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Maintenance Scheduling in the Electricity Industry: A Literature Review

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Abstract. The reliability of the power plants and transmission lines in the electricity industry is crucial for meeting demand. Consequently, timely maintenance plays a major role reducing breakdowns and avoiding expensive production shutdowns. By now, the literature contains a sound body of work focused on improving decision making in generation unit and transmission line maintenance scheduling. The purpose of this paper is to review literature. We update previous surveys and provide a more global view of the problem: we study both regulated and deregulated power systems and explore some important features such as network considerations, fuel management, and data uncertainty.

Keywords. Maintenance scheduling, optimization, regulated and deregulated power system.

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1 Introduction

The production of movement, heat, or light needs a common input: energy. Energy can be produced from fuel (e.g., oil, gasoline, uranium, gas, coal, wood) or natural forces (e.g., wind, water). The consumption of energy is growing with the development of countries and the increasing world population, and the production must meet this demand. Therefore, the reliability of power plants, and wind and solar farms is extremely important. In this context, equipment maintenance management is a major economic issue. Equipment maintenance management in electric power systems is concerned with decisions such as when to stop a generation unit for maintenance, when to re-start it again, and how much resources (e.g., technicians) are to be assigned to the maintenance of a given unit during a given period of time, just to cite a few examples. These decisions are taken under complex environments and constraints such as resource availability, demand satisfaction, and reliability thresholds.

One of the most successful contributions of operations research to improve decision making in equipment maintenance management is the application of optimization techniques to solve maintenance planning and scheduling problems. In the particular case of electric power systems, these problems range from simple technician-equipment assignments to complex problems considering interactions between different stakeholders and uncertainty in the problem parameters. In this paper, we build on the work of [22, 54, 59, 100] to update the state-of-the-art in the field and provide a global overview of the current stream of research in the field.

The paper is organized as follows. Section 1 presents a brief description of the energy industry, Section 2 reviews the literature on maintenance scheduling in *regulated* and *deregulated* environments, and Section 3 concludes the paper and outlines research perspectives.

2 Energy industry

The energy industry carries out three activities: production, transmission, and distribution. Traditionally the industry is organized in a centralized, vertically integrated way (see Figure. 1): a single company has a monopoly of the entire system in its area of operation. However, the government regulates the situation directly or indirectly: the entity must not take advantage of the end consumer. Therefore, the term *regulated monopoly utilities* is also used. With the deregulation of the electricity industry from the end of the 1990s, competition has been replacing monopolies in most places.

2.1 Deregulation of the power industry

The deregulation (or liberalization) of the power industry has opened up the electricity market to competition. Several companies can now produce or distribute energy; it is, however, more difficult to introduce competition for the transmission management. Energy prices are no longer regulated by the government (hence the terms deregulation and liberalization) but are subject to market interactions. Regulations remain (sometimes the term *restricted power system* is used) but monopolies are no longer acceptable. Given the success of this system in the aeronautics, gas, and telephone industries, this reform is promoted as a benefit for the sector. It is intended to favor innovation, to lower prices, and to lead to better service. This new system introduces challenges such as the organization of the electricity market, the price-setting mechanism, and the coordination of the various actors.

Indeed, the introduction of market players leads to the emergence of new actors or redefines the role or activities of existing actors. An independent system operator (ISO) is responsible for the reliability and security of the system. It dispatches all or part of the energy transcations and can decrease loads on the network to avoid congestion. The ISO is the leading entity in a power market, and it must be fair. It manages the interactions between three key entities: the generating companies (GENCOs), transmission companies (TRANSCOs), and distribution companies (DISCOs). When a single TRANSCO owns the entire transmission network, the ISO operates the transmission lines. The TRANSCO is then paid for the use of its lines and the maintenance of its network [90]. Retail energy service companies (RETAILCOs) act as intermediaries between GENCOs and consumers by buying energy from the former to sell to the latter. Other actors exist but their roles are relatively minor.

Many transactions can take place in this new market structure. Depending on the electricity-market model, GENCOs and RETAILCOs can negotiate bilateral contracts. The prices and quantities are negotiated independently of the ISO, but the availability of the transmission lines must be checked with the ISO to maintain security. Energy can also be traded through a balancing market. The power price is determined by the balance between supply and demand. In a pool-based electricity market, two kinds of bids are submitted to the ISO: producers' bids consist of energy blocks and their selling prices, and buyers' bids consist of energy blocks and their buying prices. With this information, the ISO calculates the market clearing prices at which energy is bought and sold. This energy market is referred to as the MinISO model when the ISO is primarily concerned with security. It is opposed to the MaxISO model (based on the UK-Poolco model) where market participants share extensive information (e.g., energy offer, start-up costs, generation costs, ramped rate for each generator) with the ISO, which is responsible for ensuring the social and economic welfare of the market while keeping the system safe. For a detailed explanation, see [94]. Moreover, a transmission market deals with the purchase and sale of transmission rights; see [90] for more details. Figure 2 summarizes the various interactions between the actors. It is however difficult to define a typical organization because several structures are possible.

Liberalization modifies and sometimes complicates power industry issues. GENCOs, TRANSCOs, and DISCOS mainly serve their own interests, which may call into question the stability of energy production and/or energy distribution. Regulations are therefore required.

After this brief presentation of the electricity industry, we discuss, in the next section, mainte-

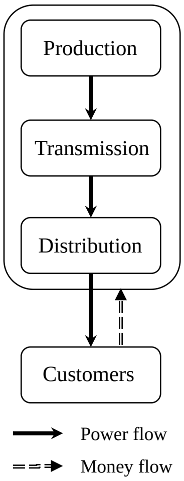


FIG. 1: Interactions in a vertically regulated utility

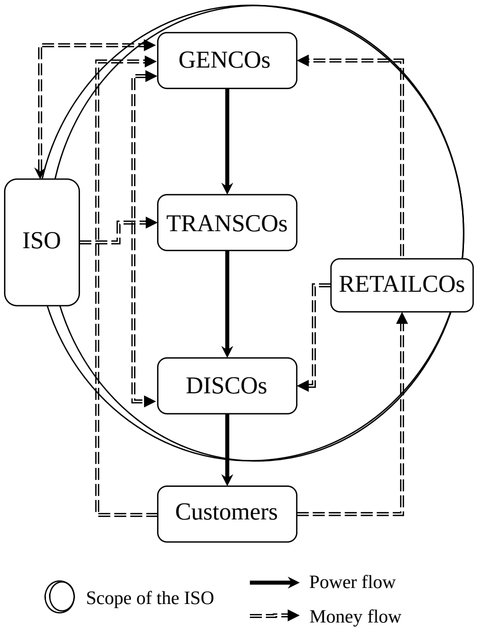


FIG. 2: Interactions between market players under deregulation

nance scheduling and present various approaches for the generation units and the transmission lines under both regulated and deregulated power systems. We focus on network constraints, on data uncertainty, and on fuel consumption and supply management.

3 Maintenance in the electricity industry

Maintenance represents the actions required to ensure that a product provides reliable service. Maintenance can be split into two categories: corrective and preventive. Corrective maintenance is performed after a breakdown. Preventive maintenance is performed at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure. Maintenance in the electricity industry concerns generation units and transmission lines; the horizon can be long-term or short-term. In this paper, we do not discuss failure prediction or maintenance policies that will manage the risks of equipment failure in the most effective way. We refer the reader to [28, 103] for literature dealing with those problems. We consider defining time intervals for preventive maintenance for the equipment, given financial and reliability considerations.

3.1 Maintenance scheduling of generating units

The maintenance scheduling of generation units has been widely studied [1–6,8–20,23–27,29–46, 48–53,55–58,61–64,66–71,73–79,81,84–87,91–93,95–99,101,102,104,105]. On its basic version, the maintenance scheduling problem consists in defining when to stop the generating units for preventive maintenance in order to maintain the system reliability and to reduce the general operational costs. We refer to it as the *generator maintenance scheduling (GMS) problem.* Additional constraints include, but are not limited to:

- maintenance tasks: maintenance window (possible time for maintenance), sequence, incompatibility, spacing, and overlapping of tasks.
- generation units: highest/lowest production levels, ramped rate[1].
- manpower: availability for each period, requirements by maintenance tasks.
- resources: availability for each period, requirements, consumption by maintenance tasks.
- network: transmission-line capacity (see Section 3.2), voltage.
- demand: fully satisfied or not, meeting of demand, energy-not-served (ENS) threshold.
- reliability: minimum reserve required by period, risk levels, ENS.

This optimization problem is generally NP-hard and may be nonlinear and nonconvex [42]. The power production is strongly impacted by maintenance decisions. To include load constraints, especially demand satisfaction, in GMS, it is necessary to simultaneously decide the production levels of the generating units and the maintenance scheduling. The solutions obtained can then be used as guidelines for *unit commitment (UC)* with a short time horizon. UC aims to schedule generating units level to meet forecasted load and reserve requirements.

In the next two sections we discuss GMS in regulated and deregulated power systems.

3.1.1 Regulated power systems

Monopolies still operate in some regions. In a vertically integrated utility, the maintenance is scheduled in a centralized way, and all the information is available (costs, network, etc.). The various studies can be classified according to objective function: reliability-based [6, 14, 19, 23–25, 29, 30, 38, 75, 76, 81, 87, 93, 95, 96, 101], cost-based [1–3, 6, 10–13, 15, 16, 26, 27, 29–32, 35, 37, 40–43, 45, 48, 50, 51, 53, 55, 57, 58, 61, 64, 67–69, 71, 73, 77, 79, 84–86, 91, 92, 102, 104], or both [50, 51, 58, 62, 78].

For reliability, the main criterion is the leveling of the net reserves on the horizon. For a given period t, the net reserves correspond to the maximal power that can be produced by the generators not in maintenance at t minus the estimated demand during t. One approach is to minimize the sum of squares of the net reserves by period [23–25,29,38,75,76,81,87,101]. [93,96] levelize the reserve rate by minimizing an objective function based on the deviation between the net reserve rate[2] and the average reserve rate (the average of the reserve rate for each period). [30] consider the deviation between the reserve by period and the average reserve on

[1] Output gap limitation between two successive periods for a generating unit

[2] Ratio of the net reserve to the sum of the generation capacity and the predicted maximum load

the horizon; [6] consider the square of this deviation. [19] maximize the reserve margin when isolated power systems are tackled, whereas they level the reserve margin for each area when a multi-area system is considered. [14] maximize the sum by period of the ratio of the net power reserves to the gross power reserves. Finally, [95] minimize the annual value of the loss of load expectation (LOLE).

Only two studies [29,93] schedule the power production. Ramped-rate constraints are considered for the generating units in [29]. Other studies ensure for each period that the generating capacities that are not in maintenance are sufficient to cover the demand plus sometimes a reserve constraint.

When the optimization is based on reliability, metaheuristics are often used: ant colony optimization [38], tabu search [30], genetic algorithms [6, 23–25, 75, 76, 81, 93, 95, 96], simulated annealing [24, 25, 75, 76, 87], and particle swarm optimization [29, 93, 101]. [23] use a fuzzy-logic objective function. [14] introduce geographical, seasonal, and coordination constraints for a problem with wind farm turbines and thermal and hydroelectric power plants. The problem is modeled as a mixed integer program (MIP) and is solved with a commercial solver. Many studies [24,25,35,75,76,81,87,93,101] are metaheuristic-based hybrid approaches ; they combine constructive and local-search metaheuristics. [93] use particle swarm optimization together with a genetic algorithm to diversify the solutions obtained. Simulated annealing is combined with a genetic algorithm in [24, 25, 75, 76]. This approach was improved in [25] by the addition of a heuristic for seeding the initial population pool. A fuzzy reliability evaluation is introduced in [75]. Finally, [81] use a genetic algorithm combined with a local search derived from extremal optimization and from another genetic algorithm.

The other common objective is to minimize the general operational costs. These are production costs (e.g., fuel consumption), maintenance costs (e.g., loss of profit), and sometimes unit start-up costs [13]. In [37], the units have to be maintained as promptly as possible to reduce the expenses related to damaged machines. The production costs depend on the generators' power output, so it is necessary to schedule their production level [1–3,10,11,13,16,27,29,31,32,35,40,42,43,45,48,53,55,61,64,67–69,71,77–79,84–86,91–93,104]. An economic dispatch problem is usually solved with an objective of satisfying the demand at a minimum cost. The units with the lowest marginal costs are used to meet the system requirements; the other units produce only during the peak periods.

Until the 1990s, dynamic programming (DP) was often used for GMS because of its sequential decision process, but the "curse of dimensionality" limits the application of this method [100]. Many metaheuristics have been used: tabu search [12, 30, 104], genetic algorithms [6, 12, 61], simulated annealing [12, 35, 61, 85, 86], ant colony optimization [35, 37, 73, 79], and particle swarm optimization [29]. [27] propose a novel method to solve GMS; it consists of a parallel cooperating cultural algorithm associated with a guided local search. El-Sharkh et al. present a fuzzy-logic evaluation in an evolutionary framework [32] and a clonal selection algorithm [31]. Among the hybrid approaches, a genetic algorithm is combined with tabu search in

[12] and simulated annealing in [61]. [73] improve an ant colony optimization by using fuzzy control rules. [41] iteratively apply constraint programming to solve a cost-bound problem; learning constraints are added to improve the efficiency of the algorithm. [47] solve a problem where network constraints are taken into account using a constraint logic programming model integrating a local search. [15] present a heuristic exchange procedure and a method based on Lagrangian relaxation; these methods are compared with a tabu search procedure. A method combining linear programming and a rule-based heuristic is used by [16] for a practical GMS where network and coal-supply constraints are considered. [26] model GMS with gas network constraints as an MIP. [57] consider production loss in wind farms and introduce the assignment of a skilled workforce. The problem is modeled and solved as an MIP. Mollahassani-pour et al. [77] include a cost reduction index in a new mixed integer linear programming formulation of GMS. [35] design two algorithms based on ant colony optimization and simulated annealing for scheduling the maintenance of generating units based on their operational hours.

Many studies have used Benders decomposition because of the problem's intrinsic two-stage structure [2, 13, 42, 67–69, 91, 92, 102]. This approach decouples the problem into a master problem and several independent subproblems. The master problem works with only a subset of the constraints (e.g., maintenance tasks, resources). Infeasibility cuts are generated in the master problem to ensure that the subproblem constraints (e.g., demand, network) are satisfied. Optimality cuts are also introduced to make the algorithm converge. The resulting algorithm iteratively solves the master problem and the subproblems until it converges or concludes that there is no solution. For more details, see the original paper [7]. One of the studies using this approach is [71]; they coordinate long-term and short-term decisions. They also propose a deterministic [67] and a probabilistic [69] approach to jointly schedule the generation and transmission maintenance (see Section 3.2).

References [3, 10, 11, 40, 43, 45, 48, 53, 55, 64, 84] deal with a more specific problem including an accurate fuel magement, see Section 3.4 for more details.

If the goal is to find a compromise between reliability and minimal operational costs, a multiobjective formulation can be used [50, 51, 58, 78]. [58] use an extension of a branch-and-bound technique. [78] propose a two-stage goal programming approach that first considers the operational costs and then the reserve margins. [50] and [51] combine dynamic programming with fuzzy logic; a genetic algorithm is used in [51] to adjust the settings. [62] present a knowledge-based system that chooses the objective function (maximize the minimum reserve margin or minimize the production costs) depending on a operation index based on expert experience. Branch-and-bound or dynamic programming is used to find the optimal solution.

3.1.2 Deregulated power systems

Deregulation changes the maintenance scheduling problem. The GENCOs and TRANSCOs are now usually responsible for maintaining their equipment. The ISO ensures the smooth running of the system in terms of reliability and security in the MinISO model. Risk is managed by guaranteeing sufficient reserves of energy for each period to meet uncertainties in, for example, the demand or the generator deterioration. The different actors may have conflicting interests: GENCOs and TRANSCOs want to maximize their profits, whereas the ISO is concerned with demand satisfaction and congestion avoidance. For example, GENCOs tend to perform maintenance when the energy price is at its lowest, which may make it difficult to meet the demand. Thus, in an iterative way (see Figure. 3), the GENCOs and TRANSCOs submit their preferred maintenance schedules to the ISO, which verifies the acceptable behavior of the system on the basis of all the market-player information. If the ISO is not satisfied, it will request modifications (e.g., the rescheduling of one or more maintenance tasks). The coordination procedure may vary from one system to another.

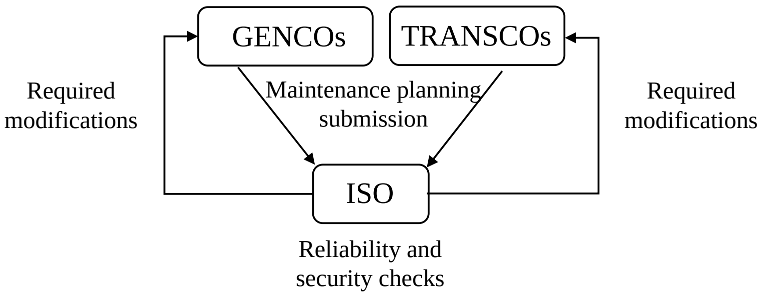


FIG. 3: Coordination procedure in a deregulated power system

Since the opening up to competition, the GMS in deregulated power systems has been widely studied [4, 5, 8, 9, 17, 18, 20, 33, 34, 36, 39, 42, 44, 46, 49, 52, 56, 63, 65, 66, 69–72, 74, 97, 98, 105]. The problem has globally the same constraints as for the vertically integrated case. Constraints on bilateral [9] or fuel [18, 70, 71] contracts may be introduced. The output levels of the generating units are calculated for each period in [4, 5, 9, 18, 20, 33, 34, 36, 42, 44, 52, 56, 65, 66, 69–72, 74, 97, 98, 105]. These levels may be introduced to take into account additional constraints or to permit effective estimation of the revenues and operating costs.

In some studies [4, 42, 52, 69–72, 98], cost minimization is still the objective. These studies generally deal with a security-constrained GMS operating under a MaxISO model or a regulated monopoly. However, profit maximization is a much more common objective [5, 9, 17, 18, 20, 33, 34, 36, 39, 44, 56, 63, 66, 74, 97, 105]. Note that these two objectives are different because profits depend on both costs and revenues. A very recent study [21] explain how maintenance costs can be modelled precisely in deregulated markets.

Under deregulation, the GENCOs have limited information about the system The coordination of the decisions and information exchange between the GENCOs and the ISO are important. The interactions between these two actors have received intensive interest [5, 20, 33, 34, 39, 44, 46, 49, 63, 66, 74, 105]. Reliability-based objectives are considered when the problem is solved from the point of view of the ISO: maximizing the reserve throughout the horizon [34], maximizing the sum of the ratio of the net reserves to the gross reserves by period [20, 39], minimizing the standard deviation of this last ratio [105], or minimizing a risk penalty factor related to an adequate level of reliability [44]. Cost minimization is considered in [5]. [39] present a game theoretic framework where GMS is solved from the GENCO point of view and from the ISO point of view.

In [5, 20, 34, 44, 66, 74] iterative coordination methods based on rescheduling signals are presented. [34] suggest a coordination procedure where at every iteration the ISO indicates permissible and impermissible maximum power for the maintenance of the generating units in each period. In the same way, [5] coordinate the decisions through corrective signals sent by the ISO to the GENCOs, indicating the maximal capacities that can be in maintenance during critical periods. These signals are calculated according to the responsibility of each GENCO for not supplying the load. These capacity-based signals can be replaced by penalties and/or incentive signals. [20, 44, 66, 74] penalize periods of maintenance during peak periods or when the reliability of the system is uncertain. The objective function associated with the GENCO problem is modified at each iteration to represent the ISO's recommendations. In [20], GENCOs that adjust their maintenance plans are paid to offset their losses compared to their initial plans; the cost is paid by the customers.

[46] seek to ensure equity between the GENCOs while protecting the system reliability. The ISO calculates prices for the maintenance windows that depend on the scenario-based electricity price. The GENCOs submit maintenance plans according to the prices defined by the ISO and according to their own strategies. A mechanism compensates for the GENCOs' financial losses and ensures fairness between the producers. [63] construct a coordination model based on a similar approach. The ISO selects maintenance plans by considering the willingness-to-pay (WTP) curve submitted by each GENCO. This curve simply represents the GENCOs' preferences for the maintenance scheduling of each unit. The transmission capacity constraints are taken into account when the system security is checked by the ISO. [49] propose an ISO coordination procedure to adjust the individual generator-maintenance schedules according to the preferences of each GENCO, while guaranteeing system reliability. [33] give the ISO the responsibility for maintenance scheduling. They take into account consumer satisfaction by maximizing the annual social welfare and also consider the profit-seeking GENCOs. They suggest a maintenance bidding approach to model the coordination mechanism.

[105] analyze the relationship between the ISO and the GENCOs in GMS and use a multi-objective evolutionnary algorithm to build a set of Pareto-optimal solutions.

Finally, some studies [42, 44, 70, 71, 98] use Benders decomposition to take into account the objectives of the ISO and the GENCOs in the long-term GMS. The GENCOs' objective is cost minimization rather than profit maximization. The master problem deals with the GENCOs' formulation of the GMS, and the reliability checks of the ISO are handled in the subproblems. Cut generation allows the coordination of the decisions. [98] use this approach to design mobile agent software to coordinate the actors.

Various algorithms are used. Game theory is appropriate [17, 39, 56, 66, 74], since every GENCO tries to predict its competitors' actions so as to stay one step ahead. The strategy adopted by the GENCOs is defined by a Nash equilibrium of the game. Other algorithms include MIP [4,5,9,18,20] and metaheuristics such as genetic algorithms [34,36,46] and simulated annealing [49]. [9] formulate the problem as a zero–one mixed integer linear problem and use a primal–dual interior point method. Benders decomposition is also used [42,44,70,71,98]. [4] consider the impact of the load curve demand by adding a penalty factor to each period, especially where peak loads prevent maintenance from being scheduled. This approach is proposed as a possible strategy to be used by the ISO. [52] design a biobjective method that minimizes the energy not supplied and the cost. The two objectives are weighted by coefficients computed by an entropy method. Finally, [33] use a clonal selection algorithm to test their approach.

3.2 Transmission maintenance scheduling and network considerations

Along with generator maintenance, transmission-line maintenance must be scheduled. This problem, usually called *transmission maintenance scheduling* (TMS) [1, 42, 44, 47, 60, 65, 67, 68, 70, 72, 88, 89, 104], has received less attention than GMS. It is necessary to ensure that taking a line out for maintenance does not impact the network reliability and security. The TMS constraints are globally the same as those for GMS (e.g., time windows for maintenance tasks, resource requirements, demand satisfaction). These are also constraints on the line capacity and sometimes voltage considerations. The network can be modeled as either a transportation model [1, 67, 68, 70, 88, 89] or a more complex but more realistic DC power flow model [42, 44, 47, 60, 65, 72, 104] (a linearization of an AC power flow model).

TMS can be addressed independently [47, 60, 65, 72, 88, 89] or jointly with GMS [1, 42, 44, 67, 68, 70, 104]. In the former case, [47] present a constraint logic programming model solved with local search. [60] use a genetic algorithm to maintain the UK electricity network in the South Wales region. For a deregulated power system, Marwali and Shahidehpour look for a trade-off between maintenance costs and loss of revenue over a short-term horizon [72] and over a long-term horizon [88]; they use Benders decomposition. In [89], the authors consider the coordination of long-term and short-term decisions. [65] use the same technique and introduce modified Benders feasibility cuts. They also define an index of critical lines—related to the system reliability—to reduce the computational complexity and the solution time. Such an isolated approach is especially valid for regulated systems but may also apply to deregulated power systems, with the state of the network appearing as a constraint during GMS.

When TMS is tackled jointly with GMS, it becomes more complex. The maintenance must take into account economic considerations while minimizing the unsatisfied demand. [67] coordinate maintenance decisions over a long-term horizon. [104] use a decomposition technique including a tabu search in the master problem and linear programming for the subproblem. These methods are more appropriate for regulated systems. In deregulated systems, the GENCOs and TRANSCOs are profit-oriented and do not have global information about the state of the system. As explained earlier, the ISO has to coordinate the submitted schedules; the cheapest transmission lines and generators might be overloaded. [70] include fuel and emission constraints in the problem, considering local transmission lines within a GENCO. [44] solve the problem for every actor (ISO, GENCOs, and TRANSCOs) by Benders decomposition and Lagrangian relaxation; they coordinate them through penalties. [42] deal with unit commitment and maintenance scheduling via Lagrangian relaxation. They propose an optimal coordination approach for a short-term to middle-term horizon that can be used by a company in a monopoly position or by an ISO. [1] design a teaching learning based optimization algorithm for the integrated maintenance scheduling problem.

Our discussion shows that network considerations and especially coordination between TMS and GMS are important. If TMS is not solved jointly with GMS, network constraints can be introduced when GMS is solved [4,5,16,19,32,52,61,63,69,71,91,92,97,98]. These constraints can implicitly include the maintenance tasks planned for the network. Maintenance and unit commitment decisions must never exceed the line capacities. To our knowledge, [19] were the first to consider these constraints in a multi-area problem, but they do not handle unexpected breakdowns. The transportation model is widely used, except by [91] who models a DC power flow.

Benders decomposition [69, 71, 91, 92, 98] allows network constraints to be moved to the subproblems.

3.3 Management of uncertainty

The load curve and the energy price may be difficult to estimate precisely. Furthermore, corrective maintenance, characterized by unexpected breakdowns, has a real impact when the maintenance is considered jointly with the production. These uncertainties must be handled with care.

Reserve constraints [2, 4, 6, 8, 9, 12–14, 19, 20, 25–27, 29, 30, 34, 35, 37–39, 50, 51, 61, 62, 71, 73, 74, 76, 77, 79, 85–87, 93, 97, 101, 105] can help to deal with these risks. Reliability objectives, as discussed earlier, can also be used. However, using only deterministic strategies may be inappropriate in the event of large disturbances.

To explicitly consider unexpected breakdowns, researchers [2, 4, 6, 8, 16, 18, 26, 36, 39, 42, 44, 46, 49, 58, 63, 65, 66, 68–71, 75, 76, 78, 81, 92, 93, 95] associate a force outage rate (FOR) with generating units or transmission lines. The FOR represents the probability that equipment will not be available for service when required. It impacts the quantity of energy that can be supplied. Thus, it prevents unsuitable maintenance schedules when load constraints are considered. However, when the FOR is taken into account based on the units' effective load carrying capacity, the energy not supplied can be overestimated.

Using only deterministic strategies may be inappropriate. Stochastic reliability indices such as the expected energy not served (EENS) [6, 18, 44, 65, 68–70, 92, 102] and the loss of load probability (LOLP) [8,46,49,66,75,76,81,93,95] are therefore employed. The EENS is minimized or a threshold for acceptability is defined. Satisfying EENS within a specific threshold results in an acceptable LOLP. The LOLP reliability index is considered in a stochastic levelized risk method [76, 81, 93] by using the effective load carrying capacity for each unit (related to the FOR) and an equivalent load for each time interval. A fuzzy LOLP is considered in [75]. In [76], the risk associated with the resulting plan is evaluated by giving a confidence interval for the LOLP, whereas in [95] the annual value of the loss of load expectation (LOLE) is minimized. [8] discuss a health levelization technique over a short-term horizon. Incorporated in a probabilistic framework, the objective is to maximize the health/security of the system, defined as the probability that the available reserves are greater than the required reserves. [18] simulates random outages using the Monte Carlo technique and proposes a stochastic optimization framework to optimize GMS. In [44, 65, 69–71] a probabilistic approach takes FOR into account in a problem with network constraints. [36] present an optimal method that maximizes the profits of a GENCO while considering unexpected unit failure. A modified superposed power law process models the unit failure rate. Its parameters are determined via the Gauss–Newton algorithm. [92] use a stochastic programming approach to dealt with a transmission constrained maintenance scheduling problem. They show that their scheduling method has a better effect on system reliability (through EENS) than a reserve levelization approach.

The demand may also be uncertain, and its stochastic nature can be explicitly considered. A set of scenarios that model alternative demands is used in [3, 10, 11, 13, 14, 43, 45, 48, 53, 64, 84]. The maintenance decisions ensure that the demand is met in all the scenarios. El-Sharkh et al. [32] simulate the demand uncertainty with a triangular membership function. Ekpenyong et al. [29] present an effective method, called model predictive control (MPC), that detects demand disturbances and makes appropriate corrections.

When the objective is profit-based, it may be necessary to take into account the volatility of market prices. [97] use a stochastic model based on hourly price-based unit commitment. The hourly electricity and fuel prices are modeled as a set of scenarios determined via a Monte-Carlo method. In [46], the ISO calculates prices for the maintenance windows using a scenario-based electricity price.

3.4 Fuel management and maintenance scheduling

Thermal production represents around 80% of the total global electricity production. Fuel is fundamental for the effective functioning of these plants, so fuel consumption and refueling have to be managed. In some cases, refueling can be done continuously without significantly affecting production, but sometimes (e.g., for nuclear reactors) it can occur only when the generators are offline. The introduction of fuel management into GMS increases its complexity, but also makes it more realistic [4, 70].

Few studies handle this problem. The refueling can be done continuously [2, 16, 18, 70, 71, 78] or can only be done when the plants are offline [3, 10, 11, 40, 43, 45, 48, 53, 55, 64, 84]. [2] focus on the case of fuel constraints for each unit. [78] are concerned with the maximum fuel storage capacities of thermal plants. [70, 71] solve a fuel dispatch problem with multiple suppliers. The fuel consumption is limited by week, month, and year and linked with the output level of the generators. They use Benders decomposition to handle fuel dispatch in a subproblem. The coordination of long-term and short-term decisions is discussed in [71]. [18] introduces fuel contracts with suppliers (with fixed fuel prices and volumes) in a GMS model and describes a successive linearization scheme to approximate the fuel consumption as a linear function. In [16], the same author discusses coal supply management with different transport modes from the mine to the power stations. Two studies [40, 55] are concerned with planning shutdowns in production to carry out refueling and maintenance operations; the fuel quantity to supply is known in advance. [40] model the problem as an MIP and solve it with a commercial solver. [55] propose an approach using constraint programming and local search.

A challenge submitted jointly by EURO[3] and ROADEF[4] in collaboration with EDF[5] has renewed interest in this last problem. It presents a large-scale energy management problem with many constraints [80]. The time horizon is long and precise (up to 277 weeks with 7 or 21 timesteps per week). Two types of production units are considered. Non–nuclear plants can refuel continuously whereas nuclear plants must be shut down when fuel is supplied. In contrast to previous studies [40, 55], the amount of fuel that is supplied for every nuclear plant is left as a decision variable. Furthermore, the production levels for the plants have to be planned under demand uncertainty modeled by a set of scenarios (up to 500). The objective is to plan the production and refueling while minimizing the production costs of non–nuclear plants and the refueling costs of nuclear plants. The problem has been proved to be NP-hard [45]. Almost twenty teams participated in this challenge, and some of them [3, 10, 11, 43, 45, 53, 64, 84] published their results. The problem is often decomposed into several components: planning of the refueling, computation of the refuel amounts, and planning of the production. Various methods are used separately or jointly: column generation [84], local search [11, 43, 45], Benders decomposition [64], matheuristics [3], constraint programming [10, 11, 45], and linear programming [53]. This problem has also been considered by [48]; some simplifications are made in their quadratic model, which is solved by semidefinite programming.

Some studies ignore refueling considerations. In [4], the fuel consumption is limited by period for every unit. If fuel shortages occur, energy can be purchased externally. In [97], the fuel allocations, which depend on a predetermined contract with a supplier, are limited by group of units.

3.5 Benchmarks

Publicly accessible data to test optimization algorithms for maintenance scheduling in electricity systems are rather scarce. Probably the most classical instance is the IEEE[6] Reliability Test

[3] Association of European Operational Research Societies
[4] Société française de recherche opérationnelle et d'aide à la décision
[5] Electricité de France
[6] Institute of Electrical and Electronics Engineers

System (IEEE-RTS) published in 1979 [82] and released in 1996 [83]. The IEEE-RTS includes data on the network, the generation units, the demand, and the costs. This benchmark has been used in several articles [4, 8, 33–36, 39, 44, 46, 47, 52, 66–71, 77, 87–89, 93, 105]. Another commonly used set of instances contributed by the IEEE[7] represent portions of the North American electricity system; this set served as a benchmark in [1, 31, 32, 42, 63, 72, 104]. Additionally, an instance with 21 generation units described by [99] regularly serves as a test case [6, 23–25, 29, 87, 93, 101]. Data associated with real cases are often used to validate proposed techniques. However, to our knowledge, the only publicly available data is that published of the EURO-ROADEF-EDF challenge [80].

4 Conclusion and perspectives

GMS and TMS are the two main maintenance scheduling problems in the electricity industry. The constraints concern the maintenance tasks (time windows, incompatibility, sequence), the resource requirements, the reliability, and the demand satisfaction. Sometimes, e.g., for nuclear power plants, fuel consumption management is required. GMS and TMS can be solved jointly or network constraints can be introduced into the former. Production planning is often incorporated into GMS, especially over a short-term horizon. This results in a complex problem that is generally NP-hard.

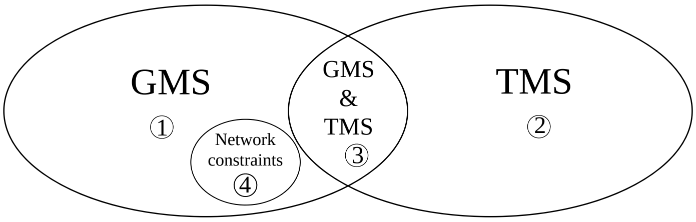
Maintenance scheduling is a major challenge in the electricity industry, especially since the liberalization of the electricity market. The objectives of regulated power systems are based mainly on the reliability (leveling, maximization of net reserves) and the costs (minimization of the operational costs). These objectives are not necessarily suitable for deregulated systems. It may be more appropriate to maximize the profits of the GENCOs and to coordinate the decisions of the various actors. The objectives of regulated systems remain relevant to the ISO—the actor that must ensure system reliability and security—but may conflict with the goals of the other actors (GENCOs, TRANSCOs, DISCOs). A multi-objective optimization is appearing as a future solution.

Many approaches have been proposed for GMS and/or TMS. They include heuristics, meta-heuristics (ant colony optimization, particle swarm optimization, simulated annealing, tabu search, genetic algorithms), hybrid approaches, mathematical programming (dynamic programming, MIP, branch-and-bound, Benders decomposition), constraint programming, and fuzzy logic. As the problem complexity increases making frontal resolution impractible, decomposition techniques become more important.

Figure.4 and Figure.5 provide an overview by classifying the references according to the problem solved and the specific features (objective function, coordination, FOR, network constraints, fuel management). It is not however exhaustive.

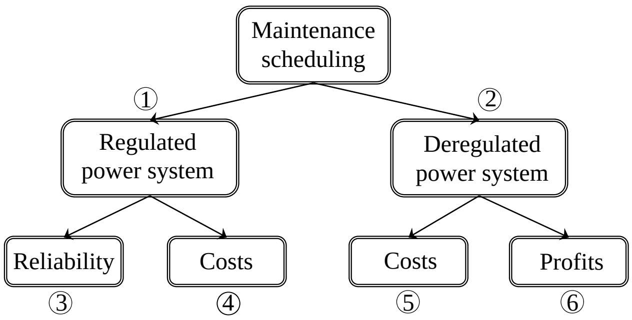
[7] University of Washington Electrical Engineering, Power systems case archive, http://www.ee.washington.edu/research/pstca/, last accessed : 2014-09-22

To the best of our knowledge, some problems have not yet been investigated. These include load uncertainty and price volatility when TMS is solved jointly with GMS or where coordination is needed between the GENCOs and the ISO. Moreover, the growing renewable energy industries and its randomness have an impact on the constraints related to UC and introduced in GMS. For energy renewable sources, demand is also non correlated to generators output. To explicitly handle these uncertainties via stochastic programming approaches rather than via reserves may lead to substantial energy and cost savings. In conclusion, future research will take into account various changes in electricity systems and will increase the number and the variety of constraints, the handling of uncertainty, and the precision of long-term horizons.



Problem solved	Associated references
1	[2–6, 8–20, 23–27, 29–41, 43, 45, 46, 48–53, 55–58, 61–64, 66, 69, 71, 73–79, 81, 84–87, 91–93, 95–98, 101, 102, 105]
2	[1, 42, 44, 67, 68, 70, 104]
3	[47, 60, 65, 72, 88, 89]
4	[4, 5, 16, 19, 32, 52, 61, 63, 69, 71, 91, 92, 97, 98]

FIG. 4: Classification of bibliographical references according to problem solved



Specificity	Associated references
1	[1–3, 6, 10–16, 19, 23–27, 29–32, 35, 37, 38, 40–43, 45, 47, 48, 50, 51, 53, 55, 57, 58, 60–62, 64, 65, 67–69, 71, 73, 75–79, 81, 84–87, 91–93, 95, 96, 101, 102, 104]
2	[4, 5, 8, 9, 17, 18, 20, 22, 33, 34, 36, 39, 42, 44, 46, 49, 52, 56, 63, 65, 66, 69–72, 74, 88, 89, 97, 98, 105]
3	[6, 14, 19, 23–25, 29, 30, 38, 50, 51, 58, 62, 75, 76, 78, 81, 87, 93, 95, 96, 101]
4	[1–3, 6, 10–13, 15, 16, 26, 27, 29–32, 35, 37, 40–43, 45, 47, 48, 50, 51, 53, 55, 57, 58, 60–62, 64, 65, 67–69, 71, 73, 77–79, 84–86, 91, 92, 102, 104]
5	[4, 42, 52, 69–71, 98]
6	[5, 9, 17, 18, 20, 33, 34, 36, 39, 44, 46, 49, 56, 63, 66, 72, 74, 88, 89, 97, 105]
Coordination of market actors	[5, 20, 33, 34, 39, 42, 44, 46, 49, 63, 66, 70, 71, 74, 88, 89, 98, 105]
FOR	[2, 4, 6, 8, 16, 18, 26, 36, 39, 42, 44, 46, 49, 58, 63, 65, 66, 68–71, 75, 76, 78, 81, 92, 93, 95, 102]
Demand uncertainty	[3, 10, 11, 13, 14, 43, 45, 48, 53, 64, 84]
Fuel management	[2–4, 10, 11, 16, 18, 40, 43, 45, 48, 53, 55, 64, 70, 71, 78, 84, 97]

FIG. 5: Classification of bibliographical references according to their specificities

References

[1] 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. *Applied Soft Computing*, 21:72–83, 2014.

[2] T.M. Al-Khamis, S. Vemuri, L. Lemonidis, and J. Yellen. Unit maintenance scheduling with fuel constraints. *IEEE Transactions on Power Systems*, 7(2):933–939, 1992.

[3] D. Anghinolfi, L.M. Gambardella, and R. Montemanni. A matheuristic algorithm for a large-scale energy management problem. In I. Van Lirkov, S. Margenov, and J. Waśniewsk, editors, *Large-Scale Scientific Computing*, volume 7116, pages 173–181. Springer Berlin Heidelberg, 2012.

[4] A. Badri and A.N. Niazi. Preventive generation maintenance scheduling considering system reliability and energy purchase in restructured power systems. *Journal of Basic and Applied Scientific Research*, 2(12):12773–12786, 2012.

[5] H. Barot and K. Bhattacharya. Security coordinated maintenance scheduling in deregulation based on genco contribution to unserved energy. *IEEE Transactions on Power Systems*, 23(4):1871–1882, 2008.

[6] S. Baskar, P. Subbaraj, M.V.C. Rao, and S. Tamilselvi. Genetic algorithms solution to generator maintenance scheduling with modified genetic operators. *Generation, Transmission and Distribution, IEE Proceedings*, 150(1):56–60, 2003.

[7] J.F. Benders. Partitioning procedures for solving mixed-variables programming problems. *Numerische Mathematik*, 4(1):238–252, 1962.

[8] R. Billinton and A. Abdulwhab. Short-term generating unit maintenance scheduling in a deregulated power system using a probabilistic approach. *Generation, Transmission and Distribution, IEE Proceedings*, 150(4), 2003.

[9] S. Bisanovic, M. Hajro, and M. Dlakic. A profit-based maintenance scheduling of thermal power units in electricity market. *International Journal of Electrical and Electronics Engineering*, 5:156–164, 2011.

[10] F. Brandt, R. Bauer, M. Völker, and A. Cardeneo. A constraint programming-based approach to a large-scale energy management problem with varied constraints. *Journal of Scheduling*, 16(6):629–648, 2013.

[11] M. Buljubasic and H. Gavranovic. Orchestrating constrained programming and local search to solve a large scale energy management problem. In *Proceedings of the Federated Conference on Computer Science and Information Systems*, pages 371–378, 2012.

[12] E.K. Burke and A.J. Smith. Hybrid evolutionary techniques for the maintenance scheduling problem. *IEEE Transactions on Power Systems*, 15(1), 2000.

[13] S.P. Canto. Application of Benders' decomposition to power plant preventive maintenance scheduling. *European Journal of Operational Research*, 184:759–777, 2008.

[14] S.P. Canto and J.C. Rubio-Romero. A model for the preventive maintenance scheduling of power plants including wind farms. *Reliability Engineering & System Safety*, 119:67–75, 2013.

[15] M. Charest and J.A. Ferland. Preventive maintenance scheduling of power generating units. *Annals of Operations Research*, 41:185–206, 1993.

[16] D Chattopadhyay. A practical maintenance scheduling program mathematical model and case study. *IEEE Transactions on Power Systems*, 13(4):1475–1480, 1998.

[17] D. Chattopadhyay. A game theoretic model for strategic maintenance and dispatch decisions. *IEEE Transactions on Power Systems*, 19(4):2014–2021, 2004.

[18] D. Chattopadhyay. Life-cycle maintenance management of generating units in a competitive environment. *IEEE Transactions on Power Systems*, 19(2):1181–1189, 2004.

[19] L. Chen and J. Toyoda. Optimal generating unit maintenance scheduling for multi-area system with network constraints. *IEEE Transactions on Power Systems*, 6(3):1168–1174, 1991.

[20] A.J. Conejo, R. Garcia-Bertrand, and M. Diaz-Salazar. Generation maintenance scheduling in restructured power systems. *IEEE Transactions on Power Systems*, 20(2):984–992, 2005.

[21] K. Dahal, K. Al-Arfaj, and K. Paudyal. Modelling generator maintenance scheduling costs in deregulated power markets. *European Journal of Operational Research*, 240(2):551–561, 2015.

[22] K.P. Dahal. A review of maintenance scheduling approaches in deregulated power systems. In *Proceedings of the International Conference on Power Systems (ICPS 2004), Kathmandu, Nepal*, pages 565–570, 2004.

[23] K.P. Dahal, C.J. Aldridge, and J.R. McDonald. Generator maintenance scheduling using a genetic algorithm with a fuzzy evaluation function. *Fuzzy Sets and Systems*, 102(1):21–29, 1999.

[24] K.P. Dahal, G.M. Burt, J.R. McDonald, and S.J. Galloway. GA/SA-based hybrid techniques for the scheduling of generator maintenance in power systems. In *Proceedings of the 2000 Congress on Evolutionary Computation. CEC00 (Cat. No. 00TH8512)*, volume 1, pages 567–574. IEEE, 2000.

[25] K.P. Dahal and N. Chakpitak. Generator maintenance scheduling in power systems using metaheuristic-based hybrid approaches. *Electric Power Systems Research*, 77(7):771–779, 2007.

[26] M.Y. Damavandi, H. Seifi, and M.M. Pedram. Generation units maintenance scheduling considering gas network constraints. In *International Conference on Electric Power and Energy Conversion Systems. EPECS '09*, pages 1–5, 2009.

[27] J.G. Digalakis and K.G. Margaritis. A multipopulation cultural algorithm for the electrical generator scheduling problem. *Mathematics and Computers in Simulation*, 60(3–5):293–301, 2002.

[28] E.K. Doyle. On the application of stochastic models in nuclear power plant maintenance. *European Journal of Operational Research*, 154(3):673–690, 2004.

[29] U.E. Ekpenyong, J. Zhang, and X. Xia. An improved robust model for generator maintenance scheduling. *Electric Power Systems Research*, 92:29–36, 2012.

[30] I. El-Amin, S. Duffuaa, and M. Abbas. A tabu search algorithm for maintenance scheduling of generating units. *Electric Power Systems Research*, 54:91–99, 2000.

[31] M.Y. El-Sharkh. Clonal selection algorithm for power generators maintenance scheduling. *International Journal of Electrical Power & Energy Systems*, 57:73–78, 2014.

[32] M.Y. El-Sharkh, A.A. El-Keib, and H. Chen. A fuzzy evolutionary programming-based solution methodology for security-constrained generation maintenance scheduling. *Electric Power Systems Research*, 67(1):67–72, 2003.

[33] S.H. Elyas, A. Akbari Foroud, and H. Chitsaz. A novel method for maintenance scheduling of generating units considering the demand side. *International Journal of Electrical Power & Energy Systems*, 51:201–212, 2013.

[34] R. Eshraghnia, H. Rajabi Mashhadi, M.H. Modir Shanechi, and A. Karsaz. A novel approach for maintenance scheduling of generating units in a competitive environment. In *Power India Conference*, 2006.

[35] 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. *Computers & Operations Research*, 2014.

[36] C. Feng, X. Wang, and F. Li. Optimal maintenance scheduling of power producers considering unexpected unit failure. *IET Generation, Transmission & Distribution*, 3(5):460–471, 2009.

[37] A. Fetanat and G. Shafipour. Generation maintenance scheduling in power systems using ant colony optimization for continuous domains based 0–1 integer programming. *Expert Systems with Applications*, 38(8):9729–9735, 2011.

[38] 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. *Annals of Operations Research*, 159(1):433–450, 2007.

[39] M.A. Fotouhi and S.M. Moghaddas Tafreshi. A game theoretic framework for generation maintenance scheduling in oligopolistic electricity markets. In *15th International Conference on Intelligent System Applications to Power Systems*, pages 1–6, 2009.

[40] F. Fourcade, E. Johnson, M. Bara, and P. Cortey-Dumont. Optimizing nuclear power plant refueling with mixed-integer programming. *European Journal of Operational Research*, 97(2):269–280, 1997.

[41] D. Frost and R. Dechter. Optimizing with constraints: A case study in scheduling maintenance of electric power units. In *Lecture Notes in Computer Science Volume 1520*, pages 469–488, 1998.

[42] Y. Fu, M. Shahidehpour, and Z. Li. Security-constrained optimal coordination of generation and transmission maintenance outage scheduling. *IEEE Transactions on Power Systems*, 22(3):1302–1313, 2007.

[43] F. Gardi and K. Nouioua. Local search for mixed-integer nonlinear optimization: A methodology and an application. In *EvoCop: 11th European conference on evolutionary computation in combinatorial optimisation, 27-29 April 2011 Torino, Italy*, pages 167–178, 2011.

[44] T. Geetha and K. Shanti Swarup. Coordinated preventive maintenance scheduling of GENCO and TRANSCO in restructured power systems. *International Journal of Electrical Power & Energy Systems*, 31(10):626–638, 2009.

[45] S. Godskesen, T.S. Jensen, N. Kjeldsen, and R. Larsen. Solving a real-life, large-scale energy management problem. *Journal of Scheduling*, 16(6):567–583, 2013.

[46] H. Golmohamadi and M. Ramezani. Generating unit maintenance scheduling in power market based on fairness and competition. In *2013 21st Iranian Conference on Electrical Engineering (ICEE)*, pages 1–6. IEEE, 2013.

[47] N. Gomes, R. Pinheiro, Z. Vale, and C. Ramos. Scheduling maintenance activities of electric power transmission networks using an hybrid constraint method. *Engineering Intelligent Systems for Electrical Engineering and Communications*, 15(3):127–134, 2007.

[48] A. Gorge, A. Lisser, and R. Zorgati. Stochastic nuclear outages semidefinite relaxations. *Computational Management Science*, 9(3):363–379, 2012.

[49] S.-M. Han, K.-H. Chung, and B.H. Kim. ISO coordination of generator maintenance scheduling in competitive electricity markets using simulated annealing. *Journal of Electrical Engineering & Technology*, 6(4):431–438, 2011.

[50] C.J. Huang, C.E. Lin, and C.L. Huang. Fuzzy approach for generator maintenance scheduling. *Electric Power Systems Research*, 24(1):31–38, 1992.

[51] S.-J. Huang. Generator maintenance scheduling: A fuzzy system approach with genetic enhancement. *Electric Power Systems Research*, 41(3):233–239, 1997.

[52] Y.R. Jafarian, H. Asgharpour, M. Rashidinejad, and M.A. Forghani. Multi objective power generation preventive maintenance scheduling. In *International Conference on Future Electrical Power and Energy Systems*, volume 9, pages 36–41, 2012.

[53] V. Jost and D. Savourey. A 0–1 integer linear programming approach to schedule outages of nuclear power plants. *Journal of Scheduling*, 16(6):551–566, 2013.

[54] A.A. Khalid and K. Ioannis. A survey of generator maintenance scheduling techniques. *Global Journal of Researches in Engineering*, 12(1), 2012.

[55] M. Khemmoudj, M. Porcheron, and H. Bennaceur. When constraint programming and local search solve the scheduling problem of Electricité de France nuclear power plant outages. In Frédéric Benhamou, editor, *Principles and Practice of Constraint Programming - CP 2006*, volume 4204 of *Lecture Notes in Computer Science*, pages 271–283. Springer Berlin Heidelberg, 2006.

[56] J.-H. Kim, J.-B. Park, J.-K. Park, and Y.-H. Chun. Generating unit maintenance scheduling under competitive market environments. *International Journal of Electrical Power & Energy Systems*, 27(3):189–194, 2005.

[57] A. Kovács, G. Erdős, Z.J. Viharos, and L. Monostori. A system for the detailed scheduling of wind farm maintenance. *CIRP Annals - Manufacturing Technology*, 60(1):497–501, 2011.

[58] B. Kralj and R. Petrovic. A multiobjective optimization approach to thermal generating units maintenance scheduling. *European Journal of Operational Research*, 84(2):481–493, 1995.

[59] BL Kralj and R Petrović. Optimal preventive maintenance scheduling of thermal generating units in power systems—A survey of problem formulations and solution methods. *European Journal of Operational Research*, 35:1–15, 1988.

[60] W.B. Langdon and P.C. Treleaven. Scheduling maintenance of electrical power transmission networks using genetic programming. In K. Warwick, A.O. Ekwue, and R. Aggarwal, editors, *Artificial Intelligence Techniques in Power Systems, chapter 10*, pages 220–237. IEE, 1997.

[61] R.-C. Leou. A new method for unit maintenance scheduling considering reliability and operation expense. *International Journal of Electrical Power & Energy Systems*, 28(7):471–481, 2006.

[62] C.E. Lin and C.J. Huang. An expert system for generator maintenance scheduling using operation index. *IEEE Transactions on Power Systems*, 7(3):1141–1148, 1992.

[63] G. Lu, C.Y. Chung, K.P. Wong, and F. Wen. Unit maintenance scheduling coordination mechanism in electricity market environment. *IET Generation, Transmission & Distribution*, 2(5):646–654, 2008.

[64] R. Lusby, L.F. Muller, and B. Petersen. A solution approach based on Benders decomposition for the preventive maintenance scheduling problem of a stochastic large-scale energy system. *Journal of Scheduling*, 16(6):605–628, 2013.

[65] C. Lv, J. Wang, and P. Sun. Short-term transmission maintenance scheduling based on the Benders decomposition. In *Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific*, pages 1–5, 2012.

[66] M. Manbachi. A new solution for maintenance scheduling in deregulated environment based on lost opportunity cost of market participation and reliability. In *Proceedings of the International Symposium*, pages 1–5. Modern Electric Power Systems (MEPS), 2010.

[67] M.K.C. Marwali and S.M. Shahidehpour. A deterministic approach to generation and transmission maintenance scheduling with network constraints. *Electric Power Systems Research*, 47(2):101–113, 1998.

[68] M.K.C. Marwali and S.M. Shahidehpour. Integrated generation and transmission maintenance scheduling with network constraints. *IEEE Transactions on Power Systems*, 13(3):1063–1068, 1998.

[69] M.K.C. Marwali and S.M. Shahidehpour. A probabilistic approach to generation maintenance scheduler with network constraints. *International Journal of Electrical Power & Energy Systems*, 21(8):533–545, 1999.

[70] M.K.C. Marwali and S.M. Shahidehpour. Long-term transmission and generation maintenance scheduling with network, fuel and emission constraints. *IEEE Transactions on Power Systems*, 14(3):1160–1165, 1999.

[71] M.K.C. Marwali and S.M. Shahidehpour. Coordination between long-term and short-term generation scheduling with network constraints. *IEEE Transactions on Power Systems*, 15(3):1161–1167, 2000.

[72] M.K.C. Marwali and S.M. Shahidehpour. Short-term transmission line maintenance scheduling in a deregulated system. *IEEE Transactions on Power Systems*, 15(3):1117–1124, 2000.

[73] X. Meng, Y. Yue, Z. Shen, and M. Li. A new optimized generator maintenance model. In *Advances in Electronic Commerce, Web Application and Communication*, volume 2, pages 185–190. Springer Berlin Heidelberg, 2011.

[74] C.G. Min, M.K. Kim, J.K. Park, and Y.T. Yoon. Game-theory-based generation maintenance scheduling in electricity markets. *Energy*, 55:310–318, 2013.

[75] D.K. Mohanta, P.K. Sadhu, and R. Chakrabarti. Fuzzy reliability evaluation of captive power plant maintenance scheduling incorporating uncertain forced outage rate and load representation. *Electric Power Systems Research*, 72(1):73–84, 2004.

[76] D.K. Mohanta, P.K. Sadhu, and R. Chakrabarti. Deterministic and stochastic approach for safety and reliability optimization of captive power plant maintenance scheduling using GA/SA-based hybrid techniques: A comparison of results. *Reliability Engineering & System Safety*, 92(2):187–199, 2007.

[77] M. Mollahassani-pour, A. Abdollahi, and M. Rashidinejad. Application of a novel cost reduction index to preventive maintenance scheduling. *International Journal of Electrical Power & Energy Systems*, 56:235–240, 2014.

[78] L. Munoz-Moro and A. Ramos. Goal programming approach to maintenance scheduling of generating units in large scale power systems. *IEEE Transactions on Power Systems*, 14(3):1021–1028, 1999.

[79] T. Mytakidis and A. Vlachos. Maintenance scheduling by using the bi-criterion algorithm of preferential anti-pheromones. *Leonardo Journal of Sciences*, (12):143–164, 2008.

[80] M. Porcheron, A. Gorge, O. Juan, T. Simovic, and G. Dereu. Challenge ROADEF/EURO 2010: A large-scale energy management problem with varied constraints. 2010.

[81] E. Reihani, A. Sarikhani, and M. Davodi. Reliability based generator maintenance scheduling using hybrid evolutionary approach. *International Journal of Electrical Power & Energy Systems*, 42(1):434–439, 2012.

[82] Reliability Test System Task Force of the Application of Probability Methods Subcommittee. IEEE reliability test system. *IEEE Transactions on Power Apparatus and Systems*, PAS-98(6):2047–2054, 1979.

[83] Reliability Test System Task Force of the Application of Probability Methods Subcommittee. The IEEE reliability test system - 1996. *IEEE Transactions on Power Systems*, 14(3):1010–1020, 1999.

[84] A. Rozenknop, R. Wolfler Calvo, L. Alfandari, D. Chemla, and L. Létocart. Solving the electricity production planning problem by a column generation based heuristic. *Journal of Scheduling*, 16(6):585–604, 2013.

[85] J.T. Saraiva, M.L. Pereira, V.T. Mendes, and J.C. Sousa. A simulated annealing based approach to solve the generator maintenance scheduling problem. *Electric Power Systems Research*, 81(7):1283–1291, 2011.

[86] T. Satoh and K. Nara. Maintenance scheduling by using simulated annealing method. *IEEE Transactions on Power Systems*, 6(2):850–857, 1991.

[87] E.B. Schlünz and J.H. van Vuuren. An investigation into the effectiveness of simulated annealing as a solution approach for the generator maintenance scheduling problem. *International Journal of Electrical Power & Energy Systems*, 53:166–174, 2013.

[88] M. Shahidehpour and M. Marwali. Coordination between long-term and short-term transmission maintenance scheduling. In *Maintenance Scheduling in Restructured Power Systems*, Springer International Series in Engineering and Computer Science, pages 147–166. Springer US, 2000.

[89] M. Shahidehpour and M. Marwali. Long-term transmission maintenance scheduling. In *Maintenance Scheduling in Restructured Power Systems*, Springer International Series in Engineering and Computer Science, pages 133–145. Springer US, 2000.

[90] M. Shahidehpour, H. Yamin, and Z.Y. Li. *Market Operations in Electric Power Systems.* Wiley-IEEE Press, 2002.

[91] E.L. Silva. Generation maintenance scheduling considering transmission constraints. *IEEE Transactions on Power Systems*, 15(2):838–843, 2000.

[92] E.L. Silva and M. Morozowski. Transmission constrained maintenance scheduling of generating units: A stochastic programming approach. *IEEE Transactions on Power Systems*, 10(2):695–701, 1995.

[93] K. Suresh and N. Kumarappan. Hybrid improved binary particle swarm optimization approach for generation maintenance scheduling problem. *Swarm and Evolutionary Computation*, 9:69–89, 2013.

[94] P. Varaiya and F. Wu. MinISO: a minimal independent system operator. In *Proceedings of the Hawaii International Conference on System Sciences*, pages 602–607, 1997.

[95] A. Volkanovski and B. Mavko. Genetic algorithm optimisation of the maintenance scheduling of generating units in a power system. *Reliability Engineering & System Safety*, 93(6):757–767, 2008.

[96] Y. Wang and E. Handschin. A new genetic algorithm for preventive unit maintenance scheduling of power systems. *Journal of Electrical Power & Energy Systems*, 22(5):343–348, 2000.

[97] L. Wu, M. Shahidehpour, and T. Li. GENCO's risk-based maintenance outage scheduling. *IEEE Transactions on Power Systems*, 23(1):127–136, 2008.

[98] X. Xu and M. Kezunovic. Mobile agent software applied in maintenance scheduling. In *Proc. 2001 North American Power Symposium*, 2001.

[99] Z. Yamayee, K. Sidenblad, and M. Yoshimura. A computationally efficient optimal maintenance scheduling method. *IEEE Transactions on Power Apparatus and Systems*, PAS-102(2):330–338, 1983.

[100] Z.A. Yamayee. Maintenance scheduling: Description, literature survey, and interface with overall operations scheduling. *IEEE Transactions on Power Apparatus and Systems*, 75(8):2770–2779, 1982.

[101] Y. Yare and G.K. Venayagamoorthy. Optimal maintenance scheduling of generators using multiple swarms-MDPSO framework. *Engineering Applications of Artificial Intelligence*, 23(6):895–910, 2010.

[102] J. Yellen and T.M. Al-Khamis. A decomposition approach to unit maintenance scheduling. *IEEE Transactions on Power Systems*, 7(2):726–733, 1992.

[103] B. Yssaad, M. Khiat, and A. Chaker. Reliability centered maintenance optimization for power distribution systems. *International Journal of Electrical Power & Energy Systems*, 55:108–115, 2014.

[104] D. Yu, Q. Zhang, X. Han, and J. Zhao. TS-based generation and transmission maintenance scheduling. In *IEEE Congress on Evolutionary Computation (CEC 2007)*, pages 2936–2941, 2007.

[105] J.P. Zhan, C.X. Guo, Q.H. Wu, and L.L. Zhang. Generation Maintenance Scheduling Based on Multiple Objectives and Their Relationship Analysis. *Journal of Zhejiang University*, pages 1–13, 2014.