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Maintenance scheduling for the generating units of a national power utility

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Abstract

Reliable energy provision is a major force in shaping the economic welfare of a developing country. For a power utility in such a country one of the key focus areas is the planned preventative maintenance of the power generating units in its generation system so as to ensure that it is in a position to satisfy power demand in a reliable manner. In the *generator maintenance scheduling* (GMS) problem, the objective is to find a schedule for the planned maintenance outages of generating units in a power system which minimises maintenance costs or maximises the probability of meeting a safety margin over and above the national power demand, which is a function of time. Previous work on the GMS problem includes the use of mixed integer programming techniques and metaheuristics to find good generator maintenance schedules. This paper builds on these approaches by advocating use of a decision support system aimed at determining good generator maintenance schedules by taking into account (1) the levels and qualities of fuel stockpiles at generating units, (2) unplanned and other energy loss factors, (3) adopting a multi-objective optimisation approach instead of a single-objective approach as is usual in the literature and (4) analysing the possible interaction between inputs and outputs from the GMS problem and other energy components of the energy supply chain of a power utility.

Key words: Electricity industry, energy sector, maintenance scheduling, simulated annealing.

1 Introduction

One of the key focus areas for a power utility is the planned preventative maintenance of the power generating units in a power system [4, 5, 9, 13] so as to satisfy demand as efficiently and effectively as possible, a problem often referred to as the *generator maintenance scheduling* (GMS) problem. The maintenance scheduling of generators has been studied and analysed by many researchers [14] and this paper contains four suggestions as to how the level of realism of GMS problem formulations may be improved. These suggested improvements are (1) taking cognisance of the fuel stockpile levels associated with generating

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units when scheduling generator maintenance, (2) including unplanned and other generation loss factors in generator maintenance planning, (3) adopting a multi-objective optimisation approach toward generator maintenance planning and (4) analysing the possible interaction between generator maintenance planning and other energy planning models.

Power utilities often employ large-scale energy flow simulation models of their energy supply chains to inform decisions on operational and strategic levels. These energy system models typically interconnect the conversion and consumption of energy [18] and include operations involved with primary fuel supplies (*e.g.* mining, petroleum extraction), conversion and processing (*e.g.* power plants, refineries), and end-use demand for energy services (boilers, residential space conditioning). The demand for energy is normally disaggregated by sector (*i.e.* residential, manufacturing, transportation, and commercial) and by specific functions within a sector (*e.g.* residential air conditioning, heating, lighting, hot water) [18]. These energy flow models serve to facilitate the investigation of what-if scenarios for decision makers [12], with some utilising optimisation techniques [6, 18]. It is within this decision support framework that maintenance scheduling solutions are expected to be incorporated in a dynamic fashion.

This paper is organised as follows. After conducting a brief survey of GMS problem formulations and solution techniques from the literature in §2, descriptions of the abovementioned four proposed improvements to GMS formulations are described in §3. This is followed by a discussion on the feasibility of the proposed model improvements in §4 and finally some concluding remarks in §5.

2 Literature review

Although the GMS problem is related to a number of classical optimisation problems, such as the assignment problem, the travelling salesman problem and the vehicle routing problem, it is not one of these [15]. Factors complicating formulations of the GMS problem result from attempts at incorporating the fact that generated electricity cannot be stored; that the transmission network is limited and hence that a required amount of electricity must be generated at every instant; that an adequate amount of reserve capacity has to be available at all times; and the parallel nature of electricity supply within a power system (due to multiple generating units) [9, 15].

2.1 GMS problem formulation

In the literature related to the GMS problem, a dominant objective is usually included in model formulations as a single function to be optimised, while the lesser important objectives are incorporated as constraints. The most typical objectives found in literature are based on economic criteria, reliability criteria, and convenience criteria [9, 16].

Economic criteria. The most common economic objectives consist of minimising the total operating cost associated with a generator maintenance schedule, which includes energy production and maintenance cost [4]. Energy production costs include fuel costs, salaries and wages, costs related to energy production and generator start-up and shut-down costs. Maintenance costs, on the other hand, include replacement part costs and salaries and wages related to unit maintenance [15]. These economic costs typically vary from generating unit to generating unit and data related to these costs are sometimes difficult to obtain [15].

Reliability criteria. Reliability objectives include minimising the expected lack of peak net reserve, expected energy not supplied or loss of load probability [4]. These reliability criteria may be either stochastic or deterministic in nature [13]. The most common choice is to minimise the reserve load, usually formulated as the sum of squares of the reserve [13, 17], because data for this criterion are usually more easily obtainable [15]. Another option is to maximise the smallest reserve load during any time period. For some power utilities, reliability objectives are more important than economic considerations [15].

Convenience criteria. Examples of convenience criteria are minimising soft constraint violations or minimising possible disruptions to the power generation schedule [15].

As mentioned, researchers have mostly adopted a single-objective optimisation approach towards formulating instances of the GMS problem [16]. Since the criteria mentioned above are, however, often conflicting in nature, the problem is inherently multi-objective.

The constraints included in formulations of the GMS problem can vary significantly, depending on the nature and assumptions of the power utility's operations [15]. Typical constraints employed in the literature include the following [1, 9].

Maintenance window constraints ensure that each unit is serviced between an earliest and latest time period. These time windows are typically dictated by annual generating unit service frequencies, as imposed either by power utility policy or by operational service levels.

Load constraints ensure that the load demand is met during each time period. This demand must, of course, be met by generating units that are not scheduled for maintenance during the relevant time period.

Reliability constraints may be incorporated by specifying a reserve/safety margin over and above the load constraints.

Service contiguity constraints are imposed to ensure that the number of time periods required to service a particular generating unit run consecutively over time.

Resource constraints specify a limit on the amount of resources available for the purpose of maintenance. These resources may involve service budgets, the availability of adequately qualified service personnel and the availability of spare parts.

Exclusion constraints are used when certain generating units are not allowed to be taken out of service simultaneously (*e.g.* two units in the same power station or too many units in the same geographical region).

Transmission/network constraints have been incorporated recently and seek to ensure the transmission capabilities of the electrical network (*e.g.* maintaining voltage levels) or that a power station meets the demands of the geographic regions within its service area via the transmission network infrastructure.

Maintenance plans usually span an annual time horizon [10, 15], but this can vary, and planning horizons in the literature range from eight weeks to five years. Common time intervals include one week [10], but this also varies with values ranging in the literature from single-day and five-day to monthly intervals [15].

2.2 Solution techniques

According to [1, 15] the most prevalent solution methods applied to solve instances of the GMS problem include heuristic search algorithms, mathematical programming techniques, dynamic programming, expert systems, fuzzy systems, and metaheuristics:

Heuristic search algorithms search and improve upon the quality of solutions based on trial and error, and are comparatively seldom used [1] due to the inferior quality solutions that they often produce.

Mathematical programming techniques are typically used for single objective instances of the GMS problem, and mostly include variations of the branch-and-bound method. Further methods include the generalised reduced gradient algorithm for nonlinear programming problems and successive linear programming, amongst other methods.

Dynamic programming ideally suits the temporal nature of maintenance scheduling problems [15] and has been used in the context of the GMS problem in [7, 8].

Expert systems develop an automated solution methodology by imitating the many years of experience of experts in the field [16].

Fuzzy set theory is employed to address multiple objectives and uncertainties in the constraints [16] and has been used in [4, 7].

Metaheuristics are used when the dimensions of a GMS problem instance increases to the point where exact solution methodologies take too long to implement. These techniques then often obtain very good (although not necessarily optimal) solutions within more acceptable computation time frames. Recently, metaheuristics have been used to solve GMS problem instances close to optimality within very limited computational times [15]. Typical metaheuristics applied to the GMS problem include genetic algorithms, simulated annealing, tabu search and ant colony optimisation.

3 Proposed adaptations to the GMS problem

We propose to build upon previous GMS-related work, most notably by Schlünz [15], by incorporating two important additional notions into the GMS problem formulation, namely (1) the level and quality of fuel stockpiles used for electricity generation and (2) unplanned and other loss factors related to energy generation.

In addition, we also advocate the simultaneous adoption of two main scheduling objectives, namely to seek acceptable trade-offs between minimising the cost associated with a generator maintenance schedule and maximising the reliability of the generating programme which results from a maintenance schedule.

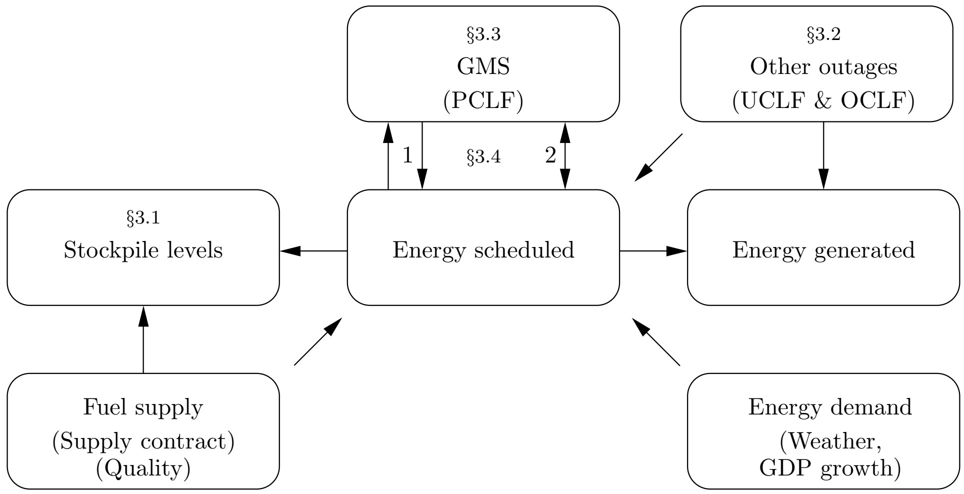

Figure 1: *Interactions between the GMS problem and the typical supply chain components of a national power utility.*

Further elucidation of how this improved GMS formulation is expected to interact with the most important components of a typical simulation model of a power utility's energy supply chain may be found in Figure 1.

3.1 Including fuel reserves in the formulation

It is important for a power utility to plan and adequately manage its fuel stockpile levels, because excess quantities of coal (one of the main fuel types used; the others being natural gas, water and uranium [15]) constitute an asset which is not producing revenue and hence incurs lost interest charges. Large coal stockpiles also require more careful management to ensure that the commodity is stored safely and does not deteriorate unduly [20]. One major problem experienced is that the coal sometimes becomes too wet as a result of intentional irrigation so as to avoid the possibility of spontaneous combustion within a stockpile [2]. Significantly increasing the moisture level of coal can reduce its combustion efficiency [15, 20]. Further coal-quality deterioration can occur on sunny days or as a result of intermittent rain [2].

Very low levels of stockpiles, on the other hand, raise the risk of a generating unit running out of fuel, which means that it will not be able to meet its expected demand [20].

The fuel stockpile of a coal power station, for example, varies according to the conservation law

$$\begin{pmatrix}\text{Stockpile levels}\\ \text{at end of period } t\end{pmatrix} = \begin{pmatrix}\text{Stockpile levels}\\ \text{at start of period } t\end{pmatrix} + \begin{pmatrix}\text{Coal delivered}\\ \text{during period } t\end{pmatrix} - \begin{pmatrix}\text{Coal burnt}\\ \text{during period } t\end{pmatrix}, \quad (1)$$

where

$$\begin{pmatrix}\text{Coal delivered}\\ \text{during period } t\end{pmatrix} = \begin{pmatrix}\text{Coal contract}\\ \text{during period } t\end{pmatrix} \pm \begin{pmatrix}\text{Delivery uncertainty}\\ \text{during period } t\end{pmatrix} \quad (2)$$

and

$$\begin{pmatrix}\text{Coal burnt}\\ \text{during period } t\end{pmatrix} = \begin{pmatrix}\text{Energy generated}\\ \text{during period } t\end{pmatrix} \times \left(\frac{\text{Heat rate}}{\text{CV}}\right). \tag{3}$$

In (3), the *calorific value* (CV) [measured in MJ/kg] is the potential energy locked up in the coal that can be converted to actual heating ability. The *heat rate* [measured in MJ/kWh] is the amount of thermal energy required to generate one KWh of electrical energy [10] and thus indicates a generating unit's efficiency to convert its fuel to electricity. Finally, the *energy generated* in (3) is governed by the relationship

$$\begin{pmatrix}\text{Energy generated}\\ \text{during period } t\end{pmatrix} = \begin{pmatrix}\text{Energy scheduled}\\ \text{during period } t\end{pmatrix} + \begin{pmatrix}\text{Additional load}\\ \text{during period } t\end{pmatrix} - \begin{pmatrix}\text{Outages}\\ \text{during period } t\end{pmatrix}. \tag{4}$$

The *energy scheduled* in (4) is usually determined by solving the problem of meeting specific electricity sector demands from the power generating units that are not scheduled for preventative maintenance during period t.

It is proposed that both the qualities and levels of fuel stockpiles should be taken into account when solving the GMS problem. It may, for example, be advantageous, in terms of time bought for stockpile replenishment to move the service time of a generating unit forward (within its window of acceptable service times) if its stockpile level or quality is observed to be dangerously low. Previous work by Schlünz and Van Vuuren [16, 17] did not include these values, but assumed that stockpile levels would always be within adequate margins.

3.2 Including generation loss factors in the formulation

Outages are a function of the *planned capability loss factors* (PCLFs), the *unplanned capability loss factors* (UCLFs), *other capability loss factors* (OCLFs) and the installed energy. This function often takes the form

$$\text{Outages} = (\text{PCLF}+\text{UCLF}+\text{OCLF}) \times \text{Installed energy}, \tag{5}$$

where PCLFs are power generation losses specifically planned by the management of a power utility for maintenance purposes and other shutdowns, UCLFs include losses due to weather conditions and transmission line failures, and OCLFs are other losses due to events outside the control of the management of a power utility [11]. The *installed energy* in (5) is the combined generating capacity of all generating units under consideration.

Schlünz and Van Vuuren [16] took unplanned and other capacity loss factors into account by representing them all as a single safety factor. However, we propose a more detailed analysis of what these values typically are, and incorporation of the *outages* value in (5) into the GMS problem formulation.

3.3 Adopting a multi-objective optimisation approach

Simulated annealing has previously been used [3, 4, 14] to solve instances of single-objective formulations of the GMS problem. We propose rather formulating the problem as a bi-objective problem, simultaneously minimising the cost associated with generator maintenance scheduling and maximising the reliability of the resulting generating programme, and using a multi-objective version of a neighbourhood metaheuristic search technique, such as simulated annealing, to find acceptable trade-offs between the values of these objectives.

3.4 Analysis of interaction with other simulation models

It is important to note that energy scheduled and power loss outages in (4) have further interlinked inputs and outputs in the energy supply chain of a power utility, as illustrated in Figure 1. The generator maintenance scheduling problem is typically solved based on parametric values representing the amount of energy generation required, or scheduled, at a power station. These values are, in turn, determined by the maintenance schedule's output, in terms of expected outages. This interaction is one-way (the arrows labelled 1 in Figure 1), *i.e.* when solving for typical decision variables of the energy scheduling problem the maintenance schedules of the various generating units are incorporated into the model as parameters, not as linked decision variables, and *vice versa*. However, we propose that these operational decision components interact dynamically (the arrow labelled 2 in Figure 1) within such a simulation and/or optimisation framework.

4 Feasibility of the proposed approach

The authors plan on demonstrating the feasibility of the GMP model formulation enhancements proposed in §3 in a real South African case study. The case company currently utilises a state-of-the-art computerised simulation tool, called the *Energy Flow Simulator* (EFS) in aid of long-term and strategic decision making [19]. This tool is currently capable of simulating the entire energy supply and demand chain in South Africa, and contains components simulating different weather conditions and economic trends, energy load scenarios, the quality and quantity of the national coal stockpile and the effectiveness of energy generation schedules for the different generating units [12, 19]. The EFS, however, does *not* currently have the capability of incorporating generating unit maintenance scheduling in its energy generation planning component. It is within the existing framework of the EFS that the authors plan to implement the above-mentioned enhanced GMP model formulation. This framework will allow for adequate testing of the robustness and efficacy of simultaneous schedule production for energy generation and generator unit maintenance downtimes.

5 Conclusion

In this paper, we proposed a number of adaptations to typical formulations of the GMS problem. Two of these adaptations were concerned with improvements to the level of realism of the formulation (incorporating the quality and level of the fuel stockpile associated with each generating unit and including a suite of power generation loss factors). Further adaptations were related to the paradigm in which the optimisation takes place (a bi-objective optimisation approach was suggested) and the way in which the inputs to and the outputs from the GMS problem interact with other components of the energy supply chain of a power utility. The paper is a report on work in progress within a larger research project at Stellenbosch University. The next step in this research project will be to attempt implementations of these adaptations, starting with the fuel stockpiles.

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