Generator Maintenance Scheduling Models for Electrical Power Systems: A Review

Shatha Abdulhadi Muthana[1] and Ku Ruhana Ku-Mahamud[2]
[1] General Company of South Electricity Distribution, Ministry of Electricity, Iraq
[2] School of Computing, Universiti Utara Malaysia, Malaysia
Email: shatha_muthana@yahoo.com; ruhana@uum.edu.my

Abstract—**Interest in generator maintenance scheduling (GMS) has increased due to the advent of demand-related expansion in size for modern power systems. Timely maintenance plays a significant role in minimizing failures and helps in averting cost incurred as a result of production shutdowns. The GMS problem is a complex and nonlinear optimization problem that specifies the schedule for carrying out planned preventive maintenance on power generation units. There is no clear concept to GMS model types and choosing the appropriate maintenance scheduling type. Thus, this paper presented a comprehensive review on GMS models in electrical power systems that covers the maintenance strategies, main elements of GMS models, and optimization methods used in solving GMS models. The list of references comprised related works from the years 2000 until 2020, which were classified into three based on the objectives. A new type of objective function for the GMS models was among the suggestions provided. A numerical example which focuses on a multi-objective GMS model and a proposed multi-objective Pareto ant colony system algorithm are also presented. The results of this review will not only enable researchers to gain a good overview of the existing GMS models for electrical power systems but also provide a source of references in choosing an appropriate maintenance scheduling strategy that is suitable with the type of generating unit and existing operating conditions.**

Index Terms—**Electrical power system, optimization, scheduling, generator, multi-objectives**

I. Introduction

Estimating energy demand is very important to both developing and developed countries for economic and resource planning purposes [1]. The major activities that are being emphasized in the electricity industry are production, transmission, and distribution [2]–[4]. There are two types of systems in the electricity industry, namely regulated (centralized) and deregulated (restructured) power systems. The traditional system is the regulated power system where there is a central control structure that fully regulates three activities (production, transmission, and distribution) and a single operator that monopolizes the whole power system. This operator is responsible to solve all the system's problems including maintenance scheduling problem [2]–[4]. The regulated power system focuses on reliability and costs [3], [4].

Toward the end of 1990s, many places have converted to deregulated power systems where monopolies were replaced due to competitive power systems [2]–[5]. Numerous countries have privatized their electricity industries where they dismantled the integrated energy system into three major sectors: generation, transmission, and distribution companies. In addition, with the deregulated system, other actors exist where their responsibilities are usually minor, like retail energy service companies. These minor companies act as a mediator between generation companies and consumers by selling energy bought from the former to the latter [3], [4]. There is also another part in the deregulated system known as an independent system operator. The role of this operator lies on operating the power system and running the interactions between the generation, transmission, and distribution companies [2]–[4]. North America countries, New Zealand, Australia, England, several South America countries, and the Scandinavian region turned to privatization of their electricity industries by adopting deregulated power systems [4]. Countries such as South Africa are still using regulated power systems, which are controlled only by a semi-governmental electricity company [4]. The focus of the deregulated power system is maximizing the profits of generation companies.

Generally, there are two major maintenance categories known as corrective (unplanned) and preventive (planned) [4], [6]–[8]. A corrective maintenance strategy is performed following the breakdown or failure of a system. This may lead to production loss and maintenance costs as a result of abrupt failure. Preventive maintenance is better since it is performed before the equipment fails [3], [4], [6], [7]. Preventive maintenance can be classified as either periodic or sequential [7]. Periodic preventive maintenance is executed at given integer multiples by constant time intervals. Sequential preventive maintenance, on the other hand, is executed at unequal time intervals. The first strategy of preventive maintenance (periodic) is considered more convenient for the scheduling process. The second strategy (sequential) is more appropriate when the system needs frequent

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Corresponding author: Shatha Abdulhadi Muthana (email: shatha_muthana@yahoo.com).

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maintenance as the generator's age increases. Generally, a preventive maintenance strategy in the electricity industry can be performed either through the experience of workers or through the recommendations of the original equipment manufacturer (OEM) [6], [9].

The efficiency of generating units after maintenance can be classified into five categories: perfect, minimal, imperfect, worse, and worst. The condition of the system will be good as new if perfect maintenance is performed. The system will be in operating status but has the same intensity of failure if minimal maintenance is performed. The status of imperfect maintenance is more realistic in terms of geometrical application and it will not restore the system's condition to good or bad. The status of worse maintenance reflects the negative state of maintenance, which makes the system even worse after the repair, but it will not break down. Finally, the worst maintenance category leads the system to one of the two cases: failure or breakdown [7].

The aim of this study is to analyze previous works on generator maintenance scheduling (GMS) models. Section II describes the main elements in GMS models. The explanation on optimization methods used to solve GMS problems are presented in Section III, while Section IV discusses the types of GMS models and the limitations of each model. Section V includes suggestions for future works in solving multi-objective GMS models. A numerical example to solve multi-objective GMS model is presented in Section VI. Finally, the conclusion in Section VII summarizes the review on GMS models for electrical power systems.

II. Main Elements in GMS Model

The elements to consider in developing any GMS model are decision variables, parameters, constraints, and objective functions. Binary resolution variables (0, 1) are used to represent the generating unit maintenance that takes place during each set of time period over a fixed planning horizon [10], [11]. Decision variables can be used to represent different situations when required and show the online status of generating units in a specific period and time [11]. The typical parameters used as input data required to solve GMS problems are: unit number, installed capacity, duration of maintenance interruption for each generation unit, earliest and latest outages for maintenance window, resources required for each unit to be served, and predicted energy demand [4], [10]. To determine the maintenance schedule activities, these parameters have to be estimated in advance [4], [10]. The major constraints in developing a GMS model are as illustrated in Fig. 1.

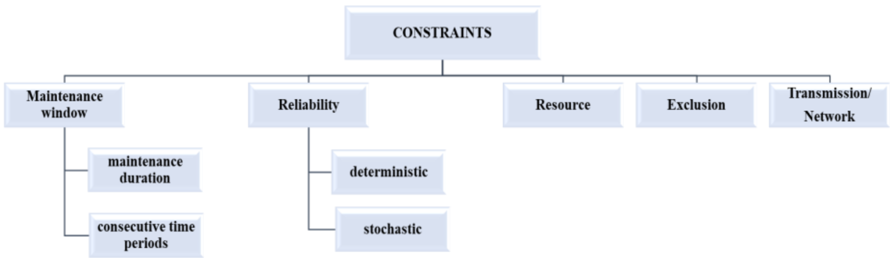

Fig. 1. Constraints of GMS model.

Maintenance window constraint, which consists of maintenance duration and consecutive time period, ascertains that a generator is maintained during a predefined time window, which is served between earlier and newer time periods [4], [10], [12]. Maintenance duration ensures that each generator unit is kept for a predetermined period [4], [10], while consecutive time period constraint warrants that each generating unit is serviced over uninterrupted periods of time [4], [10].

Reliability constraint can be specified as either deterministic or stochastic [4]. In the case of deterministic reliability, the GMS model is generally named demand constraint or reserve margin (or load constraint) and gross reserve [4], [10], [11]. This constraint is commonly imposed to assure that the obtained capacity will be sufficient to meet the demand for electricity (usually in addition to a specific safety margin). Incorporation of deterministic reliability constraints may be made via determination of a reserve/safety margin higher than the anticipated peak demand. Meanwhile, in most instances, only the probabilities of demand and enforced outage are regarded as stochastic reliability constraints under the stochastic models [4]. To minimize the risk of enforced outage, some measures of stochastic risk are enforced, such as the specification of minimum loss of load probability and an expected unserved energy [10], [13].

Resource constraint focuses on crew/manpower, which ensures that resources available for maintenance are not surpassed at any period [4], [10], [12]. Exclusion constraint guarantees that certain generating units must not be removed from service simultaneously (e.g., two or more generating units for the same power plant or geographic region) [4], [10], [12]. Finally, transmission/network constraint ensures the capabilities of electrical network transmission (e.g., voltage level maintenance) or ensures the demands of the geographic regions are met by a power station within its service area through transmission network infrastructures [4], [10].

Constraints can be categorized as either hard and/or soft constraints as depicted in Table I. Hard constraints are the constraints that must not be violated, while soft constraints need to be more or less satisfying [4], [14]. The hard and soft constraints specified by decision makers may vary depending on the power utility's operations [4]. Solutions produced during the search process usually fulfill the hard constraints [4], [14]. Several constraints (maintenance window, maintenance duration, and load demand) are sometimes considered as hard and sometimes as soft in some studies. The decision maker will decide whether the constraint is hard or soft as there is no fixed classification for these constraints.

TABLE I: HARD AND SOFT CONSTRAINT

Constraint	Hard	Soft	Study
Maintenance window	√	-	[10], [15]
	-	√	[14]
Maintenance duration	√	-	[10], [15]
	-	√	[14]
Consecutive time period	√	-	[10], [15]
System reserve	√	-	[11]
Load demand	√	-	[16], [17]
	-	√	[10]
Expected energy not served	√	-	[14]
Manpower	-	√	[10], [16], [17]
Exclusion	-	√	[10]

The maintenance window and reliability constraints are regarded as hard constraints because any violation of these constraints will have an effect on the quality of maintenance scheduling. However, exclusion constraints are used when it is not permitted to remove certain generating units from the service at one time. This constraint in some emergency situations has to be violated. Therefore, it can be considered as a soft constraint. In addition, crew/manpower is deemed as a soft constraint in order to provide the capabilities required for an effective maintenance schedule. A penalty has to be added for the purpose of reducing the degree of violations in soft constraints [10], [18].

The objective functions that are commonly used in developing GMS models are reliability, cost, and convenience [4], [13]. Some studies utilized profit as the main objective function [19], [20]. In addition, environmental criteria, which can be used to reduce emissions and cost resulting from those emissions, have recently received attention when solving GMS problems [21]–[23]. The GMS model's objective functions are illustrated in Fig. 2.

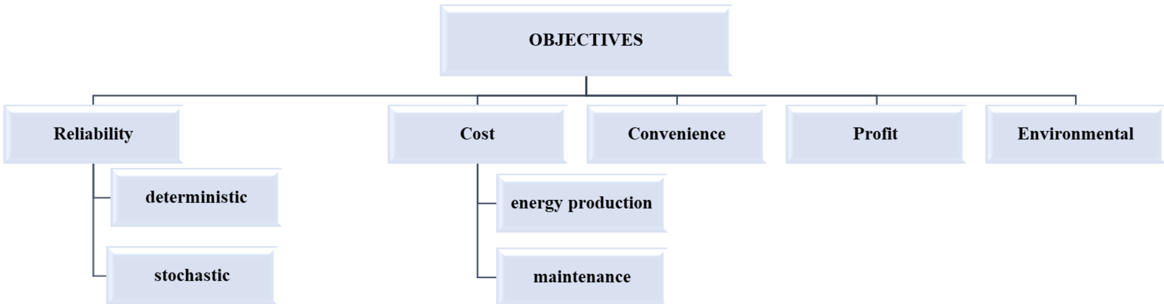

Fig. 2. GMS model objectives.

Relative to the model being used, reliability can fall under the terms of either deterministic or stochastic [4], [24]. The most common measures for reliability in terms of deterministic objectives can be either through satisfying the level of the obtained power or leveling the reserve margin. Minimizing the sum of squared reserves is the common formulation used for the objective of leveling the reserve margin [10], [18]. This will result in an even (more "reliable") band of net reserve margins [4]. The deterministic reliability models are mostly easier to implement and require minimum time consumption to resolve. However, they lead to minimal realistic models as compared to the stochastic models [4]. Thus, the deterministic model has a main drawback relating to the fact that the randomness of the existing capacity of generating units has been neglected [14]. The randomness of generating available capacity refers to stochastic reliability, which reflects the actual risk associated with the expected energy loss resulting from an inadequate power supply [13]. Minimizing the risk of forced outage is the goal of stochastic models. This can be achieved by using measures of stochastic risk such as minimum loss of load probability and expected unserved energy for minimizing the risk [4], [13], [14], [25].

Typically, optimal solutions are acceptable under either one of the two types of reliability criterion: deterministic or stochastic (although not necessarily ideal) [4]. However, the reliability constraint in terms of deterministic and stochastic has different meanings for different purposes. Therefore, both are required for consideration to fulfill the requirements of the reliability objective.

In general, cost objective can be achieved by considering energy production cost or maintenance cost. Production cost includes generator start-up and shutdown, salaries and wages as well as fuel cost. Maintenance cost includes parts replacement costs, salaries, and wages associated with maintenance [4], [13]. Various cost objectives have been adopted in GMS models. However, the objective associated with reduction in the overall operating cost of generator maintenance schedule is the most universally used. The generating unit maintenance cost and energy production cost are included under operating cost [11], [17]. Comparatively, some of the studies contained the cost of transmission line maintenance as a side of production and maintenance costs [13] as can be seen in [26]. In a typical regulated system, the aim is to minimize the total cost, which mostly focuses on production and maintenance costs [3], [4], [11].

The convenience scheduling criterion is rarely used as the main objective and is frequently incorporated into multi-objective GMS models [13] where it is difficult to satisfactorily fulfill all the constraints. Thus, it is complicated to solve such problems within a limited computing time [4].

Maximizing the profit is the most important objective of individual generation companies in the present electricity market [19]. The profit calculation can be evaluated as the difference between the expected generation companies' revenues and expenses [19], [20].

For the environmental objective, earlier studies have treated emissions as either part of the objective function or as an additional constraint [27], [28]. Emissions that cause environmental pollution can include SO_2, NO_x, and CO_2, which are caused by fossil fuels [22], [23], [27]. The advantages concerning environmental function comprise the reduction in emission pollution issued from power generating systems and the reduction of cost caused by emission pollution. The strategies to reduce emissions include: i) using fuel with low emission potential; ii) post-combustion cleaning system installation; iii) dispatching of generation to each generator unit; iv) installation of pollution removal devices; v) replacement of old devices with new ones; and vi) operation of power plants by considering environmental pollutants [22]. Table II displays the objective function components expressed in solving GMS problems.

TABLE II: GMS OBJECTIVE FUNCTIONS

Study	Reliability	Cost	Profit	Convenience	Environmental
[21]	√	√	-	-	√
[22]	-	√	-	-	√
[23]	√	√	-	-	√
[14]	-	√	-	-	-
[29]	√	√	-	-	-
[30]	√	√	-	√	-
[31]	√	√	-	√	-
[10]	√	√	-	√	-
[19]	-	-	√	-	-
[20]	-	-	√	-	-
[32]	√	√	√	-	-

It can be observed from Table II that the two most widely considered objective functions are reliability and cost. These objective functions are important in regulated and deregulated power systems, whilst the profit objective function is used in deregulated power systems. Environmental criteria have a direct effect on the cost objective function, whereby in reducing environmental pollution, the cost can be reduced for GMS. The convenience objective function is used to overcome the difficulties in fulfilling all the constraints. Penalty is utilized to limit the violation of constraints. Therefore, the convenience criterion is very seldom formulated as an objective function that needs to be achieved but it can be used to treat the constraint violations in conjunction with other objective functions.

III. OPTIMIZATION METHODS FOR GMS PROBLEM

Appropriate GMS model solution techniques are expected to obtain either good or optimal solutions to practically-sized model instances in an acceptable computational time [13]. Although GMS models have been traditionally formulated as single optimization problems that mostly integrate the dominant scheduling criterion in the objective function, other criteria have been included by some authors as constraints [4].

In general, single objective optimization methods are used to solve single objective problems, and these methods can be used with single and hybrid objective GMS models. Mathematical programming techniques (exact algorithms) are usually deployed in solving single objective instances related to the GMS problem [4]. An exact algorithm includes, but is not limited to, branch and bound, integer programming, mixed integer linear programming, decomposition approach, and dynamic programming.

There have been preferences between solutions that are obtained through mathematical programming techniques over those obtained via other techniques (such as metaheuristics). The former gives more guarantee in producing optimal solutions [4], [13]. However, one issue identified among mathematical programming techniques is the long duration that the implementation processes take, especially in instances of realistically-sized GMS problems [4], [13], [29]. Moreover, in problems associated with multiple scheduling criteria, mathematical programming techniques are found to be difficult to apply (i.e., for objectives that are multiply-conflicting) [4].

It was reported recently that metaheuristic techniques have been applied in solving instances of GMS problems that are very close to optimality in an acceptable computational time [4], [33]. Some of the common types of metaheuristic techniques used in solving instances of the GMS problem are ant colony optimization, tabu search, genetic algorithm, simulated annealing, particle swarm optimization, and differential evolution algorithms [4], [13].

Hybridization can be achieved among many forms of algorithms including heuristic and metaheuristic algorithms [34]. Therefore, several approaches use a hybrid metaheuristic for maintenance scheduling, such as hybrid simulated annealing and ant colony optimization algorithms, and hybrid particle swarm optimization by adding a mutation operator of genetic algorithm [35], [36].

Multi-objective optimization methods that are used to solve multi-objective problems can be non-pareto and pareto-based techniques [37]–[39]. Such algorithms are multiple ant colony system for vehicle routing problem with time windows algorithm [40], vector optimized evolutionary strategy, vector evaluated genetic algorithm, weight-based genetic algorithm [37], pareto-based ant colony optimization algorithm [41]–[43], strength pareto evolutionary algorithm, multi-objective genetic algorithm, non-dominated sorting genetic algorithm, non-dominated sorting genetic algorithm-II [37], dominance-based multi-objective simulated annealing algorithm [10], and multi-objective differential evolution algorithm [29]. In the GMS domain, several of the single objective optimization methods that are used in solving single and hybrid objective GMS models are [14], [18], [49], [19], [20], [35], [44]–[48]. In addition, some of the algorithms used in solving multi-objective GMS models are [10], [29], [31], [50]–[52].

IV. GMS MODEL CLASSIFICATION

In general, the most important objectives that attract the attention of many researchers in developing GMS models are reliability and cost especially in regulated power systems, and profit in deregulated power systems [3], [10]. In previous studies, the models are classified as single objective or multi-objective models. The single objective GMS model includes one single objective function that needs to be optimized, while the multi-objective GMS model includes more than one objective function that needs to be optimized.

From this review, the reliability and cost criteria fall under both the objective and constraint components. It is more practical to classify the models into three classes where single and multi-objective models will only include the criteria that fall under the objective component. The present study proposed a third class called the hybrid objective model to cater for criteria that fall under both objective and constraint GMS model components as depicted in Table III. In the hybrid objective model, the main criteria (i.e., reliability, cost, and profit) can be expressed by objective and constraint components that will be optimized by a single objective optimization method.

Table III displays a comparison between GMS models. The deterministic and stochastic reliability components are represented by "D" and "S", respectively. The reliability constraint and reliability objective function in terms of deterministic are to ensure that the available capacity will be enough in satisfying the electricity demand. In contrast, the reliability constraint and reliability objective function in terms of stochastic are to minimize the risk of enforced outage. Moreover, it can also be observed from Table III that cost criterion is expressed by cost objective function and cost constraint. However, the goal from both of them is to limit the cost and minimize it. The purpose of using reliability or cost as a constraint or using it as an objective function is to satisfy the required criteria. Nevertheless, the objective functions provide the real best value that needs to be maximized or minimized. In addition, the result from optimizing multi-objective functions is a set of optimal solutions instead of one solution. This will allow the decision maker to make a trade-off between objectives and to obtain the best compromise solution among them, which allows the change in the direction of the solution if required in the future. Therefore, explanation on the criteria by the objective functions will be more flexible and strong solutions can meet the difficult requirements in electrical power systems.

TABLE III: COMPARISON BETWEEN GMS MODELS

GMS model	Objective				Constraint			Study
	Cost	Reliability		Profit	Cost	Reliability		
		D	S			D	S	
Single objective	-	√	-	-	-	-	-	[18], [35], [44]
Multi-objective	√	√	-	-	-	-	-	[10], [29], [50], [51], [53], [54]
	√	√	√	-	-	-	-	[30], [31]
Hybrid objective	√	-	-	-	-	√	-	[12], [45]–[47], [55], [56]
	√	-	-	-	-	-	√	[14]
	-	-	√	-	√	-	-	[48], [57]
	-	-	-	√	-	√	-	[19]
	-	-	-	√	-	√	√	[20]
	√	-	-	-	-	√	√	[49]

In Table III, the single objective models include the work on reliability as an objective function, which focuses on minimizing the sum of squares of the generation reserve, as explored in [18], [35], [44]. However, these single objective models remain insufficient to represent the actual GMS problem, especially for a real power system that includes several hard constraints [4], [58].

For the multi-objective GMS models, the studies in [10], [29], [50], [51], [53], [54] considered reliability in many aspects. The focus is to provide sufficient power supply. Cost minimization is considered through maintenance cost in [50], [51], [53], while production cost has been studied in [10]. The overall operational cost has been considered in [29], [54]. The works of [30], [31] proposed cost objective by minimizing the total operating cost, and reliability objective that is achieved in two terms, minimizing the sum of squares of reserve, and minimizing the loss of load expectation. The multi models considered several different objectives to provide a solution for GMS problems. Nevertheless, most of the strategies used in the practice of scheduling maintenance outages of generating units are modeled using fixed maintenance windows during possible outages of specific generators. The maintenance strategies used in the literature with multi-objective GMS models are periodic and might not be suitable for different types of generating units because it may be quite inefficient. Evidence for this is that numerous power systems' operators, specifically in North America, have replaced the previous strategies of using fixed maintenance windows with programs that are more flexible based on their requirements [11]. However, the main disadvantages of multi-objective models are more effort and computational time are required in solving them [59].

In the third type of GMS model, which is named hybrid objective GMS model, cost has been proposed as an objective function by considering the maintenance and generation costs. Furthermore, reliability is considered through different types of security constraints that ensure the provision of sufficient power supply [12], [45], [47], [55], [56]. An objective function to minimize the whole maintenance costs is proposed by [47]. Reliability is presented by the availability and reliability constraints. The cost objective function is explored in [14] by minimizing the expected energy production cost and presenting reliability by the stochastic constraints of unserved amount of electrical power. Minimization of the whole operating risk during the midterm horizon is considered as the objective function, which is presented by two portions: the individual operating risk and the system operating risk. Moreover, cost criterion is considered through a constraint of maximum prospective preventive maintenance cost limitation [48]. Reliability using the stochastic reliability objective functions of expected unserved energy and cost criteria is presented by the maintenance cost constraint [48]. On the other hand, [19], [20] suggested profit as an objective function that meet reliability through various kinds of reliability constraints such as the reserve capacity of the system and the load satisfying constraints. In addition, [20] considered reliability in terms of stochastic through forced outage constraint to reduce the damages in power plants. The cost objective function proposed by [49] includes generating and maintenance costs with peak regulation pressure penalty fee. Furthermore, [49] proposed reliability criteria that is presented by two constraints, i.e., deterministic and stochastic.

The hybrid objective models consider more than one criterion to provide a solution for the GMS problem. However, these criteria are aggregated to form a single objective function that works toward uncovering only one solution. Therefore, the resulting solution from these models is a single optimum solution that covers multiple criteria. The overall aim from multi-objective is to produce a number of optimum solutions that provide a good approximation to the trade-off surface [42]. As a result, securing a set of optimal solutions provides the decision maker with more comprehensive understanding of all the feasible solutions to make a satisfactory final plan for GMS as compared to one single optimal solution. The resulting solution from these hybrid models can satisfy multiple criteria with single objective and cannot make a trade-off between objectives to obtain the best compromise solution between them. Therefore, these hybrid models have limitations although it may provide a solution that requires less computational effort as compared to multi-objective models.

Fig. 3 shows the trend of published papers related to the three types of GMS models that focus on the most important three criteria (i.e., reliability, cost, profit) in regulated and deregulated power systems for the period from 2015 until 2020.

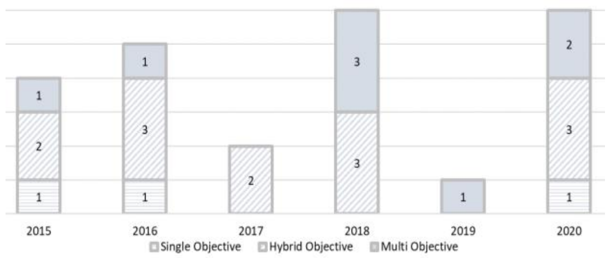

Fig. 3. Number of studies on GMS models (2015-2020)

A total of 24 studies have been published from 2015 until 2020 and slightly more that 50% of the studies are on hybrid objective models. There are also recent studies on multi-objective GMS models because both hybrid and multi-objectives models can cater for multiple criteria and each of them has its own advantage. Hybrid objective models require less computational effort while multi-objective models have the ability to cater to multiple criteria that can fulfill the requirement of a realistic power system.

V. Suggestions

Most of the studies are moving toward periodic maintenance scheduling although it is not compatible with all types of generating units. Nevertheless, the process of periodic maintenance scheduling is considered more convenient as compared to maintenance scheduling based on operational hour approach. Although maintenance scheduling that depends on the operational hours approach involves many complications, it can generally provide more efficient maintenance scheduling that can extend the lifetime of generating units and improve efficiency. Moreover, it is generally compatible with all types of generating units.

In addition to that, there is another important point that must be taken into consideration. The dependence on the number of operating hours to determine the maintenance outage of generating units is not enough. The maintenance outage of generating units that is based on the operational hours approach can be determined in two ways. The first one assumes that the system ages only when it is in operation. The second one defines age by the number of working hours and the number of times the unit has started operation since entering the service [60]. The inventors have discovered that generally, one engine start is equivalent to ten hours of operation in terms of the impact on the engine's life [61]. Thus, the maintenance outage of generating units has to be considered based on two factors, namely start time and operating hours, especially with gas turbine generating units. Although this may increase the possibility of maintenance costs because it will speed up the process of entering generating units to maintenance outage, it will in return increase the lifetime of generating units. Thus, it will avoid the many failures that may arise in the future.

Future studies should focus on multi-objective GMS problems because it represents a more realistic case. Although multi-objective problems require huge computational efforts, the solution for this type of problem increases or decreases according to the complexity of the problem. The multi-objective approach has a big advantage that can solve complex problems with more efficiency.

Other suggestions for future work are to improve the GMS model by incorporating risk or stochastic reliability measures in the formulation of a GMS model. Considera-tion can also be the combination of the transmission maintenance scheduling problem with the GMS problem. Furthermore, other constraints like resource constraints can be included with the task to assign a limit on the number of the available resources aimed of maintenance. These resources may include budgets' service and the spare parts' availability, in addition to the availability of manpower for maintenance work. Another suggestion to improve the solution for the GMS problem is to consider the transmission/network constraints which are related to the electrical network's transmission capabilities (e.g. maintaining voltage levels) or that a power station is able to satisfy the demands of the geographic regions within its service area through the infrastructure of the transmission network. Finally, work can also focus on the use of environmental objective function to improve the formulation of multi-objective GMS model.

VI. Comparison between Multi Objective Optimization Methods

A multi-objective GMS model based on [11] is proposed as a result of this review. The model in [11] is classified as a hybrid model, where hybrid term here refers to the situation when criteria are considered as objective and constraint. In the proposed model, three conflicting objectives are considered as opposed to [11] where only one objective is considered. The three conflicting objectives in the proposed model are the cost, reliability and convenience, while cost is the only objective in [11]. The first objective focuses on the minimization of the total operation cost which considers both energy production and maintenance as in [11]. The second objective is reliability which considers the system's gross reserve, and this is defined as the difference between the available capacity of system generators that are not on maintenance outage and the demand system [11]. Finally, the third objective is the convenience which focuses on minimization the violation of maintenance outage unit’s soft constraint. This constraint limits the number of units sent for maintenance outage in a specific period, which in this work is considered as a soft constraint.

The probability of sending units for maintenance outage is increased when its working hours’ time exceeded the upper endpoint of the maintenance window. For normal situation, a specific number which indicates the maximum number of units can be sent for maintenance. This constraint is considered as a soft constraint in this proposed model to make it more flexible in abnormal situation which reflects a more realistic situation. More units will be in operation to meet the higher demand and thus there is a possibility of more unit will have to be sent for maintenance when the units working hours are close to the upper endpoint of the maintenance window. The demand in abnormal situations can be satisfied when this constraint is considered as a soft constraint. Thus, the number of feasible solutions can be increased which resulted in more optimal solutions.

In addition, maintenance outage of generating units is determined in this proposed model based on the number of working hours (NUW) and the number of times (NUS) that the unit has started operation since entering the service. To optimize a solution for multi-objective GMS model, we proposed a Pareto ant colony system (PACS) algorithm to fit the three objectives. The PACS is an enhanced of the ant colony system algorithm in [11].

Table IV displays the comparison between the model in [11] and the proposed multi-objective model while Table V displays the comparison between the ant colony system algorithm in [11] and the proposed PACS algorithm.

The proposed probability (P_r) of units’ maintenance outage for the proposed PACS algorithm is given by:

$$P_r = \frac{\left(\left[C\tau^{c}_{\text{yes}}\right]+\left[R\tau^{r}_{\text{yes}}\right]+\left[V\tau^{v}_{\text{yes}}\right]\right)^{\alpha}\left[\eta_{\text{yes}}\right]^{\beta}}{\left(\left[C\tau^{c}_{\text{yes}}\right]+\left[R\tau^{r}_{\text{yes}}\right]+\left[V\tau^{v}_{\text{yes}}\right]\right)^{\alpha}\left[\eta_{\text{yes}}\right]^{\beta}+\left(\left[C\tau^{c}_{\text{no}}\right]+\left[R\tau^{r}_{\text{no}}\right]+\left[V\tau^{v}_{\text{no}}\right]\right)^{\alpha}\left[\eta_{\text{no}}\right]^{\beta}} \quad (1)$$

TABLE IV: COMPARISON BETWEEN THE PROPOSED GMS MODEL AND GMS MODEL [11]

GMS model	Criteria				Units’ maintenance outage	
	Reliability		Cost	Conv.	NUW	NUS
	Obj. function	Constr.	Obj. function	Obj. function		
Proposed multi obj.	√	√	√	√	√	√
[11]	-	√	√	-	√	-

TABLE V: COMPARISON BETWEEN THE PROPOSED PACS ALGORITHM AND ACS ALGORITHM [11]

Terms of comparison	Proposed PACS algorithm	[11]
Pheromone matrix	Three pheromone matrices for the part of *YES* & three pheromone matrices for the part of *NO*.	One pheromone matrix for the part of *YES* & one pheromone matrix for the part of *NO*
Weights	Include weights to regulate the relative objectives’ importance.	Not available

In (1) *C*, *R*, and *V* are the parameters that regulate the relative importance of each objective. The values for *C*, *R*, and *V* are randomly assigned within the range [0, 1) as in [62] and [63]. The summation of *C*, *R*, and *V* has to be equal to one. Based on PACS rules, in each period (i.e., week), the heuristic information is determined based on operational hours and start up time of each unit and the three pheromone values for cost, reliability, and convenience (violation) which are determined based on the value of cost, reliability and convenience objective functions. All these factors are needed to decide the maintenance outage for each unit. The parameters η and τ represent the heuristic and pheromone. The values of these parameters are used to guide in getting solution for optimal maintenance scheduling with low cost, high reliability and low violation.

The heuristic is for making decision either to enter or not to enter maintenance outage based on operation hours of the units. If a *YES*, then the unit should enter maintenance outage and this usually occurs when the operational hours of the unit exceeds the specified lower endpoint of maintenance window, which increases when it is close to the upper endpoint of maintenance window. On the contrary, the *No* indicates not to enter the maintenance outage usually that when the unit operational hours being far from the specified maintenance window. Similar to the heuristic, the pheromone parameter is used to make decision either to enter or not to enter the maintenance outage. However, the decision will depend on the objectives for cost, reliability and convenience as oppose to operational hours. In brief, the *YES* and *NO* parts of the heuristic and pheromone are related to the units inside maintenance and units outside maintenance respectively. The problems of GMS and unit commitment are solved simultaneously in [11] and also in this proposed model.

Experiment has been conducted to evaluate the performance of the proposed PACS algorithm in solving the multi-objective model. The benchmark dataset was obtained from [64] which consists of 32 units of generators as presented in Table A in the appendix. The demand of the 32-test system is based on benchmark demand systems [11], [64]. The metrics used to evaluate the performance of the PACS algorithm are cost, reliability and violation. Results of the PACS algorithm have been compared to four (4) other common algorithms which include the non-dominated sorting genetic algorithm (NSGA), strength pareto evolutionary algorithm (SPEA), multi-objective simulated annealing algorithm (MOSA) and multi-objective particle swarm optimization (MOPSO). These algorithms are also used in other similar studies as listed in Table VI.

TABLE VI: COMMON ALGORITHMS AND RELATED STUDY

Algorithms	Reference
NSGA	[41], [50], [51], [65]-[67]
SPEA	[41], [68]
MOSA	[10], [69]
MOPSO	[70]-[74]

The parameter settings for the experiments are displayed in Table VII. These are the commonly used parameters in GMS studies as indicated in the table. The obtained solutions are the results from ten runs, and the gray relational analysis method in [75], [76] was adopted to select the best solution from the Pareto front.

Table VIII, Table IX, and Table X show the comparison between the proposed PACS algorithm and other common multi-objective optimization algorithm used to solve the GMS problem where best results are highlighted. In general, it can observe that the cost decreases as the maintenance window for operational hours increases. The reliability (gross reserve) of the system increases as mentioned in [11], and the violation is reduced. The PACS algorithm is superior than other algorithms in terms of cost and reliability, but at par with MOSA for the violation metric.

TABLE VII: PARAMETER SETTING

Factor PACS [11]	Parameters' values	Factor NSGAII & SPEA2 [41]	Parameters' values	Factor MOSA [69]	Parameters' values	Factor MOPSO [70], [71], [74]	Parameters' values
No. of ants' groups	100	Population size	100	initial temperature	1,000,000	Swarm size	100
Global rate	0.1	Offspring population size	50	final temperature	0.01	Weight constant (w)	0.8
Local rate	0.005	Mutation probability	0.3	decreasing rate	0.98	Cognitive & social acceleration constants (c_1, c_2)	2
Initial pheromone	0.01	Crossover probability	0.8	-	-	-	
Pheromone power (α)	1	-	-	-	-	-	
Heuristic power (β)	0.005	-	-	-	-	-	
Exploration probability	0.1	-	-	-	-	-	
No. of iterations	100	No. of iterations	100	No. of iterations	100	No. of iterations	100

TABLE VIII: COMPARISON BASED ON COST WITH THREE MAINTENANCE WINDOWS

Maintenance window	PACS	NSGA	SPEA	MOSA	MOPSO
[1000-2000]	**205,146,072.03**	206,604,384.38	206,568,158.38	206,634,273.82	206,735,374.23
[2000-3000]	**185,775,386.64**	192,031,766.33	191,007,725.92	192,345,982.42	190,955,430.31
[3000-4000]	**179,335,380.59**	180,367,100.03	180,192,347.76	179,576,005.54	180,099,557.96

TABLE IX: COMPARISON BASED ON RELIABILITY WITH THREE MAINTENANCE WINDOWS

Maintenance window	PACS	NSGA	SPEA	MOSA	MOPSO
[1000-2000]	**1,431,412.00**	1,424,785.00	1,425,841.00	1,419,417.00	1,415,644.00
[2000-3000]	**1,464,603.00**	1,453,328.00	1,438,035.00	1,457,727.00	1,429,630.00
[3000-4000]	**1,458,503.00**	1,455,497.00	1,458,059.00	1,443,849.00	1,452,430.00

TABLE X: COMPARISON BASED ON VIOLATION WITH THREE MAINTENANCE WINDOWS

Maintenance window	PACS	NSGA	SPEA	MOSA	MOPSO
[1000-2000]	**12**	14	13	**12**	13
[2000-3000]	**0**	1	1	**0**	1
[3000-4000]	**0**	1	1	**0**	1

VII. Conclusion

This study concludes that any GMS model that caters for more than one objective (i.e., multiple criteria) cannot be a single model. In addition, if objectives are hybridized, the model cannot be considered as a multi model, because these hybrid models lead to uncovering only one solution. There are a number of limitations in developing the GMS models. For the single objective GMS model, it is almost impossible with several hard constraints to solve the GMS problem that represents a real power system. In contrast, for the hybrid objective GMS model, the produced solution is insufficient to fulfill the hard requirements of the company because the resulting solution takes only one direction, which will be insufficient to meet all the requirements of the company. Multi-objective GMS models consider different objective functions to provide a solution. However, most of the strategies that are used in the practice of scheduling maintenance outages of generating units are modeled using fixed maintenance windows and it would be inefficient with different types of generating units. Thus, GMS models should be developed based on the needs of generation companies and the maintenance strategy has to be appropriate with the generator type.

The numerical example provided in this paper has proven this finding of the multi-objective model. Future work in developing models for GMS problem can consider the points highlighted in the suggestion section of this paper.

Appendix A

Table A. Data for the Test System with 32 units

Units	C_u^{Fx}	C_u^p	C_u^M	$C_u^{\min}$	$C_u^{\max}$	C_u^{ini}	Up time	Down time	Ini_{hourS}
1	24.389	25.547	255,470	2.4	12	1000	1	1	-1
2	24.411	25.675	256,750	2.4	12	800	1	1	-1
3	24.638	25.803	258,030	2.4	12	1200	1	1	-1
4	24.761	25.932	259,320	2.4	12	1300	1	1	-1
5	24.888	26.061	260,610	2.4	12	2100	1	1	-1
6	118.908	37.964	379,640	4	20	100	1	1	-1
7	118.458	37.777	377,770	4	20	1900	1	1	-1
8	118.908	37.964	379,640	4	20	1900	1	1	-1
9	119.458	38.777	387,770	4	20	800	1	1	-1
10	81.826	13.507	135,070	15.2	76	540	3	2	3
11	81.136	13.327	133,270	15.2	76	800	3	2	3
12	81.298	13.354	133,540	15.2	76	3100	3	2	3
13	81.626	13.407	134,070	15.2	76	2300	3	2	3
14	217.895	18	180,000	25	100	200	4	2	5
15	219.775	18.6	186,000	25	100	1000	4	2	5
16	218.335	18.1	181,000	25	100	600	4	2	5
17	216.775	18.3	183,000	25	100	2200	4	2	-3
18	218.775	18.2	182,000	25	100	1800	4	2	-3
19	216.775	17.3	173,000	25	100	1400	4	2	-3
20	142.735	10.737	107,370	54.25	155	900	4	2	-3
21	143.029	10.715	107,150	54.25	155	1200	5	3	5
22	143.318	10.737	107,370	54.25	155	300	5	3	5
23	143.597	10.758	107,580	54.25	155	500	5	3	5
24	259.131	23	230,000	68.95	197	2000	5	4	-4
25	259.649	23.1	231,000	68.95	197	3450	5	4	-4
26	260.176	23.2	232,000	68.95	197	1000	5	4	-4
27	260.576	23.4	234,000	68.95	197	100	5	4	-4
28	261.176	23.5	235,000	68.95	197	540	5	4	-4
29	260.076	23.04	230,400	68.95	197	900	5	4	-4
30	176.057	10.842	108,420	140	350	700	8	5	10
31	310.002	7.492	74,920	100	400	500	8	5	10
32	311.91	7.503	75,030	100	400	1450	8	5	10

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The draft has been prepared by the 1st author while the review and editing has been performed by the 2nd author.

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Shatha Abdulhadi Muthana holds a bachelor degree from Shatt Al-Arab University College, Iraq in 2004 and master degree from Bharati Vidyapeeth University, India in 2014. She is currently a Ph.D. Student at the Universiti Utara Malaysia, Malaysia. All degrees are in computer science.

Ku Ruhana holds a bachelor in Mathematical Sciences and a master degree in Computing, both from Bradford University, United Kingdom in 1983 and 1986 respectively. Her Ph.D. in Computer Science was obtained from Universiti Pertanian Malaysia in 1994. As an academic, her research interests include ant colony optimization, pattern classification and vehicle routing problem.