IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 17 August 2022, accepted 27 August 2022, date of publication 8 September 2022, date of current version 23 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3205360

RESEARCH ARTICLE

Optimizing the Maintenance Schedule of a Combined Cycle Gas Turbine Considering Different Maintenance Types and Operating Hours

VINCENT F. YU[1,2], YUEH-SHENG LIN[1], PANCA JODIAWAN[1], MENG-DUO HE[1], AND SHIH-WEI LIN[3,4,5]

[1]Department of Industrial Management, National Taiwan University of Science and Technology, Taipei 106, Taiwan
[2]Center for Cyber-Physical System Innovation, National Taiwan University of Science and Technology, Taipei 106, Taiwan
[3]Department of Information Management, Chang Gung University, Taoyuan 333, Taiwan
[4]Department of Emergency Medicine, Keelung Chang Gung Memorial Hospital, Keelung 204, Taiwan
[5]Department of Industrial Engineering and Management, Ming Chi University of Technology, New Taipei 243, Taiwan

Corresponding author: Shih-Wei Lin (swlin@mail.cgu.edu.tw)

The work of Vincent F. Yu was supported in part by the Ministry of Science and Technology of the Republic of China (Taiwan), under Grant MOST 108-2221-E-011-051-MY3 and the Center for Cyber-Physical System Innovation from the Featured Areas Research Center Program within the Framework of the Higher Education Sprout Project by the Ministry of Education of the Republic of China (Taiwan). The work of Shih-Wei Lin was supported in part by the Ministry of Science and Technology of the Republic of China, (Taiwan) and the Linkou Chang Gung Memorial Hospital under Grant MOST109-2410-H-182-009MY3 and Grant BMRPA19, respectively.

ABSTRACT An efficient maintenance schedule for gas turbines of power plants ensures a reliable electricity supply. This study addresses a generator maintenance scheduling problem arising from Taiwan's combined cycle power plant with two notable characteristics, i.e., a specific sequence of various maintenance types and the concept of performing maintenance according to operational hours spent. The objective is to minimize the total maintenance cost. The problem is formulated as a Mixed Integer Linear Program which is solvable by an off-the-shelf exact solver, i.e., CPLEX. Moreover, a set of newly generated instances is proposed as benchmark instances for the problem. The instances generated are based on the realistic conditions obtained from the historical record of Taiwan's combined cycle power plant. Computational studies are presented as interesting insights regarding the complexity of the problem and the factors driving the total maintenance costs.

INDEX TERMS Combined cycle power plant, generator maintenance scheduling, mixed integer linear programming.

I. INTRODUCTION

Modern civilization depends heavily on reliable electrification which is, in part, a product of well-planned electricity generation tasks. While ensuring the generated electricity can meet requirements, another concern to be taken into account is the growing importance of sustainability-focused electricity-generating operations. As a result, renewable energy sources and natural gas gain interest as environmentally viable electricity generation.

The Taiwan government has developed an energy policy aiming to gradually increase the utilization of natural gas in the energy system as a response to sustainability concerns. The goal is to implement an integrated energy system in which natural gas becomes the most significant contributing source by 2025 [1]. To realize the plan, Taiwan is building combined cycle power plants that utilize gas turbines and steam turbines as generators to generate electricity [2].

Gas turbines are of critical components in the combined cycle power plants, thus scheduled maintenance plans are required to avoid unexpected failures which may cause negative experiences to public and private sectors.

The associate editor coordinating the review of this manuscript and approving it for publication was Yu Liu.

The maintenance decision of a gas turbine-based generator is different from that of general coal-fired and nuclear power generators. Unlike coal-fired and nuclear power generators, that follow fixed service time (periodic maintenance), the maintenance decision of a gas turbine generator is based on its operational hours [3]. The operational hours here refer to the actual operating hours and equivalent operating hours resulted from other events, e.g., startup time, starting frequency, load, to mention but a few. Thus, the above equivalent operating hours are added to the actual operating hours to obtain the total *equivalent operating hours* (EOH).

Optimizing decisions of maintenance schedules for generators has been studied for a few decades. Section II is further dedicated to explain the recent developments in this area. Despite the numerous works on this field, the literature on the optimization of maintenance schedules that involve the concept of EOH is still scarce. To the best of authors' knowledge, Fattahi *et al.* [4] is so far the only work that considers the concept of operating hours in determining the maintenance schedules for generators in North America. However, the developed model in Fattahi *et al.* [4] cannot be adopted to for the case of generators in Taiwan due to the presence of several unique characteristics.

Realizing the importance of producing appropriate maintenance schedules and the limitation on the current literatures, we consider a new variant of generator maintenance scheduling problem arising in the combined cycle power plant. Each maintenance task needs to be executed at a gas turbine within the range of allowable time interval which is calculated based on the EOH of the gas turbine. A unique characteristic presented by the combined cycle power plant is that a set of different maintenance tasks is available and their executions must follow a specific sequence. The objective of this study is to minimize the long-term maintenance cost of gas turbines. The mixed integer linear programming (MILP) model is formulated for the problem. To this end, our works contribute to the literature by adding a new generator maintenance scheduling problem that involves the concept of EOH. Finally, the contributions of this research work can be summarized as follows.

1. Develop a new variant of the Generator Maintenance Scheduling (GMS) problem by considering the real condition of Taiwan's combined cycle power plant
2. Formulate a MILP model for the problem
3. Present computational results regarding the impact of problem size and sensitivity analyses associated with varying electricity demands and maintenance time intervals.

II. LITERATURE REVIEW

The GMS problem has been widely studied and mainly involves deciding the time to perform preventive maintenances to generating units to achieve operational excellence [5]. The two common objectives commonly proposed for GMS are (1) reliability that has a measurement in terms of net reserves along the planning horizon, and (2) operational cost. The leveling of net reserves over the planning horizon is translated into the maximization of the minimum net reserves from all generating units for any period [6] or minimization of the squares of the reserves over the planning period [7], [8]. The operational costs may be of several types, e.g., refueling cost, production cost, and maintenance cost [9], [10], [11]. In addition, residual fuel refund can also be considered [9], [10]. Given these two important objectives, Lindner *et al.* [12] analyzed the trade-off between reliability and operational cost by proposing a bi-objective GMS problem in which the squares of the reserves and production cost were minimized.

Some extensions are considered in the GMS problem to address realistic situations. Abirami *et al.* [13] addressed an Integrated Maintenance Scheduling (IMS) for both generator and transmission line maintenance scheduling. Fattahi *et al.* [4] developed an original model for deciding the maintenance time of generating units based on their operational hours. The proposed approach in Fattahi *et al.* [4] is inspired by particular types of generating units, e.g. gas turbines [14]. Generators may experience unexpected breakdowns causing forced outages. Several studies have proposed various approaches to deal with uncertainty in unexpected breakdown events. Eygelaar *et al.* [15] extended the GMS problem by incorporating the failure rate of each generating unit. The adopted GMS problem thus considers the probability that no generating unit will fail during the time interval between the time a unit was activated upon its previous maintenance up to the time the unit needed to undergo the next maintenance as the objective function. Suresh and Kumarappan [8] dealt with an integrated maintenance scheduling and economic load dispatch problem considering random outages of generators and electrical demand variation. The economic load dispatch is another crucial planning task that requires decisions for allocating electricity demand between available generating units [16], [17]. Recent developments of technology have enabled advanced techniques, such as combining classical generator maintenance scheduling models with sensor-driven predictive techniques [18].

Given the importance of sustainability, more countries have fostered the utilization of renewable energy sources, such as wind power, hydropower, and solar power. Perez-Canto and Rubio-Romero [19] proposed a mathematical model for maintenance scheduling considering the integration of wind farms into the existing generator system. The operations and maintenance tasks of offshore wind turbines involve not only the scheduling of maintenance but also the routing of available resources—that is, the maintenance crews, due to the dynamically changing weather & environmental restrictions at sites. These two problems are commonly integrated to achieve higher economic benefits, often mentioned as the maintenance scheduling and routing problem [20], [21]. Foong *et al.* [22] optimized maintenance schedules for a real case study of five hydropower systems by developing an Ant Colony Optimization. The recent literature on renewable energy sources–based generator maintenance scheduling focuses on optimizing systems with generators

TABLE 1. Summary of literature review.

References	Objectives			Generator Maintenance Scheduling (GMS)			Unit Commitment (UC)			Coupling between UC and GMS		Solution Approach		
	C	R	E	Resource availability	Continuous maintenance	Maintenance pattern	Load balance	Minimum system reserve	Minimum & Maximum Generating Capacity	ON-OFF Status	Maintenance Windows	Mathematical Model	Exact methods	Heuristics/ Metaheuristics/ Math-heuristics
Dahal and Chakpitak [6]		√		√			√	√		√	√			√
Canto [33]	√	√			√		√	√	√	√			√	
Foong et al. [22]		√		√	√		√			√	√			√
Anghinolfi et al. [31]	√			√			√		√	√	√			√
Rozenknop et al. [10]	√			√			√		√	√	√			√
Reihani et al. [7]		√								√				√
Perez-Canto and Rubio-Romero [19]		√		√	√		√	√			√	√		
Lusby et al. [27]	√			√			√		√	√	√		√	
Suresh and Kumarappan [8]		√		√	√		√	√		√	√			√
Fattahi et al. [4]	√			√	√		√	√	√	√	√	√		√
El-Sharkh [11]	√			√	√		√		√		√			√
Samuel and Rajan [32]	√			√	√			√	√		√			√
Abdelaziz et al. [17]	√		√				√		√					√
Balaji et al. [30]	√			√	√		√		√					√
Han et al. [3]	√				√		√	√	√	√	√	√		
Eygelaar et al. [15]		√		√	√		√				√	√		
Lindner et al. [12]	√	√		√	√		√	√	√	√	√			√
Lakshminarayanan and Kaur [28]		√		√	√		√			√				√
Wang et al. [23]	√			√	√		√	√	√	√	√	√		
Salkuti [25]	√	√	√				√	√	√					√
Dupin and Talbi [29]	√			√			√		√	√	√			√
This work	√			√	√	√	√	√	√	√	√	√		

C: Cost
R: Reliability
E: Emission

of various energy sources. Wang *et al.* [23] developed an optimization model for multi-type renewable energy generator maintenance scheduling problems by simultaneously considering hydropower systems and wind power generators. Further, Shayesteh *et al.* [24] performed a simulation to evaluate the impact of adding renewable energy sources (e.g., hydropower, wind power, and solar power generators) into a system consisting of conventional generators. At the operational level, Salkuti [25] tackled the multi-objective unit commitment problem by considering uncertainty and various renewable energy sources.

The solution approach for the GMS problem is categorized into three classes: (1) mathematical model, (2) heuristic, and (3) hybrid methods [13]. For the mathematical model, the benders decomposition approach and mixed integer linear/ nonlinear programming are generally used [4], [26], [27]. For heuristic, population-based heuristics are most often developed, such as Genetic Algorithm [6], [25], particle swarm optimization [8], ant colony optimization [22], cuckoo search [28], and flower pollination algorithm [17]. Hybrid methods can be further categorized as hybridization between mathematical model and heuristic [29], [30], [31], and hybridization between heuristics [6], [32].

Based on the above-discussed studies, our research shares similar characteristics with Fattahi *et al.* [4]. Particularly, we considered a condition in which maintenance is performed based on cumulative operational hours since the case study is obtained from the Taiwan combined cycle plant which harnesses gas turbines for generating electricity. The notable difference from the case of Fattahi *et al.* [4] is that we considered a pattern for a set of maintenance tasks adopted from the real condition of Taiwan's combined cycle power plant. Table 1 provides a summary of features considered in various GMS problems discussed in the previous literature. The table shows the novel features of our GMS problem, which has never been addressed in the previous literature (as far as the authors' knowledge is concerned)—that is, the maintenance pattern.

III. THE MATHEMATICAL MODEL

A. PROBLEM DEFINITION

In this study, we address the GMS of Taiwan's combined cycle gas turbines that feature different maintenance types with a specific execution sequence and EOH concept by developing a mathematical model. Classical GMS problems generally set either a predefined time range for performing a maintenance task for a generating unit or a number of maintenance tasks to be performed throughout a given planning period [7], [8], [12], [33]. The concept of EOH explained in Section Introduction has a different perspective in determining the schedule of a maintenance task. In particular, a maintenance task is performed on a generating unit whenever the EOH measured from the last maintenance task was performed has reached a value between the minimum and the maximum operating time. Thus, in terms of modeling perspective, the involvement of EOH presents a new challenge,

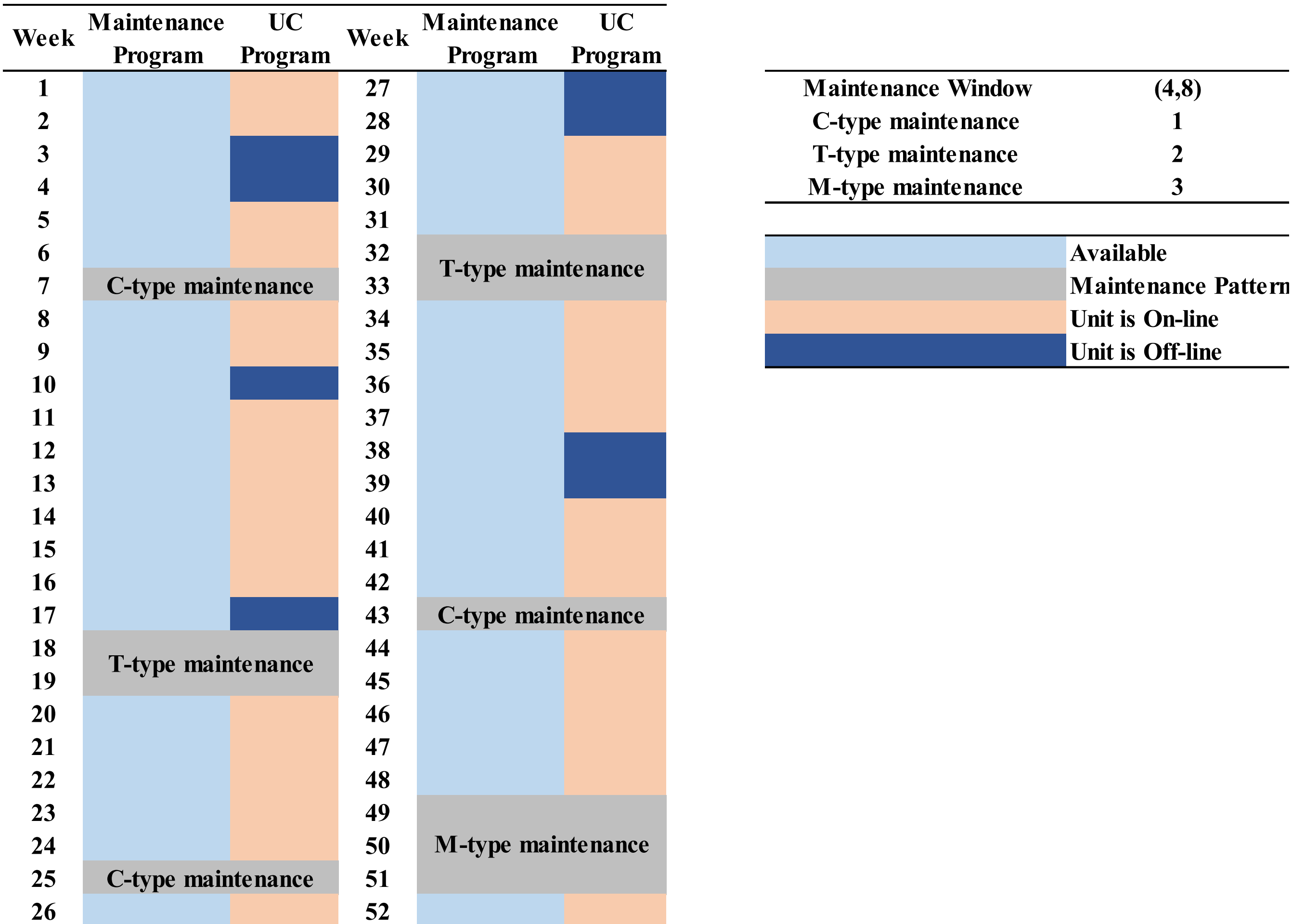

FIGURE 1. Illustration of a solution to the GMS problem of a gas turbine.

i.e., the decisions of whether a generating unit (in our case, a gas turbine) is operated or not at each time unit considering the requirement of the range of operating time.

In order to take into account the EOH concept to the classical GMS problem, we develop a novel mixed integer linear program based on the model presented by Fattahi *et al.* [4]. In this article, we use the term of gas turbine and generating unit interchangeably and hence mean the same.

B. PROBLEM ASSUMPTION

The following assumptions were made to build the mathematical model:

1. The three maintenance types include combustion inspection (C), turbine inspection (T), and major overhaul (M). Type C maintenance requires 3 weeks, type T maintenance requires 6 weeks, and type M maintenance requires 12 weeks
2. The maintenance execution of each gas turbine depends on its EOH. There exists a range of EOH in which a maintenance task must be carried out. Note that EOH in the model is expressed in terms of the week instead of the hour
3. The maintenance tasks are conducted based on the predetermined sequence: C-T-C-T-C-M
4. Only one gas turbine can be maintained every week
5. The cost of each maintenance type is different

C. SOLUTION ILLUSTRATION

FIGURE 1 illustrates how different maintenance types with a specific execution sequence and EOH concept are integrated into the GMS program. This figure shows that the maintenance window is set between 4 to 8 weeks. Three types of maintenance programs—C-type, T-type, and M-type—need 1, 2, and 3 weeks, respectively. In addition, we limit the planning period to 52 weeks, as shown in Figure 1. Three columns express the GMS program: (1) Week, (2) Maintenance program, and (3) UC program. The maintenance program shows whether the gas turbine is available or under maintenance, while the UC program shows whether the gas turbine is online or offline.

The EOH concept is illustrated through the weeks in which the gas turbine is available. The first maintenance type—C-type maintenance—takes place in Week 7. The EOH of the gas turbine can be seen in the UC program column.

Although the gas turbine has spent 6 weeks in the available state of the maintenance program, it has only been in the online state for 4 weeks in the UC program. FIGURE 1 shows that the gas turbine is scheduled for the offline state in Weeks 3 and 4. Thus, the first maintenance cannot be scheduled earlier than Week 7 because the EOH of the gas turbine has not reached the lower bound of the maintenance window—that is, 4 weeks. FIGURE 1 also shows the new feature considered in this research work—the maintenance pattern. The C-T-C-T-C-M sequence takes place in Week 7, Weeks 18 – 19, Week 25, Weeks 32 – 33, Week 43, and Weeks 49 – 51, respectively.

D. FORMULATION

Sets

U Set of gas turbine units.

T Set of maintenance weeks.

Parameters

D_c Weeks required by type C maintenance.

D_t Weeks required by type T maintenance.

D_m Weeks required by type M maintenance.

Q_t Demand at week t

$\mathrm{Lt}_{\max}$ The maximum allowable operating weeks for a gas turbine between the last maintenance outage and the next one.

$\mathrm{Lt}_{\min}$ The minimum allowable operating weeks for a gas turbine between the last maintenance outage and the next one.

$P_{\max}$ Maximum power generation of a gas turbine.

$P_{\min}$ Minimum power generation of a gas turbine.

CC Type C maintenance cost.

CT Type T maintenance cost.

CM Type M maintenance cost.

N Maximum number of units for maintenance outage in a week.

L An arbitrary large positive number.

Decision variables

$c_{u,t}^{i}$ The binary variable that shows the i-th type C maintenance status of unit u in week t (if unit u is on maintenance, the value is 1; otherwise 0), $u \in U, t \in T, i \in \{1, 2, 3\}$.

$q_{u,t}^{j}$ The binary variable that shows the j-th type T maintenance status of unit u in week t (if unit u is on maintenance, the value is 1; otherwise 0), $u \in U, t \in T, j \in \{1, 2\}$.

$m_{u,t}$ The binary variable that shows the type M maintenance status of unit u in week t (if unit u is on maintenance, the value is 1; otherwise 0), $u \in U, t \in T$.

$\mathrm{sc}_{u,t}^{i}$ The binary variable that shows the i-th type C maintenance status of unit u at the beginning of week t (if the maintenance outage of unit u is started in week t, the value is 1; otherwise 0), $u \in U, t \in T, i \in \{1, 2, 3\}$.

$\mathrm{st}_{u,t}^{j}$ The binary variable that shows the j-th type T maintenance status of unit u at the beginning of the week t (if the maintenance outage of unit u is started in week t, the value is 1; otherwise 0), $u \in U, t \in T, j \in \{1, 2\}$.

$\mathrm{sm}_{u,t}$ The binary variable that shows the type M maintenance status of unit u at the beginning of the week t (if the maintenance outage of unit u is started in week t, the value is 1; otherwise 0), $u \in U, t \in T$.

$v_{u,t}$ The binary variable that shows the online status of unit u in week t (if unit u is online, the value is 1; otherwise 0), $u \in U, t \in T$.

$p_{u,t}$ Power generation dispatch of unit u in week $t, u \in U, t \in T$.

$\mathrm{pend}_{u,t}$ Operational weeks of unit u at the beginning of week t after the last maintenance outage, if a maintenance outage is started in week t, $u \in U$, $t \in T$.

Objective function

$$Min\ z = \sum\nolimits_{t\in T}\left(\mathrm{CC}\sum\nolimits_{u\in U}\sum\nolimits_{i=1}^{3}\mathrm{sc}_{u,t}^{i} + \mathrm{CT}\sum\nolimits_{u\in U}\sum\nolimits_{j=1}^{2}\mathrm{st}_{u,t}^{j} + \mathrm{CM}\sum\nolimits_{u\in U}\mathrm{sm}_{u,t}\right) \quad (1)$$

The objective function (1) minimizes the total maintenance cost of all maintenance types.

Constraints

$$\sum\nolimits_{u\in U}\left(\sum\nolimits_{i=1}^{3}c_{u,t}^{i} + \sum\nolimits_{j=1}^{2}q_{u,t}^{j} + m_{u,t}\right) \le N \quad \forall t\in T \quad (2)$$

Constraint (2) limits the number of gas turbines allowed to be offline.

$$\mathrm{sc}_{u,t}^{i}D_c \le \sum_{n=t}^{n=\min(t+D_c-1,T)} c_{u,n}^{i} \quad \forall u\in U,\ t\in T,\ i\in\{1,2,3\} \quad (3)$$

$$\mathrm{st}_{u,t}^{j}D_t \le \sum_{n=t}^{n=\min(t+D_t-1,T)} q_{u,n}^{j} \quad \forall u\in U,\ t\in T,\ i\in\{1,2\} \quad (4)$$

$$\mathrm{sm}_{u,t}D_m \le \sum_{n=t}^{n=\min(t+D_m-1,T)} m_{u,n} \quad \forall u\in U,\ t\in T \quad (5)$$

Constraints (3), (4), and (5) ensure that an offline state is maintained for a particular period, depending on the performed maintenance type.

$$\sum_{u\in U} p_{u,t} \geq Q_t \quad \forall t \in T \tag{6}$$

Constraint (6) guarantees that the total generated amount of electricity meets the demand every week.

$$P_{\min} v_{u,t} \leq p_{u,t} \quad \forall u \in U, t \in T \tag{7}$$

$$p_{u,t} \leq P_{\max} v_{u,t} \quad \forall u \in U, t \in T \tag{8}$$

Constraints (7) and (8) define the minimum and maximum generated electrical power of a gas turbine respectively.

$$\left(\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t}\right) \times Lt_{\min} \leq \mathrm{pend}_{u,t} \quad \forall u \in U, t \in T \tag{9}$$

$$\mathrm{pend}_{u,t} \leq \left(\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t}\right) \times \mathrm{Lt}_{\min} \quad \forall u \in U, t \in T \tag{10}$$

Constraints (9) and (10) define the maintenance window of each gas turbine.

$$\left(\sum_{i=1}^{3} c_{u,t}^{i} + \sum_{j=1}^{2} q_{u,t}^{j} + m_{u,t}\right) + v_{u,t} \leq 1 \quad \forall u \in U, \ t \in T \tag{11}$$

Constraint (11) restricts the gas turbine from either staying in an offline or online state.

$$\sum_{n=1}^{t-1} v_{u,n} - \sum_{w=1}^{t} \mathrm{pend}_{u,w} \leq \left(1 - \left(\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t}\right)\right) \times L \quad \forall u \in U, \ t \in T \tag{12}$$

$$\sum_{n=1}^{t-1} v_{u,n} - \sum_{w=1}^{t} \mathrm{pend}_{u,w} \geq \left(\left(\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t}\right) - 1\right) \times L \quad \forall u \in U, \ t \in T \tag{13}$$

Constraints (12) and (13) ensure that each gas turbine is maintained only during the maintenance window.

$$\mathrm{pend}_{u,t} \geq \left(\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t}\right) \times L \quad \forall u \in U, \ t \in T \tag{14}$$

Constraint (14) ensures that $pend_{u,t}$ can take a nonzero value if and only if a maintenance outage starts at week t.

$$\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t} \leq \frac{\left(\sum_{n=1}^{t-1} v_{u,n} - \sum_{n=1}^{t-1} \mathrm{pend}_{u,n}\right)}{\times \mathrm{Lt}_{\min}} \quad \forall u \in U, \ t \in T \tag{15}$$

$$\sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t} \geq \frac{\left(\sum_{n=1}^{t-1} v_{u,n} - \sum_{n=1}^{t-1} \mathrm{pend}_{u,n} - \mathrm{Lt}_{\max}\right)}{\times L} \quad \forall u \in U, \ t \in T \tag{16}$$

Constraints (15) and (16) ensure that a particular maintenance type is performed if and only if the total number of online weeks is between the minimum and the maximum number of allowable operating weeks.

$$0 \leq \sum_{i=1}^{3} \mathrm{sc}_{u,t}^{i} + \sum_{j=1}^{2} \mathrm{st}_{u,t}^{j} + \mathrm{sm}_{u,t} \leq 1 \quad \forall u \in U, \ t \in T \tag{17}$$

Constraint (17) guarantees that only one maintenance type is performed on each gas turbine each week.

$$\sum_{t=1}^{T} \mathrm{sc}_{u,t}^{i} \leq 1 \quad \forall u \in U, \ i \in \{1, 2, 3\} \tag{18}$$

$$\sum_{t=1}^{T} \mathrm{st}_{u,t}^{j} \leq 1 \quad \forall u \in U, \ j \in \{1, 2\} \tag{19}$$

$$\sum_{t=1}^{T} \mathrm{sm}_{u,t} \leq 1 \quad \forall u \in U \tag{20}$$

Constraints (18), (19), and (20) ensure that each maintenance type occurs once at most.

$$\sum_{n=1}^{t} \mathrm{sc}_{u,n}^{1} \geq \mathrm{st}_{u,t+1}^{1} \quad \forall u \in U, \ t = \{1, 2, \ldots, T-1\} \tag{21}$$

$$\sum_{n=1}^{t} \mathrm{st}_{u,n}^{1} \geq \mathrm{sc}_{u,t+1}^{2} \quad \forall u \in U, \ t = \{1, 2, \ldots, T-1\} \tag{22}$$

$$\sum_{n=1}^{t} \mathrm{sc}_{u,n}^{2} \geq \mathrm{st}_{u,t+1}^{2} \quad \forall u \in U, \ t = \{1, 2, \ldots, T-1\} \tag{23}$$

$$\sum_{n=1}^{t} \mathrm{st}_{u,n}^{2} \geq \mathrm{sc}_{u,t+1}^{3} \quad \forall u \in U, \ t = \{1, 2, \ldots, T-1\} \tag{24}$$

$$\sum_{n=1}^{t} \mathrm{sc}_{u,n}^{3} \geq \mathrm{sm}_{u,t+1} \quad \forall u \in U, \ t = \{1, 2, \ldots, T-1\} \tag{25}$$

Constraints (21), (22), (23), (24), and (25) ensure that the maintenance task of each combined cycle gas turbine can be performed following a predetermined maintenance cycle (C-T-C-T-C-M).

IV. EXPERIMENTS AND ANALYSIS

This section explains the methodology to address the problem, involving the development of benchmark instances and

TABLE 2. Parameters' values for the proposed mathematical model.

Parameter	Value
Dc	3 weeks
Dt	6 weeks
Dm	12 weeks
P_{max}	41,596.8 MW
P_{min}	10399.2 MW
CC	10 million NTD
CT	20 million NTD
CM	40 million NTD
N	1 generating unit

TABLE 3. The computational result of solving benchmark instances.

Small				Medium				Large			
Instance	LB	UB	Time (s)	Instance	LB	UB	Time (s)	Instance	LB	UB	Time (s)
1_6_8_sh	50000	50000	4.28	1_6_8_mh*	108750	120000	36000	1_6_8_lh*	181250	210000	36000
2_6_8_sh	60000	60000	11.98	2_6_8_mh	180000	180000	5773.23	2_6_8_lh*	282083	350000	36000
3_6_8_sh	80000	80000	16.5	3_6_8_mh*	228437	240000	36000	3_6_8_lh*	366250	440000	36000
1_8_10_sh	30000	30000	0.22	1_8_10_mh	90000	90000	722.67	1_8_10_lh*	119675	160000	36000
2_8_10_sh	40000	40000	11.06	2_8_10_mh*	117750	140000	36000	2_8_10_lh*	211181	260000	36000
3_8_10_sh	50000	50000	9.34	3_8_10_mh*	127618	170000	36000	3_8_10_lh*	274856	310000	36000
1_6_8_sl	30000	30000	1.64	1_6_8_ml*	77500	90000	36000	1_6_8_ll*	117083	150000	36000
2_6_8_sl	30000	30000	6.44	2_6_8_ml	120000	120000	735.375	2_6_8_ll*	202416	230000	36000
3_6_8_sl	40000	40000	8.5	3_6_8_ml*	116491	140000	36000	3_6_8_ll*	251814	290000	36000
1_8_10_sl	20000	20000	1.17	1_8_10_ml	60000	60000	63.23	1_8_10_ll	110000	110000	396.11
2_8_10_sl	20000	20000	2.42	2_8_10_ml	80000	80000	1164.24	2_8_10_ll*	143854	170000	36000
3_8_10_sl	20000	20000	5.20	3_8_10_ml	80000	80000	25.39	3_8_10_ll	200000	200000	20936.7
Average			**6.56**	**Average**			**18707.01**	**Average**			**31777.73**

* The solution is feasible but not optimal
LB: Lower Bound
UB: Upper Bound

analyses of the results. CPLEX was utilized to solve the mathematical model proposed in Section III. A Microsoft Windows 7 Professional operating system and a computer with an Intel (R) Core (TM) CPU i7-10700 @ 2.90GHz and memory of 128GB were used for all the experiments.

A. BENCHMARK INSTANCES

We generated three sets of instances -small, medium, and large- based on historical records of combined cycle gas turbines in Taiwan. The small, medium, and large instances have different planning periods, i.e., 133 weeks, 237 weeks, and 343 weeks, respectively. Each set consists of 12 instances with different weekly electrical demands, minimum and maximum allowable operating weeks, and the number of available gas turbines. Two pairs of minimum and maximum allowable operating weeks are considered, i.e., (36, 48) and (48, 60), and three numbers of available gas turbines are considered, i.e., 3, 6, and 8. The values of the remaining necessary parameters for the model are listed in TABLE 2.

Based on generated instances, we present three types of analyses. First, an analysis of the impact of instances' dimensions toward the computational time required for solving such a problem is presented. Second, the impact of minimum and maximum allowable operating weeks toward the total maintenance costs, and third, the impact of electricity demands on the total maintenance costs are explained. The analyses are presented in Sections IV.B and IV.C.

B. COMPUTATIONAL RESULTS

TABLE 3 presents the results obtained by solving all generated instances. The meaning of an instance's name can be explained as follows. The first number (i.e., 1, 2, or 3) states the number of gas turbines considered, that is: (1) 1 means 3 gas turbines, (2) 2 means 6 gas turbines, and (3) means 8 gas turbines. The second and third numbers (i.e. 6 & 8, or 8 & 10) represent the pair of minimum and maximum allowable operating weeks: (1) 6 and 8 mean (36, 48) and (2) 8&10 means (48, 60). The last two characters represent the size of the instance and type of electricity demand: (1) "s", "m", and "l" mean small, medium, and large, respectively, and (2) "h" and "l" means high and low electricity demands, respectively.

Based on TABLE 3, the computation increases significantly as the size of the instance grows. The problem size also influences the capability of CPLEX to obtain optimal solutions. The CPLEX can obtain all optimal solutions for solving small instances and only needs 6.56 s, on average. For medium-size instances, 6 out of 12 solutions are optimal. Lastly, 2 out of 12 instances were solved to optimality for large-size instances. However, the CPLEX managed to obtain feasible solutions for the remaining medium and large instances within 36,000 s. Based on Table 2, we can also observe that the larger the size of an instance, the larger the computational time required to provide a solution.

C. ANALYSES AND DISCUSSIONS

This section elaborates on the impact of minimum and maximum allowable operating weeks and the magnitude of electricity demands. As explained before, we provided two pairs of minimum and maximum allowable operating weeks, i.e., (36, 48) and (48, 60). In addition, there were two types, i.e., high and low electricity demand scenarios.

TABLE 4 shows the impact of minimum and maximum allowable operating weeks on the total maintenance cost. When the values of minimum and maximum allowable operating weeks are lower, the total maintenance costs are higher. The average maintenance costs of small, medium, and large instances with lower minimum and maximum allowable operating weeks are 61.11%, 43.54 %, and 38.01% higher compared to those of higher minimum and maximum allowable operating weeks. The main rationale of this phenomenon is that a lower number of maintenances are required for a higher

TABLE 4. The impact of time requirement for performing maintenance tasks on a generating unit toward the total maintenance cost.

instance size	maintenance interval	Average Cost	Average number of maintenances
Small	(36,48)	48333.33	4.67
	(48, 60)	30000.00	3.00
Medium	(36,48)	148333.33	11.67
	(48, 60)	103333.33	8.67
Large	(36,48)	278333.33	20.17
	(48, 60)	201666.67	15

TABLE 5. The impact of the magnitude of electricity demand toward the total maintenance cost.

instance size	Demand Type	Average Cost	Average number of maintenances
Small	High	51666.67	5.00
	Low	26666.67	2.67
Medium	High	156666.67	12.17
	Low	95000.00	8.17
Large	High	288333.33	20.67
	Low	191666.67	14.5

number of minimum and maximum allowable operating weeks. As seen in TABLE 4, the averages of maintenances required by scenarios with (36, 48) as the minimum and maximum allowable operating weeks are higher than that of scenarios with (48, 60) as the minimum and maximum allowable operating weeks. The aforementioned observation provides a motive for the generator company to consider the investment of a more advanced technology in order to increase the value of minimum and maximum allowable operating weeks.

TABLE 5 describes the impact of electricity demand on the total maintenance cost. The total maintenance cost increases when the electricity demand is higher. This occurs because the number of active gas turbines is higher to meet the requirement of electricity demand. Since the maintenance of a gas turbine is determined by EOH, the longer a gas turbine is active, the shorter is the inspection interval time required by a gas turbine to be maintained. The result in TABLE 5 validates our arguments. The averages of maintenance tasks performed are 2.67, 8.17, and 14.5 for small, medium, and large instances with low electricity demand, respectively, and 5, 12.17, and 20.67 for small, medium, and large instances with high electricity demand. The numbers of maintenance tasks for instances with high electricity demand are higher than that of instances with low electricity demand. The second observation regarding the impact of electricity demand leads to an alternative for the generator company to analyze demand sharing schemes in order to find the most beneficial strategy in terms of operational cost.

V. CONCLUSION

To address the challenge of providing a reliable electricity supply, a GMS of Taiwan's combined cycle power plant was addressed. A novel mathematical model incorporating two realistic features, i.e., maintenance of each gas turbine based on a given sequence of maintenance types (C-T-C-T-C-M) and the maintenance task of each gas turbine based on its EOH, was established and solved by CPLEX, an off-the-shelf exact solver. A set of realistic instances is generated based on the historical record in Taiwan's combined cycle power plant.

The results show several interesting insights. First, the size of an instance significantly affects the computational time required by the CPLEX. As shown in TABLE 3, the larger the size of an instance, the higher is the computational time. Second, the total maintenance cost depends on two factors: (1) the minimum and the maximum allowable operating weeks, and (2) the magnitude of electricity demand. The higher the values of the minimum and the maximum allowable operating weeks, the lower is the total maintenance cost. On the contrary, the higher the magnitude of electricity demand, the higher is the total maintenance cost.

Some studies in the future are proposed as follows. First, the computational time of an exact solver increases significantly as the instance grows in size. Therefore, an alternative solution is to propose a heuristic to obtain a nearly optimal solution. The uncertainty factor can also be included to further analyze the optimization results. Different objective functions can be considered to analyze the trade-off between those objectives.

REFERENCES

[1] H.-H. Yu, K.-H. Chang, H.-W. Hsu, and R. Cuckler, "A Monte Carlo simulation-based decision support system for reliability analysis of Taiwan's power system: Framework and empirical study," *Energy*, vol. 178, pp. 252–262, Jul. 2019.

[2] W. C. Xu. (2018). *The age of Natural gas is Coming! Analysis of Domestic and Foreign Natural gas Policy Development Trends*. Accessed: Apr. 7, 2022. [Online]. Available: https://magazine.twenergy.org.tw/Cont.aspx?CatID=&ContID=2961

[3] S. Han, H. Kim, S. Lee, and W. Kim, "Optimization of generator maintenance scheduling with consideration on the equivalent operation hours," *J. Electr. Eng. Technol.*, vol. 11, no. 2, pp. 338–346, Mar. 2016.

[4] M. Fattahi, M. Mahootchi, H. Mosadegh, and F. Fallahi, "A new approach for maintenance scheduling of generating units in electrical power systems based on their operational hours," *Comput. Oper. Res.*, vol. 50, pp. 61–79, Oct. 2014.

[5] A. Froger, M. Gendreau, J. E. Mendoza, É. Pinson, and L.-M. Rousseau, "Maintenance scheduling in the electricity industry: A literature review," *Eur. J. Oper. Res.*, vol. 251, no. 3, pp. 695–706, Jun. 2016.

[6] K. P. Dahal and N. Chakpitak, "Generator maintenance scheduling in power systems using metaheuristic-based hybrid approaches," *Electr. Power Syst. Res.*, vol. 77, no. 7, pp. 771–779, May 2007.

[7] E. Reihani, M. Najjar, M. Davodi, and R. Norouzizadeh, "Reliability based generator maintenance scheduling using hybrid evolutionary approach," in *Proc. IEEE Int. Energy Conf.*, Dec. 2010, pp. 847–852.

[8] K. Suresh and N. Kumarappan, "Hybrid improved binary particle swarm optimization approach for generation maintenance scheduling problem," *Swarm Evol. Comput.*, vol. 9, pp. 69–89, Apr. 2013.

[9] F. Brandt, R. Bauer, M. Völker, and A. Cardeneo, "A constraint programming-based approach to a large-scale energy management problem with varied constraints," *J. Scheduling*, vol. 16, no. 6, pp. 629–648, Dec. 2013.

[10] A. Rozenknop, R. W. Calvo, L. Alfandari, D. Chemla, and L. Létocart, "Solving the electricity production planning problem by a column generation based heuristic," *J. Scheduling*, vol. 16, no. 6, pp. 585–604, Dec. 2013.

[11] M. Y. El-Sharkh, "Clonal selection algorithm for power generators maintenance scheduling," *Int. J. Electr. Power Energy Syst.*, vol. 57, pp. 73–78, May 2014.

[12] B. G. Lindner, R. Brits, J. H. van Vuuren, and J. Bekker, "Tradeoffs between levelling the reserve margin and minimising production cost in generator maintenance scheduling for regulated power systems," *Int. J. Electr. Power Energy Syst.*, vol. 101, pp. 458–471, Oct. 2018.

[13] M. Abirami, S. Ganesan, S. Subramanian, and R. Anandhakumar, "Source and transmission line maintenance outage scheduling in a power system using teaching learning based optimization algorithm," *Appl. Soft Comput.*, vol. 21, pp. 72–83, Aug. 2014.

[14] Y. Zhao, V. Volovoi, M. Waters, and D. Mavris, "A sequential approach for gas turbine power plant preventative maintenance scheduling," *J. Eng. Gas Turbines Power*, vol. 128, no. 4, pp. 796–805, 2005, doi: 10.1115/1.2179470.

[15] J. Eygelaar, D. P. Lötter, and J. H. van Vuuren, "Generator maintenance scheduling based on the risk of power generating unit failure," *Int. J. Electr. Power Energy Syst.*, vol. 95, pp. 83–95, Feb. 2018.

[16] A. Chakrabarti and S. Halder, *Power System Analysis: Operation and Control*, 3rd ed. New Delhi, India: PHI Learning, 2010.

[17] A. Y. Abdelaziz, E. S. Ali, and S. M. A. Elazim, "Implementation of flower pollination algorithm for solving economic load dispatch and combined economic emission dispatch problems in power systems," *Energy*, vol. 101, pp. 506–518, Apr. 2016.

[18] M. Yildirim, X. A. Sun, and N. Z. Gebraeel, "Sensor-driven condition-based generator maintenance scheduling—Part I: Maintenance problem," *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4253–4262, Nov. 2016.

[19] S. Perez-Canto and J. C. Rubio-Romero, "A model for the preventive maintenance scheduling of power plants including wind farms," *Rel. Eng. Syst. Saf.*, vol. 119, pp. 67–75, Nov. 2013.

[20] L. Dai, M. Stålhane, and I. B. Utne, "Routing and scheduling of maintenance fleet for offshore wind farms," *Wind Eng.*, vol. 39, no. 1, pp. 15–30, Feb. 2015.

[21] J. Feng, X. Jia, F. Zhu, Q. Yang, Y. Pan, and J. Lee, "An intelligent system for offshore wind farm maintenance scheduling optimization considering turbine production loss," *J. Intell. Fuzzy Syst.*, vol. 37, no. 5, pp. 6911–6923, Nov. 2019.

[22] W. K. Foong, A. R. Simpson, H. R. Maier, and S. Stolp, "Ant colony optimization for power plant maintenance scheduling optimization—A five-station hydropower system," *Ann. Oper. Res.*, vol. 159, no. 1, pp. 433–450, Mar. 2008.

[23] Y. Wang, C. Shao, P. Sun, X. Wang, X. Wang, and D. Li, "Generator maintenance schedule considering characteristics of multi-type renewable energy," in *Proc. Int. Conf. Power Syst. Technol. (POWERCON)*, Nov. 2018, pp. 4050–4055.

[24] E. Shayesteh, J. Yu, and P. Hilber, "Maintenance optimization of power systems with renewable energy sources integrated," *Energy*, vol. 149, pp. 577–586, Apr. 2018.

[25] S. R. Salkuti, "Day-ahead thermal and renewable power generation scheduling considering uncertainty," *Renew. Energy*, vol. 131, pp. 956–965, Feb. 2019.

[26] J. Yellen, T. M. Al-Khamis, S. Vemuri, and L. Lemonidis, "A decomposition approach to unit maintenance scheduling," *IEEE Trans. Power Syst.*, vol. 7, no. 2, pp. 726–733, May 1992.

[27] R. Lusby, L. F. Müller, and B. Petersen, "A solution approach based on benders decomposition for the preventive maintenance scheduling problem of a stochastic large-scale energy system," *J. Scheduling*, vol. 16, no. 6, pp. 605–628, Dec. 2013.

[28] S. Lakshminarayanan and D. Kaur, "Optimal maintenance scheduling of generator units using discrete integer cuckoo search optimization algorithm," *Swarm Evol. Comput.*, vol. 42, pp. 89–98, Oct. 2018.

[29] N. Dupin and E.-G. Talbi, "Matheuristics to optimize refueling and maintenance planning of nuclear power plants," *J. Heuristics*, vol. 27, nos. 1–2, pp. 63–105, Apr. 2021.

[30] G. Balaji, R. Balamurugan, and L. Lakshminarasimman, "Mathematical approach assisted differential evolution for generator maintenance scheduling," *Int. J. Electr. Power Energy Syst.*, vol. 82, pp. 508–518, Nov. 2016.

[31] D. Anghinolfi, L. M. Gambardella, R. Montemanni, C. Nattero, M. Paolucci, and N. E. Toklu, "A matheuristic algorithm for a large-scale energy management problem," in *Proc. Int. Conf. Large-Scale Sci. Comput.* Sozopol, Bulgaria: Springer, 2011, pp. 173–181.

[32] G. G. Samuel and C. C. A. Rajan, "Hybrid: Particle swarm optimization–genetic algorithm particle swarm optimization–shuffled frog leaping algorithm for long-term generator maintenance scheduling," *Int. J. Electr. Power Energy Syst.*, vol. 65, pp. 432–442, Feb. 2015.

[33] S. P. Canto, "Application of benders' decomposition to power plant preventive maintenance scheduling," *Eur. J. Oper. Res.*, vol. 184, no. 2, pp. 759–777, 2008.

VINCENT F. YU received the Ph.D. degree in industrial & operations engineering from the University of Michigan, Ann Arbor. He is currently a Professor of Industrial Management at the National Taiwan University of Science and Technology. He had published articles in *Applied Mathematical Modeling*, *Applied Soft Computing*, *Computers & Industrial Engineering*, *Computers & Operations Research*, *European Journal of Operational Research*, *Industrial Marketing Management*, *International Journal of Production Research*, *Journal of Cleaner Production*, *Journal of Intelligent Manufacturing*, *Omega*, *Renewable and Sustainable Energy Reviews*, and *Transportation Research—Part E: Logistics and Transportation Review*. His current research interests include operations research, logistics management, soft computing, energy system optimization, and artificial intelligence.

YUEH-SHENG LIN received the M.B.A. degree from the Institute of Business and Management, National Chiao Tung University, Taiwan. He is currently pursuing the Ph.D. degree in industrial management with the National Taiwan University of Science and Technology, Taiwan. His current research interests include generator maintenance scheduling, power demand forecast, and industrial safety and health management.

PANCA JODIAWAN received the Ph.D. degree in industrial management from the National Taiwan University of Science and Technology, Taiwan. He has published articles in *Applied Soft Computing*, *Computers and Operations Research*, IEEE Access, and *Transportation Research—Part E: Logistics and Transportation Review*. His current research interests include logistics management and metaheuristics.

MENG-DUO HE received the M.B.A. degree in industrial management from the National Taiwan University of Science and Technology, Taiwan. His research interests include vehicle routing problem and scheduling problem.

SHIH-WEI LIN received the bachelor's, master's, and Ph.D. degrees in industrial management from the National Taiwan University of Science and Technology, Taiwan, in 1996, 1998, and 2000, respectively. He is currently a Professor with the Department of Information Management, Chang Gung University, Taiwan. He is also with the Department of Emergency Medicine, Keelung Chang Gung Memorial Hospital, Keelung City, Taiwan, and the Department of Industrial Engineering and Management, Ming Chi University of Technology, Taipei, Taiwan. His current research interests include meta-heuristics and data mining. His papers have appeared in *Computers & Operations Research*, *European Journal of Operational Research*, *Journal of the Operational Research Society*, *European Journal of Industrial Engineering*, *International Journal of Production Research*, *International Journal of Advanced Manufacturing Technology*, *Knowledge and Information Systems*, *Applied Soft Computing*, *Applied Intelligence*, and *Expert Systems with Applications*.