



# Tri-objective generator maintenance scheduling for a national power utility

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## Abstract

Providing reliable energy 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 power system. The well-known *generator maintenance scheduling* (GMS) problem is the problem of finding a schedule for the planned maintenance outages of generating units in a power system. A novel tri-objective model formulation is proposed for the GMS problem in this paper. The first (and most commonly adopted) objective involves minimising the squared reserve levels, which serves to create an even (“reliable”) margin of generating capacity over and above expected demand. The second objective involves the production cost associated with a maintenance plan for the generating units in a system, where planning maintenance of a power generating unit which is cheap to operate during a high demand period will incur a higher production cost. The third objective involves minimising the risk (on expectation) of generating units breaking down, where the longer the time period since the last maintenance service of a generating unit, the larger the risk of it breaking down.

**Key words:** Energy sector, Maintenance scheduling, Multiple objective optimisation, Reliability.

## 1 Introduction

Power outages in South Africa are mainly brought about by higher than expected demand, infrastructure failure, and a diminishing reserve capacity (available capacity over and above demand). The reserve margin for generating capacity has decreased in recent years from the desired 15% to less than 8% [11]. As a result, South African power stations have recently been forced to operate virtually continuously at high load factors (how near to maximum a plant is operating on a percentage basis). In addition, the generating units

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of South African power stations are relatively old, which means that they require above-average levels of maintenance. These two aspects contribute significantly to the prevalence of unplanned outages [24]. Appropriate preventative maintenance planning is crucial to mitigate the above risks and is one of the key focus areas for a power utility [3, 5, 13, 18] — especially for a power utility such as the South African utility, which has been postponing maintenance plans on its already ageing stations [6].

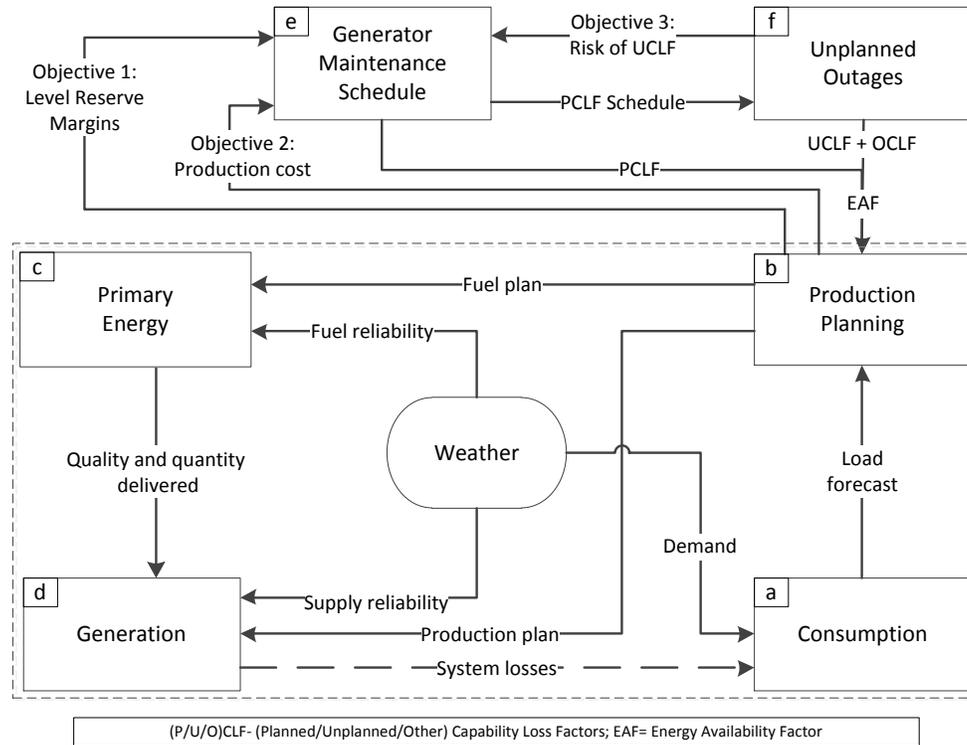
A schedule for the planned maintenance outages of generating units in a power system is sought in the well-known *generator maintenance scheduling* (GMS) problem [22] and we propose a novel tri-objective model formulation for the GMS problem in this paper as well as how solutions to this problem may be included in a national power utility’s decision support software.

The paper is organised as follows. The working of typical energy flow simulators is described in §2, after which a brief survey is conducted in §3 of existing single and multi-objective model formulations of the GMS problem. This is then followed by a methodology section (§4) in which our novel tri-objective approach towards formulating the GMS problem is described. Preliminary GMS results are presented in §5, and this is followed by a discussion on possible future work in §6.

## 2 Energy flow simulators

Power utilities often use decision support software tools in the form of energy flow simulators in which the entire energy supply chain is modelled “from fuel to fridge.” The working of and various constituent components of such a software tool are elucidated in Figure 1. An energy flow simulator is typically designed to function as a what-if analysis tool in the context of possible different future scenarios. This allows for the accommodation of different *Energy Availability Factors* (EAFs) per power station, different weather patterns, a variety of *Gross Domestic Product* (GDP) levels, varying supply levels and qualities, *etc.* of generation fuel. The main simulation technique employed in such an energy flow simulator is typically Monte-Carlo simulation [8, 9, 16].

A simulation is typically initiated by a *consumption module* (Figure 1(a)) which forecasts the total energy demand per geographic region and customer type (residential, manufacturing, mining, *etc.*) according to some estimated level of GDP (high, medium or low) and weather scenario (hot, normal or cold). The demand thus forecast may then be used by a *production planning module* (Figure 1(b)) to schedule the planned energy production per power station (including coal, nuclear, gas-turbine, hydro-electric and renewable energy units) so as to minimise production cost. Demand must be met whilst taking into account production capacity. A *primary energy module* (Figure 1(c)) usually facilitates what-if analyses in terms of a variety of different plans and scenarios, including unplanned power station maintenance, and variation in the quality and quantity of generation fuel. The final main component is a *generation module* (Figure 1(d)). The production plan, supply reliability, and the quality and quantity of generation fuel are fed into a *generation module*, which then quantifies emissions, such as sulphur and nitrogen oxides. System losses are usually also incorporated into a typical energy flow simulator [9].



**Figure 1:** High-level representation of a typical energy flow simulator (dashed area) and how it is anticipated that the proposed GMS modelling approach may form part of it (adapted from [9]).

Energy flow simulators usually have no optimisation capacity (other than possibly in their energy production planning components (Figure 1 (b))). Many variable and parameter values employed within such a simulator are typically known to be sub-optimal, and hence there is a need to be able to optimise decision variables within such simulators [8]. The GMS modelling approach proposed in this paper has been designed specifically to allow for its incorporation into a typical energy flow simulator’s decision support software framework (see Figure 1(e)).

### 3 Literature review

The GMS problem is well-known in the operations research literature. The most prevalent solution methods applied to solve instances of the GMS problem include heuristic rules, mathematical programming techniques, dynamic programming, expert systems, fuzzy systems, and metaheuristics [1, 24]. Three dominant criteria are usually incorporated in formulations of the GMS problem, namely economic criteria, reliability criteria and convenience criteria [13, 25].

The most commonly adopted economic criterion consists of minimising the total operating cost associated with a generator maintenance schedule, including both energy production cost and maintenance cost [3]. The most popular reliability-related objectives, on the

other hand, are to minimise the expected lack of peak net reserve, to minimise the expected energy not supplied and to minimise the loss of load probability [3]. Examples of convenience-related objectives include minimising soft constraint violations or minimising possible disruptions to the power generation schedule [24]. These three categories of objectives are conflicting, ultimately making the GMS problem multi-objective in nature. Both single and multi-objective formulations have, however, been proposed for the GMS problem in the literature [25].

### 3.1 Single-objective GMS formulations and solution methodologies

In single-objective GMS problem formulations the two dominant objectives usually involve economic or reliability criteria, with some authors including other objectives as constraints [13, 25].

Single-objective GMS formulations incorporating economic criteria (operating cost of some composition) are widespread [24], with Canto [2] adopting a 0/1 mixed integer linear programming approach and applying Bender's decomposition, Edwin & Curtius [7] following an integer linear programming model approach, and Mromlinski [19] preferring an integer programming model formulation and solving it with the branch-and-bound method.

Reliability criteria may either be modelled in a deterministic or stochastic fashion [18]. The most commonly adopted reliability-related objective is levelling the reserve load over all the time periods, which is generally achieved by minimising the sum of squares of the reserve [18, 26]. This approach has successfully been followed in [3, 4, 18], for example. In these studies, metaheuristics were employed as approximate solution techniques (typically a genetic algorithm, simulated annealing or a hybrid of the two). An alternative reliability-related objective is to maximise the minimum reserve during any time period.

We are not aware of any work in the literature in which single-objective formulations of the GMS problem involve only convenience criteria. The multi-objective formulations in [12, 14, 15], however, include it as an optimality criterion within a multi-objective modelling paradigm, as described in the following section.

### 3.2 Multi-objective GMS formulations and solution methodologies

Huang *et al.* [10] used fuzzy dynamic programming to solve instances of a bi-objective GMS model formulation in which the objectives were to level the reserve margins (a reliability criterion) and to minimise the lost opportunity production cost of generating units undergoing maintenance (an economic criterion). Goal programming was used by Munoz & Ramos [20] to solve instances of another bi-objective GMS model formulation involving thermal generating units under both economic and reliability criteria.

Leou [15] combined a genetic algorithm with the method of simulated annealing to solve a GMS model with objectives including convenience criteria (minimisation of reliability and cost constraint violations) and economic criteria (cost of operation and maintenance).

Krajl [12, 14] used the multi-objective branch-and-bound algorithm to solve instances of a tri-objective GMS model formulation including an economic objective (minimisation of

fuel costs), a reliability-related objective (minimisation of the expected unserved energy over time) and convenience-related objectives (minimisation of constraint violations).

## 4 Proposed modelling approach

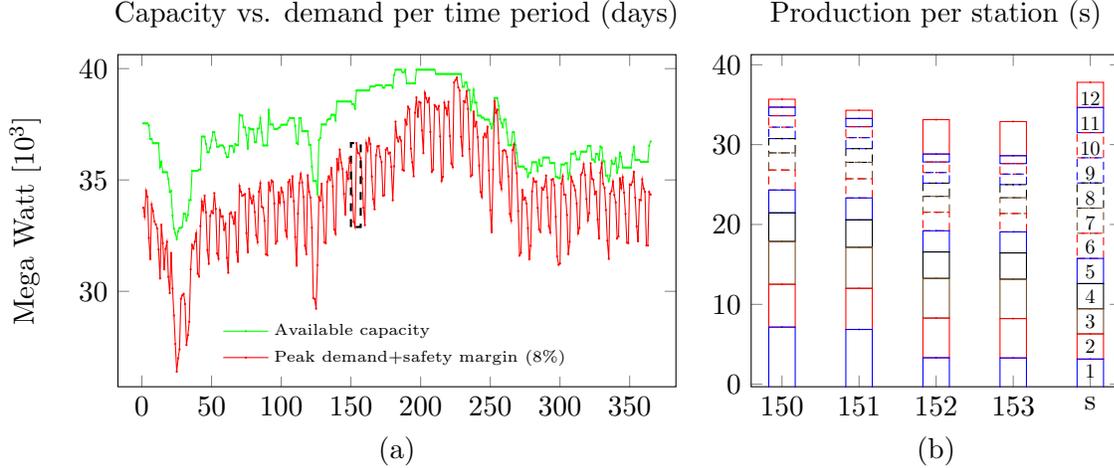
As we previously suggested in [16], a multi-objective modelling approach is required in the context of GMS because of the inherent trade-offs between the conflicting scheduling objectives. The three objectives we propose for inclusion in a GMS formulation are two common objectives found in the literature on GMS, namely levelling reserve margins and minimising production cost, together with the novel objective of minimising the risk of generating unit failure.

A maintenance schedule is defined as follows. Suppose there are  $n$  generating units in the power system and  $m$  time periods during the planning horizon. Let  $\mathcal{I} = \{1, \dots, n\}$  be the set of generating units and let  $\mathcal{J} = \{1, \dots, m\}$  be the set of time periods. Finally, define the binary decision variable  $x_{ij}$  to take the value 1 if maintenance of generating unit  $i \in \mathcal{I}$  commences during time period  $j \in \mathcal{J}$ , or zero otherwise. Then a maintenance schedule is an assignment of zeros and ones to the  $n \times m$  matrix  $\mathbf{X} = [x_{ij}]$  of decision variables satisfying a variety of constraints, including maintenance window constraints, load constraints, resource constraints, and exclusion constraints amongst others [16].

We propose the use of simulated annealing for computing high-quality maintenance schedules as the method has been adopted successfully a number of times in the GMS literature [3, 22, 23, 25]. The simulated annealing hybrid developed by Schlünz and van Vuuren [25] has outperformed a genetic algorithm and genetic algorithm/simulated annealing hybrid, and has matched the best known solution found via ant colony optimisation in the context of documented case studies [25]. An innovative multi-objective simulated annealing algorithm, developed by Smith *et al.* [27, 28] may be used to find a maintenance schedule, as described above, which achieves acceptable trade-offs between the three objectives proposed here. In this approach, the conventional “energy” difference between a current and neighbouring candidate solution in standard single-objective simulated annealing algorithms is replaced by a measure of the difference in dominance (in terms of an archived non-dominated front).

### 4.1 Objective 1: Levelling of reserve margins

We endorse the standard objective of levelling the reserve energy over and above demand over all time periods by minimising the sum of squared reserve margins over time [25]. The reserve margin during a particular time period is the difference between the available capacity and the expected demand (see Figure 2(a)). Minimising this sum of squared reserve margins results in an even (“reliable”) band of reserve margins. Let  $r_j$  represent the reserve margin during time period  $j$ . Then this objective involves minimising  $\sum_{j=1}^m r_j^2$ .



**Figure 2:** (a) Available capacity versus peak demand (including an adequate safety margin) from a hypothetical South African case study [26]. The difference between these two is the reserve level (used in the first objective). (b) Output of a typical energy flow simulator’s production planning module (used in the second objective). 1-Cheapest power station, 12-Most expensive power station (measured in R/MWh).

## 4.2 Objective 2: Minimising production cost

As mentioned, the production planning module of an energy flow simulator (see Figure 1(b)) typically schedules the planned energy production by making use of available power generating units (including coal, nuclear, gas-turbine, hydro-electric and renewable generating units) with a view to minimise production cost. Power stations associated with cheaper production costs are typically scheduled first until demand is met, whilst taking into account production capacities of the various power stations [9].

The production cost minimisation may be achieved using a linear programming model. The decision variables in such a linear programming model should represent the amount of energy production planned per power station (MW). Important model parameters should include the associated energy production rate (measured in R/MWh) and the *Energy Availability Factor* (EAF) of power station  $s$  during time period  $j$ , denoted by

$$\text{EAF}_{sj} = 1 - (\text{PCLF}_{sj} + \text{UCLF}_{sj} + \text{OCLF}_{sj}), \quad (1)$$

where  $\text{PCLF}_{sj}$  refers to power generation losses specifically planned by the management of a power utility for maintenance purposes and other planned shutdowns at power station  $s$  during time period  $j$ . Furthermore,  $\text{UCLF}_{sj}$  refers to breakdowns (often as a result of a lack of planned maintenance) at power station  $s$  during time period  $j$ , while  $\text{OCLF}_{sj}$  refers to other losses due to extraordinary events outside the control of the management of the power utility at power station  $s$  during time period  $j$ , such as employee strikes or theft of transmission cables [8, 17].

To illustrate how a maintenance schedule may affect production cost, an example of a production plan is shown in Figure 2(b). If power station 1 (cheapest) has to undergo maintenance during days 152–153, this will increase its PCLF (as illustrated in Table 1), which will, in turn, decrease the station’s EAF in (1). This latter value is an input

parameter to the production planning module (in the form of capacity constraints in the linear programming model), translating into less energy production being scheduled for the station (although it is the cheapest power station), which will increase the overall production cost. The GMS solution approach should attempt (if possible) to ensure that maintenance of cost-efficient power stations does not occur during high energy demand periods.

**Table 1:** An example of how a maintenance schedule may affect a station's Planned Capability Loss Factor (PCLF) during time period  $j$ .

Power Station	Energy Production Rate (R/MWh)	Generating Unit	Maintenance Schedule	PCLF <sub><math>s_j</math></sub>
$s = 1$	110	$i = 1$	$x_{1j} = 1$	33.33%
		$i = 2$	$x_{2j} = 0$	
		$i = 3$	$x_{3j} = 0$	
$s = 2$	150	$i = 4$	$x_{4j} = 0$	50%
		$i = 5$	$x_{5j} = 1$	
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$s = 12$	2300	$i = 54$	$x_{54j} = 0$	0%
		$i = 55$	$x_{55j} = 0$	

### 4.3 Objective 3: Minimising risk of unit breakdown

The third objective proposed for inclusion in our GMS model formulation is a risk function. The objective quantifies the risk of generating unit breakdown associated with a specific maintenance schedule. Based on the schedule there will be an ever-increasing risk of generating unit breakdown per time period over which the unit has been operating continually without maintenance. The process of estimating the expected risk of breakdown of a power generating unit over time will involve obtaining and cleaning historical failure time series data for the unit. A trend test, such as the Laplace trend test, may then be performed on the data [21] in order to classify the power generating unit as either a repairable or a non-repairable system. After the units have all been classified in this manner, an appropriate lifetime distribution model may be chosen (such as an exponential or a Weibull model for non-repairable systems, or a *homogeneous poisson process* (HPP) or a *non-homogeneous poisson process* (NHPP) following an exponential or power law for repairable systems), based on the nature of the failure data of the power generating unit [29]. Next, the parameters for each model selected for each unit may be estimated by either the method of least squares or the maximum likelihood method.

It is advocated that the risk be weighted according to the importance of the power generating unit to the network as a whole, because some units may be more essential in respect of grid integrity, such as those that have the highest rated capacity. The risk of generating unit failure may, for example, be weighted according to the rated capacity of the unit.

In addition to the above objective, it is also proposed that the expected failure data of a unit should be used to constrain its maintenance window in the GMS problem. An earliest and a latest starting time are usually specified as input parameters (in the form

of maintenance window constraints) in traditional formulations of the GMS problem. We advocate that the decision maker should instead specify some maximum tolerable risk of generating unit failure and that this input parameter should rather be incorporated into the GMS formulation. Using these parameter estimates as described above, a time instant can be estimated at which the next failure of each unit is expected to occur. This time may then be used to identify a date before which the specific unit should be scheduled for planned maintenance so as to avoid UCLFs as far as possible.

## 5 Preliminary results

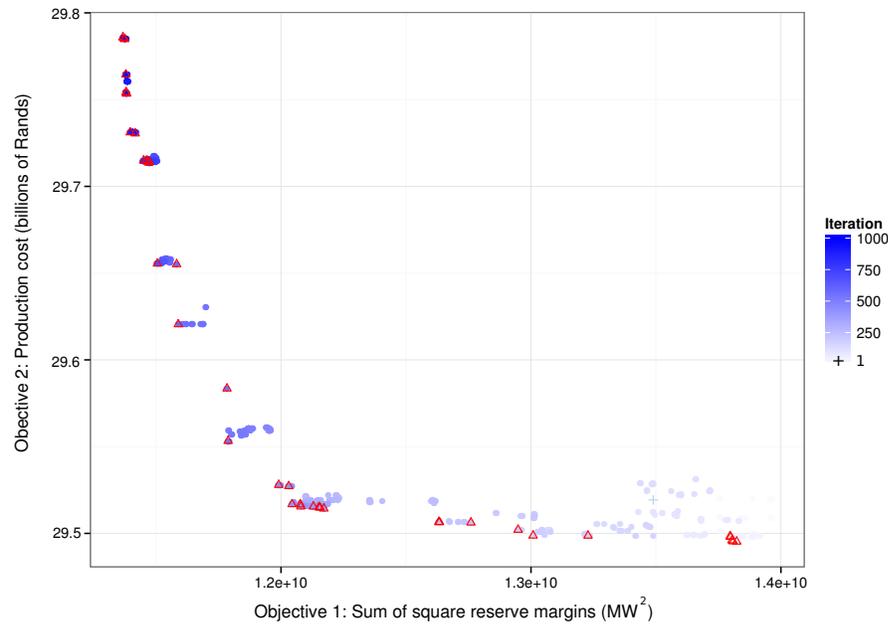
In 2012, Schlünz and van Vuuren [26] solved a hypothetical South African case study instance of the GMS problem with the single objective of levelling the reserve energy margins using the method of simulated annealing. The data included in their GMS problem instance do not represent the exact South African generation system due to confidentiality concerns, but the case study nevertheless represents a realistic GMS scenario. Constraints in the scenario were restricted to the adherence to maintenance windows, the system meeting the load demand together with a safety margin (Figure 2(a)), and respecting simultaneous generating unit maintenance exclusion constraints. The case study consists of a GMS problem instance containing 157 generating units requiring maintenance over a 365-day planning horizon. These dimensions are considerably larger than other test systems in the literature.

We used the same data set, but instead solved a bi-objective version of the GMS problem in which two of the three objectives proposed in §4 were pursued: minimising the sum of square levels of reserve margins and minimising the energy production cost associated with a maintenance schedule. Each maintenance schedule has an associated available capacity of the entire system of power stations (Figure 2(a)), which may be used to calculate the reserve margins for the first objective (the horizontal axis in Figure 3). In addition, the maintenance schedule per power generating unit may be translated into the PCLF for each station (as illustrated in Table 1) and may then be used by the linear programming model within the production planning module of the energy flow simulator (see Figure 1(c)) to construct an energy production plan and its associated cost (the vertical axis in Figure 3). These two outputs are the objectives we minimised. As may be seen in Figure 3, the bi-objective simulated annealing algorithm of Smith *et al.* [27, 28] converges towards the final non-dominated front over the course of 1 000 iterations.

## 6 Conclusion and future work

A novel tri-objective GMS modelling approach was proposed in this paper, which may easily be incorporated into a national power utility's decision support software. Preliminary results found by solving a problem instance including two of the proposed three objectives seem to indicate that the modelling approach and proposed solution methodology are capable of producing a sensible non-dominated front of solutions in objective space.

The work reported in this paper forms part of a larger, ongoing research project at Stel-



**Figure 3:** Optimisation results for two (of the three) GMS objectives proposed in this paper, namely the minimisation of the sum of squared reserve margins and the minimisation of energy production cost.  $\circ$  — Dominated solutions,  $\triangle$  — final non-dominated solutions.

lenbosch University aimed at providing support for the complex planning decisions of a power utility. The next step will be to conduct further experiments (by varying parameters and cooling schedules) of the multi-objective simulated annealing algorithm employed, in addition to collecting further data so as to be able to construct further real-life instances of the GMS problem for testing purposes. Also, the authors will begin to incorporate the third objective proposed. It is envisaged that the results of this GMS modelling approach may be incorporated into the energy flow simulation framework of Figure 1 as a GMS decision support software tool to be used by the managers of a national power utility.

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