# MATHEMATICAL MODELLING FOR SHORT TERM OPERATION PLANNING OF COGENERATION SYSTEMS

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## Contents



## Summary

The aim of short term operation planning of electricity supply or combined power and water cogeneration systems is to find the optimal operation performance by solving a unit commitment and a load dispatch problem. It defines the elements of cogeneration systems and explains the structure of the cogeneration network. The production processes and the interlinkages are described by input-output functions and operational and steam demand-supply constraints. As a result the system is represented by mathematical models using different programming techniques that can be used for formulating and solving the short term operational planning problem for cogeneration systems.

## 1. Problem Formulation

The aim of short term operation planning of electricity supply or combined power and water cogeneration systems is to find the optimal operation performance by solving a unit commitment and a load dispatch problem. Numerous solution procedures have been developed for electricity supply systems in the last decades. In recent years, the investigation of unit commitment and load dispatch have been expanded to cogeneration systems.

### 1.1. Introduction

The short term electricity demand is not constant throughout time but changes from day to day and hour to hour. The daily demand profile depends on the type of day which may be a normal working day, a semi-working day or a holiday. The hourly demand is influenced by factors such as domestic and economic activity levels, heating, air-conditioning and street lighting. The change of demand requires the planning of supply for one or some days ahead. The problem to be solved is known as unit commitment and consists of an operation scheduling and a load dispatch problem. The first one is to decide which of the operation available units are to be turned on in each hour of the planning period. The second one is to determine the operating capacities of the operating units to meet final demand at least cost. The unit commitment is therefore an optimization problem subject to system and unit constraints. On a system level, the constraints to be observed are the demand and the reserve requirements where the operating reserve must be sufficient to accommodate emergencies at short notice. At unit level, the operation is restricted by operation and availability constraints. The operation constraints refer to the minimum and maximum operating capacities and to prefixed output levels. In any hour of the planning period, a unit might be operation available, prescheduled for operation or not available due to prior failure or maintenance. The problem may further be complicated by dynamic constraints comprising minimum down-time and minimum up-time requirements and ramping restrictions. Another difficulty is added by considering start-up and shut-down costs.

The unit commitment problem is solved for one day ahead up to one week. The result serves as reference solution in real-time operation. In case of an increase or decrease in real-time demand, a load dispatch procedure is applied to adjust the output levels of the operating units to the real-time demand.

In real-time operation, the planning horizon is in the minute range. Therefore, the load dispatch procedure used in real-time operation must be very efficient to provide answers at a moment's notice.

### 1.2. Objectives

The principal components to be distinguished in cogeneration systems are boilers, generators and distillers. The production processes may be single purpose processes generating either power or water or dual purpose processes linking boilers, generators and distillers and producing power and water simultaneously. The processes are controlled by operation restrictions, the dual purpose production processes are subject to additional cogeneration constraints. The unit commitment for cogeneration systems becomes more complex than the one for power systems. It must not only take into account a considerable number of supplementary constraints but has to schedule and dispatch all the boilers, generators and distillers of the system.

Due to storage tanks, the water production in real-time operation is not influenced by a change in the water demand. Therefore, the load dispatch in real-time operation is similar to the one used in power supply systems and evaluates the output levels of the operating generators to meet the power demand at least cost. The only difference is that the operation costs and the capacity limits of the generators depend on the operation modes of the turbines which are either the single purpose power generation modes or the cogeneration modes.

In summary, the objectives of short term operation planning of combined power and water supply systems are defined as follows:

- Unit commitment: minimization of the operation costs of given sets of boilers, generators and distillers for a certain planning period subject to power and water demand, reserve requirements and to availability, operation, cogeneration and dynamic constraints.
- Load dispatch: minimization of the operation costs of a given set of operating generators subject to power demand, operation modes and operation constraints.

Unit commitment and load dispatch are constrained optimization problems. The constraints and the results to be provided by short term operation planning are schematically shown in Figure 1.

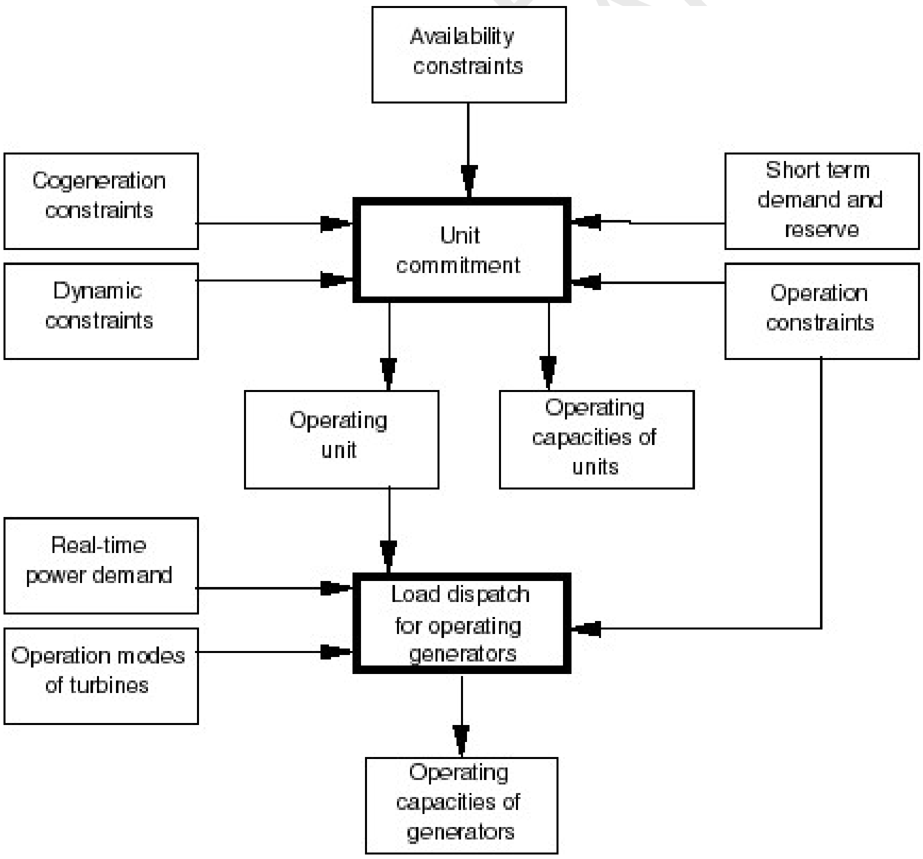


Figure 1. Constraints and results of short term operation planning.

The problems of short term operation planning are solved by identifying the system variables, formulating mathematical models for short system operation, unit commitment and load dispatch and finding optimal values for all system variables. The steps involved are:

- Analysis of system structure.
- Calculation of the operation costs by establishing functional relations between heat consumed and power and water supplied.
- Formulation of objective function and constraints for the unit commitment and load dispatch problem.
- Application of some mathematical method (incremental cost analysis, full load average cost principle, mixed integer linear programming, dynamic programming, principle of Lagrange, Lagrangian relaxation) to determine the least cost values of the variables involved.

## 2. Operation Costs

The objective functions to be minimized in short term operation planning consist of the operation costs of the units and cogeneration blocks.

Before deriving the operation costs of single purpose generation units and dual purpose cogeneration blocks, the structure of the cogeneration system must be investigated to describe the conversion of fuel into power and water by mathematical expressions.

### 2.1. Structure of Cogeneration Systems

Cogeneration systems consist of the following subsystems:

- The combustion system.
- The electricity generation system.
- The water production system.

The elements of the combustion system are the combustion chambers of diesel generators and gas turbines, the boilers with subsequent steam condensing or back pressure turbines, the boilers, auxiliary boilers and waste and exhaust heat recovery boilers for the water production and the waste heat recovery boilers of combined cycles.

The electricity generation system is composed of diesel generators, gas turbines without and with subsequent exhaust or waste heat recovery boilers, combined cycles, back pressure turbines without and with subsequent distillers and steam condensing turbines without and with turbine steam extraction. The principle components of the water production system are the brine heaters, multi-stage flashes, ejectors and the water and brine recirculation pumps of the distillers.

As indicated in Figure 2, the combustion system provides combustion gas and steam to be converted into power and water. The electricity generation system satisfies the power demand and supplies exhaust gas to the waste and exhaust heat recovery boilers and turbine steam to the brine heaters. The output of the water production system is potable water to be stored or be consumed.

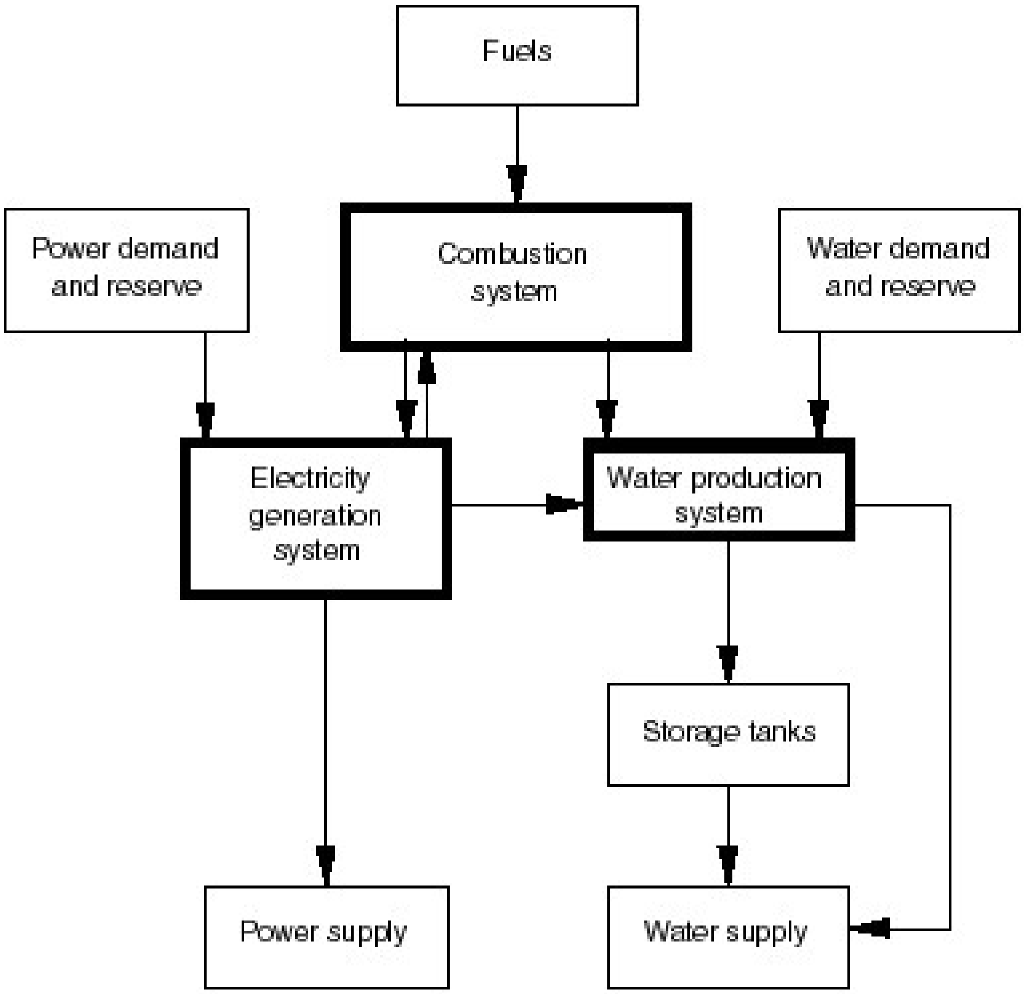


Figure 2. Structure of cogeneration system.

The system comprises single purpose generation units, combined cycles and dual purpose cogeneration blocks. The combustion, electricity generation and water production systems of cogeneration blocks are connected by high and low steam pressure headers. The operation costs are derived in the next chapter for the following units and cogeneration blocks:

- Single purpose diesel generators, steam condensing turbines, back pressure turbines and gas turbines.
- Single purpose desalination units.
- Combined cycles.
- Cogeneration blocks of gas turbines, waste and exhaust heat recovery boilers, auxiliary boilers and distillers.
- Cogeneration blocks of boilers, steam condensing and back pressure turbines and distillers.
- Cogeneration blocks of boilers, steam condensing turbines and distillers.

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