	300	kg/day	Maximum inventory level for utility type $e2$.
$\xi_{(g,l)}^{FP,min}$	0	kg/day	Minimum inventory level for final products.
$\xi_{(g,l)}^{FP,max}$	150	kg/day	Maximum inventory level for final products.
$\rho_{(i,e1)}$	1		coefficient of utility units that produces utility type $e1$
$\rho_{(i1,e2)}$	4		coefficient of utility units $i1$ that produces utility type $e2$
$\rho_{(i2,e2)}$	2		coefficient of utility units $i2$ that produces utility type $e2$
$\rho_{(i3,e2)}$	3		coefficient of utility units $i3$ that produces utility type $e2$
$\rho_{(i4,e2)}$	0		coefficient of utility units $i4$ that produces utility type $e2$
$\rho_{(i5,e2)}$	3		coefficient of utility units $i5$ that produces utility type $e2$

Table 9. Case Study 3: Stoichiometry of utility needs for processing units per product.

	$\alpha_{(n,g1,e)}$	$\alpha_{(n,g2,e)}$	$\beta_{(n,g1,e)}$	$\beta_{(n,g2,e)}$

$n1$	$e1$	0.90	0.80	17	15
	$e2$	2.25	3.38	45	39
$n2$	$e1$	0.80	0.70	14	18
	$e2$	3.38	5.25	54	30
$n3$	$e1$	0.75	0.90	16	10
	$e2$	2.63	3.00	36	48

Table 10. Case Study 3: Costs for operational tasks in utility and production systems.

Symbol	Value	Unit	Description
ϕ_i^S	2,450	m.u./startup	Cost of startup for small utility units.
ϕ_i^S	3,400	m.u./startup	Cost of startup for large utility units.
ϕ_i^F	1,250	m.u./shutdown	Cost of shutdown for small utility units
ϕ_i^F	1,350	m.u./shutdown	Cost of shutdown for large utility units.
$\phi_{(e,n,t)}^{UT,ex}$	4,000	m.u./kg	Cost for purchasing utilities.
$\chi_{(g,t)}^{FP,ex}$	4,000	m.u./kg	Cost for purchasing final products.
$\chi_{(n1,g1)}^{FP,var}$	1.2	m.u./kg	Variable operating cost for processing unit $n1$ that produces final product $g1$.
$\chi_{(n1,g2)}^{FP,var}$	1.0	m.u./kg	Variable operating cost for processing unit $n1$ that produces final product $g2$.
$\chi_{(n2,g1)}^{FP,var}$	1.5	m.u./kg	Variable operating cost for processing unit $n2$ that produces final product $g1$.
$\chi_{(n2,g2)}^{FP,var}$	1.4	m.u./kg	Variable operating cost for processing unit $n2$ that produces final product $g2$.
$\chi_{(n3,g1)}^{FP,var}$	1.4	m.u./kg	Variable operating cost for processing unit $n3$ that produces final product $g1$.
$\chi_{(n3,g2)}^{FP,var}$	1.9	m.u./kg	Variable operating for processing unit $n3$ that produces final product $g2$.
$\chi_{(n1,g1)}^{FP,fix}$	200	m.u.	Fixed operating cost for processing unit $n1$ that produces final product $g1$.
$\chi_{(n1,g2)}^{FP,fix}$	400	m.u.	Fixed operating cost for processing unit $n1$ that produces final product $g2$.
$\chi_{(n2,g1)}^{FP,fix}$	600	m.u.	Fixed operating cost for processing unit $n2$ that produces final product $g1$.
$\chi_{(n2,g2)}^{FP,fix}$	200	m.u.	Fixed operating cost for processing unit $n2$ that produces final product $g2$.
$\chi_{(n3,g1)}^{FP,fix}$	400	m.u.	Fixed operating cost for processing unit $n3$ that produces final product $g1$.
$\chi_{(n3,g2)}^{FP,fix}$	700	m.u.	Fixed operating cost for processing unit $n3$ that produces final product $g2$.

Table 11 gives the values of initial condition of cumulative time of operation before scheduling horizon and the initial values of storage tanks.

Table 11. Case Study 3: Initial state of utility and production systems.

	$i1$	$i2$	$i3$	$i4$	$i5$	$i6$

$\tilde{\rho}_i$	2	3	4	2	0	2
$\tilde{\beta}^{UT}_{(e1,z1)}$	10	Initial inventory for utility type $e1$.				
$\tilde{\beta}^{UT}_{(e2,z2)}$	20	Initial inventory for utility type $e2$.				
$\tilde{\beta}^{FP}_{(g,l)}$	50	Initial inventory for final product.				

Figure 24 shows the normalized demand for final products $g1$ and $g2$, having as a reference the highest demand value of both products (i.e., 120). The demand for $g1$ follows a uniform distribution from 40 to 100 and the demand for $g2$ a uniform distribution from 50 to 120.

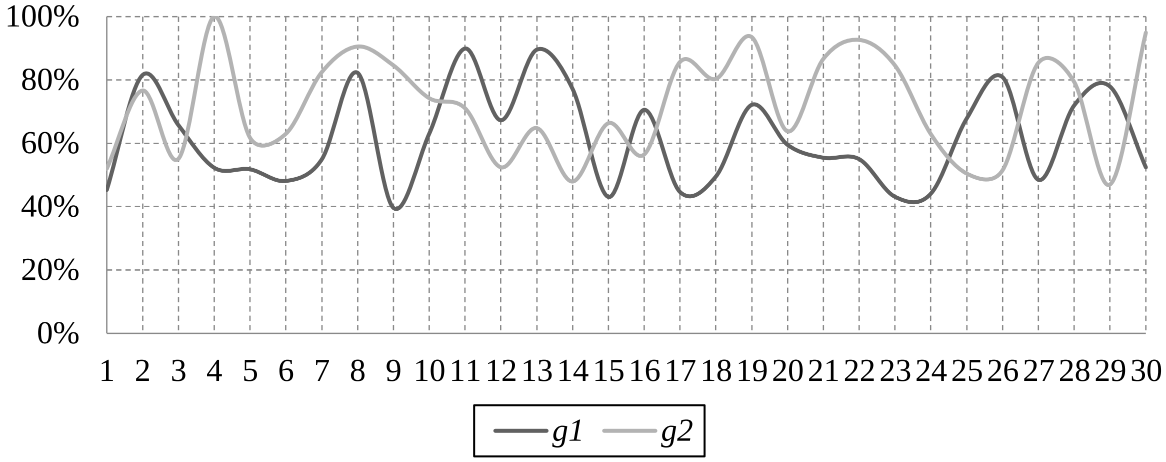


Figure 24. Case Study 3: Normalized daily demand profile for final products.

7.2 Results of Case Study 3

The resulting optimization problem has been solved using GAMS/CPLEX 12 in an Intel(R) core(TM) i7 under standard configurations, and the optimal solution was found in few seconds.

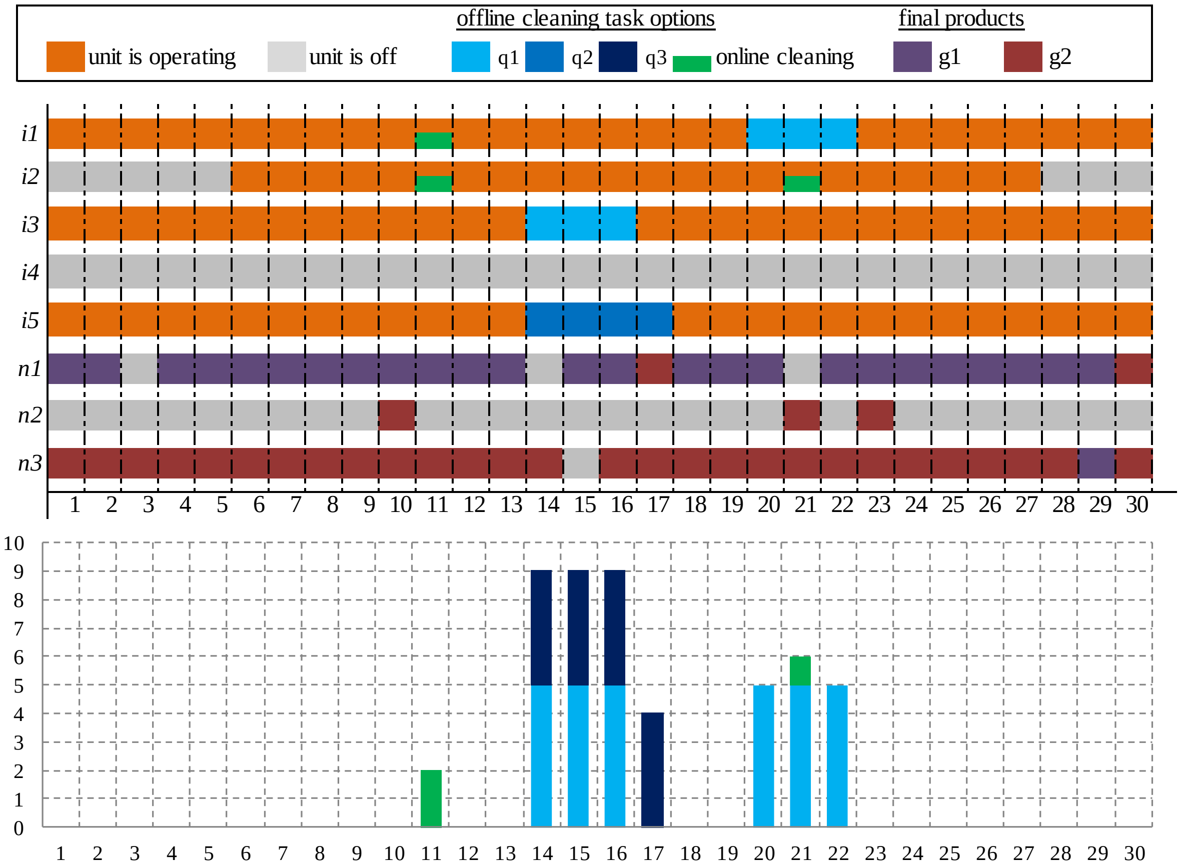


Figure 25. Case study 3: Optimal operational and cleaning plan for the production and utility system and total cleaning resources utilization profile.

Figure 25 displays the optimal plan for the operational and cleaning tasks for the utility system and the total cleaning resources. For each utility unit: (i) its operational status at each time period, (ii) the selected offline and online cleaning tasks options and their corresponding timing are observed. For each processing unit, the operational status of producing final products at each time period is shown. Offline cleaning task option $q1$ is selected for both utility units $i1$ and $i3$. While cleaning task option $q2$ is selected for utility unit $i5$. Utility unit $i2$ undergoes online cleaning twice. Utility unit $i5$ undergoes an offline cleaning task option $q2$ instead of $q1$, because there is low utility demand from processing units on day 14 to 17. Moreover, cleaning task option $q2$ is cheaper than $q1$. Cleaning task $q1$ is usually selected if utility demand from processing units is high. Throughout the planning period, day 14 until day 16 has the highest cleaning resources requirements because two offline cleaning tasks for $i3$ and $i5$ are performed at the same time.

Utility unit $i4$ remains shutdown throughout the planning horizon. This could be because it can only generate utility type $e1$ (refer to Table 8) which seems that it has enough supply from the other utility units that cogenerate both utilities.

Processing unit $n1$ produces final product $g1$ at most of the time periods mainly because its values for $\alpha_{(n,g,e)}$ and $\beta_{(n,g,e)}$ are generally higher than those of $g2$. While processing unit $n3$ produces final product $g2$ at most of the time periods because of the same reason. Also, one can observe that at certain time periods, there is no production of some of the final products while the demand for these products is satisfied through the corresponding product inventories.

For instance, no processing unit produces final product $g1$ in day 3, 14, 21, and 30 while in day 15 and 29 there is no production of final product $g2$ from any processing unit.

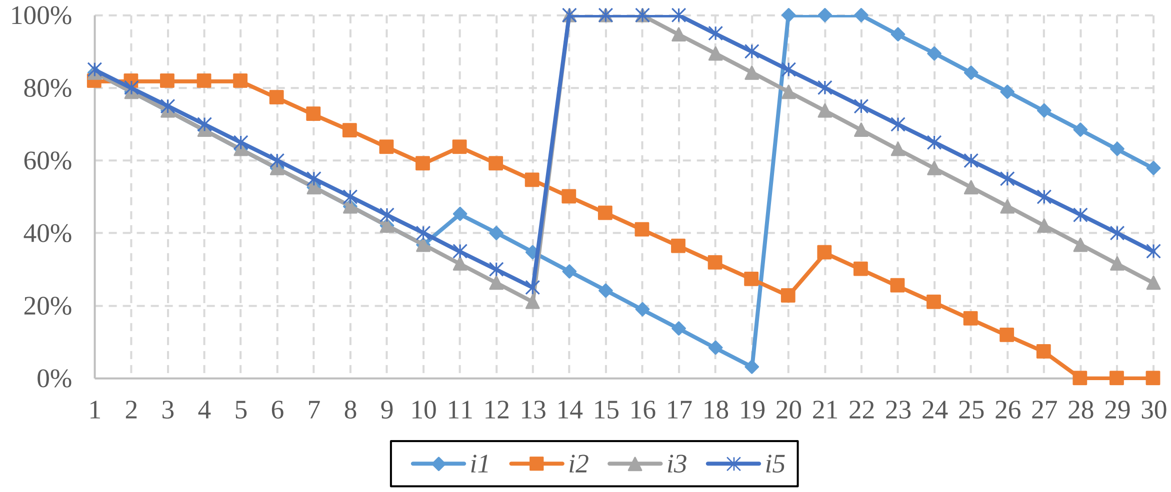
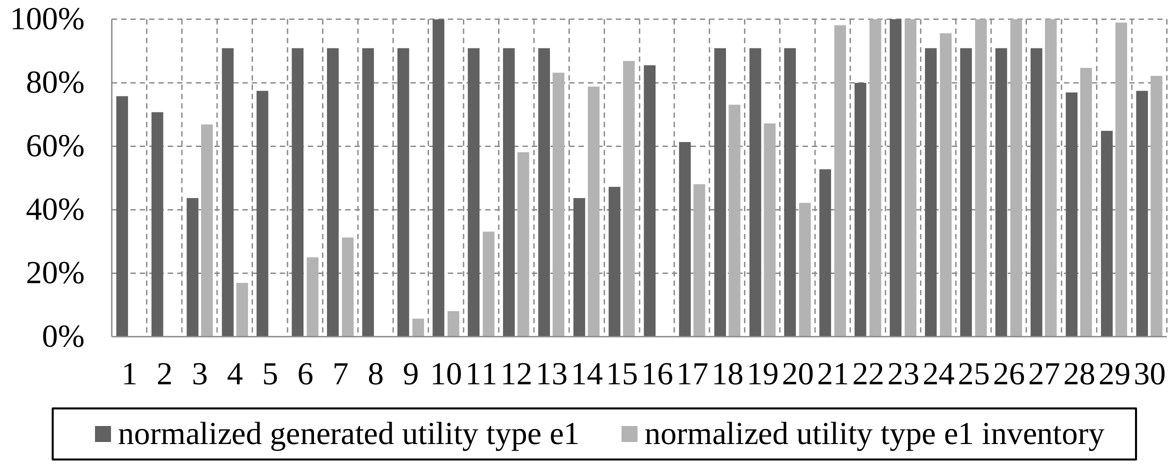


Figure 26. Case Study 3: Performance level profiles for utility units per time period.

All online and offline cleaning tasks can be seen in Figure 26 as an increase in the performance level of the utility units. For instance, it is observed that full recovery of the performance of utility unit $i1$, $i3$ and $i5$ when their associated offline cleaning tasks occur. For utility unit $i2$, a partial performance recovery is observed after online cleaning tasks in day 11 and 21. Most cleaning tasks take place when the performance levels get lower than 50%.

Utility unit $i1$ has one online cleaning on day 11 to partially restore its performance level and continue operating until reaches critical performance level on day 19. The next day, utility unit $i1$ shuts down to undergo an offline cleaning task to restore its full performance.



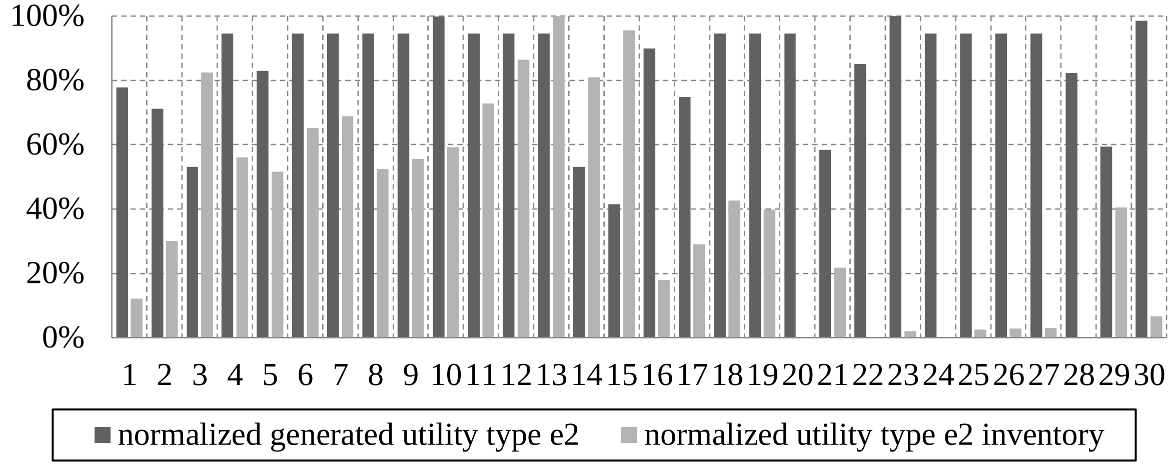
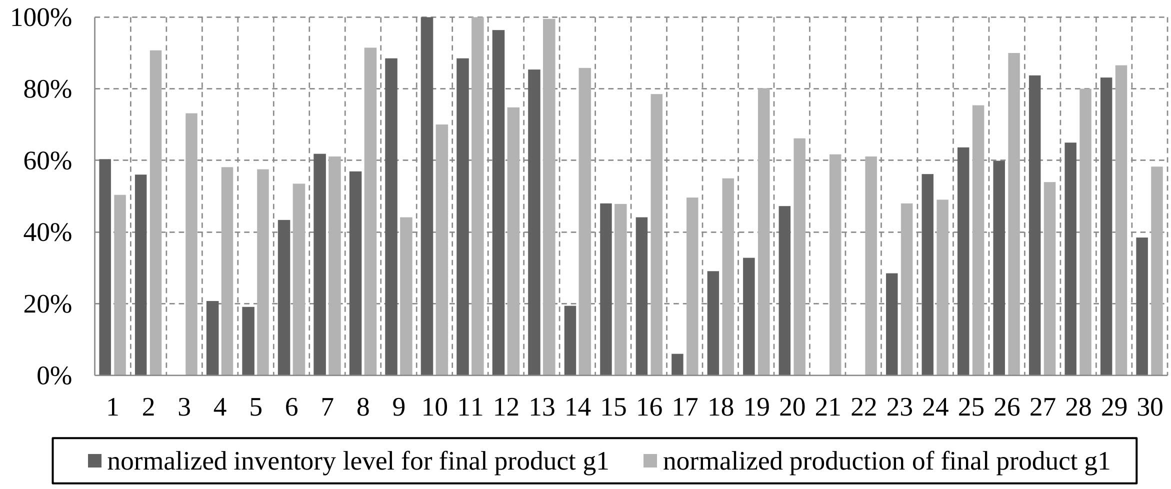


Figure 27. Case Study 3: Normalized total generated utility and inventory profiles.

Figure 27 shows the normalized total generated utility and inventory profiles for utility type $e1$ and $e2$. The generated utility profiles for both utility type $e1$ and $e2$ report quite a similar trend. At most of the time periods, the generation levels for $e1$ and $e2$ are above 60% as it can be seen in this figure. The generated utilities on day 14 and 15 are lower than the other days because some utility units are under offline cleaning tasks. Low or none inventory levels are observed for utility type $e1$ and $e2$ on certain days, demand for final products is high and the inventory level of final products or utilities on the previous day is low.



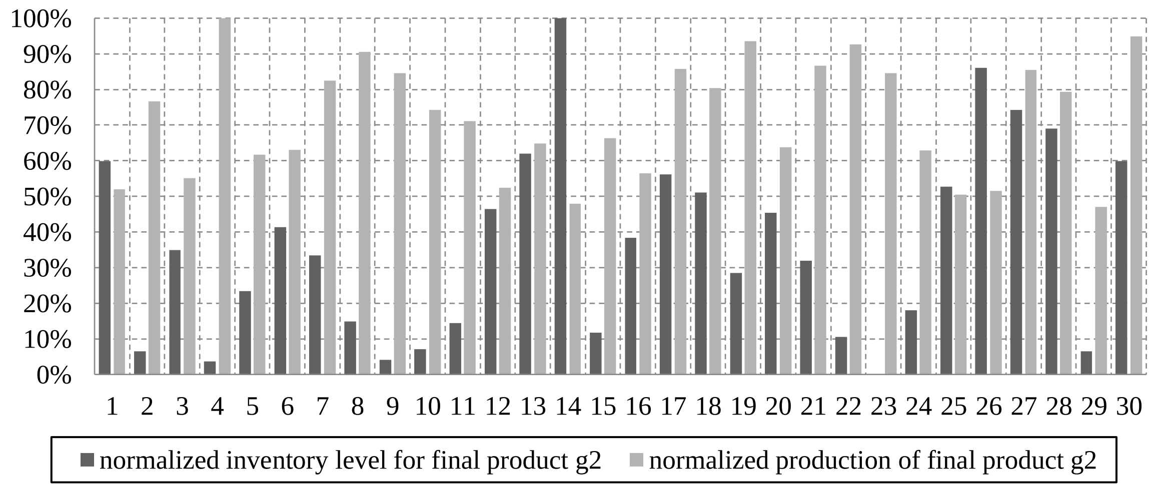


Figure 28. Case Study 3: Normalized total production and inventory profiles for final products.

Figure 28 shows the normalized total production and inventory profiles for final products. The normalized production of final product $g1$ and $g2$ is quite similar to the profile of the demand for products shown in Figure 24. In certain days, there is none or low final products inventory level. For example, there is a zero inventory level for final product $g1$ in day 3, 21 and 22, because the inventory is used to meet a part of the demand for $g1$ in these days. Of great importance is the fact that there are no purchases of final products from external sources, since the demands for final products is fully satisfied by the production system. Furthermore, there are no purchases of utilities at any time periods.

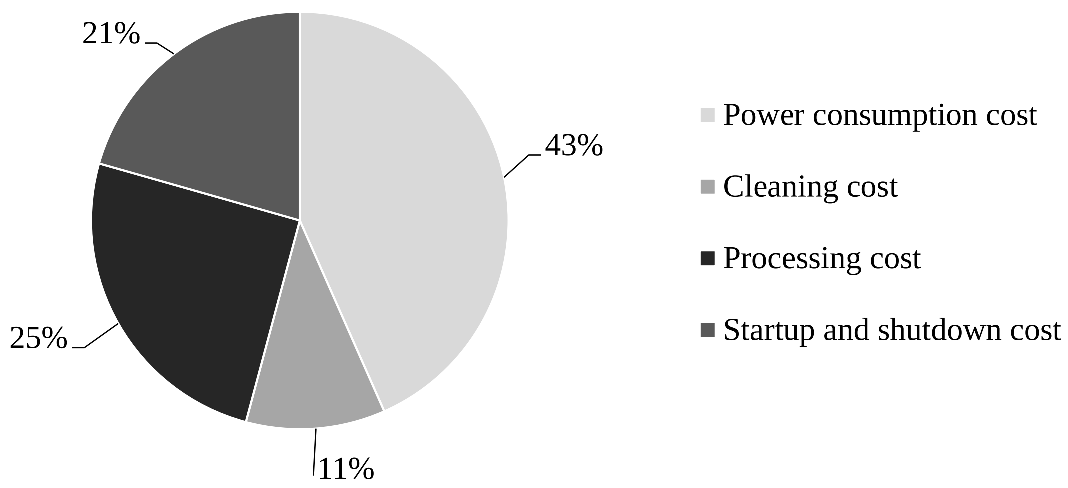


Figure 29. Case Study 3: Total percentage of operational and cleaning costs.

Figure 29 displays the breakdown of the total costs for the utility and the production systems. The types of cost are divided into: (i) the startup and shutdown operations for the utility units, (ii) the power consumption of the utility system, (iii) the online and offline cleaning tasks, and (iv) the operation of production system. Startup and shutdown cost for processing units have been considered negligible in this example. The power consumption remains the highest cost term at about 43% of the total cost, followed by the processing unit cost at 25%. The total power consumption associated with utility units' operation and performance degradation. Finally, the startup and shutdown cost for the utility system and the cost for online and offline cleaning are 21% and 11% of the total cost, respectively.

7.2.1. Sequential approach vs simultaneous planning of production and utility systems.

At this point, in order to highlight the importance of the simultaneous planning of the production and utility systems, the same case study has been solved considering a sequential approach. More specifically, the planning problem of the production system is first solved using upper bounds on the total utility production at each time period. Then, the variables associated to the production of final products (i.e., $Q^{FP}_{(n,g,t)}$ and $K_{(n,g,t)}$), which actually define the utility requirements of the production system at each time period, are fixed. These utility targets are then used in the planning of the utility system. The most important observation of the solution of the sequential approach is that there is a need for purchases of utilities from external sources at more than half of the time periods. More specifically, there is a need for purchasing a total of 1,750 units of utility $e2$. That means that planning problem of the utility system would become infeasible if there is no option in practice of acquiring utilities from external sources. Figure 30 displays the operational and cleaning plan for the production and utility system along with the total purchases profile for utilities obtained by following the sequential approach.

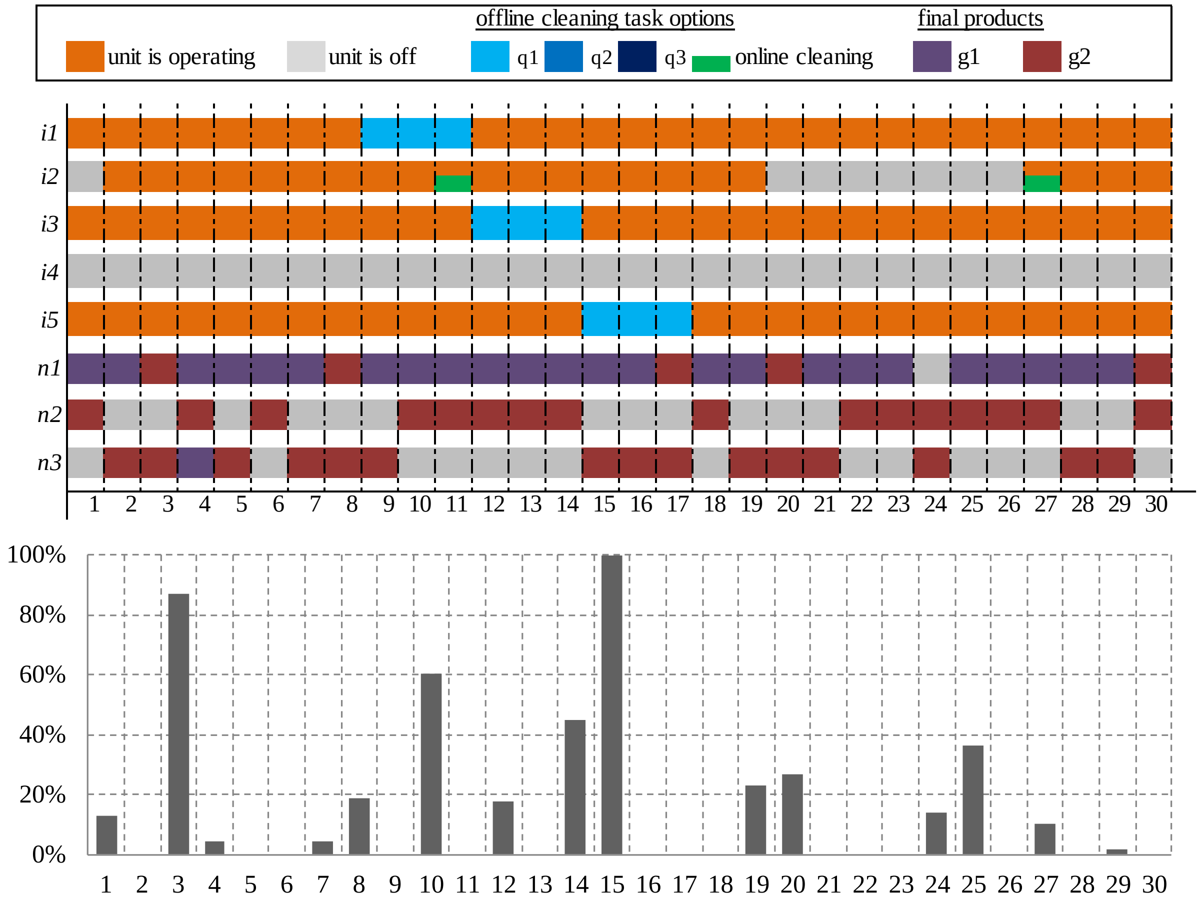


Figure 30. Case study 3: Sequential Approach. Operational and cleaning plan for the production and utility system and total purchases profile for utilities.

To continue with, the sequential approach reports a solution where the total startup and shutdown cost is increased by more than 11%. This means more major operating status changes that in the long-term could result in a shorter lifetime of the utility units, which will eventually result in a higher capital investment cost. Total cleaning cost is also increased by 14% if a sequential approach is used.

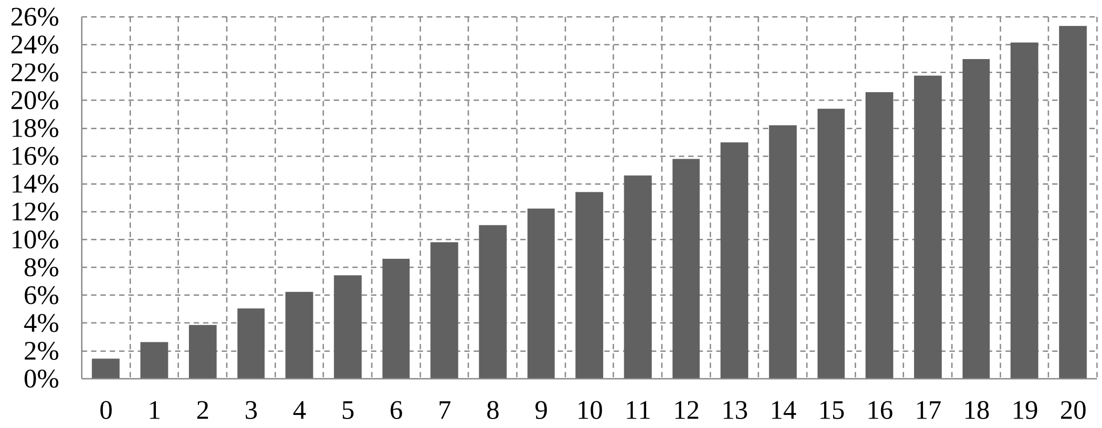


Figure 31. Case study 3: Sequential Approach. Total cost percentage increase in comparison with that of the proposed approach over different utilities purchase prices.

Figure 31 shows how the total cost of the sequential solution increases (in comparison with that of the proposed integrated approach) with the increase of the purchase prices for utilities. It can be observed that even when a zero purchase price for utilities is considered, the total cost of the sequential approach solution is about 1.5% higher than that of the integrated approach. Since there is an important amount of utility that should be acquired from external sources, the purchase price of it will affect strongly the total cost of the sequential solution.

8. Conclusions

In this paper, a general mathematical model for the simultaneous operational planning of utility and production systems has been introduced. The proposed optimization framework considers for the utility units: (i) unit commitment constraints, (ii) performance degradation and recovery aspects, (iii) different cleaning policies, (iv) alternative cleaning tasks options, and (v) limited availability of cleaning resources. Operating costs for the overall system, cleaning costs for utility systems, and energy consumption costs are optimized. To the best of our knowledge, this is the first work that addresses the integrated planning of production and utility systems considering all the above mentioned aspects. The proposed approach is a systematic means for a better coordination between the production and the utility systems resulting in more efficient utilization of equipment and reduction of energy consumption. A number of representative industrial-inspired case studies showed the applicability and the salient features of the proposed approach. Especially, the last case study has clearly demonstrated the superiority of the solution derived from the proposed integrated approach in comparison with the poor solution given by the traditional sequential approach. In particular, important reduction in startup/shutdown and cleaning costs, and most importantly in utilities purchases can be achieved by the simultaneous planning of the production and utility systems. The main limitation of the proposed approach is that for very complex industrial applications (i.e., large number of utility and production units and more complex production processes) the large size of the mathematical model may render intractable the solution of the resulting problem. Ongoing research tasks mainly focus on the modeling of more operational characteristics of the production system, the incorporation of uncertainty in the proposed optimization framework and the development of decomposition methods for the effective solution of more complex industrial systems.

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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
$\eta_t^{\max}$	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 j 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
$\tilde{\omega}_i$	total number of time periods at the beginning of the planning horizon that utility unit i has been continuously operating since its last startup

Continuous variables (non-negative)

$B_{(e,z,t)}^{UT}$	inventory level for utility type e in storage tank $z \in Z_e$ at time period t
$B_{(g,l,t)}^{FP}$	inventory level for final product g in storage tank $l \in L_g$ at time period t
$B_{(e,z,n,t)}^{UT,-}$	flow of utility e that leaves storage tank $z \in Z_e$ and goes to processing unit n at time period t
$B_{(g,l,t)}^{FP,-}$	flow of final product g that leaves storage tank $l \in L_g$ at time period t
$B_{(e,z,t)}^{UT,+}$	flow of utility e that gets in storage tank $z \in Z_e$ at time period t
$B_{(g,l,t)}^{FP,+}$	flow of final product g that gets in storage tank $l \in L_g$ at time period t
$NS_{(e,n,t)}^{UT}$	purchases of utility e to be utilized in processing unit n in time period t
$NS_{(g,t)}^{FP}$	purchases of final product g in time period t
$\bar{Q}_{(i,t)}$	operating production level of utility unit i in time period t
$Q_{(n,g,t)}^{FP}$	production level of final product g from processing unit n in time period t

$Q^{UT}_{(i,e,t)}$	production level of utility e from utility unit i in time period t
$\hat{Q}^{UT}_{(i,j,e,t)}$	production level of utility e from utility unit i that is send to connecting line $j \in J_i$ in time period t
$R_{(i,t)}$	cumulative time of operation for utility unit i at time period t
$U_{(i,t)}$	extra power consumption of utility unit i due to its performance degradation

Binary variables

$X_{(i,t)}$	= 1, if a utility unit i is operating during time period t
$S_{(i,t)}$	= 1, if a utility unit i starts up at the beginning of time period t
$F_{(i,t)}$	= 1, if a utility unit i shuts down at the beginning of time period t
$V_{(i,t)}$	= 1, if an online cleaning task for utility unit $i \in CB_i^{on}$ occurs in time period t
$W_{(i,t)}$	= 1, if an offline cleaning task for utility unit $i \in (CB_i^{off} \cup FM_i)$ starts at the beginning of time period t
$H_{(i,q,t)}$	= 1, if an offline cleaning task option for utility unit $i \in (CB_i^{off} \cup FM_i)$ starts at the beginning of time period t
$K_{(n,g,t)}$	= 1, if final product g is produced in processing unit n during time period t
$Y_{(i,j,t)}$	= 1, if utility unit i serves connecting line j during time period t
$D_{(i,t)}$	= 1, if utility unit i changes connecting line at the beginning of time period t

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

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