Economic Dispatch from Cogeneration:  
An Evolutionary Computation Approach

Cameron Algie

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Abstract

Cogeneration is the conversion of one energy source into two or more different forms of useful energy. Today it commonly refers to the generation of electricity and "process" steam from a single generation unit. The preferred technology is natural-gas-fired gas turbine generator and heat recovery steam generator packages. Conventional, (steam expansion turbines) cogeneration options have been in use since the late nineteenth century and are viable options for some industries.

Industrial sites and large residential complexes that generate electricity to meet their own demands, rather than importing power from utilities, are known as independent power producers. When these producers also have large thermal energy demands cogeneration can be an attractive option. Deregulation and privatisation of state owned, integrated utilities since the 1980s has allowed IPP to expand into retailing their excess power capacity through host-utilities joint ventures, competitive pools / markets, or direct to the public through electricity supply brokers. This recent development of deregulation and open market policy for electricity supply has focused attention on the economic dispatch problem for independent power producers operating cogeneration systems.

In electrical engineering, economic dispatch is the problem of finding the outputs of a set of generators to meet power demands for the minimum possible fuel cost. For cogeneration systems there must be at least one cogeneration unit present, and a heat / thermal energy demand must be met simultaneously as well as the power demand. Cogeneration units' heat and power outputs are non-separable, making the cogeneration economic dispatch considerably more complex than the standard, power-only economic dispatch problem.
This thesis is an investigation of the heat and power dispatch problem for cogeneration systems, involving the development of an evolutionary programming algorithm to solve this class of problem. Evolutionary programming, an evolutionary computation optimisation methodology, was chosen as the optimisation method due to the improved accuracy it can offer system operators compared to first-derivative, quadratic-programming-based solution methods. The Cogeneration Economic Dispatch – Evolutionary Program ("CED-EP"), which implements the algorithm, has been validated on a test system.

Subsequent to validation of the base algorithm, the impact of an evolution computation acceleration technique, Analytical Solution Acceleration, has been investigated.

Cogeneration dispatch is a relatively new field of research; currently there are no standard test problems or modelling protocols. As part of this research, the cogeneration combined heat and power feasible operating region models have been examined in terms of thermodynamics. A new test system and accompanying set of test cases solutions has also been created.
Summary of Original Contributions

Below is a summary of the original contributions made in the course of this research.

(a) An evolutionary programming based algorithm for combined heat and power, i.e. cogeneration, dispatch (CHPD) problems. Developed parallel to this is a comprehensive input format for fully specifying CHPD problems. (Chapter 3, Appendix A)

(b) The developed algorithm has been specifically tailored to the constraints of the CHPD problems. Mechanisms of particular note include: a random loading procedure for cogeneration units during the creation of the initial population; a combined dispatch order for multiple generator types (steam-only, power-only, cogeneration units); and an advanced gene mutation process that satisfies the FOR constraint of cogeneration units. (Chapter 4)

(c) The developed algorithm, CED-EP, has been validated on a simple, published test system. A new test system better suited to general CHPD problems has been developed. (Chapter 5)

(d) The impact of using the analytical solution acceleration technique in conjunction with CED-EP has been investigated. (Chapter 6)

(e) A detailed explanation of current cogeneration unit FOR models and a reduced gas turbine heat recovery steam generator (GT-HRSG) model have been developed. (Chapter 7)

The majority of these contributions have been published, either partially or in full, during the course of the research. The publications are listed below.
Chapter 5


Chapter 6


Chapter 7

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Glossary

EC Evolutionary Computation
EP Evolutionary Programming
ES Evolution Strategy
GA Genetic Algorithm
ASA Analytical Solution Acceleration
ED Economic Dispatch
CHPD Combined Heat and Power Dispatch - also "CED"
CED Cogeneration Economic Dispatch – also CHPD
IPP Independent Power Producer - also "On-site Power Producer"
MWe Megawatt of Electricity - i.e. "Active Power"
MWth Megawatt of Thermal Energy - usually in the form of steam
POC Products of Combustion
GT Gas Turbine
HRSG Heat Recovery Steam Generator
GT-HRSG Gas Turbine and Heat Recover Steam Generator package
CHP Combined Heat and Power – also "Cogeneration"
CCGT Combined Cycle Gas Turbine – power only set up of GT-HRSG package
FOR Feasible Operating Region – applies to cogeneration units
FDR Feasible Demand Region – applies to cogeneration systems
List of Principal Symbols

Generation Unit Variables

pi \quad \text{Electrical power output of } i^{\text{th}} \text{ generation unit, real-value MWe}

p_{\min} \quad \text{Minimum electrical power output of } i^{\text{th}} \text{ generation unit, real-value MWe}

p_{\max} \quad \text{Maximum electrical power output of } i^{\text{th}} \text{ generation unit, real-value MWe}

p'_i \quad \text{Marginal cost of power production of } i^{\text{th}} \text{ generation unit, real-value "$"}

p'_i \quad \text{Scaled electrical power output of } i^{\text{th}} \text{ generation unit, } [0,1]

h_i \quad \text{Thermal power output of } i^{\text{th}} \text{ generation unit, real-value MWth}

h_{\min} \quad \text{Minimum thermal power output of } i^{\text{th}} \text{ generation unit, real-value MWth}

h_{\max} \quad \text{Maximum thermal power output of } i^{\text{th}} \text{ generation unit, real-value MWth}

h'_i \quad \text{Marginal cost of heat production of } i^{\text{th}} \text{ generation unit, real-value "$"}

h'_i \quad \text{Scaled thermal power output of } i^{\text{th}} \text{ generation unit, } [0,1]

System Variables

P \quad \text{Electrical power demand of a system's generation units, real-value MWe}

P_{\min} \quad \text{Minimum possible electrical power demand of a system, real-value MWe}

P_{\max} \quad \text{Maximum possible electrical power demand of a system, real-value MWe}

P' \quad \text{Scaled electrical power demand of a system, } [0,1]

H \quad \text{Thermal power demand of a system's generation units, real value MWth}

H_{\min} \quad \text{Minimum possible thermal power demand of a system, real-value MWth}

H_{\max} \quad \text{Maximum possible thermal power demand of a system, real-value MWth}

H' \quad \text{Scaled thermal power demand of a system, } [0,1]
Chapter 1

Introduction

1.1 The Modern "IPP CHPD" Problem

On-site, or independent, power producers (IPP) have played a continuous role in electricity markets since Thomas Edison retailed the first metered power in 1882. Due to the short distance (about 1 mile) inherent in low-voltage DC power transmission, all electric power was effectively IPP generated. By the early 1900s, centralised, utility-supplied AC power generation and long-distance transmission networks had been developed. Due to economies of scale made possible by use of steam expansion turbines and AC/DC converters, most small, DC IPP generation had been replaced by centrally supplied AC power.

Commercial issues, e.g. price, power quality and guarantee of supply, were sufficient to make IPP a viable option for electricity-intensive industrial plant operators. Nationalisation and / or government regulations of the power supply industry during the inter-war period saw the further decline in the need for IPP. The very large capital costs associated with power plant construction meant that largest of IPP DC plants did not become obsolete until the 1940s. Between the mid-1940s and the 1980s IPP generation was restricted to niche markets, these include geographically isolated operations, very energy intensive refining and backup for vital infrastructure, e.g. hospitals, defence bases, etc.

In last two decades there has been a global shift away from centralised government control of public infrastructure (telecommunications, railroads, electricity, gas, etc.) to free-market models. This was greatly accelerated by the end of communism in the former USSR, and is epitomised by the European Union’s attaching market reform requirements to former-East European countries’ applications for membership [5-7].
Economic dispatch from cogeneration

Primarily disintegrating monopolistic, regional utilities to multiple, separate electricity retailers and power generators competing in regions have implemented market reform. Though not always the case, open market policy was meant to accompany the establishment of these competitive markets. Open market policy is reduction of entry barriers to new electricity generators and retailers entering the markets. Under free-market conditions, stable prices, guarantee of supply, adequate network transmission and generation capacity expansions are no longer a certainty. Into this environment IPP, particularly from high-efficiency gas turbine generation sets, is re-emerging as an attractive option for users with high electricity demands.

Gas turbines (GT) use products of combustion (POC) directly as their working fluid. After POC have lost pressure due to the expansion turbine stages, they are still very hot, and can be used to raise steam for process heat in cogeneration set-ups, or to superheat steam for further power generation in combined-cycle power generation set-ups. Conventional cogeneration, or combined heat and power (CHP), options using steam-expansion turbines and steam tapping, rather than GT, are also available and are used widely in regions where natural gas is in short supply and / or expensive. Steam transmission networks are limited in range, so steam has to be generated on-site to meet industrial thermal loads. Industries that require significant amounts of heat for production processes (primarily paper producers, petrochemical and mineral refineries) are natural candidates for also producing their own power.

Economic dispatch is the problem of finding the outputs of a set of generators to meet power demands for the minimum possible fuel cost. Cogeneration systems have thermal and electrical power demands that must be met simultaneously. This thesis investigates the problem of economic dispatch (ED) for cogenerating IPP, i.e. the IPP CHP Dispatch (CHPD) problem, through the development of a solution algorithm for this type of problem.

1.2 Literature Review

The literature review undertaken as part of this research focussed on five areas of study. Three primary areas of investigation were comprehensively reviewed: cogeneration / CHP research; existing ED approaches and modelling techniques; and evolution
computation (EC) optimisation methods. Two secondary areas of study were encountered in the course of this research: EC optimisation technique acceleration; and CHP unit output modelling.

1.2.1 Cogeneration Research

Cogeneration did not get much attention in engineering literature until the early 1980s. Four factors led to an increase in interest: the 1973 Oil shock, the "PURPA" efficiency incentives, the "DARPA" jet engine research, and the tapping of Alaskan natural gas fields.

When the Organization of Petroleum Exporting Countries (OPEC) raised oil prices arbitrarily in 1973 it became imperative for utilities around the world to invest in alternatives to oil for thermal generation, and to utilise ways of increasing efficiency. Natural-gas-fired GT-based combined-cycle and cogeneration was briefly embraced in the US and Europe. In the late 1970s it was commonly believed that there were not enough exploitable natural-gas reserves left in the world, on this basis power utilities were prevented from commissioning new gas-fired plant. Gas turbine manufactures, with the exception of General Electric, stopped gas turbine research and development programs.

In the face of oil supply uncertainty and natural gas shortages, the US government passed the Public Utilities Regulatory Policies Act of 1978 (PURPA), containing carrot-and-stick incentives to utilities and IPP to use fossil fuels more efficiently. Between 1980 and 1983 cogeneration feasibility studies were a hot topic in the literature [8-14].

However, the interest had dwindled again by 1983: the natural gas fields of Alaska had been tapped and other deposits were being located around the world. Efficiency was no longer the issue it had been and utilities were free to use gas firing again. During this period the U.S. Reagan administration, through the US Defense Advanced Research Projects Agency (DARPA) fast-tracked the development of new, high-temperature-resistant jet engine components. General Electric, having maintained a GT development program, benefited greatly from this, and by the mid 1980s adapted their DARPA-
funded research to commercial aviation jets and a new generation of high-efficiency stationary GT: cogeneration was about to experience another boom.

In the late 1980s Western Europe, having secured its own natural gas supplies, allowed natural gas firing of power stations again and ABB and Siemens recommenced European-based GT development. There was renewed interest in cogeneration, or combined heat and power, for use as on-site supplementation of utility / pool imports [5-7].

Through the 1990s the focus has switched IPP dispatch [18-22], although there has also been interest in urban planning [23], Fuel Cell technology [24-27] and distributed / embedded generation co-ordination [28].

1.2.2 Economic Dispatch

In the power industry economic means "lowest fuel cost", and dispatch refers to coordinating the outputs of a set of on-line generators to the meet a demand. Extensions of the economic dispatch problems [29-36] are the unit commitment and economic scheduling problems. Unit commitment looks at which generation units should be in the set of generators that are on-line to meet power demands, and economic scheduling problems look at what outputs generators should have to meet a series of demands in consecutive scheduling intervals.

Emerging in the early 1970s concerns over the environmental impact of emission from fossil fuel fired power stations led to the formulation of the emission dispatch problem [37-42]. This has since been combined with the standard economic dispatch problem to from the environmentally constrained economic dispatch problem [43-60].

1.2.3 Non Linear Programming Methods

Analytic, non-linear programming (NLP) techniques such as Quadratic Programming [21, 33, 34, 61], Dual Programming [19], and Lagrangian Relaxation [18, 46, 52] have been successfully applied to standard and cogeneration dispatch problems. These methods are suited to problems containing continuous, monotonic functions. Most
models used in the power dispatch problems are limited to quadratic functions [32, 42, 44, 45, 46, 54, 58, 62], but some use cubic monotonic, continuous functions [37, 46].

Piecewise, discontinuous functions [29, 35, 47, 48, 62] offer greater accuracy than continuous monotonic generator output models. Non-linear programming techniques can be adapted to accept piecewise functions [34].

1.2.4 Evolution Computation Methods

Evolution computation [63-66] is a very powerful optimisation tool. Using gene pools of individuals, these methods can perform parallel searches of complex search spaces, containing non-linear functions and / or discontinuities, quickly and efficiently to locate global optima. The individual search paths are evolved, via emulation of elements of biological evolution, iteratively over a number of generations.

Monotonic polynomial functions smooth out the "bumps", such as valve points in thermal generation stations, and hence cannot guarantee finding the genuine, "physical" optimal settings. By using EC optimisation methods, discontinuous and non-monotonic function models, such as "polynomial + sine" models [29, 30], can be used in systems models; these modelling techniques are more accurate and systems utilising them are more likely to find the real-world optimal operating settings for economic dispatch problems.

Evolution computation optimisation methods developed with the proliferation of computers since the 1960s. Two branches in particular are applicable to non-linear optimisation problems: genetic algorithms (GA) and evolutionary programming (EP). Both of these techniques have been successfully applied to power dispatch problems. Concepts from the related fields of simulated annealing and evolution strategies have also been incorporated into these areas of research.

Evolution Computation methods had been successfully applied to the standard, thermal electricity generation-only, economic dispatch problems prior to the commencement of the present research: EP [22,43], GA [45, 48], and GA / simulated annealing hybrids [30]. A visiting researcher to the Artificial Intelligence and Power Systems research
group in The University of Western Australia published a paper incorporating elements of evolution strategies into EP for hydrothermal economic dispatch [67].

1.2.5 Solution Acceleration Techniques

After successfully developing a CHPD-tailored EP algorithm, the effectiveness of generic, "population" acceleration technique was investigated. The virtual population acceleration methodology [68] contains two acceleration techniques suitable to EP, GA and evolution strategies, analytical and numerical solution acceleration. Virtual populations have been successfully implemented in conjunction with a GA for solving optimal power flow problems [69].

1.2.6 Cogeneration Feasible Operating Region Modelling

Gas turbine (GT) generation sets feature prominently in modern cogeneration. The principles of the power-heat feasible operating regions (FOR) for GT units are known to their designers and experienced operators, but in the published literature the modelling is simplistic and generally insufficient. More realistic GT FOR modelling was examined as part of the research.

The IPP CHPD problem is still fairly new and does not have a standard suite of test problems, or a standard set of modelling techniques for unit heat-power FOR. The most common model is an irregular quadratic [19], however a more complex, GT-specific model has appeared [18]. Using mechanical engineering principles and thermodynamics [70, 71], the operation of GT and heat exchangers were related to existing FOR models. The merits of model simplification were demonstrated in a study of hydrothermal power dispatch problems [72]; it was decided to see if the GT-specific FOR could also be simplified in terms of operating constraints [73-77].

1.3 Research Approach

The IPP CHPD problem has been well formulated and methods exist for solving it [18,19], but only where the heat / fuel cost characteristics are described by continuous,
monotonic and/or linear quadratic functions. More accurate representations of these characteristics are available, particularly for electricity-only generation units, but they are not suited to these existing optimisation methods.

Evolution computation methods are, however, capable of efficiently searching problem spaces containing discontinuous and/or non-monotonic functions. The primary research objective in the present study is the development of an evolution computation algorithm for solving IPP CHPD problems, "CED-EP".

CED-EP stands for Cogeneration Economic Dispatch – Evolutionary Program. It uses evolutionary programming, with "μ+μ" strategy and stochastic tournament competition, as its means of searching. The initialisation and mutation stages of this algorithm have been specifically tailored to the IPP CHPD problem.

After evaluating the performance of the CED-EP algorithm [1,2] the impact of the addition of a general EC acceleration technique was investigated. Acceleration is only considered to work if can reduce significantly the amount of time a base algorithm takes to solve a problem. The Analytical Solution Acceleration (ASA) technique was chosen for this set of studies, using CED-EP as the base algorithm [3].

Gas turbine generators play a very important part in the modern IPP CHPD problem, however very little has been reported in the literature about the models used to describe the FOR models used. The application of basic thermodynamic principles and known operating constraints was used to assess the how FOR models currently used in academic research compare to the physical reality. As a result of this investigation a simpler, reduced area FOR model is suggested for modelling GT cogeneration heat and power output in study systems [4].

1.4 Thesis Layout

Chapter 1 provides a brief introduction to the areas covered in the course of this research and the published literature on these topics.
Chapter 2 goes into further detail on cogeneration systems and formulates the Independent Power Producer Combined Heat and Power Dispatch Problem.

Chapter 3 describes the data required to describe an IPP CHPD problem fully and the practical limitations placed on this data by the algorithm developed in Chapter 4.

Chapter 4 develops the final version of the CED-EP algorithm. This algorithm uses EP as a base and is tailored specifically to IPP CHPD problems.

Chapter 5 presents the results of evaluation study of the CED-EP algorithm at three different stages of development. Attention paid to the intermediate results used in [2], as this intermediate version of the program was used as a base for comparison of the results reported in Chapter 6. An evaluation study was carried out using the final version of the algorithm to demonstrate the performance improvements over the published intermediate results.

Chapter 6 introduces the Analytical Solution Acceleration technique. Evaluation studies assessing the benefits of using ASA in conjunction with the CED-EP algorithm are described.

Chapter 7 describes modelling cogeneration unit FOR in terms of basic thermodynamics and operating principles. A simpler, reduced area FOR model for GT cogeneration is suggested and implemented as a modification of validation test system.

Chapter 8 restates chapter conclusions and presents overall conclusions drawn from this research.

Appendices A-C relate to the program developed around the algorithm described in Chapter 4. Appendix A demonstrates the input file format required to properly specify IPP CHPD problems to the executable program. Appendix B lists the arguments required by the executable C++ coded program to run trials. Appendix C contains examples of the output files generated by the executable program.
Chapter 2

Independent Power Producer

Cogeneration Dispatch Problem

2.1 Cogeneration and Independent Power Producers

Cogeneration is the conversion of one energy source into two different forms of useful energy as shown in Figure 2.1. More specifically in electricity generation, it refers to the generation of electricity and "process" steam from a single "cogeneration unit". It is also referred to in the literature as combined heat and power (CHP) production. The current preference is for cogeneration is natural gas-fired gas turbine generator (GT) and heat recovery steam generator (HRSG) packages, providing natural gas is readily available and not too expensive. Conventional, steam turbine generator, cogeneration options have been used since the late nineteenth century and are still viable for some industries, and also where natural gas is not viable as a fuel. In small power demand applications, fuel cell technology is also proving to be a viable option.

![Figure 2.1: Cogeneration Schematic](image)

All modern industry requires significant amounts of electricity for lighting, motors, heating, process control and monitoring and staff facilities; some also employ energy-intensive electrochemical processes. Individual industrial facilities, or shared industrial...
parks, that choose to generate their own electricity, rather than importing power from a utility through a network authority, are known as independent power producers (IPP).

Industrial processes that require large amounts of thermal energy in the form of steam, or heat as piped steam, also require electricity. Process steam has to be generated on site and is almost exclusively generated from fossil fuels, though biomass options are available in some cases. Low pressure, "waste" heat from a plant can be piped for domestic heating up to a few kilometers away, but is still effectively a geographically local load. Top cycling cogeneration makes use of energy that would be otherwise dissipated as waste, either as steam and hot water from electricity generators' hot, low-pressure working fluid. Bottom cycling cogeneration produces electricity while depressurising and/or cooling steam in processes that requires multiple specifications (temperatures and pressures) of steam as the source of thermal energy.

2.2 Cogeneration History

In the late 19\textsuperscript{th} century electric power was developed into a commercially viable energy source. Initially only direct current power was available, and due to its high transmission losses, factories using it for lighting and motors had to have on-site generation units; this would now be called distributed generation, and the factories IPP. The subsequent commercialisation of alternating current power and the development of the steam expansion turbine led to power being generated off-site at very large electricity-only plants, i.e. utilities. Utilities could take advantage of economies of scale offered by large steam expansion turbines, and the use of step-up and step-down voltage transformers in the export of AC power greatly reduced transmission losses. Regulation of the utilities came into effect during the inter-war period, greatly improving reliability, and quality, of the electricity supplied.

In this new environment, as old on-site generating equipment wore out, it was more economic for most IPP to switch to utility-supplied electricity. Many cogenerating IPP who only had small heat demands switched to using boilers for thermal demands and importing power from utilities. By the end of the Second World War, IPP were restricted to remote locations, such as mine sites, and industrial sites with extremely
large power demands. Likewise, cogeneration only remained at sites with very large thermal energy demands.

The development of the gas turbine jet engines into marine propulsion applications, and then to stationary GT electricity generators during the 1950s and 1960s paved the way for cogeneration to re-emerge as a competitor to conventional steam generators. Gas turbine generators are compact and very quick to run-up to generating speed compared to conventional steam generators, though limited in total output capacity per unit, so were able to stake a place in the peaking generator market. The thermal efficiency of GT was initially significantly lower than conventional steam and produced a lot of very hot products of combustion (POC) in the exhaust. The heat recovery steam generator (HRSG) was developed in the 1960s to recapture the energy in the low pressure POC, ducted from a feeder GT, as useful steam. This steam could be used to power further conventional generation, as combined cycle gas turbine (CCGT) packages, or for industrial process steam, GT-HRSG cogeneration.

Other methods for improving energy efficiency from GT units through re-pressuring POC, inter-cooling and using exhaust preheating combustion air were also explored during the 1960s and 1970s. However, GT-HRSG packages have proved to be the simplest and most efficient means of making GT units a viable alternative to conventional steam generation.

Most generator manufacturers researched and developed GT product lines throughout the 1970s, as the oil price shock and increasing environmental concerns were making natural gas a preferred option to coal and oil fired steam generators. When the United States gas reserves ran low during the late 1970s, a law was passed banning the commissioning of new natural gas burning power stations. The resulting slumps in demand for GT saw most companies drop their GT research and production lines. A notable exception was General Electric, who was able to maintain research due to their aviation interests.

The discovery and tapping of large natural gas reserves in Alaska during the early 1980s saw the ban on new natural gas burning plant revoked. The Reagan administration also instigated a program for new fighter jet engines. Advances that General Electric's
gained from the aviation turbine research flowed through to commercial jet airliner engines and a new generation of highly efficient GT generators. Electricity market reforms, primarily deregulation and open access policy, and increasingly stringent environmental legislation were being introduced during this time. IPP cogeneration and CCGT for large power users again became a viable alternative to utility-supplied electricity.

Throughout the 1990s, the popularity of GT-HRSG packages increased. The simple cycle efficiency of latest generation of GT with no attached HRSG is greater than that of conventional generators, and their output capacity as part of CCGT packages is approaching that of large steam expansion turbine units. New sources of natural gas and technological breakthroughs in the abatement of oxides of nitrogen (NOx) make GT the cleanest form of fossil fuel derived power available to day.

### 2.3 Role of Cogeneration in Electricity Markets

Cogeneration "units", electricity generators linked to some form of heat extraction system, roughly fall into four categories based on their electrical power output: micro < 500 kWe, small scale < 3 MWe, medium <10 MWe and large scale > 10 MWe. Combined heat and power dispatch problems deal with systems that they have *at least* one cogeneration unit, but they can also have boilers (steam-only units) and conventional electricity generation units. The number and types of units in these systems varies depending upon the size and purpose of the heat loads.

Small and micro cogeneration units can achieve above 90% thermal efficiency, using internal combustion generators, micro turbines, and fuel cell technology. Medium and large units tend to be gas turbines, but some conventional options are available. Larger units cannot achieve high efficiencies as high as those of the micro scale units, but have cost advantages through economies of scale. The boundary between domestic and industrial cogeneration is a maximum power output of 10 MWe, as adhering to residential noise and air quality regulations becomes impractical above this level.
Small scale and micro cogeneration systems are aimed at smaller, non-industrial users where the purpose of the power generation is to supplement electricity purchased from utilities, with heat used for air conditioning and hot water. Such systems will usually consist of one or two cogeneration units. Micro units can be used for individual households, while small units are found in hospitals, apartment buildings and hotels. The appropriate economic scheduling problem is one of matching on-site generation to utility imports based on spot prices for electricity.

Medium scale cogeneration systems are useful for small industrial users, where the electricity and/or steam demand is large, but can still be met by a single large cogeneration unit. For these systems, the scheduling problems are a matter of meeting the internal steam demands and electricity supply contracts to external customers. It is common for HRSG units in these systems to have auxiliary firing capability to allow additional steam generation when total electrical demand is lower than is necessary to meet thermal energy requirements.

Large-scale IPP cogeneration economic dispatch problems assume at least two generators (boilers, cogeneration packages or conventional electricity generators) in the system and that all on-site power and steam will be met. Large refineries and industrial parks are candidates for such systems. For these sites either the electricity demand or the steam demand is likely to be much greater than the other demand, so auxiliary boilers or conventional generators are used in addition to at least one large scale cogeneration unit. Steam networks are local, but some form of electricity export can be assumed.

Under full deregulation of electricity supply markets, and equal access to customers and transmission networks, IPP cogeneration could have a major impact. For IPP overhead costs for electricity production are absorbed as part of the cost of meeting internal energy demands, allowing IPP to sell additional generating capacity at marginal production cost plus a mark up. Utilities have to include their overhead costs in their sale price, giving IPP a market advantage. The preference for new cogeneration is GT-HRSG packages. Gas turbines decrease in marginal electricity production cost as they approach full generating capacity. This creates a further incentive for IPP using GT to sell excess capacity and increases their competitive edge over utilities.
Having large industrial IPP meeting the electricity demands of geographically local residential customers is part of the modern distributed power generation concept. Modern gas turbines are cleaner to run and quicker to commission than large coal fired conventional units, but in general their capacity is not large enough to rival utilities' conventional units for meeting base loads, making them more suitable for smaller regional plants and industrial complexes. Encouraging large industrial users of electricity to generate their own demand from GT reduces the pressure to expand existing utility capacity, having IPP meet residential demands as well further reduces this pressure. Total system losses would also be reduced, as locally generated power would not have to be transmitted over long distances.

2.4 IPP CHPD vs. Traditional ED Problems

The focus of the research for this thesis is on medium and large scale cogenerating IPP, assuming some capacity for power export either to utilities or private customers. In particular the role GT-HRSG cogeneration packages for IPP has been investigated. The cogeneration, or CHP, problem is considerably different to the traditional economic scheduling problems for conventional steam generation plants as part of utilities' networks.

The defining feature of a CHP system is the presence of at least one cogeneration unit. Cogeneration units have two useful energy outputs for one fuel input, requiring two variable functions to model the cost. In addition to the cogeneration unit, it is common to have back-up electrical capability, from smaller conventional units, and additional steam generation, from auxiliary firing and / or conventional boilers, at large and medium IPP facilities. The traditional economic dispatch (ED) problem only deals with one type of unit and one type of variable: generators that only produce electricity, where active electrical power is the variable. The CHP dispatch problem needs to handle up to three types of generation units and two types of variables: heat and electricity outputs for cogeneration units; electricity from power only units, and; heat output from steam only units, boilers and auxiliary firing of HRSG.
Chapter 2: Independent Power Producer Cogeneration Dispatch Problem

The dispatch problem for cogenerating IPP is a single area one. In practice, thermal loads, as piped steam or circulated hot fluid, cannot be transported far from site, meaning all thermal demands either have to be locally connected or on-site. Only electricity demands can be exported off-site, and even this only requires one transmission line to the host network. Relative to the size of the economic dispatch (ED) problems of utilities, with multiple generating sites feeding into an interconnected network, the number of generating units in the IPP CHP dispatch problem is small. Unlike the utility ED problem, the amount of reactive power generated only need be considered at the point where exported power is injected into the transmission network, and the only transmission loss that is considered is that of the line between the IPP site and network. The distribution of the cost of transmission losses in a network amongst the generators is a separate issue to IPP cogeneration dispatch.

2.5 Formulating the IPP CHP Dispatch Problem

The general case of the IPP cogeneration system described in the previous section is represented schematically in Figure 2.2. This diagram will be used to formulate the CHP dispatch (CHPD) problem. The general system contains a set of "n" generation units, which has the following subsets:

- electricity only, or "thermal", units ∈ [1 - α]
- cogeneration units ∈ [α+1 - β]
- heat only, or "boiler, units ∈ [β - n]

Figure 2.2: Schematic of an IPP Cogeneration System
The objective in all ED problems is to minimise the production cost of a set of generators given a demand. The objective function to be minimised in the CHPD problem is the sum of the production cost of each generation unit in the system:

\[ \sum_{i=1}^{\alpha} f_{ti}(p_i) + \sum_{i=\alpha+1}^{\beta} f_{ci}(p_i, h_i) + \sum_{i=\beta+1}^{\gamma} f_{bi}(h_i) \]  

(2.1)

where:

- \( f_{ti}, f_{ci} \) and \( f_{bi} \) are the respective fuel characteristics of the conventional thermal generators, cogeneration units and boiler units.
- \( p_i \in [1 - \alpha] \) are the conventional generators' and cogeneration units' active power loads.
- \( h_i \in [\alpha+1 - n] \) are the cogeneration units' and boilers' heat loads.

The CHPD problem has to simultaneously meet heat and power loads. In the case of the cogeneration units, the production (fuel) cost is a non-separable function of both their heat and power loads. The CHP system also has to meet heat and power demands simultaneously. It is assumed that the only heat load being considered in the cogenerating IPP case is the on-site process steam demand. The IPP active power demand consists of the on-site internal demands, the power scheduled for exporting to / through the host network, and any transmission losses incurred between the IPP site and consumption by the customer. The power and heat demand constraints of the CHPD problem can be written as:

\[ \sum_{i=1}^{\alpha} p_i + \sum_{i=\alpha+1}^{\beta} p_i = P_{\text{int}} + P_{\text{ext}} + L \]  

(2.2)

\[ \sum_{i=\alpha+1}^{\beta} h_i + \sum_{i=\beta+1}^{n} h_i = H \]  

(2.3)

where:

- \( P_{\text{int}} \) is the on-site power demand (MWe)
- \( P_{\text{ext}} \) is the host utilities power demand (MWe)
- \( L \) is the active power loss in transmission host network (MWe)
- \( H \) is the heat demand (MWth)
The operation ranges of boilers and conventional generator units treated by expressions (2.4) and (2.5), and those of the cogeneration units are shown in expressions (2.6) and (2.7). For the cogeneration units, the heat and power outputs are non-separable and the current setting of one output will affect the possible range of the other output. These are usually modelled as linear inequalities, and the region encompassed by them is called the feasible operating region (FOR).

\[
\begin{align*}
\pi_{\text{min}} & \leq \pi_i \leq \pi_{\text{max}} \\
hi_{\text{min}} & \leq hj \leq hi_{\text{max}} \\
p_{\text{min}}(hi) & \leq \pi_i \leq p_{\text{max}}(hi) \\
h_{\text{min}}(pi) & \leq hj \leq h_{\text{max}}(pi)
\end{align*}
\]

(2.4) (2.5) (2.6) (2.7)

where:

- \(\pi_{\text{min}}\) and \(\pi_{\text{max}}\) are the minimum and maximum power generation of generator \(i\).
- \(hi_{\text{min}}\) and \(hi_{\text{max}}\) are the minimum and maximum heat production of generator \(i\).
- \(p_{\text{min}}(hi)\), \(p_{\text{max}}(hi)\), \(h_{\text{min}}(pi)\) and \(h_{\text{max}}(pi)\) are the linear inequalities that define the FOR of the cogeneration units.

In summary, the CHPD problem is to minimise total fuel cost in equation (2.1), subject to demand constraint equalities of equations (2.2) and (2.3), and the generator constraint inequalities in expressions (2.4), (2.5), (2.6) and (2.7). The FOR of cogeneration units and system feasible demand region will be introduced in the next section.

### 2.6 System Feasible Demand Region

The heat and power demands of the cogenerating IPP system are non-separable due to the non-separable cost characteristics and FOR of the cogeneration units. The heat and power output ranges of each types of generation unit in a cogeneration system are shown in Figure 2.3.
The conventional power units and boiler units' constraint inequalities of expressions \((2.4)\) and \((2.5)\) are represented by Figure 2.3 (A) and (B) respectively. In Figure 2.3 (C), the irregular quadrilateral (a-b-c-d) offset from the heat (H) and power (P) axes, is a simple representation of a cogeneration unit FOR.

From expression \((2.6)\), for \(i^{th}\) cogeneration unit \((i \in [\alpha+1-\beta])\), the minimum power output, \(p_{i,\text{min}}(h_i)\), is shown in Figure 2.3 (C) as line (d-c), likewise, the maximum power output, \(p_{i,\text{max}}(h_i)\), is shown as line (a-b). Similarly, from expression \((2.7)\), lines (a-d) and (b-c) in the same figure are the minimum and maximum heat outputs, \(h_{i,\text{min}}(p_i)\) and \(h_{i,\text{max}}(p_i)\), respectively.

By combining the cogeneration units' FORs and the heat and power output ranges of the conventional thermal power units and boiler units, a system feasible demand region (FDR) can be constructed. The both the system heat demand and system power demand, from the right hand of equation \((2.3)\), must fall within the bounds of the System FDR if the problem is to be feasible. An example of a system FDR is show in Figure 2.4.

In Figure 2.4, the system minimum and maximum power demands, \(P_{\text{min}}\) and \(P_{\text{max}}\), are the sums of all the conventional generators' and cogeneration units' minimum and maximum power outputs. Likewise the systems' minimum and maximum heat demands, \(H_{\text{min}}\) and \(H_{\text{max}}\), are the sums of all the boiler units' and cogeneration units' minimum and maximum heat outputs.
Chapter 2: Independent Power Producer Cogeneration Dispatch Problem

Figure 2.4: Cogeneration System Feasible Demand Region

The upper, lower and right-hand slopes of the system FDR, that cut the corners off the "minimums-maximums" rectangle, are determined by the system's cogeneration units' FORs. For systems that contain more than one cogeneration unit, the slopes are simplified to a single, continuous linear slope from what would otherwise be a piecewise set of slopes. The reduction in feasible demands is insignificant, and the demand cases lost are borderline situations where generators would be operating at uneconomically low outputs, or dangerously high outputs that risk damaging the generators. Examples of the loss of FDR from collapsing multiple segment slopes down to a single line are shown in Figure 2.5

Figure 2.5: System FDR Corner Slope Simplification
In Figure 2.5 (A) shows the true lower slope of a system FDR containing two cogeneration units is shown by the two-segment line (a-b-c). The reduced single line (a-c) would be used as the system FDR lower slope, as shown on Figure 2.4. The loss of FDR would be the area of the triangle (a-b-c). Likewise for Figures 2.5 (B) and (C), the area of the triangles (d-e-f) and (g-h-i), respectively, would be the reduction of FDR due to simplifying the right hand and upper slopes from two-segment lines (d-e-f) and (g-h-i), to singles lines (d-f) and (g-i).

2.7 Conclusions

In this chapter, cogeneration and independent power production have been introduced in Section 2.1. The history and role of IPP cogeneration in electricity supply markets have also been described in Sections 2.2 and 2.3. The specifics of the economic dispatch for IPP cogeneration systems with power export commitments have been discussed and the dispatch problem formulated in Sections 2.4 and 2.5, before the detail presentation of the feasible demand region in Section 2.6 of the cogeneration system.
Chapter 3

Data Requirement for CHPD Problems

3.1 CED-EP Input Data

Chapter 2 has described the cogeneration economic dispatch (CED) problem. An evolutionary programming (EP) approach for solving this problem, the CED-EP algorithm, will be developed in Chapter 4. Data required for specifying CED problems in the CED-EP algorithm will be described in this chapter.

The input data that defines a specific combined heat and power dispatch (CHPD) problems, another name for CED problems, fall into four categories: system information, scheduling interval data, generation unit cost characteristics and generation unit output constraints. The types of input data used by the CED-EP algorithm, and the reasons for choosing those forms, will be discussed in this chapter. Appendix A contains a guide on to how to create "*.CED3" input files used in the CED-EP algorithm.

3.2 System Information

System data defines the size of the problem being considered. It specifies how many of each type of generation unit are in the system, the number scheduling intervals being considered and characteristics of the transmission line linking the IPP to the host network.

The definition of a CHPD problem is that it has at least one cogeneration unit; it does not necessarily have boilers or electricity-only units. A practical consideration of the problems to be handled by CED-EP is that there must be at least two generators in the
system; a system with only one generator doesn't need a dispatch algorithm! The CED-
EP algorithm has been designed to solve static dispatch problems, an accepted
assumption of current CHPD problems.

Transmission line characteristics are only relevant if power is being exported during a
scheduling interval. The transmission line characteristics needed are the transmission
voltage (kV), resistance (Ω/km) and transmission distance (km). Currently the accepted
CHPD problem only deals with active power loss for an exported load, but in the future
may have to deal with complex (active and reactive power) loads.

It is assumed that any power transmission can be modelled using the short transmission
line model (less than 80 km), i.e. a single lumped-impedance parameter [78]. It is
assumed that connection will be at distribution level, typically 22 kV or 33 kV, and
resistance in hundredths (10⁻²) of (Ω/km). Equation (3.1) determines the active power
loss of the short transmission lines delivering "P" MWe of active power to a host
network.

\[ L = I^2 x R = \left(\frac{P}{V}\right)^2 x R \quad (3.1) \]

Where:
- \( R \) = Resistance (Ω/km) x Distance (km)
- \( V \) = Transmission Voltage (kV)
- \( L \) = Active power loss due to transmission (MWe)
- \( P \) = Active power delivered (MWe)

### 3.3 Scheduling Interval Data

The duration of scheduling intervals is measured in hours and half-hours. In regard to
current scheduling practices [79], the smallest interval duration allowed is half an hour.
For each interval the on-site heat demand, on-site power demand and expected off-site
export demand must be specified. The heat demands are in MWth, megawatts of
thermal energy, and active power demands as MWe, megawatts of electrical energy.
Any security constraints regarding spinning reserve or expected load-following variations can be factored into on-site and off-site power demands.

The total power demand for scheduling intervals, including transmission losses from equation 3.1 if power is being exported, is determined. The interval heat demand and power demands for intervals are used in the equality constraints of equation (2.2) and equation (2.3) in Chapter 2.

The total power and heat demands of intervals must fall with in the system's feasible demand region (FDR), which was discussed in Section 2.6.

### 3.4 Generation Unit Cost Characteristics

The heat and/or power outputs of generation units are measured in MWth, megawatts of thermal energy, and MWe, megawatts of electrical energy, respectively. The megawatt is an energy consumption rate unit, i.e. one million joules per second, so the energy consumption modelled by the heat characteristic also has to be measured in an energy consumption rate. Where the metric system is used, energy released from combustion is measured in GJ/hr ($10^9$ Joules per hour). In North America MBtu/hr ($10^6$ Btu per hour) is used. One British thermal unit (Btu) is equal to 1055 Joules, the amount energy required to raise the temperature of one pound of liquid water by one degree Fahrenheit. Metric units will be used as standard throughout this chapter.

To convert heat characteristic to fuel cost characteristics, a cost multiplier is used [62]. The cost multiplier is expressed in $/GJ. The "$" symbol is used to denote the monetary aspect as the US$ is the most common pricing unit used in international energy trading. Fossil fuels are sold in standard sale units (e.g. tons of coal, m$^3$ of natural gas, barrels of oil). Different grades of oil and coal are specified by "energy per sale unit" and pollutant content (primarily sulfur as a percentage). Energy ratings can easily be converted to "Joules per sale unit", and then the $/GJ cost factor is determined. The fuel cost of individual generation units is determined by equation (3.2). The models used to determine heat consumption for the various types of generators are discussed in the following sub-sections.
Fuel Cost \([$/hr]\) = fuel price \([$/GJ]\) x heat consumption \([GJ/hr]\)  

(3.2)

### 3.4.1 Steam-Only Units

The process by which boiler units produce steam is very simple: fuel is burnt, hot gaseous products of combustion (POC) are released into a furnace, which raises steam in boiler tubes that pass through the furnace. When Gas Turbine and Heat Recovery Steam Turbine (GT-HRSG) cogeneration packages are used, auxiliary firing of HRSG units can be used to raise additional steam. Figure 3.1(a) shows the conventional boiler principle, while Figure 3.1(b) shows the auxiliary firing principle.

![Figure 3.1: Conventional and Auxiliary-Fired HRSG Steam Production](image)

Monotonic, single-variable quadratic functions using the heat output in MWth suffice to model both conventional and auxiliary-fired HRSG steam production. In equation (3.3a), the boiler's heat characteristic, "\(f_b(h)\)", is modelled by coefficients "\(c_{b0-2}\)", where "\(h\)" is heat output in MWth. The HRSG auxiliary firing heat model shown in equation (3.3b) is the same as equation (3.3a), except its variable is additional heat generated, "\(h_{add}\)". Steam generation from HRSG units will be further discussed in Subsection 3.4.3.

\[
f_b(h) = c_{b0} + c_{b1} h + c_{b2} h^2 \quad (3.3a)
\]

\[
f_b(h_{add}) = c_{b0} + c_{b1} h_{add} + c_{b2} h_{add}^2 \quad (3.3b)
\]

### 3.4.2 Electricity-Only Generators

Generating electricity from conventional thermal units has additional complexity compared to the standard boiler unit. After the steam has been raised in boiler tubes, it is sent to the steam chest and then released into the primary turbine through sets of inlet valves. Valve-points, multiple turbine stages, inter-stage re-pressurising and steam tapping for preheating feed water complicate the "fuel in - power output" models. The
shape of the "heat in - power out" characteristic is convex, reflecting a decrease in thermal efficiency as the maximum capacity of a generator is approached.

Open-cycle, non-cogeneration GT generators may be part of the system's back up / auxiliary generators. Open cycle GT directly use the high temperature POC as working fluid for their expansion turbines and have only one, permanently open, set of valves. As full capacity is approached the pressure of POC in the inlet valves, and hence efficiency of the turbine, increases. Open cycle GT heat characteristics can be modelled as concave, monotonic polynomial functions. The open cycle GT energy conversion process, Figure 3.2a, with that of conventional thermal generation, Figure 3.2b.

![Figure 3.2: Open Cycle GT and Conventional Thermal Generation](image)

The following labelling conventions will apply to heat characteristic model equations for electricity-only generators in this subsection: heat characteristic, "$f_t(p)$"; power output in MWe, "$p$"; coefficients "$c_{tx}$". The subscript "t" in coefficients indicates the characteristic is for a conventional thermal generator, subscript "x" indicates the polynomial order of coefficient, i.e. $x = 2$ indicates a $p^2$ term.

3.4.2.1 Continuous Models

Monotonic quadratic models \[32, 42, 44, 45, 46, 54, 58, 62\], of the form of equation 3.4, can be used to model the heat characteristics. Though not the most accurate models available, they are the most common in the literature. They are suitable for the linear and quadratic programming optimisation techniques.

\[
f_t(p) = c_{t0} + c_{t1} p + c_{t2} p^2
\]  
(3.4)

Other continuous functions have also been used to model the heat characteristics of thermal generation units. The least different of these is the reduced cubic \[35\] model of equation 3.5, which uses a cubic term, "$c_{t3}$", in place of a quadratic term.
\[ f(t) = c_{t0} + c_{t1} t + c_{t3} t^3 \] (3.5)

The most obvious way to increase model accuracy is to increase the number coefficients in the model. The full cubic [37, 46] includes the cubic term, "c_t3", as well as the quadratic term, "c_t2", as shown in equation (3.6).

\[ f_t(t) = c_{t0} + c_{t1} t + c_{t2} t^2 + c_{t3} t^3 \] (3.6)

The cubic heat characteristic of equation 4.6 is the form used by the CED-EP algorithm for electricity-only generators. Apart from full-cubic models, it can be adapted for quadratic and reduced-cubic forms as well. It adequately covers heat characteristics for GT and conventional thermal generators. Having a standard monotonic polynomial input formula is convenient from a programming point of view, as common subroutines can be reused and a number of computationally efficient techniques for manipulating polynomials exist.

3.4.2.2 Discontinuous Models

Conventional thermal electricity generators have multiple sets of valves admitting steam to their primary turbines. As described in the discussion of open cycle GT generators, the efficiency improves as the maximum flow-through capacity of a set of valves is approached. When the steam flow capacity of a set of valves is exceeded an additional set is opened. The result is an immediate pressure drop in all inlet valve sets and a decrease in efficiency. Continuous, differentiable function models, like those of equations (3.4)-(3.6), smooth these variations out to form a continuous, differentiable curve.

The heat characteristic model accuracy can be improved by using piecewise functions [34, 35, 62]. Piecewise modelling can be used when modelling multi-fuel units, though after different fuel cost factors are included they are usually discontinuous [47, 48]. As mentioned previously, GT generators only have one set of inlet valves, so piecewise modelling does not represent a tangible benefit. An n-segment model example is represented by equations (3.7a)-(3.7c), where "bp_{y, min}" and "bp_{y, max}" indicates break
mentioned previously, GT generators only have one set of inlet valves, so piecewise modelling does not represent a tangible benefit. An n-segment model example is represented by equations (3.7a)-(3.7c), where "bp_{y,min}" and "bp_{y,max}" indicates break points of the power output range of segment "y". For coefficients, "c_{xy}", the additional descriptor "y" indicates the model segment. If the model is continuous-piecewise, segment break points will abut, i.e. "bp_{n,max}", the maximum of segment n ranges, will be the same as "bp_{n+1,min}", the minimum of the next ("n+1") segment's range.

\[
f_{i1}(p) = c_{t10} + c_{t11} p + c_{t12} p^2 \quad \text{for } p_{min} \leq p \leq bp_{1,max} \tag{3.7a}
\]

\[
f_{i2}(p) = c_{t10} + c_{t11} p + c_{t12} p^2 \quad \text{for } bp_{2,min} \leq p \leq bp_{2,max} \tag{3.7b}
\]

\[
\ldots
\]

\[
f_{in}(p) = c_{t10} + c_{t11} p + c_{t12} p^2 \quad \text{for } bp_{n,min} \leq p \leq p_{max} \tag{3.7c}
\]

In the continuous-piecewise models, as formed by equations (3.7a)-(3.7c), the interval between each valve point is modelled by a separate set of coefficients. Another modelling technique is the quadratic-sinusoid, where all of the inter-valve point curves are modelled by the same sinusoid. The absolute value of the sine wave is added to a continuous polynomial function [29, 30]. In equation (3.8), coefficient "c_{ts1}" describes the magnitude of cost variation due valve points and "c_{ts2}" models the valve point locations within the power output range.

\[
f_i(p) = c_{t0} + c_{t1} p + c_{t2} p^2 + |c_{ts1} \sin (c_{ts2} \times (p - p_{min})| \tag{3.8}
\]

For more accurate CHPD results, the discontinuous models discussed in this section should be used whenever possible. However, current practice for cogeneration systems is to only model units to quadratic accuracy, in line with the quadratic programming derived solution methods that are used. The CED-EP algorithm, to be developed in Chapter 4, can handle these more complicated heat characteristics, however in current practice there are no CHPD test cases available using discontinuous models, so the inclusion of discontinuous input formats is not warranted.
3.4.3 Cogeneration Units

Cogeneration exists in three forms: recovering lower pressure steam from conventional thermal generators; producing electricity while lowering the pressure of process steam, and; from gas turbine (GT) and heat recovery steam generator (HRSG) linked packages. A diagram of conventional, top-cycle cogeneration is shown in Figures 3.3. Bottom-cycle cogeneration is shown in Figure 3.4. The schematic of GT-HRSG cogeneration is shown in Figure 3.5.

**Figure 3.3: Conventional Top-cycle Cogeneration**

In top-cycle cogeneration electricity is produced before the process heat / steam is extracted from the system. In Figures 3.3 - 3.5, "B" stands for boiler, "T" for expansion turbine and "G" for generation set.

**Figure 3.4: Conventional Bottom-cycle Cogeneration**

In bottom-cycle cogeneration steam is primarily raised for an industrial steam / heat process. Usually there is more than one specification of heat and pressure required for industrial processes. Expansion turbines linked to a generation set can be used to lower the heat and pressure of the initial high-pressure (HP) steam to lower pressure (LP) steam specifications.
As mentioned in Subsection 3.4.2, gas turbine generators use high temperature POC directly as the working fluid in their expansion turbines. After passing through the turbine, the POC are still hot enough to raise steam, but do not have enough pressure to be used economically in further expansion turbine stages. Instead, the hot, low-pressure POC can be ducted through HRSG units, which are boilers that use second-hand POC to raise steam. By nature GT-HRSG cogeneration is top-cycle, POC is used primarily for electricity, and then for steam generation. As described in subsection 3.4.1, HRSG units can use additional "fresh" POC from auxiliary firing for additional steam output.

The CED-EP algorithm currently requires two-variable, quadratic functions for heat characteristic models for cogeneration units. In theory, evolutionary computation algorithms can accept any models, e.g. higher order polynomials and/or piece-wise models, but currently only continuous, monotonic quadratic models are available in the literature. In Equation (3.9), which will adequately handle all three sources of cogeneration, the heat characteristic, \( f_c(h,p) \), is modelled by coefficients \( c_{c0} \) to \( c_{c5} \), where \( h \) is heat output in MWth and \( p \) is active power output in MWe.

\[
f_c(h,p) = c_{c0} + c_{c1} p + c_{c2} p^2 + c_{c3} h + c_{c4} h^2 + c_{c5} hp
\] (3.9)

### 3.5 Generation Unit Output Constraints

The various unit output constraints, as defined in Section 2.5, will be shown diagrammatically, with an example characteristic from Section 3.4, and discussed briefly. Steam-only and electricity-only units require only minimum and maximum
outputs to be described. The cogeneration units require the feasible heat and power operating region (FOR) bounds to be described.

3.5.1 Steam-Only Units

Figure 3.6 is representative of both conventional boiler steam generation and auxiliary firing of HRSG units. The minimum steam output, in MWth, is near zero, though this would not be economic. The maximum capacity, "100" in Figure 3.6, is practically unlimited. In practice steam consumption is monitored in tons per hour. The steam used by a given process will have a specified pressure and temperature. Using the American Society of Mechanical Engineers steam table [71], the energy content (J/Kg) of a specified steam can be calculated and its equivalent in energy usage rate (MWth) determined.

![Figure 3.6: Steam-only Heat Characteristic](image)

The thermal efficiency at which a boiler operates is dependent on the specification of the steam. Lower pressure, lower temperature steam can be produced very quickly in a single pass through a boiler, and the average temperature of POC in the boiler does not have to be much hotter than the final temperature of the required steam. At higher pressure and temperature specifications of steam, the POC in the boiler have to be much hotter, especially if the rate of consumption is relatively high, and do not get the opportunity to transfer as much of their energy into boiler tubes before existing the boiler stack as exhaust.

Hot water, commonly used for central heating in colder climates, is the most efficient use of boilers. Super-heating of steam for use in expansion turbines, which requires multiple passes through the boiler's furnace area, is the least efficient use of boilers. However, if multiple grades of steam are generated from one boiler, such as combined
cycle and lower pressure cogeneration steam from an HRSG unit, significant efficiency improvements can be made.

3.5.2 Electricity-Only Generators

The electrical output of conventional thermal generation units, in MWe, is determined by how much mechanical energy the expansion turbines can generate to drive the load shaft. The greater the rotational power of the load shaft, the more electrical torque that can be overcome within the generation unit, and the greater the electrical output. A convex heat rate curve of thermal generation unit is shown in Figure 3.7. The rated output, "100" in Figure 3.7, is the maximum output that a unit can sustain indefinitely. With multiple turbine stages on the same load shaft and inter-stage re-heating of steam, this maximum output can be hundreds of MWe per unit.

![Figure 3.7: Conventional Thermal Generator Electricity Output](image)

As a safety measure, all industrial rotating machines (generation sets, motors, pumps, etc.) have to be able to sustain an output slightly higher than the rated output for a "reasonable" amount of time. This absolute maximum output is indicated as "115" on the MWe axis in Figure 3.7. Boilers are not required to have this safety margin.

Unlike the case with boilers, the minimum output is not zero. The temperature of the whole system has to be raised, and a sufficient pressure differential established, before the expansion turbines rotate fast enough for power generation at 50 or 60Hz. Typically the minimum output is 20-25% of the rated electrical output of the generation unit.

As mentioned in Subsection 3.4.2, open cycle GT generators have concave heat rate curves, as shown in Figure 3.8. The rated output of GT, "100" in Figure 3.8, is currently less than 200 MWe, much less than those achievable by conventional thermal units. There are no really efficient methods of re-pressurising exhaust POC for use in further expansion turbine stages; using the exhaust POC to superheat steam in HRSG units for
combined cycle generation is much more effective. Gas turbine generators also have to meet the 10-15% overrated output safety constraint, as shown by the maximum at "115" in Figure 3.8.

![Figure 3.8: Open Cycle Gas Turbine Generator Electricity Output](image)

Open cycle GT must achieve self-sustained reaction before they can be connected to their generation sets; prior to self-sustaining operation an external spinner can be used to reduce run-up time. The minimum output is typically 40-50% of rated output, as shown by "40-50" on the MWe axis in Figure 3.8.

### 3.5.3 Cogeneration Units

There are two types of cogeneration FOR model in the literature. One is for conventional top-cycle cogeneration plants [19] and the other is for GT-HRSG cogeneration packages [18], another form of top-cycle cogeneration. Bottom-cycle cogeneration produces heat / steam as the primary output, hence electricity output is steam demand dependent. Bottom-cycle cogeneration system dispatch problems generally deal with supplementing power imports from host utilities rather than IPP exporting cogeneration problem developed in Chapter 2. Linear bounds are used in both models to describe the FOR, allowing simple and efficient implementation within algorithms.

In Figure 3.9, a FOR model of a conventional top-cycle cogeneration plant, which was the dominant form of cogeneration before the 1990s, is shown. Cost contours of two-variable quadratic heat characteristics, as described in Subsection 3.4.3, are indicated by curved dotted lines. The FOR is defined by linear inequalities to form an irregular quadrilateral, "a-b-c-d-a". The heat / cost contours intersecting the FOR bounds are accurate for this type of unit, as will be discussed in Subsection 5.2.3.
Ten parameters are used in Figure 3.9 to describe the FOR: "L-Rise", "L-Run", "R-Rise", "R-Run", "U-Rise", "U-Run", "P-Max", "P-Min", "H-Max" and "H-Min". Respectively "L", "R", "U", "P" and "H" stand for lower, right hand, upper, power and heat. These parameters are used for checking the feasibility of randomly regenerated load points and generating the feasible demand region of Section 2.6. They are also used to create a transformation matrix for randomly setting the initial population of candidate solutions in the evolutionary programming solution method to be developed in Chapter 4. A conventional cogeneration units FOR's minimum heat, "H,Min" or line "a-d", does not have to be zero; the FOR may be off set from the Power axis [19].
The FOR shown in Figure 3.10 is that of a GT-HRSG unit. It is characterised by two segments and heat / cost contours that follow closely the upper and lower bounds. As long as it is noted that a FOR model has two segments instead of one, it can be adequately described by the same 10 parameters as used for the conventional top-cycle cogeneration unit FOR, as shown in Figure 3.10.

The low heat output quadrilateral, "a-b-e-f-a", must abut the power axis, that is "H,Min" must be zero. The heat-power trade-off quadrilateral, "b-c-d-e-b", would ideally have quadrilateral, instead of linear, boundary inequalities so heat / cost contours (indicated by curved dotted lines) matched with the FOR bounds. However, in current practice solutions derived from linear programming and quadratic programming are the most commonly used. As such, constraint inequality modelling is typically restricted to linear models.

3.6 Conclusions

In theory there are no limits to the complexity, hence accuracy, of heat characteristic models that an evolutionary programming approach can handle. However, the majority of established modelling techniques are based on the assumption of solution methods based on linear and quadratic programming. More accurate conventional thermal heat characteristics could be incorporated into the CED-EP algorithm when more systems are modelled to such a degree.

Piecewise and higher order modelling techniques for the heat characteristics and FOR of GT-HRSG cogeneration packages could be useful. Again however, until more accurate characteristics modelling techniques are established, and used by industrial customers and utilities, there is no benefit in using cogeneration models beyond the currently available models.
Chapter 4

CED-EP Algorithm:
Cogeneration Economic Dispatch using Evolutionary Programming

4.1 CHPD Problem Solution

Solutions to economic dispatch (ED) problems are obtained by finding settings for all of the generators in the systems. As long as all of the individual generator outputs are within their limits, and the total demands for the scheduling intervals are met, the solution is feasible. The generator output values are used in the objective function; see Chapter 2 equation (2.1), and a total fuel cost for that solution is calculated. The optimal solution to an ED problem is the one in which generators exactly meet the interval demand and have the lowest possible fuel cost. This chapter develops an evolutionary programming algorithm for solving the CHPD problem. A user guide for the executable program developed around the CED-EP algorithm is in Appendix B. An example of solution output file, *.SOL3, and log of screen statements generated by the program is contained in Appendix C.

4.1.1 CHPD Solution Representation

As discussed in Chapter 2, the variables of the cogeneration economic dispatch (CED) [19,20] problem, also known as the combined heat and power dispatch (CHPD) problem [18], are real values with widely differing individual generator limits and interdependence between cogeneration unit heat and power variables. A vector representing a general solution is shown as Figure 4.1. Power and heat load variables are denoted by \( p_i \) and \( h_i \) respectively. The heat and power loads of the cogeneration units are set as a pair. The notation is for a system with "n" generators, where \( i \in \)
\{1,2,\ldots,\alpha\} are conventional electricity only generators, \(i \in \{\alpha+1,\alpha+1,\ldots,\beta\}\) are cogeneration units and \(i \in \{\beta+1,\beta+2,\ldots,n\}\) are boiler units. The \(p_i-h_i\) couplets for the cogeneration units should be considered together.

<table>
<thead>
<tr>
<th>Conventional Units</th>
<th>Cogeneration Units</th>
<th>Boiler Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_1)</td>
<td>(p_\alpha)</td>
<td></td>
</tr>
<tr>
<td>(\ldots)</td>
<td>(p_{\alpha+1})</td>
<td></td>
</tr>
<tr>
<td>(h_{\alpha+1})</td>
<td>(p_\beta)</td>
<td>(h_\beta)</td>
</tr>
<tr>
<td>(\ldots)</td>
<td>(h_{\beta+1})</td>
<td>(\ldots)</td>
</tr>
</tbody>
</table>

**Figure 4.1:** Individual in EP-CHPD algorithm

### 4.1.2 Analytical vs. Evolution Computation Optimisation

Analytical [18,19] optimisation methods start with one solution, and then refine that solution iteratively via the first derivative of function until the optimal solution is found. In ED problems the marginal fuel costs of the system's generators are used to adjust current settings. However, when non-monotonic, piece-wise and / or discontinuous fuel cost characteristics are used in the objective function, *local optima* occur depending on which segment and/ or side of a polynomial's turning point the generator setting starts at. One of these local optima will be the *global optimum*, the genuine optimal solution for the system in question. To avoid the problem of local optima first derivative, or analytical, methods tend to compromise the accuracy of their solutions by restricting objective function's fuel characteristics to continuous, monotonic functions.

Evolution computation (EC) optimisation methodologies are capable of searching arbitrary fuel characteristics without getting stuck in any one zone. When EC methodologies are applied to ED problems, the more accurate, discontinuous and non-monotonic heat / cost characteristics described in Chapter 3 can be included in a system's objective function. A drawback of EC is that it cannot guarantee finding the global optimum as the methods are based on the concepts of evolution, including random factors and evolutionary dead-ends.
4.2 Evolution Computation Optimisation Methods

Evolution computation (EC) optimisation methods have developed since the advent of affordable computers in the late 1960s. Three main areas of EC have evolved independently: evolutionary programming (EP), genetic algorithms (GA) and evolution strategies (ES). These methods all rely on a pool of candidate solutions, sometimes called individuals or chromosomes, exploring their search space for the global optimum over a number of iterations, or generations. Evolution computation methods mimic elements of genetic reproduction and some form of competition based on the fitness scores of an individuals, where fitness is derived from the complete strings of variables, or genes, of each individual, i.e. "survival of the fittest", as part of the iterative search method [66].

Evolutionary search methods start with the variables of parent candidates. Discrete "jumps" (mutation) and / or gene "swaps" (crossover) are used to set the variables of child candidates. When discontinuous and non-monotonic cost characteristics are used, evolutionary "swaps" and "jumps" are not restricted to particular segments. The primary purpose of this thesis is to develop an EC algorithm for CHPD problems, with the intent so that CHP system operators can utilise the more accurate cost characteristics described in Chapter 3.

4.2.1 Evolutionary Programming

The basic EP approach uses gene mutation to mutate a single child candidate solution, or chromosome, from each parent chromosome. Figure 4.2 shows the concept of gene mutation, each variable, X, Y and Z, of the parent candidate solution's chromosome is mutated by a random factor, x, y and z, to form a child candidate. If gene mutation is used the variables in the chromosome must be continuous.

<table>
<thead>
<tr>
<th>Parent i</th>
<th>Child i</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Y</td>
</tr>
</tbody>
</table>

Figure 4.2: Gene Mutation
Usually mutation is via a zero mean Gaussian distribution, \( N(0, \sigma) \), where the standard deviation, \( \sigma \), is a function of the parent candidates fitness. The pool of \( \mu \) parents will produce \( \mu \) children, i.e. in Figure 4.1 \( i \in \{1, 2, \ldots, \mu\} \). Parent and child genes then compete against each other in a tournament, selecting \( \mu \) candidates to form the next generation of parents. This form of competition is called the plus strategy, and is denoted as \((\mu+\mu)\) as the number of children is the same as the number of parents.

4.2.2 Genetic Algorithms

Genetic algorithms use genetic crossover as the evolutionary search mechanism. Genetic crossover takes pairs of parent chromosomes and swap genes to produce new child genes that are combinations of the parents' genetic material. Selection mechanisms for pairing parents are based on fitness, with the guiding principle of "higher fitness, higher likelihood of reproducing".

<table>
<thead>
<tr>
<th>Parents</th>
<th>Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_i</td>
<td>A  B  C</td>
</tr>
<tr>
<td>P_j</td>
<td>a  b  c</td>
</tr>
</tbody>
</table>

**Figure 4.3: Genetic Crossover**

In Figure 4.3 parent candidates, \( P_i = [A, B, C] \) and \( P_j = [a, b, c] \), have been selected from the pool of \( \mu \) parents, i.e. \( i, j \in \{1, 2, \ldots, \mu\}, i \neq j \). The second genes of the chromosomes, i.e. \( B \) and \( b \), have been chosen for crossover. This forms child candidates, \( C_a = [A, b, C] \) and \( C_b = [a, B, c] \). The number of child candidates formed does not have to be \( \mu \), i.e. \( \alpha, \beta \in \{1, 2, \ldots, \lambda\} \), and individual parents may be selected more than once for pairing. The form of competition is still a plus strategy but is denoted by \((\mu+\lambda)\), with parents and children competing for the \( \mu \) places available in the next generation.
4.2.3 Evolutionary Strategies

Evolutionary strategies explore the limits and / or properties of the solution variables, i.e. the "problem space", as well as refining the candidate solution's variables, eventually the candidates with the best problem space models produce the best solutions. Each candidate contains two elements; real values required for solution information, and search information that describe search spaces. In Figure 4.4 a pair of genes, \( P_i \) and \( P_j \) where \( i, j \in \{1,2,...,\mu\} \) and \( i \neq j \), from an ES parent population are shown; they will be used to demonstrate the ES search process. Though the example of Figure 4.4 and 4.5 assumes at least two parents per generation, some ES algorithm work with only one parent.

<table>
<thead>
<tr>
<th>Parents</th>
<th>Search</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_i )</td>
<td>A</td>
<td>X</td>
</tr>
<tr>
<td>( P_j )</td>
<td>a</td>
<td>x</td>
</tr>
</tbody>
</table>

**Figure 4.4: Evolution Strategy Parent Candidate Solutions**

Search information, e.g. \([A, B, C]\) and \([a, b, c]\) in Figure 4.4, is first randomly modified, then exchanged amongst groups/pairings of parent chromosomes via genetic crossover to form new sets of search information. These new search information strings are then combined with existing sets of solution data to create \( \lambda \) complete (search and solution information) child chromosomes. In the basic ES, the child chromosomes' solution variables undergo a form of gene mutation dependent on the search information variables.

<table>
<thead>
<tr>
<th>Children</th>
<th>Search</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_\alpha )</td>
<td>A'</td>
<td>( X \pm \delta X(A') )</td>
</tr>
<tr>
<td>( C_\beta )</td>
<td>b'</td>
<td>( Y \pm \delta Y(b') )</td>
</tr>
<tr>
<td>( C_\gamma )</td>
<td>C'</td>
<td>( Z \pm \delta Z(C') )</td>
</tr>
<tr>
<td>( C_\delta )</td>
<td>a'</td>
<td>( X \pm \delta X(a') )</td>
</tr>
<tr>
<td></td>
<td>B'</td>
<td>( Y \pm \delta Y(B') )</td>
</tr>
<tr>
<td></td>
<td>c'</td>
<td>( Z \pm \delta Z(c') )</td>
</tr>
</tbody>
</table>

**Figure 4.5: Evolution Strategy Child Candidate Solutions**

In Figure 4.5, parents \( P_i \) and \( P_j \) from Figure 4.4, have first had their search information randomly modified, \( P_{\text{search},i} = [A', B', C'] \) and \( P_{\text{search},j} = [a', b', c'] \), then swapped their
second gene of search data, b' <-> B'. Each set of solution information, \( \mathbf{P}_{\text{sol},i} = [X, Y, Z] \) and \( \mathbf{P}_{\text{sol},j} = [x, y, z] \), is then combined with both \( \mathbf{P}'_{\text{search},i} \) and \( \mathbf{P}'_{\text{search},j} \). To complete the child candidates, where \( \alpha, \beta, \chi, \varepsilon \in \{1, 2, \ldots, \lambda\} \), solution information has been mutated in relation to the relevant search information, e.g. the first solution variable mutation, \( \pm \delta X \) or \( \pm \delta x \), is dependent on the first gene of search data, a or A, hence the first solution gene of \( C_a \) is "\( X \pm \delta X(A) \)".

Due to the complexity of the ES evolution search mechanism, it is desirable to keep the parent pool size small, e.g. the 1-parent ES. The number of child candidates generated in an ES is usually considerably greater than the number of parent candidates, and the similarity between parents and their child candidates is high. The effect of strong parent candidates contributing strong, similar child candidates from generation to generation is to reduce diversity, hence decreasing the ability to search broadly in future generations. To counter this, the competition for the next generation's pool of parent candidates is amongst only the child candidates. This is from of competition is called the comma strategy and is denoted as \( (\mu, \lambda) \).

4.2.4 Evolutionary Computation Hybrids

In the last fifteen years the three branches of EC methods have converged, and it is now common to find concepts from the basic EP, ES and GA approaches incorporated into hybrid EC techniques. Common examples of this are the incorporation gene mutation into GA and the use of the comma strategies in GA and EP.

Even thought there is significant overlap between the EC methods, each basic method has particular strengths depending on the nature of the problem to be solved. For systems where the search space is well defined, GA and EP approaches are best suited for the core of an algorithm. If the search space is poorly defined an ES approach is suitable. If the solution data variables are scaleable or discrete and independent GA genetic crossover can be used as the primary search method. If solution variables are continuous, real-valued (and not readily scaleable) or interdependent, EP gene mutation is suitable.
As described in Chapter 2, CHPD problems are considerably more complex than standard ED problems. The constraints of standard economic dispatch problems are well defined, and the primary solution variables are independent and all the same type, e.g. power outputs $p_i$ within ranges $[p_{i,\text{min}}, p_{i,\text{max}}]$ (which can be easily scaled to $[0,1]$ variables ranges for crossover), with associated power factors necessary for meeting reactive load constraints. GA and hybrid-GA approaches have been used to solve the economic dispatch [30], and optimal power flow problems [69]. The EP approach has also been used to solve ED problems [43].

Evolutionary programming has been chosen as the base methodology for this EC algorithm, from now on referred to as CED-EP. The variables of the CHPD problem are continuous real values (generator outputs in MWe and / or MWth) with varying constraints (differing typical output ranges) and some interdependence ( cogeneration unit heat / power linkages). These variables are not suited for genetic crossover; hence GA is not readily suitable. As shown in the Section 2.5 of Chapter 2, the constraints of CHPD problem are well defined; hence the more complex ES methodology is not necessary. The flow of the ($\mu+\mu$) strategy EP methodology is shown in Figure 4.6.

4.2.5 CED-EP Algorithm

A specific EC optimisation algorithm follows the broad rules and principles of an EC methodology, but input and data manipulation processes have to be tailored to suit the specific problem environment. Augmentation and modification of the evolution rules and concepts is also required to improve the performance of a specific EC algorithm.

Section 4.3 will discuss how the CED-EP algorithm organises the input data into a form that could be handled by ($\mu+\mu$) strategy EP methodology. Section 4.4 describes the adaptations of the gene mutation evolution process that enables CED-EP effectively search the CHPD problem space. There is a wide selection of competition formats and termination rules that can be applied in EC algorithms, Section 4.5 discusses the ones used in CED-EP. Gene correction and CHPD specific applications of it in the CED-EP algorithm are described in Section 4.6.
4.3 Initialisation

From the information supplied about the specific combined heat and power dispatch problem, as described in Chapter 3, the CED-EP algorithm has to define internally the test system environment, including the feasible demand region (FDR) described in Section 2.6. Interval demands are checked to confirm that the CHPD demand case presented is feasible. The algorithm creates a dispatching order for generators before generating a random initial population. If random initialisation cannot generate a complete pool of viable pool of candidates, CED-EP then uses a semi-deterministic variable setting scheme to complete the pool. The initialisation scheme is developed in the sections below.
4.3.1 Dispatch Order

The order in which the generators are loaded during initialisation and mutation will affect the ability of the CED-EP algorithm to find the optimal solution. Units that have their outputs assigned earlier in the dispatch queue have a greater chance of being assigned a larger portion of demand; this leaves less of the demand available for dispatch by the units further down in the queue, increasing the likelihood of small outputs being assigned to those generators. In general, the algorithm will slow down, taking a larger number of iterations to find the optimal, if the solution requires "early" units to have small loads.

A dispatch order has been used based on first considering power, i.e. electricity-only and cogeneration, units and lastly heat-only boiler units. For the IPP cogeneration system it is assumed that producing electricity takes priority. Ensuring that internal demands are met avoids the need to buy power from the utility, and meeting external demands of customers avoids penalty payments for non-delivery to customers. Part of the heat demand will be met during the power dispatch ordering, as all cogeneration system must contain at least one cogeneration unit, and cogeneration units dispatch their heat and power outputs at the same time, the remainder of the heat demand will be met by boiler units.

4.3.1.1 Dispatch Order for Loading Generators

In setting dispatch order, preference is given to the units with the lower marginal costs. After checking that all the interval heat and power demands, H and P, of the CHPD problem are within the system FDR, individual generators are loaded are in direct proportion to H and P demands within the FDR. The marginal cost/s of each unit is then obtained using these settings.
In Figure 4.7 the points "A" and "B" are heat and power demands that would be specified by real values with MWth and MWe units. Point "B" is outside of the FDR and not feasible, so CED-EP would not attempt to find a solution for it. The algorithm converts feasible demands to proportional representations for use in the initialisation process. Real value demands, P and H are scaled by the possible heat and power demands available for dispatch, i.e. \([P_{\text{max}} - P_{\text{min}}]\) and \([H_{\text{max}} - H_{\text{min}}]\), to \(H'\) and \(P'\) values both with the range \([0,1]\). For demonstration purposes, real value demand "A" is represented, \(H' = \%H\) and \(P' = \%P\). The values of \(H'\) and \(P'\) are used in the algorithm to "load" generators during the determination of the dispatch order.

In Figure 4.8, the heat and power output of each generator, \(h_i\) and \(p_i\), are scaled by the range of possible output, \([h_{\text{max}} - h_{\text{min}}]\) and \([p_{\text{max}} - p_{\text{min}}]\). Variables \(h_i\) and \(p_i\) are the real-value generator loads used by the algorithm to determine dispatch order; they are set by
making their scaled equivalents equal %H and %P from Figure 4.7. The load restrictions of the cogeneration units are partially relaxed during initialisation. Load "x" in Figure 4.8(c), though outside the feasible operating region (FOR), would be accepted.

4.3.1.2 Marginal Costs for Determining Dispatch Order

Using the heat characteristics of electricity-only units, \( f_i(p_i) \) where \( i \in \{1,2,...,\alpha\} \), and cogeneration units, \( f_i(h_i,p_i) \) where \( i \in \{\alpha+1,\alpha+2,...,\beta\} \), units described in Subsections 3.4.2 and 3.4.3, the marginal power generation costs for electrical power generating unit are then calculated:

\[
p_i' = \frac{d f_i(p_i)}{d p} \quad i \in \{1,2,...,\alpha\} \quad (4.1)
\]
\[
p_i' = \frac{\partial f_i(h_i,p_i)}{\partial p} \quad i \in \{\alpha+1,\alpha+2,...,\beta\} \quad (4.2)
\]

The first \( \beta \) places in the dispatch order places are assigned by ascending \( p_i' \) values, i.e. the first position in the queue is assigned to the generation unit that produces power at the lowest marginal cost. If there are no boilers in the system the last place in the queue is assigned to the cogeneration or electricity-only unit with the highest marginal power production cost.

If boiler units are part of the system, their marginal heat production costs, \( h_i' \), are also calculated. The boiler heat characteristics, \( f_i(h_i) \) where \( i \in \{\beta+1,\beta+1,...,n\} \), described in Subsection 3.4.1 are used in equation 4.3.

\[
h_i' = \frac{d f_i(h_i)}{d h} \quad i \in [\beta+1, n] \quad (4.3)
\]

For systems with boilers, the final \( (n-\beta) \) positions in the dispatch order are assigned in ascending order based on the \( h_i' \) values, i.e. the last place in the queue is assigned to the boiler unit with the highest marginal production cost.
4.3.2 Setting Generators Randomly

The EP methodology specifies that members of the initial pool of solution be set randomly. If the properties of the problem are known, initial pools can be \textit{seeded} with deterministically set candidates to speed up solution time. Though relying on a deterministic backup system (Section 4.3.4), CED-EP does not use deterministic seeding.

A Gaussian (Normal) distribution number generation subroutine, "ran2" from "Numerical Recipes in C" [80] has been used for research in this thesis. Random loading of single variable generators is represented in equation (4.4) and (4.5). In these equations \( p_i \) and \( h_i \) are the randomly generated real-value loads for electricity-only and heat-only units respectively, \( p'_i \) and \( h'_i \) are randomly generated numbers in the range [0,1].

\[
\begin{align*}
    p_i &= p_{i,\text{min}} + p'_i \times [p_{i,\text{max}} - p_{i,\text{min}}] & i \in [1, \alpha] \\
    h_i &= h_{i,\text{min}} + h'_i \times [h_{i,\text{max}} - h_{i,\text{min}}] & i \in [\beta+1, n]
\end{align*}
\]

Loading the cogeneration units is not as simple. A set of transformation matrices can be derived from the FOR model parameters described in Section 3.5.3. These matrices will re-map a random point within the "1 x 1 square" defined by \( h'_i \) and \( p'_i \) to a real-value cogeneration unit load. Equation (4.6) shows the transform. The transformations of the single-segment and two-segment cogeneration FOR are shown in Figures 4.9 and 4.10.

\[
\begin{bmatrix}
    h_i \\
    p_i
\end{bmatrix} =
\begin{bmatrix}
    a_{11} & a_{12} \\
    a_{21} & a_{22}
\end{bmatrix}
\begin{bmatrix}
    h'_i \\
    p'_i
\end{bmatrix} +
\begin{bmatrix}
    b_1 \\
    b_2
\end{bmatrix}
\begin{bmatrix}
    h_i \times p'_i \\
    h'_i \times p_i
\end{bmatrix} +
\begin{bmatrix}
    c_1 \\
    c_2
\end{bmatrix}
\]

Figure 4.9: Single Segment FOR Transformation
The relevance of $p^\text{r}_{i,\text{max}}$ and $h^\text{r}_{i,\text{max}}$ values shown in Figure 4.9 will be explained in Section 4.3.3. The required coefficients for equation (4.6) in the single segment FOR case of Figure 4.9 are calculated by equations (4.7a-h).

\begin{align*}
a_{11} &= L_{\text{Run}} \\
a_{12} &= R_{\text{Run}} - U_{\text{Run}} + L_{\text{Run}} \\
a_{21} &= -L_{\text{Drop}} \\
a_{22} &= P_{\text{Max}} - P_{\text{Min}} - L_{\text{Drop}} \\
b_1 &= U_{\text{Run}} - L_{\text{Run}} \\
b_2 &= L_{\text{Drop}} - U_{\text{Drop}} \\
c_1 &= H_{\text{Max}} - R_{\text{Run}} - L_{\text{Run}} \\
c_2 &= P_{\text{Min}} + L_{\text{Drop}}
\end{align*}

\textbf{Figure 4.10: Two-Segment FOR Transformation}

There are two sets of matrix coefficients required to carry out the transformation shown in Figure 4.10. Firstly the area of each segment is determined and expressed as a percentage of the total area:

\begin{align*}
\text{Area}\%_{[1]} &= \frac{\text{Area}_{[1]}}{(\text{Area}_{[1]} + \text{Area}_{[2]})} \quad (4.8a) \\
\text{Area}\%_{[2]} &= \frac{\text{Area}_{[2]}}{(\text{Area}_{[1]} + \text{Area}_{[2]})} \quad (4.8b)
\end{align*}

If randomly generated $h^r_i < \text{Area}\%_{[1]}$, the coefficients determined equations (4.9a-h) are used in the transformation matrices to place the loads in segment 1 of cogeneration unit FOR of Figure 4.10.
\begin{align}
    a_{11}[1] &= \frac{(H_{\text{Max}} - H_{\text{Min}} - R_{\text{Run}} - L_{\text{Run}})}{\text{Area}\%[1]} \quad (4.9a) \\
    a_{12}[1] &= 0.0 \quad (4.9b) \\
    a_{21}[1] &= 0.0 \quad (4.9c) \\
    a_{22}[1] &= P_{\text{Max}} - P_{\text{Min}} - L_{\text{Drop}} \quad (4.9d) \\
    b_{1}[1] &= \frac{(R_{\text{Run}} + L_{\text{Run}} - U_{\text{Run}})}{\text{Area}\%[1]} \quad (4.9e) \\
    b_{2}[1] &= 0.0 \quad (4.9f) \\
    c_{1}[1] &= H_{\text{Min}} \quad (4.9g) \\
    c_{2}[1] &= P_{\text{Min}} + L_{\text{Drop}} \quad (4.9h)
\end{align}

If \( h_i > \text{Area}\%[1] \), the random variables are mapped to segment 2 of Figure 4.10 using the coefficients calculated by equations (4.10a-h).

\begin{align}
    a_{11}[2] &= \frac{L_{\text{Run}}}{\text{Area}\%[2]} \quad (4.10a) \\
    a_{12}[2] &= R_{\text{Run}} - ((U_{\text{Run}} - L_{\text{Run}})/\text{Area}\%[2]) \quad (4.10b) \\
    a_{21}[2] &= \frac{-L_{\text{Drop}}}{\text{Area}\%[2]} \quad (4.10c) \\
    a_{22}[2] &= P_{\text{Max}} - P_{\text{Min}} - U_{\text{Drop}} - ((L_{\text{Drop}} - U_{\text{Drop}})/\text{Area}\%[2]) \quad (4.10d) \\
    b_{1}[2] &= \frac{(U_{\text{Run}} - L_{\text{Run}})}{\text{Area}\%[2]} \quad (4.10e) \\
    b_{2}[2] &= \frac{(L_{\text{Drop}} - U_{\text{Drop}})}{\text{Area}\%[2]} \quad (4.10f) \\
    c_{1}[2] &= H_{\text{Max}} - R_{\text{Run}} - (L_{\text{Run}}/\text{Area}\%[2]) \quad (4.10g) \\
    c_{2}[2] &= P_{\text{Min}} + (L_{\text{Drop}}/\text{Area}\%[2]) \quad (4.10h)
\end{align}

4.3.3 Dispatching the Demands

The CED-EP algorithm treats all generators as cogeneration units; power-only units are cogeneration units with heat parameters \( h_i = h_{i,\text{max}} = h_{i,\text{min}} = 0 \). Likewise boilers are cogeneration units with power parameters \( p_i = p_{i,\text{max}} = p_{i,\text{min}} = 0 \). During dispatch the ranges of variables are modified to reflect loads already dispatched. The maximum heat or power available to be dispatched from a generator, \( h_{i,\text{avail}} \) and \( p_{i,\text{avail}}, \) is determined via equations (4.11a-c) and (4.12a-c), modifications of the demand equalities of equations (2.2) and (2.3). For the first and the last generators in the queue, the sum of previously dispatched loads and the sum of minimum output terms disappear respectively, as shown in equations (4.11b-c) and (4.12b-c).
\[ P_{j,\text{avail}} = P_{\text{Dem}} - \sum_{i=1}^{j-1} p_i - \sum_{i=j+1}^{n} P_{i,\text{min}} \quad j \in [2, 3, \ldots, n-1], i \in [1, 2, \ldots, n] \quad (4.11a) \]

\[ P_{j,\text{avail}} = P_{\text{Dem}} - \sum_{i=j+1}^{n} P_{i,\text{min}} \quad j = 1, i \in [1, 2, \ldots, n] \quad (4.11b) \]

\[ P_{j,\text{avail}} = P_{\text{Dem}} - \sum_{i=1}^{j-1} p_i \quad j = n, i \in [1, 2, \ldots, n] \quad (4.11c) \]

\[ h_{j,\text{avail}} = H_{\text{Dem}} - \sum_{i=1}^{j-1} h_i - \sum_{i=j+1}^{n} h_{i,\text{min}} \quad j \in [2, 3, \ldots, n-1], i \in [1, 2, \ldots, n] \quad (4.12a) \]

\[ h_{j,\text{avail}} = H_{\text{Dem}} - \sum_{i=j+1}^{n} h_{i,\text{min}} \quad j = 1, i \in [1, 2, \ldots, n] \quad (4.12b) \]

\[ h_{j,\text{avail}} = H_{\text{Dem}} - \sum_{i=1}^{j-1} h_i \quad j = n, i \in [1, 2, \ldots, n] \quad (4.12c) \]

The available heat and power for dispatch amongst remaining generators is then used to truncate the ranges of the random setting variables to increase the likelihood of generating a viable new candidate. The truncated minimum values of the ranges, \( p''_{i,\text{min}} \) and \( h''_{i,\text{min}} \), remain unchanged at zero, the truncated upper limits, \( p''_{i,\text{max}} \) and \( h''_{i,\text{max}} \), are set by equations (4.13) and (4.14).

\[ p''_{i,\text{max}} = \begin{cases} 1 & \text{if } p_{i,\text{max}} \geq p_{i,\text{avail}} \\ \frac{[P_{i,\text{avail}} - P_{i,\text{min}}]}{[P_{i,\text{max}} - P_{i,\text{min}}]} & \text{if } p_{i,\text{min}} < p_{i,\text{avail}} < p_{i,\text{max}} \\ 0 & \text{if } p_{i,\text{min}} \geq p_{i,\text{avail}} \end{cases} \quad (4.13) \]

\[ h''_{i,\text{max}} = \begin{cases} 1 & \text{if } h_{i,\text{max}} \geq h_{i,\text{avail}} \\ \frac{[h_{i,\text{avail}} - h_{i,\text{min}}]}{[h_{i,\text{max}} - h_{i,\text{min}}]} & \text{if } h_{i,\text{min}} < h_{i,\text{avail}} < h_{i,\text{max}} \\ 0 & \text{if } h_{i,\text{min}} \geq h_{i,\text{avail}} \end{cases} \quad (4.14) \]

Random loading of generators in the dispatch queue is achieved by using equations (4.4), (4.5) and (4.6), but with truncated random numbers \( p''_i \) and \( h''_i \), using ranges \([0, p''_{i,\text{max}}]\) and \([0, h''_{i,\text{max}}]\) respectively, instead. Figure 4.9 demonstrates truncated random setting ranges within a cogeneration unit.

\[ p_i = p_{i,\text{min}} + p''_i \times [P_{i,\text{max}} - P_{i,\text{min}}] \quad i \in [1, \alpha] \quad (4.15) \]

\[ h_i = h_{i,\text{min}} + h''_i \times [h_{i,\text{max}} - h_{i,\text{min}}] \quad i \in [\beta+1, n] \quad (4.16) \]
The CED algorithm designates dependent generation units to ensure the entire power load and the heat load has been dispatched. For queue position $\beta$, the final power unit, $p"_\beta$ is set to $p"_{\beta_{max}}$ instead of being randomly generated. Likewise for queue position $n$, the final heat unit loading, $h"_n$ is set to $h"_{n_{max}}$.

### 4.3.4 Semi-Deterministic Setting of Individuals

Each potential member of the initial population is given a number of opportunities to randomly generate a viable solution. During initialisation this made easier by relaxing FOR constraints, as mentioned in Section 4.3.1, and setting the demand constraints for total heat and power dispatched by candidate to greater than or equal, equation (4.18) and (4.19). The CED-EP algorithm allows 50 chances to each candidate.

\[
\sum_{i=1}^{a} p_i + \sum_{i=a+1}^{\beta} p_i \geq P_{Dem} \tag{4.18}
\]

\[
\sum_{i=a+1}^{n} h_i + \sum_{i=\beta+1}^{n} h_i \geq H_{Dem} \tag{4.19}
\]

The $(\mu+\mu)$ strategy requires a full initial population to start. If a candidate fails to generate a set of viable generator loads using the random setting procedures, its variables are then set semi-deterministically. The proportional loads of Section 4.3.1 are used as the deterministic part of this variable setting process. In a purely deterministic process, into equations (4.15)-(4.17) $p"_i$ would be made equal to $%P$ and $h"_i$ made equal to $%H$, and the individual generator loads be as demonstrated in Figures 4.7 and 4.8.

However, if one potential individual needs to be set deterministically it is likely that many, or even all, members of the initial population will not be able to be set randomly. To overcome this a random factor is added to create candidates "around" the area of the purely deterministic load points. In equations (4.20) and (4.21) $%p$ and $%h$ are respectively equal to $(1 - %P)$ and $(1 - %H)$.  

\[
\begin{bmatrix}
  h_i \\
  p_i
\end{bmatrix} = \begin{bmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
\end{bmatrix} \times \begin{bmatrix}
  h"_i \\
  p"_i
\end{bmatrix} + \begin{bmatrix}
  b_1 \\
  b_2
\end{bmatrix} \times \begin{bmatrix}
  h"_i \times p"_i \\
  h"_i \times p"_i
\end{bmatrix} + \begin{bmatrix}
  c_1 \\
  c_2
\end{bmatrix}
\]  

\( (4.17) \)
Equation (4.20) is used to set all power variables, electricity-only and cogeneration units, if a candidate has to resort to this process. Likewise, equation (4.21) is used to set cogeneration and boiler unit heat output variables. The presence of candidates in the initial population which may not meet all constraints, such as load "x" from Figure 4.8(c), is not a problem as during the mutation process CHPD gene correction mechanisms are employed. These mechanisms will ensure that within a few generations the majority of candidates meet cogeneration unit FOR constraints.

### 4.4 Mutation

In the EP methodology the fitness of candidate solutions should be used to guide the mutation in a search for better candidate solutions. A standard deviation, $\sigma$, determination process was developed for the CED-EP algorithm for the Gaussian distribution mutation operation. This process greatly increases the likelihood of producing valid child candidates.

#### 4.4.1 Candidate Fitness

The fitness score, $F_k$, is a measure of the strength of the $k^{th}$ candidate solution in a pool of "m" individuals. In ED optimisation problems it is usual to make the fitness a function of the total fuel cost, $C_k$, of a valid candidate solution. After investigating various fitness schemes, the scheme for a mutation control operator, $f_k$, shown in equation (4.22) was chosen. Normalising the fuel cost by the minimum possible fuel cost of the system, $C_{\text{min}}$, was found to give a large range of scores while maintaining high sensitivity to small difference between current value, $f_k$, and the best values so far, $f_{\text{best}}$, in the mutation operations.

$$f_k = C_k / C_{\text{min}} \quad k \in \{1, 2, \ldots, m\}$$  \hspace{1cm} (4.22)
The range of $f_k$ is $[1, C_{\text{max}}/C_{\text{min}}]$, where $C_{\text{max}}$ is the maximum possible generation cost when all generators are fully loaded. The best theoretical value of $f_k$ is 1, but by definition the fitness score, $F_k$, must increase as the strength of the candidate improves, so the fitness, $F_k$, score for competition is calculated by equation (4.23).

$$F_k = 1/f_k = C_{\text{min}}/C_k \quad k \in [1, 2, \ldots, m] \quad (4.23)$$

Though the possible $f_k$ range is $[C_{\text{min}}/C_{\text{min}}, C_{\text{max}}/C_{\text{min}}]$, the reasonable range of $f_k$ is generally much smaller. For practical ED cases the solution cost will be considerably above $C_{\text{min}}$, and rarely will the initialisation process produce candidate solutions with fuel costs near $C_{\text{max}}$.

### 4.4.2 Mutation Operation

Each of the $m$ individuals in the parent population spawns a child individual. Each power and heat variable of the $k^{th}$ parent individual, respectively $p_{ik}$ and $h_{ik}$, is mutated to a new variable, $p_{i,m+k}$ or $h_{i,m+k}$ respectively, in a child individual. In equations (4.24) and (4.25), $N$ is a Gaussian distribution with zero mean and variance (standard deviation squared) $\sigma_{ikp}^2$ or $\sigma_{ikh}^2$, for power and heat loading respectively. The standard deviations for the power and heat mutations are evaluated according to equation (4.26) and (4.27) respectively.

$$p_{i,m+k} = p_{ik} + N(0, \sigma_{ikp}^2) \quad i \in [1, 2, \ldots, \beta] \quad (4.24)$$

$$h_{i,m+k} = h_{ik} + N(0, \sigma_{ikh}^2) \quad i \in [\alpha+1, \alpha+2, \ldots, n] \quad (4.25)$$

$$\sigma_{ikp} = [(p_{i,\text{max}} - p_{i,\text{min}})/D] \times \left[ \frac{(f_k - f_{\text{best}})/(f_{\text{weak}} - f_{\text{best}}) + S_{ozp}/3} \right] \quad (4.26)$$

$$\sigma_{ikh} = [(h_{i,\text{max}} - h_{i,\text{min}})/D] \times \left[ \frac{(f_k - f_{\text{best}})/(f_{\text{weak}} - f_{\text{best}}) + S_{ozh}/3} \right] \quad (4.27)$$

In equations (4.26) and (4.27) $D$ is the divisor used to control the size of the mutation search range in relation to the range of the variable. The value $f_{\text{weak}}$, is the highest fitness operator, $f_k$, in the current parent generation, hence belonging to the weakest individual. The value $f_{\text{best}}$, is the lowest value of $f_k$, hence strongest candidate obtained so far. $S_{ozp}$ and $S_{ozh}$ are off-zero search coefficients.
The Gaussian distribution has a 99.73 % confidence interval for 3 standard deviations. In terms of the EP search mechanism it means 9973 out of every 10000 of settings randomly generated should fall within ±3σ of the start position, i.e. a total search range approximately equal to 6σ. The divisor is necessary to keep the search range practical. The largest σ can be is approximately 1/6 of the range before a significant quantity of redundant space is searched. In Figure 4.11, the mean is centred at the mid-point of the h_i range, and the grey area is redundant search space due to D value being less than 6.

![Figure 4.11: Divisor Values < 6, Using Heat Axis](image)

Using D > 6 means that not all of the variable range can be searched at any one time, however this proved to be desirable. In most ED problem systems, the majority of the generators will be at, or near, their lower output and maximum outputs limits; generally the middle ground does not need be searched as thoroughly. D = 12 was found to be a very good value, thoroughly searching the areas close to the current position, but wide enough to "move through the middle ground" if necessary, as demonstrated in Figure 4.12.

![Figure 4.12: D =12 Mutation Search Range](image)

The "range / D" parts of equations (4.26) and (4.27) sets the outer envelope of the i-th generator search range throughout all mutations. To improve the effectiveness of a search, it has been found that weaker solutions should search widely for new settings, while stronger solutions should search locally for improvements on current settings. In equation (4.26) and (4.27) the "f-fraction" inversely adjusts the search magnitude to
reflect relative fitness of an individual in the current generation. It spreads the portion of search envelope used by parent candidates from 100%, for the weakest candidate, to 0%, for the strongest candidate.

A side effect of the f-fraction is that the best individual is prevented from mutating, i.e. envelope set to 0% of search range. Every parent candidate in a generation should be able to spawn a child candidate, so "off-zero" search coefficients, \( S_{ozp} \) and \( S_{ozh} \), were added to allow this. This allows the strongest individuals to searching within ± \( S_{oz} \)% of their current positions, where \( S_{oz} \) is the collective reference to \( S_{ozp} \) and \( S_{ozh} \). The \( S_{oz} \) coefficients are divided by 3, as they are in the \( \sigma \) calculations prior to random number generation. Figure 4.13 demonstrates the mutation search envelopes, the current \( h_i \) setting of the current worst candidates uses the full search, while the \( h_i \) setting of the best candidate uses only ± \( S_{oz} \)% of the search envelope.

![Figure 4.13: Effect of the Spreader Function with Off-Zero Search](image)

The revised spread of percentage of search envelope used is now (100 + 2 \( S_{oz} \))% of range, for the weakest candidate, down to (2 \( S_{oz} \))%, for the strongest candidate used. Since it is undesirable to have deterministic elements, such as \( S_{oz} \), interfering too heavily with the "random" mutation search process, it was decided to limit the strongest candidate's search range to 10% of the total envelope, i.e. \( S_{oz} = 0.05 \).

However, for demand cases where either the total heat demand, \( H_{Dem} \), or power demand, \( P_{Dem} \), was near the edge of the Feasible Demand Region (FDR) \( S_{oz} = 0.05 \) still interfered significantly. To create non-intrusive \( S_{oz} \) values, provisional off-zero coefficients are determined via equation (4.28a) and (4.29a). They are then subjected to the maximum value cut off equation (4.28b) and (4.29b). %\( P \) and %\( H \) within the FDR are shown in Figure 4.7 of Section 4.3.1.1, above.
\[ S_{ozp} = \frac{(P_{max} - P_{Dem})}{(P_{max} - P_{min})}/2 = (1 - \%P)/2 \]  \hspace{1cm} (4.28a)

\[ S_{ozp} = \begin{cases} (1 - \%P)/2 & \text{if } (1 - \%P)/2 < 0.05 \\ 0.05 & \text{if } (1 - \%P)/2 > 0.05 \end{cases} \]  \hspace{1cm} (4.28b)

\[ S_{ozh} = \frac{(H_{max} - H_{Dem})}{(H_{max} - H_{min})}/2 = (1 - \%H)/2 \]  \hspace{1cm} (4.29a)

\[ S_{ozh} = \begin{cases} (1 - \%H)/2 & \text{if } (1 - \%H)/2 < 0.05 \\ 0.05 & \text{if } (1 - \%H)/2 > 0.05 \end{cases} \]  \hspace{1cm} (4.29b)

4.4.3 Constraint Satisfaction in Mutation

Each generator is mutated in turn according to its position in the dispatch order. During the mutation process, when mutated child loads fall outside of the operation ranges, equation (2.4)-(2.7) from Section 2.6, the loads are brought back to their limiting values. Figure 4.14 demonstrates this. Mutated point A goes back to the minimum and point C shifts back to maximum.

![Figure 4.14: Correcting Overshoots](image)

To assist the mutation operator find valid mutations of parent candidates, the available load and range truncation procedures are used. Equations (4.11a-c) and (4.12a-c) are reused prior to each generator being mutated. Variations of equations (4.13) and (4.14), are used to determine truncated real-value maxima, \( p''_{i,max} \) and \( h''_{i,max} \), equation (4.30) for power-only units and equation (4.31) for boilers. In Figure 4.14, point B demonstrates the truncated maximum limit.

\[ p''_{i,max} = \begin{cases} p_{i,max} & \text{if } p_{i,max} \geq p_{i,avail} \\ p_{i,avail} & \text{if } p_{i,min} < p_{i,avail} \leq p_{i,max} \\ p_{i,min} & \text{if } p_{i,min} = p_{i,avail} \end{cases} \]  \hspace{1cm} i \in [1, 2, \ldots, \alpha] \hspace{1cm} (4.30)

\[ h''_{i,max} = \begin{cases} h_{i,max} & \text{if } h_{i,max} \geq h_{i,avail} \\ h_{i,avail} & \text{if } h_{i,min} < h_{i,avail} < h_{i,max} \\ h_{i,min} & \text{if } h_{i,min} = h_{i,avail} \end{cases} \]  \hspace{1cm} i \in [\beta+1, \beta+2, \ldots, n] \hspace{1cm} (4.31)
The interdependent nature of heat and power variables of cogeneration units is shown in equation (4.32) and (4.33).

\[
p_{i,\text{max}}(h_i) = \begin{cases} p_{i,\text{max}}(h_i) & \text{if } p_{i,\text{max}}(h_i) \geq p_{i,\text{avail}} \\ p_{i,\text{avail}}(h_i) & \text{if } p_{i,\text{min}}(h_i) < p_{i,\text{avail}} < p_{i,\text{max}}(h_i) \\ p_{i,\text{min}}(h_i) & \text{if } p_{i,\text{min}}(h_i) = p_{i,\text{avail}} \end{cases} \quad (4.32)
\]

\[
h_{i,\text{max}}(p_i) = \begin{cases} h_{i,\text{max}}(p_i) & \text{if } h_{i,\text{max}}(p_i) \geq h_{i,\text{avail}} \\ h_{i,\text{avail}}(p_i) & \text{if } h_{i,\text{min}}(p_i) < h_{i,\text{avail}} < h_{i,\text{max}}(p_i) \\ h_{i,\text{min}}(p_i) & \text{if } h_{i,\text{min}}(p_i) = h_{i,\text{avail}} \end{cases} \quad (4.33)
\]

After all variables for the child candidate have been set, the validity of cogeneration unit load points, \( h_i \) and \( p_i \) pairs, are checked via linear inequalities expressed by equations (4.34)-(4.36). Equation (4.34) checks that the load is within the upper bound of the FOR, equation (4.35) the lower bound and equation (4.36) the right-hand bound. The left-hand bound of the FOR is tested by equation (4.37); to avoid the issue of vertical / infinite gradients the test has been switched to use the heat output instead of power output. The \( u_0, u_h, l_0, r_0, r_h, m_0 \) and \( m_h \) coefficients are calculated from terms of the 10-parameter FOR model shown in Figures 9 and 10.

\[
p_i \leq u_0 - u_h \times h_i \quad (4.34)
\]
\[
p_i \geq l_0 - l_h \times h_i \quad (4.35)
\]
\[
p_i \geq r_0 + r_h \times h_i \quad (4.36)
\]
\[
h_i \geq m_0 + m_p \times p_i \quad (4.37)
\]

For the single region FOR of Figure 9, and loads that fall within region 2 of the two-segment FOR model of Figure 4.10, equations (4.38a-h) are use to determine the coefficients.

\[
u_h = \frac{U_{\text{Drop}}}{U_{\text{Run}}} \quad (4.38a)
\]
\[
u_0 = P_{\text{Max}} + [u_h \times (H_{\text{Max}} - U_{\text{Run}})] \quad (4.38b)
\]
\[
l_h = \frac{L_{\text{Drop}}}{L_{\text{Run}}} \quad (4.38c)
\]
\[
l_0 = P_{\text{Min}} + L_{\text{Drop}} + [l_h \times (H_{\text{Max}} - L_{\text{Run}} - R_{\text{Run}})] \quad (4.38d)
\]
\[
r_h = \frac{R_{\text{Drop}}}{R_{\text{Run}}} \quad (4.38e)
\]
\[
r_0 = P_{\text{Min}} - [r_h \times (H_{\text{Max}} - H_{\text{Min}} - R_{\text{Run}})] \quad (4.38f)
\]
\[
m_p = \frac{(H_{\text{Max}} - H_{\text{Min}} - U_{\text{Run}})}{(P_{\text{Max}} - P_{\text{Min}} - L_{\text{Drop}})} \quad (4.38g)
\]
\[
m_0 = \frac{(P_{\text{Min}} + L_{\text{Drop}}) - (m_p \times (P_{\text{Min}} + L_{\text{Drop}}))}{(4.38h)
\]

If the cogeneration unit uses the two-segment FOR model of Figure 10 and the load point falls within region 1, the coefficients of equations (4.39a-h) are used in the tests.
\begin{align*}
\eta_h &= 0 & (4.39a) \\
\eta_0 &= P_{\text{Max}} & (4.39b) \\
\lambda_h &= 0 & (4.39c) \\
\lambda_0 &= (P_{\text{Min}} + L_{\text{Drop}}) & (4.39d) \\
\beta_h &= (P_{\text{Max}} - P_{\text{Min}} - L_{\text{Drop}}) / (R_{\text{Run}} + L_{\text{Run}} - U_{\text{Run}}) & (4.39e) \\
\beta_0 &= (P_{\text{Min}} + L_{\text{Drop}}) - \left[ \beta_h \times (H_{\text{Max}} - H_{\text{Min}} - R_{\text{Run}} - L_{\text{Run}}) \right] & (4.39f) \\
\mu_p &= 0 & (4.39g) \\
\mu_0 &= H_{\text{Min}} & (4.39h)
\end{align*}

Lastly the demand constraints, equations (2.2) and (2.3) in Chapter 2, are checked before a newly mutated candidate is accepted. It was found that looking for exact equalities between a candidate's total dispatched loads and the interval scheduling demands was too difficult. Instead equal or greater than constraints were applied as per equations (4.18) and (4.19).

### 4.5 Competition and Termination

After a population of valid child candidates has been formed, the total cost of each child is calculated, via the objective function of equation (2.1) from Chapter 2, and then the fitness score, discussed in Subsection 4.3.1, is determined. In the EP methodology, the fitness scores of candidates should be the prime determinant in selecting members for the next generation.

The purpose of a plus strategy is not that the best from a population are selected, but that they *favoured* to be selected. If only the best are selected, as in a comma strategy, genetic diversity decreases and results tend to *cluster* around one dominant result, which may not be the global optimum. The EP methodology generally uses a stochastic tournament as means of candidate selection for the next generation's parent pool. After the competition has been the completed, termination rules are checked to see if search process should be terminated.

#### 4.5.1 Stochastic Tournament

In a stochastic tournament each candidate competes against a number, designated as $\text{rnd}$ from here on, of randomly selected opponents from the pool of parents and
candidates. If the candidate being tested has a higher fitness, $F_k$, than its current opponent its score is increased by one, otherwise it remains unchanged. After its final round of competition it will have a score in the range $[0, \text{rnd}]$. After all scores have been determined the members of the next generation are then selected according to highest score, and, if necessary, by fitness to resolve competition for the last few places.

The random survival probability of weaker candidates for genetic diversity is controlled by the \textbf{rnd} value. If \textbf{rnd} is too low compared to the population size tournament selection is practically random and the strong candidates are not favoured. If \textbf{rnd} is set too high the tournament will tend toward a comma strategy of "m fittest from 2m". If \textbf{rnd} is "hardwired" into an algorithm irrespective of population size, the competition strategy of the algorithm during evaluation study is not the same across all population sizes. The CED-EP algorithm sets \textbf{rnd} = $m/2$, i.e. a candidate will face one quarter of the total tournament pool, size 2m, during each competition.

As stated in Subsection 4.4.2, the best candidate is the strongest solution found so far, it is not necessarily the strongest candidate in the current population. After the individuals have been selected for the next generation, the fitness of this pool's strongest member is compared to that of the best candidate; if it is fitter, its genes, fitness score and total cost are copied into the best candidate position, outside of the pool. The mutation process accesses $f_{\text{best}}$ and $F_{\text{best}}$ values from this external location.

4.5.2 Elimination of Non-Mutating Individuals

In the mutation process, each parent individual is given many chances to produce a viable child individual. If a parent individual fails to mutate to a new individual, the child individual is set as a copy of the parent. As both child and parent are unlikely to be able to mutate new individuals in the next generation, both of them are marked for discarding during the tournament. The CED-EP algorithm allows each parent 50 chances to mutate before implementing this measure.

Marked candidates have their tournament score set to zero after the stochastic competition; this ensures they will not appear in the next generation. If the best candidate so far is no longer mutating it will be removed from the pool, but its data will
not be eliminated, as it remains stored outside of the pool until a stronger candidate replaces it.

4.5.3 Stopping Rules

The primary stopping rule of an EP is to allow it run for its maximum number of generations, typically set as an input argument. The CED-EP algorithm employs two additional stopping rules, one that terminates if there is not enough genetic diversity, and another that terminates if it is probable that the optimum answer has been found.

The EP will terminate unsuccessfully if too many non-mutating individuals are present; this is set at 50% or more of candidates in a single generation. When small population size (typically less than 10) is being used, it generally indicates that the initialisation routine has been unable to create a diverse initial population. If "large" population sizes (which will be problem specific) are being used it indicates that a dominant solution, not necessarily the global optimum, has been found a number of iterations ago and has caused the majority of the population replicate it.

The convergence stop rule will terminate the process early if the best candidate has not changed in a significant number of generations; this indicates the algorithm has converged on a candidate solution representing the global optimum. The CED-EP algorithm uses 10% of the maximum allowed generations, with the proviso of a minimum of 10 and a maximum of 100, without change as the convergence period. For "large" population sizes convergence will usually occur before significant clustering can stop the algorithm.

4.6 CHPD Specific Acceleration

The purpose of acceleration is to reduce the time an optimisation algorithm takes to find the global solution. It seeks to do this by reducing average number of iterations, while not overly increasing the duration of iterations, or by reducing the size of population, hence the iteration duration, required to find the solution.
Acceleration can work on two levels: knowledge of the specific problem and; knowledge of the optimisation search process being used. The drawback of all acceleration is that it is deterministically applies preconceptions to partially override the search process: if the preconceptions are inappropriate, or inappropriately applied, "acceleration" can slow the solution process.

*Gene correction* uses deterministic methods to ensure that candidate solutions meet most, if not all, of the constraints imposed by the problem. The mutation processes described in Section 4.4 shows how gene correction is used internally to ensure solutions created by it will meet generator output constraints.

It was observed in a comprehensive study of a CHPD system [21] that for the majority of cases most generator settings tend to be at extreme load points, i.e. boilers and electricity generators at minimum or maximum outputs, cogeneration units operating along FOR bounds. This knowledge was combined with gene correction to act as CHPD specific acceleration techniques. Incorporated into the gene correction processes were catchment areas around these extreme load points, then if a newly mutated load setting appears in one of these it was accelerated to that extreme load point. This technique can be misapplied by setting the catchment areas too wide, resulting in a significant number of randomly set mutations being overridden.

Gene correction acceleration techniques are incorporated into CED-EP were applied in two different ways: incorporated into the mutation process or; as external routines carried out after mutation. The application of problem specific accelerations into EP is shown in Figure 4.15.

### 4.6.1 Boilers and Generators

If the load of a conventional power unit or boiler falls close to either the minimum or maximum limit of the operation range, it will be set to that limit. The CED-EP algorithm uses 5% of current variable range as the catchment size. This is shown for the case of a boiler's heat variable in Figure 4.16. If the boiler or generator is a dependent heat or power unit this acceleration is not applied.
In Figure 4.16 point A is a setting that occurs by random mutation within 0-5% range being moved back to the minimum. Point B is a setting that occurs within 95-100%, when full range is available, being moved to the maximum. Point C demonstrates acceleration to the allowable maximum, 80% of full range in this example, when the heat variable range has been truncated.

**Figure 4.16:** Near Minimum / Maximum Acceleration of a Boiler
4.6.2 Cogeneration Units

If the heat-power load pair of a cogeneration unit falls within a close vicinity of a FOR corner point, the load setting will be moved to that corner position. If the vicinity triggers for boundary adjustment, as shown as zones "a" and "b" in Figure 4.17, are too large, heat-power loads that should not go to the corner in the optimal solution will be incorrectly dragged to corner. CED-EP determines catchment radii for corner zones "a" and "b" via equation (4.39) and (4.40).

\[
a\text{-radius} = \frac{\text{Up-Run} + \text{RH-Rise}}{40} \\
b\text{-radius} = \frac{\text{Low-Run} + \text{RH-Rise}}{40}
\]

During its early development and testing, the program using the CED-EP algorithm would find near-optimal solutions with cogeneration units settings very close to the corner points, but could not mutate solution settings to the required corner points. The addition of a corner-acceleration scheme overcame this. It was found that this scheme required "tight" catchment radii, e.g. divide by 30 or greater in equation (4.39) and (4.40).

The catchment zones of a FOR edge acceleration scheme are indicated in Figure 4.17 as zones "c", "d" and "e". It was unlikely that CED-EP would benefit from a FOR edge acceleration routine because the EP, with or without corner acceleration, was able mutate solutions exactly which required cogeneration unit loading along the FOR bounds.
4.6.3 Interval-Demand Correction

Gene correction ensures that all generator settings are within allowable limits after mutation, however the total power and heat demands are partially relaxed, as stated in equation (4.18) and (4.19). Interval-demand correction is an "acceleration" process used to shed any excess power or heat from candidates prior to the competition stage. It was originally designed for the implementation of the analytical solution acceleration technique, and is discussed in Subsection 6.2.3.

4.7 Conclusions

Evolution computation approaches offer accuracy advantages over first-derivative numerical methods for solving electricity generation dispatch problems. Considerable development is required to tailor an EC methodology to a specific problem. Of the available EC methodologies, a \((\mu+\mu)\) strategy EP was the chosen for applying to the CHPD problem.

The solution variables required were coded into chromosome vectors for the algorithm. A system for entering linear-bound cogeneration unit FOR models was developed, this system also allowed random loading transformation matrices for cogeneration units to be formed. A deterministic backup system for the cases where populations could not be randomly initialised was made part of the algorithm.

The mutation process used was based on the zero-mean Gaussian distribution. The standard deviation calculation process was designed to maximise the search efficiency of the mutation process. The standard gene mutation process was adapted to meet the needs of the cogeneration units, and knowledge of CHPD problem was incorporated to improve the candidate variable settings.

A stochastic tournament was used to carry out the \((\mu+\mu)\) competition strategy, with a non-mutating candidate removal measure to improve the pool of individuals search efficiency. Stopping conditions applied to the evolution process included maximum
number of iterations elapsed, population no longer mutating effectively and probable optimal solution found.

Being able to use more accurate models is not a sufficient criterion of successful application of an EC algorithm. In order to be successful, an EC optimisation algorithm must also be able to find the global optimal solutions and find them in a reasonable time. In the next chapter the results of CED-EP algorithm evaluation study on a published test system [18] will be presented.
Chapter 5

Validation of CED-EP Algorithm

5.1 Validating the CED-EP Algorithm

In established fields of research there exist benchmark test procedures, test systems and test cases. The field of cogeneration / combined heat and power (CHP) dispatch optimisation is fairly recent and has not developed a suite of standard test systems. Furthermore, of the systems available none include discontinuous heat / cost characteristics. The test system and test / demand case in [18] was used for the validation study. Subsequent to validation, a new test system and set of optimal solutions to demand cases was developed. There is however a standard procedure for testing evolution computation (EC) optimisation algorithms.

5.1.1 Evolution Computation Evaluation Studies

When testing EC algorithms the standard form of test is an evaluation study, which charts evaluation scores against population size. The evaluation score is the product of the iteration of solution (i.e. the number of iterations taken to find the optimal solution) and the population size. As stated in Chapter 4, solution time is primarily determined by the iteration "length", i.e. the number of operations per iteration, and the number of iterations required to find the optimal solution reliably.

In EC methods iteration length cannot be calculated: some parent candidates may obtain viable child candidates with the minimum random number generations; other parents may use their maximum allowed attempts and revert to deterministic backup procedures; most will be somewhere in between. However, larger population size will result in longer average iteration lengths.
The advantage of larger population sizes is that more paths, and presumably a wider variety of paths, are being searched simultaneously. Though the average iteration length increases, usually the average iterations at which the optimal solution is found decreases. The evaluation score gives a comparable indication of computational effort in finding the optimal solution. It is expected that at a certain point the advantages of larger scale parallel searching will be cancelled out by the increases in iteration length.

5.1.2 Trial Success

Every time the program built around the CED-EP algorithm was run, referred to as a trial, the success of the algorithm in finding the optimal solution to a particular demand case was noted. If successful, the number of iterations taken to find the optimal solution was recorded. Success criteria can differ for particular demand cases within the same system. The algorithm does not have a priori knowledge about the optimal variable settings; the investigator has this knowledge and has to judge whether or not the trial was a success.

For economic dispatch (ED) algorithms, the key output generated by candidate solutions is the total fuel cost, obtained from equation 2.1 for CHPD problems. If the particular case is "clear-cut", only one set of variable settings will produce the optimal cost; solutions with higher costs are failures. However, depending on the accuracy of the variables reported, a range of costs may all correspond to same settings. The CED-EP solution algorithm is only sensitive to generator outputs to 0.005MW, i.e. variables are reported only to 0.01 MW accuracy. An example of this will be discussed in Section 5.2.

The reverse of the above case is where the solution accuracy required allows multiple, similar settings to return the optimal solution cost. In the CED-EP algorithm, and generally for ED problems, cost differences are only noted down to the nearest $0.005, allowing solutions to accurate to the nearest cent. Examples of this occurred for demand cases on the new test system and will be discussed in Section 5.4.

There can also be cases where the algorithm has great difficulty in obtaining the exact solution settings. In these cases, a "near-optimal" cost cut-off may be used instead.
Though not exactly the optimal solution, the solutions found should be close enough so that a deterministic operation could move / infer the optimal solution settings. In the testing stage the investigator will know the optimal solution and can set the success benchmark as a "+%" above the optimal cost. For example if the optimal cost were $100.00 and a "+0.5%" near-optimal solution cut off in use, all solutions that produced costs in the range $100.00-$100.50 would be counted as optimal.

5.1.3 Trial Group Success

Due to the underlying random processes, EC algorithms can never guarantee finding optimal solutions. Multiple trials for each group of settings, i.e. demand case, population size, maximum number of iterations, must be run to obtain data of statistical significance. In general at least 25 trials are required but this research used 50 trials. Because of this the average iteration of solution is the variable used to determine the evaluation score for the settings of a trial group.

The settings used by a trial group are not considered reliable if the individual trials are not finding the optimal solution regularly. Some researchers have used a 100% success rate, though in this research a 95% success rate, i.e. 48+ out of 50, was used. Of the successful groups of trials, the average iteration at which the optimal solution was successfully found was calculated, i.e. if 1 trial failed, the average was taken over only the 49 successful trials.

5.2 Test System

The CHP test system used to evaluate the CED-EP algorithm was published in [18] and used Lagrangian Relaxation as the means of optimisation. This "test" case was designed to illustrate how Relaxation could be used to solve a CHPD problem and is very simple and unrealistic. The cost characteristics, $C_{1-4}$, with results in $$/hour units, are listed in equations (5.1)-(5.4). The power output ranges for the boiler and electricity generator are indicated in equations (5.1) and (5.4).
\[ C_1(p_1) = 50 p_1 \quad 0 \leq p_1 \leq 150 \] (5.1)
\[ C_2(h_2, p_2) = 2650 + 14.5 p_2 + 0.0345 p_2^2 + 4.2 h_2 + 0.03 h_2^2 + 0.031 p_2 h_2 \] (5.2)
\[ C_3(h_3, p_3) = 1250 + 36 p_3 + 0.0435 p_3^2 + 0.6 h_3 + 0.027 h_3^2 + 0.011 p_2 h_2 \] (5.2)
\[ C_4(h_4) = 23.4114 \quad 0 < I_14 < 2695.2 \] (5.4)

The feasible operating regions (FOR) of the cogeneration units are shown in Figure 5.1. The heat and power demand case used [18] was 200 MWe electricity and 115 MWth of thermal energy; one-hour interval duration was assumed. Indicated within each FOR are three generator outputs for optima. The global optimal load point, G, and three local-optima, "Soln 1", "Soln 2" and "Soln 3", are listed in Table 5.1.

![Figure 5.1: Cogeneration Units' FOR and Solution Output Loads](image)

<table>
<thead>
<tr>
<th>Optima</th>
<th>Cost ($)</th>
<th>G ( (p_1) )</th>
<th>C1 ( (h_2, p_2) )</th>
<th>C2 ( (h_3, p_3) )</th>
<th>B ( (h_4) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soln 1</td>
<td>-10390</td>
<td>0</td>
<td>(0, 150)</td>
<td>(50, 50)</td>
<td>65</td>
</tr>
<tr>
<td>Soln 2</td>
<td>-9900</td>
<td>0</td>
<td>(0, 150)</td>
<td>(75, 50)</td>
<td>40</td>
</tr>
<tr>
<td>Soln 3</td>
<td>-8390</td>
<td>0</td>
<td>(30, 160)</td>
<td>(75, 40)</td>
<td>10</td>
</tr>
<tr>
<td>Global</td>
<td>9257.07</td>
<td>0</td>
<td>(40, 160)</td>
<td>(75, 40)</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 5.1: Generator Outputs for Optima of Test System**

In Table 5.1, column "G" contains the electricity-only generator output, \( p_1 \), "C1" is the first cogeneration units outputs, \( h_2 \) and \( p_2 \), "C2" the second cogeneration unit outputs, \( h_3 \) and \( p_3 \), and "H" the boiler unit output, \( h_4 \). The occurrence and significance of the local optima, "Soln 1-3", will be discussed in Subsection 5.2.1. In the source paper [18], the fuel cost of the optimal solution was listed as $9257.10. However due to 0.01 MW
accuracy of reported generator outputs, as discussed in Subsection 5.1.2, the solution fuel cost is in the range of $9257.07-$9257.12.

5.2.1 Test System Cost Characteristics

The mix of generation units in the test system was designed to make an interesting demonstration of Lagrangian Relaxation, but presented problems to the CED-EP algorithm. The first concern is the "cost characteristics" of the electricity and boiler units: their linear coefficients have been chosen to always make their marginal costs higher than the cogeneration units' marginal costs. Effectively the problem is reduced to allocating the interval demand between the cogeneration units (see Table 5.1).

5.2.2 Inappropriate Interval Demands

The heat and power demands, compared to feasible demand region, are very small and create a lot of "dead" search space for EP to contend with. The output range of the electricity generator was comparable to the electricity outputs of both cogeneration units and the CED-EP algorithm, partly through the near minima acceleration described in Subsection 4.6.1, was able to discount it easily when evolving candidate solutions.

However, the interval heat demand, 115 MWth, is very small in comparison to boiler's maximum output of nearly 2700 MWth, and interfered with the solution process. The range of the boiler is so large that any mutation that assigned heat to the boiler unit would have trouble later evolving solutions with cogeneration unit heat outputs above their minimum. It is due to this that the local optima (Soln 1, 2 and 3 in Table 5.1) occurred during testing.

5.2.3 Cogeneration Unit Characteristic – FOR Mismatch

The Lagrangian Relaxation demonstration system introduced the two-segment FOR model, i.e. cogeneration unit 2 FOR in Figure 5.1. While useful for creating more accurate cost characteristic and FOR model sets, it introduced the problem of characteristic – FOR mismatch. In the single segment FOR model [18-21], each equal-
cost contour of the characteristics intersects the lower FOR bound only once. As a result
the lower right hand corners always the lowest operating cost, as shown in Figure 5.2.

![Figure 5.2: Single Segment FOR](image1)

The two-segment FOR model's upper and lower bounds attempt to follow closely the
cost characteristic contours, resulting in some contours crossing the FOR bound twice.
In Figure 5.3 a section of the power axis has been magnified to highlight the problem of
mismatch; when shown on equal MWe and MWth scales the problem is hard to
identify. From this diagram it can be seen that the lowest cost generation load does not
occur at intersection "c" (75 MWth, 40MWe) but at intersection "a" (0 MWth, 44
MWe). The value of equal-cost contours decreases as power axis intersection decrease.
Intersection b is the lowest cost on the downward sloping segment of the FOR bound.
For heat outputs in the range 16-50 MWth cost contours will intersect the bound twice.

![Figure 5.3: Characteristic-FOR Mismatch](image2)
Chapter 5: Validation of CED-EP Algorithm

Characteristic-FOR mismatch does not represent a problem for first-derivative methods. Marginal costs will show that for a slightly higher cost much more useful energy is recouped at the corner point "c" than at point "a". However, EC methods rely on absolute costs rather than marginal costs, as a result they are drawn to the "false" minima of points "a" and "b" rather than "c". When the CED-EP algorithm was able to place solution near point "c", due to absolute cost savings, it would move the solutions to "near-true" minima instead, e.g. point "d" (70 MWth, 40.5 MWe). The CHPD specific corner acceleration was incorporated into CED-EP to overcome this tendency.

5.3 Validation Study

The issues concerning the validation system were identified during the early development of the CED-EP algorithm. It was decided that investigation of a range of demand cases within this system would be of minimal value in testing the ability of the CED-EP algorithm to solve CHPD problems, so only the (115 MWth, 200MWe) demand case was used in the following studies. Evaluation results of the algorithm were published during the early stages of development [1] and toward the end of the development [2]. The final algorithm as described in Chapter 4 was developed further after the Analytical Solution Acceleration (ASA) method [68] was investigated in conjunction with CED-EP (see Chapter 6).

5.3.1 Early Evaluation Study Results

When the preliminary results of the CED-EP algorithm validation were published [1], the "near-optimal cut off" from Subsection 5.1.2 was used as the success criterion for individual trials. Initially this study was run for population sizes 15 to 50 (increments of 5). It was found that a population size of 25 gave the lowest evaluation score with acceptable success rates.

This early study was extended in population size increments of 5 up to 100. As part of an investigation of algorithm performance for small population sizes, the study was extended back to population size 10 in decrements of 1. It was found that for population sizes 10-14 the early algorithm was unreliable.
The performance of the algorithm improved dramatically as it was developed, with two developments being of particular note. The corner acceleration technique enabled the exact optimal settings of generators to be used as the trial success test (section 4.6.2). The use of the off-zero search mechanisms \(S_{oz}\) in Subsection 4.4.2 allowed the convergence stop rule described in Subsection 4.5.3 to be used. Improvements resulted in reductions in the average iteration of solution and a greater success rate for lower population sizes.

A very important improvement was reduction in solution times. The machine used during the development of the algorithm has a Pentium Pro 200MHz CPU, 66 MHz motherboard and 64 Mb RAM. The first working version of algorithm took nearly an hour to complete a trial, for the results published in [1], the solution time of trials was down to 3-5 minutes, while the results from algorithm as published in [2] took less than 15 seconds per trial.

5.3.2 Intermediate Evaluation Study Results

Using the earlier study results [1] as a guide, the version of the CED-EP algorithm published in [2] was evaluated for population \((Pop)\) sizes between 20 and 40, incremented in steps of 5. As a part of the ASA study (see Chapter 6) smaller population sizes were investigated; the results from this later study for population sizes 6, 8, 10 and 15 are reported here as well. The maximum number of iterations allowed for each trial was 1000, and the convergence stop rule, i.e. no change in 100 iterations, was used. The results of the study are presented in Tables 5.2 and 5.3 and Figures 5.4 and 5.5.

Recorded in Table 5.2 are: the number of trials run for each population size \((No.\ Trials)\), the number of failed trials \((Fail)\) that did not get near the optimal solution, the number of trials that got stuck at the local optima listed in Table 5.1 \((Non-Opt)\) and the number of trials that succeeded in finding the optimal solution \((Success)\).
Chapter 5: Validation of CED-EP Algorithm

<table>
<thead>
<tr>
<th>Pop</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Trials</td>
<td>100</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Fail</td>
<td>15</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Non-Opt</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Success</td>
<td>80</td>
<td>46</td>
<td>43</td>
<td>47</td>
<td>47</td>
<td>49</td>
<td>50</td>
<td>48</td>
<td>49</td>
</tr>
</tbody>
</table>

Table 5.2: Trial Success Data

Pop size 6 had to be run for two separate sets of 50 trials in the ASA study; the combined results for all 100 trials are reported in Table 5.2. Some of the Non-Opt solutions found for Pop sizes 6, and 10 were actually invalid solutions that were outside of the FOR of cogeneration unit 2. The invalid optima can be attributed to the partial relaxation of constraints during the initialisation processes (see Subsection 4.3.1) and a lack of diversity due to the small population size.

The trend suggests that number of Fails for Pop size 8 should be higher than for Pop size 10, but this was not found to be the case. After initial observation, another set of 50 trials was run for Pop size 8 to confirm the results were representative. Throughout the development of the algorithm, unexpectedly “bad” and “good” fail rates were obtained for particular population sizes, i.e. they did not fit trends observed; there is no obvious explanation for this finding. However, it was found that when the trials were run on another computer (a Pentium II 450 MHz CPU) the population failure rates would fit the expected trend. To be consistent, only the results from the Pentium Pro 200 MHz computer have been reported in Table 5.2.

Recorded in Table 5.3 are the average iteration of solution (Ave), described Subsection 5.1.3, the highest number of iterations (Max) and lowest number of iterations (Min) taken to find the optimal solutions during the set of trials. The Fail Rate (expressed as a decimal) from Table 5.2 and evaluation score (Eval), the product of iteration of solution and population size, are also shown.
Table 5.3: Trial Performance Data

The \( \text{Ave} \) values are considered the key performance indicators as they are used to generate evaluation scores (\( \text{Eval} \)). The range of iterations of solution \([\text{Min}-\text{Max}]\) is very important when analysing \( \text{Eval} \) score plots as very large or very small iterations of solution (see Subsection 5.1.1) can skew \( \text{Ave} \) value of a set of trials. More importantly, when making recommendations for use of the CED-EP algorithm they indicate "safe" maximum numbers of iterations to be used for particular \( \text{Pop} \) size ranges. For example, on \( \text{Pop} \) sizes 15 and 20, the maximum number of iteration recommended is 100, while for \( \text{Pop} \) sizes 25-40 the recommendation is only 50. These recommendations were used to save time during the ASA investigation. The \( \text{Ave} \) values and their \( \text{Min} - \text{Max} \) envelopes are plotted against \( \text{Pop} \) size in Figure 5.4.

From Table 5.3 it is seen that lowest \( \text{Eval} \) score occurs for \( \text{Pop} \) size 10, but the fail rate is higher than the 5% cut-off required for trial group success stated in Subsection 5.1.3. \( \text{Pop} \) sizes 25 and greater meet the success criteria of less than 5% \( \text{Fail Rate}, \) and \( \text{Eval} \) scores increase with population. Applying the success criterion exactly, \( \text{Pop} \) size 25 produced the best set of results during this evaluation study. The \( \text{Eval} \) scores and \( \text{Fail Rate} \) are plotted against \( \text{Pop} \) size on a double axis chart in Figure 5.5.
Chapter 5: Validation of CED-EP Algorithm

5.3.3 Final Evaluation Study Results

The additional features included in the final version of the algorithm, as described in Chapter 4, had a positive effect on algorithm performance. An evaluation study for population sizes 10-40, incremented in steps of 5, was run for comparison with the corresponding results reported in Table 5.3. In this study to save time the convergence stop rule was turned off, but the maximum number of iterations allowed (Max It) was lowered significantly for each case. Each population size was in sets of 50 trials.
Table 5.4: Evaluation of the Final CED-EP Algorithm

<table>
<thead>
<tr>
<th>Pop</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max It</td>
<td>75</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Max</td>
<td>67</td>
<td>49</td>
<td>34</td>
<td>23</td>
<td>23</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>Min</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Fail Rate</td>
<td>0.12</td>
<td>0.04</td>
<td>0.04</td>
<td>0</td>
<td>0.02</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>Eval</td>
<td>235.68</td>
<td>265.00</td>
<td>297.92</td>
<td>312.00</td>
<td>342.86</td>
<td>398.85</td>
<td>427.20</td>
</tr>
</tbody>
</table>

The fail rate performances of the two versions of the algorithms are very similar. For the final version of the algorithm $Pop_{10}$ is again too high to be reliable. $Pop_{15-40}$ returns fail rates between 0 and 0.04, slightly better than the 0 and 0.06 achieved by intermediate version of the CED-EP algorithm. This indicates that underlying EP processes, with respect to the population required for adequate parallel solution searching, have not been significantly changed.

The final version of the algorithm returns lower $Ave$ and $Max$ results for all populations. This indicates that the "fine-tuning" elements added to the final version of the algorithm have produced tangible benefits in helping the parallel search paths of the population find the optimal solution faster.

A benefit unable to be expressed in terms of Tables 5.3 and 5.4 is the reduction in run time due to the improved initialisation routine used in the final version. The semi-deterministic loading routine used as a back-up to the random initialisation process (described in Subsection 4.3.4) greatly reduced the time taken by each trial to generate its initial population, hence reducing the average run time of each iteration.
5.4 New CHPD Test System

As explained in Section 5.2, the validation test system was adequate for demonstrating the Lagrangian Relaxation optimisation technique but is not a particularly good test system for CHPD problems. Drawing on a number of sources, a new test system for testing CHPD optimisation algorithm was designed.

5.4.1 Test System Cost Characteristics and Output Constraints

Despite the characteristic-FOR mismatch problem, the second cogeneration unit from [18] was used because its two-segment FOR model presented a challenge. A single region cogeneration FOR model and cost characteristic were used from [21], as was a boiler unit with a quadratic cost characteristic. The continuous, cubic cost characteristic of conventional, electricity-only unit was also part of the test system.

The new test system's (denoted by subscript "nt") cost characteristics, \( C_{nt,i} \), expressed as functions of generator heat and power outputs, \( h_{nt,i} \) and \( p_{nt,i} \), are presented in equation (5.1)-(5.4). The output ranges of the boiler and conventional generator units are listed in equation (5.5) and (5.6). The FOR of the cogeneration units are shown in Figure 5.6 and the feasible demand region ("FDR", see Section 2.6) constructed from the output limits is shown in Figure 5.7.

\[
C_{nt,1} = 254.8863 + 7.6997 p_{nt,1} + 0.00172 p_{nt,1}^2 + 0.000115 p_{nt,1}^3 \\
C_{nt,2} = 2650 + 34.5 p_{nt,2} + 0.1035 p_{nt,2}^2 + 2.203 h_{nt,2} + 0.025 h_{nt,2}^2 + 0.051 p_{nt,2} h_{nt,2} \\
C_{nt,3} = 1250 + 36 p_{nt,3} + 0.0435 p_{nt,3}^2 + 0.6 h_{nt,3} + 0.027 h_{nt,3}^2 + 0.011 p_{nt,3} h_{nt,3} \\
C_{nt,4} = 950.002 + 2.0109 h_{nt,4} + 0.038 h_{nt,4}^2
\]

\[
\text{Generation Unit 1 Output Limits: } 35 \text{ MWe} \leq p_{nt,1} \leq 135 \text{ MWe} \\
\text{Boiler Unit 4 Output Limits: } 0 \text{ MWth} \leq h_{nt,4} \leq 60 \text{ MWth}
\]
5.4.2 Demand Cases and Optimal Settings

Shown in Figures 5.7 are 28 demand cases, labelled "1" through "28". The final version of the CED-EP algorithm, except for demand case 7, was used to find the optimal settings and lowest costs for demand cases after the test system was constructed. Batches of 5 trials, using a population size of 25 and maximum of 500 iterations and no convergence stopping, were run for each demand case.

The optimality of the solutions obtained by the CED-EP algorithm were verified by comparing them to manually determined "likely alternate" candidates. From previous experience [21], it was known that most optimal solutions had one or more generators operating at an extreme setting, i.e. cogeneration units in the corners of their FOR, boiler and generators at either minimum or maximum output. Some of the likely alternate candidate solutions produced featured units in combinations featuring at least one extreme generator settings. The rest of the likely alternate candidates produced for comparison were small variations of the CED-EP optimal settings to see if improvements were to be found in the local vicinity.
Demand case 7 (240 MWth, 200 MWe), presented special problems to the initialisation routine. It was very close to the boundary and random initialisation could not find a population of valid solutions. The semi-deterministic back-up procedure was also unable to make near valid solutions. However, by using demand case 8’ optimal solution as a start point for experimentation, the optimal solution was determined.

With a few exceptions, the algorithm was able to find optimal generator outputs for the demand cases at least 2 times out of 5 for each batch of trials; these were designated "simple" cases. The exceptions are by marked open markers in Figure 5.7, e.g. "1", "17", "28". For these cases the CED-EP algorithm program was unable to precisely find the optimal generators settings, however they were close enough to be determined by local vicinity search during the optimality verification.
Table 5.5 lists for each case: the interval heat \( (H) \) and total power \( (P) \) demands; the lowest fuel cost \( (\text{Cost}) \); and the optimal outputs of the conventional power generator \( (G1) \), cogeneration units \( (C2, C3) \) and the boiler unit \( (B4) \). According to the demand cases position in relation to FDR, the demand cases are classified as being in the vicinity of the FDR bounds \( (\text{Edge}) \), inner region \( (\text{Inner}) \) or central to the FDR \( (\text{Centre}) \). The difficult demand case number designations are bold typed. The asterisk next case 7 indicates that CED-EP was not able to find the optimal solution.

<table>
<thead>
<tr>
<th>Edge</th>
<th>( H ) (MWth)</th>
<th>( P ) (MWe)</th>
<th>Cost ($)</th>
<th>( G1(p_{nt,1}) )</th>
<th>( C2(h_{nt,2}) )</th>
<th>( C2(p_{nt,2}) )</th>
<th>( C3(h_{nt,3}) )</th>
<th>( C3(p_{nt,3}) )</th>
<th>( B4(h_{nt,4}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>110</td>
<td>7778.69</td>
<td>52.25</td>
<td>25.00</td>
<td>13.75</td>
<td>0.00</td>
<td>44.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>110</td>
<td>7764.26</td>
<td>57.30</td>
<td>40.00</td>
<td>10.00</td>
<td>35.00</td>
<td>42.70</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>110</td>
<td>7802.03</td>
<td>59.00</td>
<td>40.00</td>
<td>10.00</td>
<td>60.00</td>
<td>41.00</td>
<td>0.00</td>
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<td>200</td>
<td>10122.59</td>
<td>121.04</td>
<td>40</td>
<td>10</td>
<td>100</td>
<td>68.96</td>
<td>60</td>
</tr>
<tr>
<td>7*</td>
<td>240</td>
<td>200</td>
<td>12111.84</td>
<td>69.7</td>
<td>44.4</td>
<td>20.1</td>
<td>135.6</td>
<td>110.2</td>
<td>60</td>
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<tr>
<td>8</td>
<td>240</td>
<td>250</td>
<td>12671.41</td>
<td>119.7</td>
<td>44.4</td>
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<td>135</td>
<td>50.3</td>
<td>33.9</td>
<td>91.5</td>
<td>81.1</td>
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<tr>
<td>10</td>
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<td>12942.46</td>
<td>135</td>
<td>47</td>
<td>42</td>
<td>93</td>
<td>98</td>
<td>60</td>
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<td>150</td>
<td>300</td>
<td>13778.05</td>
<td>135</td>
<td>21</td>
<td>53</td>
<td>77</td>
<td>112</td>
<td>52</td>
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<td>12</td>
<td>100</td>
<td>300</td>
<td>13502.41</td>
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<td>60</td>
<td>109</td>
<td>40</td>
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<td>75</td>
<td>300</td>
<td>13386.16</td>
<td>135</td>
<td>0</td>
<td>55.6</td>
<td>45.5</td>
<td>109.4</td>
<td>29.5</td>
</tr>
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<td>135</td>
<td>0</td>
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<td>110.5</td>
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<tr>
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<td>135</td>
<td>0</td>
<td>40</td>
<td>19.2</td>
<td>75</td>
<td>5.8</td>
</tr>
<tr>
<td>16</td>
<td>25</td>
<td>175</td>
<td>8467.08</td>
<td>117.25</td>
<td>25</td>
<td>13.75</td>
<td>0</td>
<td>44</td>
<td>0</td>
</tr>
</tbody>
</table>

**Inner**

| 17   | 75             | 150           | 8167.18  | 97.3           | 40             | 10             | 35             | 42.7           | 0              |
| 18   | 125            | 150           | 8274.31  | 100            | 40             | 10             | 75             | 40             | 10             |
| 19   | 175            | 150           | 8507.86  | 100            | 40             | 10             | 75             | 40             | 60             |
| 20   | 175            | 200           | 9550.15  | 135            | 44             | 19.2           | 80             | 45.8           | 51             |
| 21   | 190            | 250           | 11758.73 | 135            | 45.8           | 34.5           | 88.4           | 80.5           | 55.8           |
| 22   | 175            | 250           | 11666.98 | 135            | 39.4           | 35.5           | 83.3           | 79.5           | 52.3           |
| 23   | 125            | 250           | 11390.99 | 135            | 17.6           | 38.5           | 67.2           | 76.5           | 40.2           |
| 24   | 75             | 250           | 11160.59 | 135            | 0              | 41             | 48.4           | 74             | 26             |
| 25   | 75             | 200           | 9088.81  | 135            | 4.8            | 23.23          | 48.8           | 41.77          | 21.4           |

**Centre**

| 26   | 125            | 205           | 9498.48  | 135            | 24.5           | 24             | 65.5           | 46             | 35             |
| 27   | 125            | 195           | 9094.50  | 135            | 26.6           | 19.3           | 65.1           | 40.7           | 33.3           |
| 28   | 125            | 185.01        | 8728.20  | 135            | 39.96          | 10.01          | 75             | 40             | 10.04          |

**Table 5.5:** Demand Case with Optimal Costs and Generator Settings

Demand case 28 (125 MWth, 185 MWe) differs from the other difficult case (1, 5, 6, 7, 8, 16 and 17); it is a simple but "unstable" demand case. Following the series of 125 MWth demand cases (18, 28, 27, 26), it is seen that the power demand of 185 MWe is last demand case where that the cogeneration units \( (C2 \) and \( C3 \) from Table 5.5) are
loaded at their lower right hand corner operating points. The mutation process appears to get caught by the dilemma of staying in the "old" optimal corner positions (case 18) or moving on to new optimal settings (cases 26 and 27). However, it was found that moving the power demand by the smallest increment, i.e. using 185.01 MWe or 184.9 MWe instead, was enough to break the "confusion" of evolution process, allowing the optimal answer to be found consistently.

5.5 Conclusions

The intermediate [2] and final versions of the CED-EP algorithm performed well on the chosen the test system [18] for the validation study. Despite some issues that impeded the evolution process, the algorithm was able to find solutions quickly, in terms of both iterations and elapsed time, and reasonably reliably for population sizes 15, 20 and 25. For population sizes 30 and above the evaluation study indicated little improvement, in terms of iterations until solution was found, compared to using smaller population sizes. The CED-EP algorithm was unreliable when population sizes less than 15 were used.

A new test system was assembled, with the aim of producing a system better suited to validating general CHPD optimisation methods. Though not fully investigated or evaluated for robust EP settings, i.e. maximum iterations and population size, the CED-EP algorithm performed very well, and without any a priori knowledge was able obtain, or get very near, the optimal solutions for 28 demand cases using a population size of only 25.

Two interesting cases of "transient" faults within the algorithm / program appeared during these studies. The first concerns "unexpected" performance of particular population sizes mentioned in Section 5.3.2. The second is the existence of "difficult" demand cases; where demands are near to the bounds of the feasible demand region there is only a small viable range for the algorithm's mutation process to work in. The existence of "unstable" demand cases was not anticipated, though once observed the cause of occurrence was easily identified.
Comparison of Subsection 5.3.3 results, the final version of the algorithm as reported in Chapter 4, and Subsection 5.3.2 results, the “intermediate” version of the algorithm reported in [2], show a great improvement in the final, fine-tuned version of the CED-EP algorithm.

The final version of CED-EP had not been developed at the time of the investigation described in Chapter 6. As such, investigation of the analytical solution acceleration (ASA) technique, as described in following chapter, was done in conjunction with the intermediate CED-EP algorithm, using results of Subsection 5.2.3 as the base case for comparison.
Chapter 6

Analytical Solution Acceleration of the CED-EP Algorithm

6.1 Population Acceleration

The purpose of using acceleration techniques is to reduce elapsed time taken by a base algorithm to find the optimal solution. The CED-EP algorithm already incorporates gene correction acceleration measures specific to the combined heat and power dispatch (CHPD) problems in its initialisation and mutation processes. The virtual population acceleration methodology [68] is an acceleration scheme that works by creating, after competition, a new, "virtual" population of candidates that have been modified via non-problem specific techniques for subsets of candidates. The virtual population is then competed against the non-accelerated population so that the next pool after this second round of competition should be stronger than the pre-acceleration pool.

The virtual population methodology uses three techniques to create the new population: analytical solution acceleration (ASA); forward numerical solution acceleration (Forward NSA); and reverse numerical solution acceleration (Reverse NSA). Based on the first derivative of heat / fuel cost characteristics, the ASA technique seeks to "nudge" current settings toward the current best. Using a vector of the difference between current and best variable settings, the NSA techniques either accelerate current settings "forward" of the current best settings or "reverses" settings away from the current best. The techniques are demonstrated for a single dimensional variable in Figure 6.1.
The CED-EP algorithm had already performed well on the validation test case presented in Chapter 5. It was decided to investigate whether the ASA technique could improve the performance of CED-EP in solving this test case. Reduction of the run time of an algorithm can be produced by two means: reducing the size of the population required to solve the problem reliably, or; significantly reducing the number of iterations taken by an accelerated algorithm to find the optimal solution.

From the validation study, the published results [2] showed that for a version of the CED-EP algorithm population size 25 had been the minimum population to achieve a 95% success rate, though population size 20 was only just below the required success rate. The first aspect of acceleration effectiveness was investigated by attempting to solve the validation test case with smaller population sizes using the CED-EP algorithm with ASA incorporated. To investigate the second aspect of acceleration effectiveness, it was decide to see if ASA could reduce the average number of iterations required to find the optimal solution for population sizes 20 and 25.

In the investigation of ASA four implementation variables were investigated: heat variable vs. power variable acceleration; "Top of Pool" vs. "Bottom of Pool" candidate selection for acceleration; the percentage of candidate pool members accelerated, and; frequency at which acceleration was applied.

### 6.2 Analytical Solution Acceleration

In broad terms, the purpose of an economic dispatch optimisation is to minimise a cost function, \( f(V) \), where \( V \) is a vector containing the outputs of generation units within the system. This is shown in equation (6.1).
\[
\min f(V) = \min f(v_1, v_2, \ldots, v_n) \tag{6.1}
\]

In the EP methodology, after each competition stage the pool of candidates, \(V_k, k \in \{1, 2, \ldots, m\}\), are ranked according their fitness, i.e. \(V_1\) is the strongest candidate, \(V_m\) is the weakest\(^1\). The aim of ASA is to shift the variables of a candidate \(V_j, j \subseteq k \neq 1\), toward the settings of the best candidates, \(V_1\), settings via equation (6.2) to a new, accelerated set of variables, \(V_{j,acc}\).

\[
V_{j,acc} = V_j + \mu U [f(V_1) - f(V_j)] \tag{6.2}
\]

In equation (6.2) \(U = [1, 1, \ldots, 1]'\), and \(\mu\) is a matrix of reciprocals of gradients, as shown by equation (6.3).

\[
\mu = \begin{bmatrix}
\frac{\partial f}{\partial v_1}^{-1} & 0 & \cdots & 0 \\
\vdots & \frac{\partial f}{\partial v_2}^{-1} & \cdots & 0 \\
0 & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \frac{\partial f}{\partial v_n}^{-1}
\end{bmatrix} \tag{6.3}
\]

The ASA scheme relies upon first-derivatives of the cost functions; as such it is not readily suitable for system containing discontinuous cost / heat characteristics models.

6.2.1 Applying ASA to CHPD Problems

Prior to this research the ASA technique had only been applied to standard, "power only" economic dispatch problems [69]. The general CHPD system has "n" generators, with subsets of power-only generation units, heat-only boiler units and power and heat cogeneration units. The objective function, and candidate solution vectors, of CHPD problems are represented in the CED-EP algorithm by equation (6.4).

\(^1\) In Chapter 4 the Greek letter \(\mu\) was used to denote the standard evolutionary programming (EP) competition strategy as \((\mu+\mu)\). However in the ASA methodology \(\mu\) has a defined meaning; to avoid confusion the number of candidates in pool is denoted as "m", and the competition strategy is denoted as \((m+m)\), in this chapter.
\[
\min f(V) = \min f(p_1, \ldots, p_\alpha, (p_{\alpha+1}, h_{\alpha+1}), \ldots, (p_\beta, h_\beta), h_{\beta+1}, \ldots, h_n)
\] (6.4)

As described Section 4.6, a risk in all acceleration techniques is that, if inappropriately implemented, they can override and impede the base search mechanisms. To minimise this risk, ASA acceleration is only applied to either thermal or power variables at any one time. Modifications to the \(\mu\) matrix of equation (6.3) are required for the ASA of only power, or only heat, variables. To demonstrate this, the \(\mu\) matrix has been partitioned as per equation (6.5).

\[
\mu = \begin{bmatrix}
A & 0 & 0 \\
0 & B & 0 \\
0 & 0 & C
\end{bmatrix}
\] (6.5)

Partition "A" covers power-only units' variables, \(p_{(1, \alpha)}\), "B" cogeneration units' variable couplets \((p_{(\alpha+1, \beta)}, h_{(\alpha+1, \beta)})\), and "C" the heat-only units' variables, \(h_{(\beta+1, n)}\). In equations (6.6a)-(6.6c) and (6.7a)-(6.7-c), the \(p\) and \(h\) subscripts identify matrices for use in applying ASA to power variables or heat variables respectively.

\[
A_p = \begin{bmatrix}
\frac{\partial f}{\partial p_1} & 0 & 0 \\
0 & \ddots & 0 \\
0 & 0 & \frac{\partial f}{\partial p_\alpha}
\end{bmatrix}
\]

\[
B_p = \begin{bmatrix}
\frac{\partial f}{\partial p_{\alpha+1}} & 0 & \cdots & 0 & 0 \\
0 & 0_{\alpha+1} & \cdots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \cdots & \frac{\partial f}{\partial p_\beta} & 0 \\
0 & 0 & \cdots & 0 & 0_{\beta}
\end{bmatrix}
\] (6.6a&b)

\[
C_p = \begin{bmatrix}
0_{\beta+1} & 0 & 0 \\
0 & \ddots & 0 \\
0 & 0 & 0_{\alpha}
\end{bmatrix}
\]

\[
A_h = \begin{bmatrix}
0_{\alpha+1} & 0 & \cdots & 0 & 0 \\
0 & \frac{\partial f}{\partial h_{\alpha+1}} & \cdots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \cdots & 0_{\beta} & 0 \\
0 & 0 & \cdots & 0 & \frac{\partial f}{\partial h_\beta}
\end{bmatrix}
\] (6.7a&b)
Chapter 6: Analytical Solution Acceleration of the CEP-EP Algorithm

6.2.2 ASA in the CED-EP Algorithm

When polynomial cost / heat characteristic models are used in test systems the marginal costs, i.e. first derivatives, are computationally simple to implement; this was a factor in choosing to investigate the ASA technique ahead of the NSA techniques. The ASA augmentation of the CED-EP algorithm was incorporated as a separate subroutine within the EP methodology iteration "loop" after the competition stage had selected the parent pool for next generation. Using ASA increases the number of operations per iteration of the EP, i.e. "iteration length", so reducing the average number of iterations required to find the solution with ASA may not actually reduce average solution time.

Rather than creating a full "m candidates" virtual population and run a competition phase between accelerated and non-accelerated pools, a sub group of candidates are selected for acceleration via the ASA technique. If an accelerated candidate is fitter, i.e. has a lower total fuel cost, than its non-accelerated base candidate, and meets all constraints, it replaces it in the pool of the next generation individuals.

Two versions of the accelerated CED-EP algorithm were developed: CED-ASP for Analytical Solution acceleration of Power variables and CED-ASH for Analytical Solution acceleration of Heat variables. The programs for these algorithms required an additional input argument to control the use of ASA within the modified algorithms. The EP methodology with ASA incorporated is shown in Figure 6.2.

6.2.3 Heat and Power Interval-Demand Correction

For CED-ASH and CED-ASP to operate correctly, all individuals chosen from a pool of candidates for acceleration should have the same interval heat output, or interval power output respectively. The total heat and power demand constraints that were relaxed
during the mutation process (see equations (4.18) and (4.19)) had to be fully applied in order for the effects ASA technique to be verified.

For the CED-ASP algorithm, the extra power above the interval-demand, if any, supplied by child candidate solutions formed during mutation is calculated. Then, according to the reverse of the dispatch order routine described in Section 4.3.1, the extra power is subtracted from generators until the interval power demand is met exactly. This results in all individuals having the same total amount of power prior to acceleration. For the CED-EP and CED-ASH algorithms a similar heat interval-demand correction routine was incorporated.
The interval-demand correction routines are deterministic and interfere with the random nature of the mutation search mechanisms used by the CED-EP algorithm. To minimise the interference, only heat or power interval-demand correction was used in the CED-ASH and CED-ASP algorithms respectively.

It was found that the effectiveness of the competition stage was improved by applying the interval-demand correction routines between mutation and competition stages (see Figure 6.2). If the generator output settings of an individual were almost optimal, but due to the relaxed greater-than or equal constraints, one generator was producing more power and / or heat than necessary, hence incurring additional cost, it would be penalised during the competition stage. The interval demand correction process would remove the excess heat or power load, and excess cost associated with that excess heat or power, thus strengthening candidates and improving their chances of selection for the next generation of parents. The heat interval-demand correction routine was used specifically in the intermediate [2] and final version of the CED-EP algorithm an acceleration technique.

6.2.4 "Top of Pool" vs. "Bottom of Pool" Implementation

The ASA scheme can be varied as to what constitutes the group of candidates to be accelerated, i.e. the set "j" from equation (6.2). Within a population there is an assumption of clustering. This assumes the stronger candidates are strong because they resemble the strongest candidate, i.e. $V_1 \approx V_2 \approx V_3$, and weak candidates are weak because they are different from the current best, i.e. $V_1 \neq V_{m-1}, V_1 \neq V_m$. A "Top of Pool" (ToP) scheme searches the area surrounding the strongest candidate, $V_1$, for marginal improvements by accelerating the stronger candidates, i.e. $j \in \{2, 3, \ldots\}$. A "Bottom of Pool" (BoP) scheme searches for new optima away from the current best settings, accelerating the weaker candidates, i.e. $j \in \{\ldots, m-1, m\}$.

The level of deterministic interference by ASA in the CED-EP search mechanisms is influenced by the percentage of individuals in a pool that are chosen for acceleration. An input argument of the algorithm programs was used set the percentage of candidates accelerated by either ToP or BoP implementations. It is possible to negate (partially or fully) the intended effect of ToP / BoP implementations by accelerating too great a
percentage of the population. The most extreme case is accelerating 100% of candidates in the pool, whereby ToP and BoP implementation should have the same effect.

6.2.5 Frequency of Implementation

An acceleration technique can be made to be overly intrusive by applying it too often; this issue also affects computational efficiency / intensity. Every candidate accelerated extends the run time of the EP algorithm's iterations; efficiency "gains" achieved by reducing average number of iterations for convergence can be negated by excessively long run times for each iteration. Through the initial stages of the investigation, ASA was implemented as part of every iteration.

The implementation variables already discussed were investigated to establish an implementation of ASA that would improve performance compared to the base CED-EP algorithm. Using this good combination as starting point, the last sets of trials examined the effect of reducing the frequency at which acceleration is applied.

6.3 Evaluation Study Results

The evaluation of CED-ASP and CED-ASH algorithms was assessed on solution-finding ability improvements compared to the non-accelerated CED-EP algorithm. Improvements are identifiable by two criteria: significantly improved performance for population sizes that already have acceptable trial group fail rates; or obtaining acceptable trial group fail rates from lower populations. Population sizes 20 and 25 were studied for solution time improvements (lower average iterations for solution) while not increasing trial failure rates. Small population sizes of 6, 8, 10 and 15 were investigated to see if the trial failure rates could be reduced to an acceptable level.

For each evaluation study the particular scheme was run for 50 or 100 trials. The maximum trial failure rate allowed was set at 5%, though in the case where sets of 50 trials were run this was relaxed slightly so as to accept 3 fails from 50 as a "marginal" success. Using the results of Section 5.3 as guide, the maximum number of iterations
(Max Its) allowed for each population size (Pop) is shown in Table 6.1. The convergence stop rule was not used in these trials.

<table>
<thead>
<tr>
<th>Pop</th>
<th>Max Its</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 6.1: Maximum Number of Iterations for Population Sizes

In the following discussions of results "Pop X" will refer to data in trials that used a population of "X" candidates. For each trial the iteration at which the optimal solution was found was recorded; for each group of trials the maximum (Max), minimum, (Min), and average (Ave) of these iterations of solution was recorded; their abbreviation (Min, Max and Ave) is used in the following discussions. The "fail rate" of the set of trials is represented as decimal, e.g. if 2 trials fail from a group of 50, that group of trials has a fail rate of 0.04.

Evaluation scores, the product of the population size and the Ave values, are used as comparable measures of the "average" computation intensity for each group of trials. Though not always discussed, they are recorded as "Eval" in Tables 6.4, 6.6 and 6.8 are used as a measure of computational intensity. When evaluating the effectiveness of acceleration schemes it is common to plot the evaluation scores of the non-accelerated algorithm against population size, i.e. an evaluation study, on the same chart as those obtained through the acceleration schemes being evaluated. However, in this study comparative evaluation study plots were not useful. This is due to erratic behaviour expected to be exhibited by small population sizes 6, 8 10 and 15, and very similar results for all schemes seen in populations sizes 20 and 25 cases.

6.3.1 Integration of ASA into CED-EP

Before proceeding with data collection from CED-ASH and CED-ASP algorithms, it was imperative to ensure that the ASA code had been integrated properly into the base CED-EP C++ code. An option available, via the additional input argument used in
CED-ASP and CED-ASH algorithm programs, was to run the programs so as to bypass ASA subroutine in the EP loop (see Figure 6.1). Also, at the compiling stage of the programs, it has to be decided whether the algorithm is going to use the ToP or the BoP candidate selection schemes in ASA subroutine.

Using groups of 50 trials and population sizes of 20 and 25, the CED-ASH and CED-ASP algorithm were run under "ASA off" conditions. If the coding is correct the difference, in performance in terms of the fail rates and Ave values, between CED-ASH and CED-ASP should be minimal. Under these conditions the only difference between the algorithms is that CED-ASH uses heat interval-demand correction after the mutation stage of the EP loop and CED-ASP uses power interval demand correction (see Figure 6.2). The results of these tests are shown in Table 6.2.

<table>
<thead>
<tr>
<th>Pop</th>
<th>Fail</th>
<th>Ave</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2</td>
<td>16.82979</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>20.14583</td>
<td>54</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>16.51022</td>
<td>31</td>
<td>4</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>16.64</td>
<td>36</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 6.2: CED-ASH and CED-ASP "ASA Off" Study

As expected, the number of fails and Ave value for the groups of trials are similar enough between CED-ASH and CED-ASP say that the ASA subroutine has been implemented properly. Comparison of the ranges of values obtained for iterations of solution (Min-Max) show that CED-ASP in on average a little slower, i.e. higher Max values. This suggests that accelerating heat variables is likely to produce better results, i.e. lower Ave values, than accelerating of power variables.

Using the CED-ASH program and a population size of 6, four groups of 50 trials were run to check that ToP and BoP implementation of ASA were coded properly. The first test was to compare results from "ToP-0%" and "BoP-0%" to make sure results were similar under "ASA off" conditions. In Tables 6.3 and 6.4 below, the data for non-accelerated CED-ASH (Non-H) and Pop 6 is reported for 100 trials, the combination of the 50 trials of ToP-0% and 50 trials of BoP-0% data.
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As mentioned in Subsection 6.2.4, accelerating 100% of candidates under the ToP selection scheme is the same as accelerating 100% of candidates under the BoP selection scheme. This property was also used to verify that the two candidate selection schemes had been coded properly in the ASA subroutine.

6.3.2 Heat Variable "ToP" and "BoP" Implementations

The results in Table 6.2 suggest that acceleration of heat variables would result in better performance than acceleration of power variables. It was assumed that only candidates ranked in the upper 50% of the pool would be similar enough to the best candidate to find marginal improvements via ToP implementation. The concurrent assumption is that only candidates ranked in lower 50% (particularly the lowest 25%) would differ sufficiently from the best candidate for new local optima to be located via BoP implementation. It was recognised that these assumptions were not likely to hold for the small populations (Pop 6, 8 and 10). It was therefore decided that ToP-25%, ToP-50% and BoP-25% implementations of the ASA scheme for Heat variables would be investigated first.

In Table 6.3 the results obtained with “ASA off” and heat interval-demand correction only (Non-H) are used as the base for comparison. These results have already been discussed in their own right in Subsection 5.3.2 of the Chapter 5.

<table>
<thead>
<tr>
<th>Pop</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-H</td>
<td>0.2</td>
<td>0.08</td>
<td>0.14</td>
<td>0.06</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>ToP - 25%</td>
<td>0.2</td>
<td>0.08</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>ToP - 50%</td>
<td>0.18</td>
<td>0.04</td>
<td>0.16</td>
<td>0.1</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>BoP - 25%</td>
<td>0.2</td>
<td>0.26</td>
<td>0.1</td>
<td>0.02</td>
<td>0.12</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 6.3: Fail Rates of ToP and BoP ASA Implementations for Heat Variables

In Table 6.3 groups of the trials that returned acceptable, or marginally acceptable, fail rates have been shaded in grey. As mentioned in Subsection 5.3.2, Pop 8 results tended to go against the trend; this again was the case. The “ASA off” CED-ASH (Non-H) and ToP-50% implementation results for this Pop 8 are lower that expected, while BoP-25% are unexpectedly high. Overall the results in Table 6.3 suggest that the ToP-25% CED-ASH implementation reduced to 10 the required population size to solve this demand case reliably. Population size and ASA implementation combinations which meet the...
marginal, 0.06, fail rate criteria, and are considered reliable, are shaded in grey in Table 6.4.

<table>
<thead>
<tr>
<th>Pop</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>62.4</td>
<td>40.5</td>
<td>32</td>
<td>23.68</td>
<td>18.83</td>
<td>16.51</td>
</tr>
<tr>
<td>Max</td>
<td>180</td>
<td>126</td>
<td>83</td>
<td>64</td>
<td>44</td>
<td>31</td>
</tr>
<tr>
<td>Min</td>
<td>14</td>
<td>11</td>
<td>9</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Eval</td>
<td>374.4</td>
<td>324</td>
<td>320</td>
<td>355.21</td>
<td>376.60</td>
<td>412.761</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pop</th>
<th>7</th>
<th>11</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>61.32</td>
<td>32.30</td>
<td>25.94</td>
<td>21</td>
<td>18.773</td>
</tr>
<tr>
<td>Max</td>
<td>185</td>
<td>137</td>
<td>53</td>
<td>68</td>
<td>42</td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Eval</td>
<td>367.95</td>
<td>258.43</td>
<td>259.38</td>
<td>315</td>
<td>375.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pop</th>
<th>10</th>
<th>Ave</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>38.73</td>
<td>38.25</td>
<td>29.38</td>
<td>23</td>
</tr>
<tr>
<td>Max</td>
<td>126</td>
<td>182</td>
<td>78</td>
<td>77</td>
</tr>
<tr>
<td>Min</td>
<td>11</td>
<td>10</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Eval</td>
<td>232.39</td>
<td>306</td>
<td>293.81</td>
<td>345</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pop</th>
<th>14</th>
<th>Ave</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>49.4</td>
<td>39.16</td>
<td>29.56</td>
<td>25.04</td>
<td>19.45</td>
<td>16.20</td>
</tr>
<tr>
<td>Max</td>
<td>121</td>
<td>156</td>
<td>100</td>
<td>53</td>
<td>51</td>
<td>34</td>
</tr>
<tr>
<td>Min</td>
<td>14</td>
<td>11</td>
<td>14</td>
<td>10</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Eval</td>
<td>296.4</td>
<td>313.30</td>
<td>295.56</td>
<td>375.61</td>
<td>389.09</td>
<td>404.89</td>
</tr>
</tbody>
</table>

Table 6.4: Solution of Iteration Data for Heat Variable Acceleration

For the ToP-25% ASA implementation results, the Pop 10 Ave value is only 2 higher than the CED-EP (Non-H) Pop 15 Ave value. In effect, for population size 10, ASA is only applied to the 2nd and 3rd ranked candidate during iterations, so is adding a relatively small amount of computation to the iteration length throughout the trials. Comparison of the Eval scores between these two cases suggest that, on average, using a population size of 10 with a Top-25% ASA implementation is much less computationally intensive than using non-accelerated CED-EP with population size of 15.

The ToP-50% CED-ASH implementation did not improve upon the performance of the CED-EP, with marginal success (0.06 fail rate) up to Pop 20 from Pop 15 for non-ASA, CED-EP results. Like CED-EP alone, the first fully successful fail rate results (0.05 or less) occurred for Pop 25, but this produced a marginally higher corresponding Ave value, and a significantly longer iteration length due to the use of the ASA routine. The "successful" set of trials for Pop 8 is discounted as unreliable, as the trend of the surrounding sets of results suggests that a higher fail rate is likely to occur.
Of the BoP-25% candidate selection implementation, the only set of results that improved on the fail rate of the non-accelerated algorithm was Pop 15. However due to the wide variation of results across the population sizes studied, the BoP-25% implementation was not considered reliable enough to warrant further study.

6.3.3 Power Variable "ToP" Implementation

Having established that BoP implementation was not likely to yield positive results, the next variable of ASA implementation investigated was whether the heat variables were better suited to acceleration than power variables. In these evaluation studies ToP-25% CED-ASP and ToP-50% CED-ASP implementations were run in trial groups of 50 for each population size investigated. The base case, non-accelerated results used in the Subsection 6.3.2 utilised the heat interval-demand correction, i.e. "Non-H"; for the present set of results it was decided to run the base case results using power interval-demand correction. Initially non-accelerated results (Non-P) were run in sets of 50 trials, however the fail rates were so high that another set of 50 trials was run for each non-accelerated CED-ASP case. The Non-P results shown in Tables 6.5 and 6.6 have been extracted from the combined data sets of 100 Trials.

<table>
<thead>
<tr>
<th>Pop</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-P (100)</td>
<td>0.14</td>
<td>0.14</td>
<td>0.12</td>
<td>0.12</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>ToP - 25% (50)</td>
<td>0.14</td>
<td>0.12</td>
<td>0.06</td>
<td>0.06</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>ToP - 50% (50)</td>
<td>0.2</td>
<td>0.14</td>
<td>0.08</td>
<td>0.04</td>
<td>0.02</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Table 6.5: Fail Rates of ToP ASA Implementations for Power Variables

When compared to Non-H results in Table 6.3, the Non-P fail rates for Pop 8, 10, 15 and 20 indicate that power interval-demand correction alone is not as good as heat interval-demand correction. When comparing the ToP-25% fail results of Tables 6.3 and 6.5, both power and heat variable acceleration brings down to 10 the minimum population with marginally acceptable fail rate (0.06). For the ToP-50% comparisons between Table 6.3 and 6.5, power variables perform better, returning the less than 0.05 fail rate for Pop 15 and 20, while the heat variable acceleration could only produce 0.06 fail rate on Pop 20.
The ASA implementation and population size combinations with marginally acceptable or lower fail rates are shaded in Table 6.6. Though the fail rate data are not very different for power and heat variable ASA implementations, the Ave value comparison between Tables 6.4 and 6.6 shows that heat variables are better suited to the acceleration technique. While ToP-25% implementation of CED-ASP produced the same fail rate for Pop 10 and 15, the Pop 10 Ave results were significantly higher for 15. This suggests that on average there would be very little difference in solution time whether using Pop 15 or Pop 10 with a ToP-25% ASA implementation on power variables. The ToP-50% CED-ASP implementation Ave values for Pop 15, 20 and 25 offer no significant improvement over the Non-P and Non-H results, but add significantly to the computational intensity.

### Table 6.6: Iteration of Solution Data for Power Variable Acceleration

<table>
<thead>
<tr>
<th>Pop</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>51.71</td>
<td>44.41</td>
<td>34.78</td>
<td>24.44</td>
<td>19.61</td>
<td>16.60</td>
</tr>
<tr>
<td>Max</td>
<td>146</td>
<td>146</td>
<td>175</td>
<td>77</td>
<td>54</td>
<td>37</td>
</tr>
<tr>
<td>Min</td>
<td>11</td>
<td>1</td>
<td>2</td>
<td>8</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Eval</td>
<td>310.26</td>
<td>355.26</td>
<td>347.84</td>
<td>366.65</td>
<td>392.26</td>
<td>415.05</td>
</tr>
</tbody>
</table>

**ToP-25%**

| Ave  | 71.67 | 46.93 | 37.49 | 23.96 | 19.41 | 17.65 |
| Max  | 204   | 149   | 88    | 53    | 42    | 53    |
| Min  | 17    | 11    | 12    | 12    | 7     | 7     |
| Eval | 430.05 | 375.45 | 374.89 | 359.36 | 388.18 | 441.33 |

**ToP-50%**

| Ave  | 64.00 | 48.58 | 31.57 | 23.71 | 20.57 | 15.32 |
| Max  | 158   | 127   | 85    | 78    | 45    | 52    |
| Min  | 3     | 9     | 10    | 11    | 3     | 7     |
| Eval | 384.00 | 388.65 | 315.65 | 355.63 | 411.43 | 382.98 |

6.3.4 Reduced Frequency of Population Acceleration

Having established that a 25% ToP implementation of ASA of heat variables provided a tangible improvement in algorithm performance for Pop 10 and 15, it was decided to examine the effect of reducing the frequency at which the acceleration routine is applied. As seen in Tables 6.8 and 6.9 Pop 20 and 25 were also included in the study. Tables 6.7 and 6.8 have the non-ASA accelerated (Non-H) and ToP-25% implementation (Freq=1) data for CED-ASH from Tables 6.3 and 6.4, as well as new data for the ASA scheme only being applied every second iteration (Freq=2) and every fifth iteration (Freq=5).
In Tables 6.7 and 6.8 the "best" cases have been shaded. These best cases are the ASA frequency implementation and population size combinations that produced the fail rates of 0.06 or lower (see Table 6.7) and the lowest evaluation score, i.e. measure of computational intensity.

<table>
<thead>
<tr>
<th>Pop</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-H</td>
<td>0.14</td>
<td>0.06</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>Freq=1</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Freq=2</td>
<td>0.06</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Freq=5</td>
<td>0.12</td>
<td>0.08</td>
<td>0.04</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 6.7: Fail Rates for Reduced Frequencies of ASA

Table 6.7 fail rate data show that halving the frequency (and hence the number of additional computations used) of the ASA will still reduce to 10 the required population size for CEP-EP to find the optimal solution reliably. Using ASA acceleration only once in 5 iterations is not often enough to improve the fail rates notably.

For Pop 10, the Ave value for Freq=1 is approximately 26, so the scheme will have used 26 applications of ASA, while the Freq=2 Ave value is approximately 30 but is achieved with only 15 applications of ASA. Likewise, for Pop 15 the Freq=2 results have an Ave value approximately 2 higher than those of Freq=1 but achieved this with
around 10 fewer applications of ASA. These results suggest that for this test case it is computationally more efficient to only use acceleration as a part of every second iteration.

Due to the low \textit{Ave} values, it would be expected that applying the ASA only in every fifth-iteration (\textit{Freq}=5) would have no notable effect compared to the non-accelerated (\textit{Non-H}) cases. For harder test cases, which, on average, the CED-EP algorithm will take more iterations to solve, less frequent application of ASA, e.g. every 5\textsuperscript{th} or 10\textsuperscript{th} iteration, may be of use.

### 6.4 Conclusions

The results in Table 6.4, 6.6 and 6.8 suggest that \textit{Pop} 20 is a critical limit for the usefulness of the ASA acceleration in the CED-EP algorithm for this test case. Some implementation schemes of ASA were able to improve performance for \textit{Pop} 10 and 15, however for \textit{Pop} 20 and 25 when actual elapsed time and additional computation is taken into account the performance is worse.

It was suggested in the concluding remarks of Subsection 5.3.2 that the borderline fail rate, i.e. 0.06 or 3-from-50, achieved by the non-accelerated algorithm for \textit{Pop} 15 and 20 may indicate that 15 is the minimum population size needed to obtain the optimal solution reliably. However, in light of the \textit{Freq}=5 results shown in Table 6.7, it is safer to say that 20 is the minimum population size required by the non-accelerated CED-EP algorithm; this is also in accord with the observations of the previous paragraph.

Of the ASA implementations investigated in these evaluation studies, it was found that the "Top of Pool" selection of candidates, which looks for marginal improvements on the current best solution, was the most successful. The "Bottom of Pool" candidate selection for acceleration did not show much promise. Of the ToP candidate selection schemes investigated, it was found that accelerating the top 25\% of candidates close to the current best candidate achieved the better results than accelerating the top 50\% of candidates.
Comparison of the results presented in Subsections 6.3.2 and 6.3.3 suggests heat variable acceleration produce better results than accelerating power variable acceleration.

Lastly the results of Subsection 6.3.4 show that the ASA scheme can be effective when used in moderation. The purpose of using acceleration techniques is to reduce elapsed time taken by a base algorithm to find the optimal solution; by using an acceleration technique only once in every few iterations the additional run time can be significantly reduced while still improving algorithm performance.

Some settings are suggested to enable the heat variable ASA accelerated CED-EP ("CED-ASH") algorithm to find optimal solution for this test case in minimal time reliably; again it is recommend that trials always be run in batch of at least 3. The settings are: population size of 10; a maximum of 100 iterations allowed; 25% ToP candidate selection for acceleration, and; ASA applied in every second iteration. In comparison to the revised Subsection 5.3.2 recommendation, these settings of the accelerated algorithm should find the solution faster than the non-accelerated CED-EP algorithm using a population 20 and a maximum of 100 iterations.
Chapter 7

Cogeneration Feasible Operating Region Modelling

7.1 Current Heat-Power FOR Models

One element affecting the performance of algorithms for finding optimal solutions to the economic dispatch problem is the shape and extent of the feasible operating region (FOR) of the various units in the system. A single, irregular quadrilateral is adequate for approximating conventional, steam expansion turbine, cogeneration units' (FOR) [18,19, 21]. However, since the early 1980s, electricity market deregulation [14], environmental legislation [38,39], high thermal efficiency gas turbine (GT) designs, and plentiful supplies of natural gas have made gas-fired GT cogeneration, combined cycle plants (GTCC) and gas turbine heat recovery steam generators (GT-HRSG) increasingly important in electricity supply markets. The FOR applying to GT-HRSG are better represented by models describes by two abutted, irregular quadrilateral-segments [18].

In this chapter the thermal efficiency of GT and HRSG units, and the practicalities of energy conversion within these units, will be considered. The bounds of the FOR model will be explained in terms of operating characteristic [73-77], thermodynamic principles [70], and thermodynamic properties of products of combustion (POC) [71]. These considerations provide a firm basis for more accurate modelling of GT based CHP systems.

Furthermore, these considerations of GT characteristics demonstrate that certain areas of the FOR, while technically feasible, are operationally undesirable. Specification of these areas leads to a reduced FOR, which in turn reduces the area that algorithms need to explore in seeking an optimal static economic dispatch solution.
7.2 Single Region FOR Models

The single, irregular quadrilateral form is adequate for describing the FOR of conventional, steam expansion turbine, cogeneration. Linear inequalities are used as the bounds of FOR models [19-21], though accuracy of these models when applied to GT cogeneration has not been satisfactorily validated in the literature. These models are tailored for use in quadratic programming and non-linear CHPD optimisation methods.

In Figure 7.1A a three-dimensional representation of a cogeneration unit's cost function and FOR is shown. A two-dimensional projection of the same cost model and FOR, with equal-cost contours, is shown in Figure 7.1B. Points "a", "b", "c" and "d" are the same in both figures.

![Figure 7.1: Conventional Top Cycle Cogeneration Unit Cost Function](image)

The FOR of Figure 7.1 is a single region, irregular quadratic that abuts the power axis; it characteristics would satisfy those of a conventional, top-cycling cogeneration plant. The indication that the unit is top-cycling (see Section 2.1), i.e. recovering steam after power generation, is that the thermal energy demand can go to zero while electrical power is required; this shown by line "a-d" in Figure 7.1B. Another characteristic, as mentioned in Subsection 5.2.3, is that the equal-cost contours only intersect the lower
bound, shown by line "d-c", at one point. This will be explained via examination of the steam cycle of a conventional, top-cycling cogeneration plant in the following subsection.

7.2.1 Steam Expansion Turbines

In Figure 7.2, the "P" axis refers to the steam pressure and "T" axis refers to the temperature of the steam. When raising steam, pressure and temperature will rise until the maximum energy content per volume of steam for the current pressure is reached; at this point steam is said to be saturated (left hand curve). However if the pressure is dropped after saturation, the temperature of the steam can be increased significantly, increasing the energy content per volume beyond the saturation energy content; this is called superheating (upper curve). Thermal energy released from the combustion of hydrocarbon fuels, as very hot gaseous POC, is used to raise and then superheat steam in conventional generation stations.

![Figure 7.2: Steam Cycle of Top-Cycle Cogeneration](image)

The superheated steam is transferred to a "steam chest" and stored temporarily. "Generation" of electricity is achieved by the flow of high-pressure working fluid (i.e. superheated steam from a steam chest) through expansion turbine stages to create rotational movement; the rotational movement is then used to turn the rotor stage of a generation set.
For an expansion turbine, as shown in Figure 7.3, to function, the working fluid entering the turbine must be at a higher pressure at the inlet than at the outlet. As working fluid flows through a turbine it imparts part of its energy content to the rotating blades of the turbine rotor stages. The energy loss in the working fluid is reflected by reduced pressure and temperature (right hand curve in Figure 7.2).

7.2.2 Steam Cycle of a Conventional Cogeneration Plant

As the water (steam) is continually recycled in conventional plants, the lower exit pressure is achieved by cooling / condensing unused steam back to warm water after it has been through the expansion stages of the turbo electric generator (bottom curve in Figure 7.2). The turbine stage/s will not start to turn their load shaft until the pressure differential between the initial steam inlet point and the condensation point is sufficiently high.

For fuel consumption below the normal minimum (point "d" in Figure 7.1), extracting cogeneration steam between turbine exit and condensation stages (lower part of right hand curve in Figure 7.2) can be used to increase the pressure differential between plant inlet (steam chest) and exit (condenser tubes) steam. The more steam extracted, the greater the pressure differential, and the lower the fuel consumption required for sustainable electricity output (cost contour / line "d-c" intersections in Figure 7.1B), up to a limit (point "c" in Figure 7.1B).
Within a conventional plant's steam cycle, steam is tapped at various points for deaerating, pre-heating and pressuring condensed water before it enters the boiler tubes and is exposed to "fresh" POC from combusted fuel, as indicated by the arrow in Figure 3.10. As the electrical power output increases, the amount of energy being drawn on to meet these internal demands increases, reducing the amount energy available for cogeneration heat extraction in the post-turbine and pre-condensation region of the steam cycle. This is seen in Figure 7.1B as the intersection cost/heat contours and the line "a-b".

After energy has been absorbed from superheated steam for high-pressure and low-pressure expansion turbines for electricity generation, and then for internal pre-processing of feed water, there is only so much energy that can be further extracted as heat in the cogeneration heat exchange. The limit is then also dependent on the specification of water / steam from the cogeneration heat exchange. This limit is seen as line "b-c" in Figure 7.1B.

### 7.3 Gas Turbines Generation Sets

The "standard" single-segment FOR, as shown in Figure 7.1 B, has been used to model FOR GT-HRSG cogeneration packages. However, upon examination of the differences between the operating principles of GT and conventional generation it will be seen that this model is not ideally suited for this purpose.

The principle of GT electricity generation is shown in Figure 7.4. At its simplest, a GT generation set consists of a common shaft with compressor stages at the air inlet end, and expansion turbine stages at the exhaust end. The shaft will extend from either end to connect, directly or through a gearbox, with a two-pole AC electricity generation set. As the shaft rotates it draws in and compresses air; this compressed air is then mixed with fuel and combusted, creating very high temperature, high-pressure POC, i.e. high energy content. The high energy POC flows through the expansion turbine stages, converting some of energy into the rotational energy used to turn the shaft.
When running at rated maximum electrical output, about 66% of the rotating, mechanical energy imparted from expansion turbine stages into the shaft will be required by the compressor stages to maintain sufficient air intake. Only around 33% will be used to drive the generation set’s alternator. If the load-shaft is connected through a gearbox there will be an additional small energy loss.

Figure 7.4: Operation Principles of Gas Turbine Electricity Generation

Gas turbine generators are physically compact (measured in MWe/m³ of plant space), simple in design and have very quick start-up times compared to conventional coal plants. However, prior to the mid-1980s their thermal efficiency was low compared to conventional steam-turbine power plants. Methods developed for improving thermal efficiency of stand-alone GT generators include partial re-pressuring of POC for use in additional low-pressure turbine stages, and "regenerative cycle" uses of exhaust POC: inter-cooling, intake air cooling, and combustion air pre-heating [70]. All of these options significantly increase the complexity and space requirement of the GT for relatively small efficiency gains.

The most effective way of boosting power output is to use a simple, or open, cycle GT, as shown in Figure 7.4, and use the hot exhaust gas to fuel a boiler, known as a heat recovery steam generator (HRSG). The steam output of the HRSG can be used to drive conventional steam expansion turbines for further power generation. When this is done it is called combined cycle power generation. There are two main designs for open-cycle GT: single shaft and multi-shaft. Single shaft designs are the simplest and most compact, having the generation set, air compressor and turbine on a single, common shaft. Multi shaft designs "split" the central shaft, usually via concentric, independently
advantages over single shaft designs but are more expensive and are less compact and more mechanically complex.

7.3.1 Differences Between Gas Turbine and Conventional Power Generation

Both conventional and GT power generation rely on high-pressure working fluid to drive expansion and load shafts attached to AC generators; the key difference is the nature of the working fluids. Products of combustion are considerably hotter than superheated steam and cannot readily be reused, as is steam / water in the steam cycle of a conventional power plant. The high temperatures offer significant benefits in plant thermal efficiency, but at the expense of specialised materials and fuel constraints.

7.3.1.1 Thermal Efficiency

Thermal efficiency is measured as the percentage of energy released from combustion of fuel that is recovered as electricity, e.g. if 100 MJ of energy is released from combustion of fuel per second, and 33 MWe of electricity is generated, the efficiency is 33%. Gas turbine of open, "simple", cycle design have achieved 40+% thermal efficiency, [73], but older designs from the 1960s and 1970s are as low as 25% [74]. The energy from the combustion that the GT cannot convert to electricity is contained in hot\(^1\), low-pressure exhaust POC.

Coal-fired, conventional power plant, through use of steam re-pressurisation and multiple expansion turbine stages, have been able achieve high-20s to low-30s percentage thermal efficiencies for decades. In order for older GT units to be economically viable in the 1960s and 1970s, simple cycle efficiencies had to be augmented. The most effective method is to use them in conjunction with HRSG. The HRSG of combined cycle plants (CCGT) produce superheated steam for use in conventional steam expansion turbine generators for additional electricity production. Thermal efficiency of CCGT plants designed in the 1970s had mid-30s percentages, keeping level with best conventional coal-fired plants of the day, but modern CCGT

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\(^1\) Typically 430-585 °C (800-1085 °F) [75].
plants are reliably producing at mid-50s percentage efficiencies [74] and are "technically" capable of 60+% efficiencies.

7.3.1.2 Heating of Working Fluid

The primary fuels for GT are fuel oil (FO) and natural gas (NG). Natural gas is the preferred fuel because it is ash-free and SO$_2$-free, minimising emission cleaning requirements, as well as being gaseous at ambient temperature. Commonly, low-sulfur No. 2 FO and No. 6 FO are available as backup fuels to NG. Fuel oil is not as desirable as NG because it requires vaporising prior to combustion, SO$_2$ "scrubbing" of emissions during firing, as well as periodic ash collection and disposal.

"Biomass" gaseous fuel obtained from the decomposition of garbage, and volatile hydrocarbon gases from oil refineries are sources of fuel for some GT operators. Though more environmentally friendly, and requiring less emission cleaning, FO and NG are typically expensive compared to coal in most countries. Pulverised coal can be used as a cheap alternative to NG, but the coal requires additional processing, i.e. pulverising, compared to conventional plants. Also, compared NG-firing, the combustion flame is not as hot and SO$_2$ and NOx emission cleaning of the stack gas is required.

7.3.1.3 Materials

Gas-fired GT can use 1300+°C POC as working fluid, while conventional power plants will use steam around 540°C; mass-for-mass, the POC working fluid contains more recoverable energy than the steam. This is the why a GT with a single high-pressure expansion turbine stage can achieve greater thermal efficiency than a multistage conventional plant with steam re-pressurising. However, this comes at a greater material cost, and hence capital cost at the time of construction.

To maintain the combustion flame, the POC released during combustion has to be extremely hot. However, by designing to maintain jackets of cool air, combustion chamber materials are able to stand these temperatures in both convention power plant boilers and GT units. In conventional power plants the POC heat boiler tubes and hence
boilers and GT units. In conventional power plants the POC heat boiler tubes and hence the working fluid (steam / water) passing through these tubes, but in gas turbines the POC is used directly as the working fluid. The air "jacket" effect will be discussed further in Subsection 7.3.2.3.

Superheating steam is a multiple stage process; it has be de-aerated, initially pressurised, heated, de-pressurised, and then superheated. The advantage of this process is that the volume and temperature of steam can be controlled. Stainless steel is a relatively cheap material and will not start to deform until it reaches temperatures round 550-600°C. Limiting the temperature of superheated steam to roughly 1000°F, or 540°C, greatly reduces the cost of construction of conventional power plants.

The ability to control of the volume and temperature of POC in GT is limited and not easily achieved. Furthermore, cooling the POC will reduce the potential thermal efficiency of the units. Consequently the GT turbine blades have to be able to cope with very high temperatures. The turbine blades have to be made of expensive, high-temperature-resistant alloys. The development of mono-crystal casting techniques and porous blades for bleeding "jackets" of "cool" gases have allowed maximum POC inlet temperature to rise from around 1000°C in the mid 1970s to 1300+°C in the late 1990s.

7.3.2 Gas Turbine Operation Factors

In order for a GT to operate continuously, the air intake has to match the fuel consumption, then the flow of POC from the combustion of air (oxygen) and fuel has to be sufficient to drive the expansion turbine stages driving the compressor stages, which are drawing in the intake air. As the desired electrical output rises, the amount of energy required by the load shaft to overcome the electrical torque of the generation set increases, which increases the amount mechanical energy required to be generated by the expansion turbine stages. To generate more rotational energy requires more POC, which require more fuel and more oxygen, hence more energy for the compressor stages as well. Maintaining the compression-combustion-turbine reaction is the key GT operation.
7.3.2.1 Load Shaft Speed

To generate electricity the load shaft has to maintain correct speed for power generation. When directly connected to a two-pole AC generation set, the speed is 3000 rpm for 50 Hz power, or 3600 rpm 60 Hz power. The load shaft revolution rate can be higher if it is geared down to 3000 or 3600 rpm, but still has to be constant.

Before electrical output can be obtained from a GT generation set the shaft has to be run up to speed. During self-starting, the load is disconnected and as much rotational energy as possible is used by the intake air compressor stages to ramp up the fuel consumption levels. Power can be generated "instantly" if an external spinner motor is used; initially the spinner motor will be do all of work, but as the as air and fuel consumption increases, the GT takes over and very soon the external motor can be disconnected.

Once up to speed, single-shaft GT designs have the least variability in electrical output. Additional flexibility is possible if some compressor stages (sets of impeller blades arranged axial around the shaft) are equipped with variable geometry control. While compressor shaft speed is fixed, the angle at which impeller blades force intake air toward the combustion chamber can be altered, changing the increase of air velocity after that compressor stage, and hence the final compression ratio.

In multi-shaft GT designs the compressor shaft is able to run at various speeds while maintaining correct load-shaft speed. This gives them a considerable advantage over single-shaft designs in their ability control power output and improves thermal efficiency, but requires greater maintenance and more installation space.

7.3.2.2 Maintaining Combustion Flame

Combustion is the self-sustained oxidation of a fuel. In the combustion flame of hydrocarbon fuels, i.e. fossil fuels and biomass, "C_{xH_y}" molecules react with oxygen (O_2) to form gaseous POC (mainly carbon dioxide (CO_2) and superheated steam (H_2O)), and release thermal energy, which raises the temperature of the POC. This conversion will not begin until oxygen-fuel mix temperature exceeds the temperature of ignition,
and will not be self-sustaining unless the rate of thermal energy release is sufficient to keep the flame hotter than temperature of ignition.

It is of great importance to the life cycle and maintenance of the GT that there should be no unscheduled extinguishing of the combustion flame, particularly if liquid fuels and/or steam injection is used. The velocity of the air and POC moving through the GT is very high, and the impact of liquid fuel or water droplets on the initial stage of the expansion turbine can do significant pitting damage to the blades. This happens when the fuel is left flowing after an unscheduled extinguishing of the flame. Pitting damage will require additional maintenance work and the early replacement of the very expensive alloy blades.

In gas turbine operation, two combustion failures are possible due to an imbalance between the compression stage shaft-power usage and the fuel consumption rate. These events are back-pressure flame out and flame blow out. Both are caused by sudden, large magnitude changes in electrical output, i.e. amount energy required by load shaft to overcome electrical torque in the generation set, without appropriate changes in fuel supply rate.

As fuel oxidises to form very hot gases, it requires a greater volume to maintain constant pressure. The volume (V) of the combustion chamber and path to the turbine inlet is constant, and as the temperature (T) increases so does the pressure (P) of the POC. This thermodynamic relationship is known as the ideal gas law [70], which can be simplified to the expression \( P \propto \frac{T}{V} \).

The pressure of the freshly combusted POC seeks to exert force in all directions, but the force of the incoming air from compressor stages and suction through the expansion turbine stages is great enough to keep it moving forward through the GT. If there is a drop in power available to the compressor stages, the "backward" pressure within the combustion chamber can restrict the air supply from the compressor stages. This can set up a vicious cycle: less-oxygen; reduced combustion temperature; reduced POC pressure; reduced mechanical power output from expansion turbine; even less power available to compressor, etc. Left unchecked, this will quickly lead to the combustion
temperature not being hot enough to maintain the flame. This is called "back-pressure flame out".

If there is an unplanned surge in power available to the compressor stages, "flame blow out" is possible. The surge in compressor power causes greater compression, and hence greater velocity, of air entering the combustion chamber. Like blowing out a candle, the sudden "gust" shifts the combustion flame away from the fuel-inlet point. Once the high temperature flame moves away, the temperature of the oxygen-fuel mix drops below ignition temperature and combustion stops.

7.3.2.3 Flow of Intake Air

Under normal operating conditions, a GT will only use part of the compressed air supplied to it in the combustion process. The stoichiometric ratio of air-to-fuel is that which would produce neither excess air nor non-combusted fuel in the POC under perfect laboratory conditions. However, stoichiometric ratios are not practical in industrial situations, as the homogenous mixing of air and fuel cannot be guaranteed on such large scales and rapid fuel consumption rates. Emissions of major concern from GT plants are; carbon monoxide (CO), methane (CH4) and volatile organic compounds (VOCs). All of these are due to the incomplete, or non-, combustion of fuel. Supplying more the stoichiometric oxygen requirement, known as excess air, greatly reduces the incidents of incomplete combustion and its associated emissions.

In conventional steam expansion plants excess air ratio 1.03-1.06, or 3 to 6 % more air than is necessary to supply the stoichiometric oxygen requirement, are sufficient to control emissions. However for GT excess air ratios of 3.00 are assumed as normal conditions, and 15% O2 by "dry" volume in exhaust is used as the standardised condition for emission monitoring. The use of compressed air in a GT is shown in Figure 7.5.

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2 The exhaust gas to be "dry", i.e. all gaseous products except H2O, because additional, non-POC steam is used to control oxides of Nitrogen, "NOx", in many GT models.
Under normal operating conditions, GT use around 70% of the intake air for cooling the GT casing and POC; only about 30% is actually ducted to the combustion chamber. The average temperature of POC at combustion can exceed 1400°C, with the temperature of hottest parts of the flame 1500+°C, but the material of most turbines can only handle POC in the temperature range 1100-1300°C [75]. The combustion air from the compressor stages forces the high-pressure, very hot POC from the combustion chamber toward the expansion turbine inlet, as it does so it mixes with a jacket of "cold" air that by-passed the combustion chamber. The mixing of the greater volumes of the cool, jacket air with POC from the combustion chamber is sufficient to lower the average temperature of the POC entering the expansion turbines to an acceptable level.

![Intake Air Use In and Around Combustion Chamber](image)

**Figure 7.5: Intake Air Use In and Around Combustion Chamber**

7.3.2.4 Minimum Fuel Consumption

Moving the shaft at the correct speed is not the only consideration before the load shaft of a GT can be connected to an AC power generation set. The fuel consumption, i.e. POC generation rate for power the expansion turbine stages, must be also be sufficient

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3 The "cold" air is considerably warmer than the ambient air, due to adiabatic heating during compression. This cool air jacket prevents GT casing from reaching temperatures that would burn human skin, typically this is around 65°C.
to produce enough rotational energy to overcome the electrical torque of the generation set and provide enough power to the compression stages to maintain the combustion flame.

If the electrical output of the generator set is to be lowered, the fuel consumption also needs to be lowered to maintain the combustion flame. However, this also reduces the energy available from the expansion turbine available to drive the compressor stages. As power output is reduced, the fuel consumption will reach a level where the turbine will be unable to generate enough mechanical energy to supply air at a compression ratio sufficient to avoid back-pressure flame-out and overcome electrical torque on the load shaft.

A vicious circle known as compressor stall will then begin: insufficient oxygen reaches the combustion chamber; POC is reduced in energy content; turbine rotating mechanical energy output is reduced; leading to lower electrical output (or incorrect frequency) and less power available to the compressor stages. Uncorrected, this cycle will lead to the cessation of combustion.

7.3.2.5 Maximum Fuel Consumption

From a purely thermodynamic perspective it desirable to consume more fuel and have hotter POC; as fuel consumption rises, the combustion flame temperature and POC pressure rises, leading to greater thermal efficiency. However, there are limits imposed by the thermal-resistance of blade materials and emission of thermal NOx to consider. There are technologies that circumvent blade deformation from heat and abate NOx emissions, but these have their limits, which in turn limit how much fuel can be consumed.

The latest turbine blade technology uses mono-crystal casting, heat-resistant alloys to prevent creep deformation during operation. Also, the leading set of blades can be cast so they are porous, allowing the seeping of a layer of "cool" gas (around 430-650°C),
recycled exhaust POC or steam, to jacket the blades from temperatures that would normally be too high.

The *rated output*, i.e. load factor = 1.00, for a GT is the highest power output where the blades are not in danger of deforming. The actual power is dependent on the density of inlet air, for commercial specification purposes 15°C ambient air temperature and site elevation approximately equal to sea level are assumed. The rated power output of a GT at a particular time and place will have to be moderated by actual ambient temperature and the elevation of the GT site above sea level.

To meet American Standards Association rotating machinery recommendations, GT have to able to operate at 15% above rated output for "sustainable" periods [77]. As an operating guide, GT can be run 4 hours at a load factor slightly above 1.00, with the duration decreasing to 1 hour for maximum output at a load factor of 1.15.

As the average temperature of the combustion flame rises above 1100°C *thermal NOx* emissions start to occur. In the presence of hydrocarbons *and* temperature above 1200 °C, such as the centre of an "1100°C" flame, nitrogen in air will break down, or *crack*, to individual, free N atoms. As combustion temperatures rise above 1200 °C, the nitrogen-cracking rate increases exponentially.

The free nitrogen (N) combines with oxygen (O₂) to form the NOx compounds, NO, NO₂ and N₂O, with the ratio of O₂ to free N required for NOx formation being roughly quadratic, i.e. \( xN + x^2O_2 \rightarrow xNOx \). Conventional steam turbine plants operate fairly economically at sub-1200°C combustion temperatures, and only have excess air ratios of around 1.03-1.06, so the rate of NOx formation is significantly limited. However, since GT have practically infinite excess oxygen available and require 1200+°C flames to be economically viable, thermal NOx is the major emission concern for GT operators.

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4 As solid materials are heated under stress they are subject to deformation in the direction of stress by atomic diffusion along grain boundaries, this called creep. In the case of expansion turbines the blades lengthen due to the centrifugal force of rotation and risk contact with the casing.
Abatement of NOx can be achieved by two means, reduction of nitrogen cracking or NOx “removal” in the emission stack; not producing NOx in the first place is best solution. In the combustion chamber "cool" steam or POC can be injected into the hottest part of the flame, as shown Figure 7.5, to reduce the rate of cracking. Recent technology uses partial combustion in a multiple stage combustion chamber to reduce maximum flame temperature, and hence nitrogen cracking rate, while allowing high average POC temperatures.

The formation of smog and ground level ozone (O₃), both of which are highly dangerous to humans, fauna and flora, is greatly dependent on the levels of carbon monoxide (CO) and NOx in the atmosphere. If a GT plant is near a major roadway, where CO emissions from internal combustion engines are significant, locally imposed NOx emission restrictions may prevent the plant operators from running GT at above, or even at, rated power.

In Section 7.6 these operating factors will be demonstrated in relation to FOR models specific to GT-HRSG cogeneration.

7.4 Heat Recovery Steam Generators

Heat recovery steam generators operate as normal boilers, but they use hot exhaust POC from GT, rather than "fresh" POC, to heat water and steam passing through boiler tubes. Auxiliary firing of the HRSG can boost steam production, as GT exhaust has relatively high oxygen content due to large excess air ratios. In practice the output is measured in tons per hour of steam, at certain pressure and temperature specifications. Using the American Society of Mechanical Engineers steam table [71], the energy content per mass of steam can be calculated and the thermal energy output converted to MWth.

The amount of energy that HRSG units can recovery is dependent on the initial temperature of the exhaust POC, and the pressure/s and temperature/s of the steam

5 Ammonia (NH₃) can be injected after combustion, and then a catalyst injected in the exhaust POC in the emission stack in order to cause NOx and NH₃ to convert to stable nitrogen gas (N₂) and steam (H₂O).
being generated. The type of fuel used in the feeder GT and whether NOx abatement measures are being used also affects the heat recovery efficiency. Primarily, the hotter GT feed POC, the more energy is available for recovery. Secondarily, the lower the temperature and pressure of the steam required, the greater the amount of it that can be generated with greater net thermal energy content. The use of steam / water injection for NOx formation avoidance reduces HRSG efficiency.

![Heat Recovery Steam Generator Operating Principle](image)

**Figure 7.6:** Heat Recovery Steam Generator Operating Principle

### 7.4.1 Thermal Pollution

Thermal pollution is the significant altering of ambient air and/or water temperature due to plant operations. Thermal pollution from power plants is inevitable, though most

---

6 The ammonia-catalyst reaction for NOx dissipation requires temperatures between 315-430°C to be maintained for a time, imposing additional limits upon heat recovery.

7 Changing the local air temperature affects the growth rates and species of plants that can survive in the area, which in turn affects the animal life that can be supported. The emission of warm cooling-water back into local waterways affects the marine environment in a similar manner. The heat from cooling towers causes artificial thermal updrafts, which can attract and misdirect migratory birds.
local authorities restrict the temperature of stack gases and cooling water to limit its effects. Due these restrictions, GT-HRSG plants have "free steam" operating zones. If the GT exhaust from electricity generation is more than required for the current steam demand, the steam produced is effectively free. On the other hand, if not enough heat is being recovered from exhaust POC as steam, that excess heat has to be dissipated through other means, incurring additional costs.

As the electrical output rises, the amount of "free" steam will also rise. For a GT-HRSG cogeneration plant to be economically viable, the plant must have a sufficient heat demand [8,23] to absorb the "free" heat. Oil and mineral refineries use processes that can make sufficient use of HRSG output, and other GT operators can supply steam for CCGT electricity production or municipal district heating contracts.

7.4.2 Emission Stack Corrosion

The gross energy content, "higher heating value" (HHV), of natural gas is typically 37-38 MJ/m³, but recoverable energy content, or lower heating value (LHV), is typically only 32-33 MJ/m³ [71]. Gaseous H₂O, as saturated steam, is a POC; to reduce corrosion in exhaust stacks cool gas leaving the HRSG must be at least 130-150 °C to ensure that H₂O does not precipitate as water. If the feeder GT unit is using fuel oil or bio-mass gas the stack exhaust temperature has to around 180-200 °C due to the presence of sulfur in the fuel.

The latent energy required to keep the saturated steam in POC from returning to water vapour is responsible for the energy content difference between HHV and LHV. Energy consumption of generators is calculated using the HHV of the fuel used, hence around 10% of total thermal released from combustion is lost due to POC H₂O. Water injected into the combustion flame to reduce NOx formation adds to these losses; this reduces

---

8 A temperature "T" gas is non-homogeneous; to obtain the average of temperature "T", some parts of the will be hotter, some will be cooler. For 130-150 °C steam very little H₂O will be sub-100 °C water vapour.

9 The vapour point of sulphates, "SO₄²⁻", at ambient pressure is around 125°C, vaporous SO₄²⁻ readily combines to form H₂SO₄, sulphuric acid [76].
efficiency, as the additional H2O absorbs energy released from combustion to keep it as steam at the exhaust stack’s outlet.

In practice industrial processes do not have much use for steam below 230°C (450 °F). The heat differential from 230°C between 150°C can be readily dissipated through cooling towers and cooling water without impacting significantly upon the local environment. Non-industrial users, like hotels, hospitals and local councils, can use sub-230°C steam / water for district heating, air conditioning and bulk hot water and achieve greater useful heat recovery than IPP plant operators.

7.4.3 Heat Extraction for Combined Cycle Plants

When HRSG generate superheated steam for further power generation in CCGT mode, the temperature of the GT exhaust POC is required to be around 540°C (1000°F). The temperature of the exhaust POC increases as electrical output of the GT increases; low electrical output will not be useful for superheating steam. Superheating steam is a multiple phase operation, as show in Figure 7.6, and is the least efficient way of raising steam. Added to this, the steam expansion turbines of the CCGT plant can achieve around 50%\(^\text{10}\) thermal efficiency from the steam raised, restricting the total plant efficiency further. i.e. CCGT max efficiency approximately 60% compared to 90+% for "domestic" cogeneration, and around 80% for cogenerating IPP.

The operating factors of the HRSG units will be used in conjunction with GT operating factors in the GT-HRSG cogeneration FOR models described in Section 7.6.

7.5 GT - HRSG Cogeneration Packages

A theoretical example of a modern industrial GT-HRSG cogeneration package at maximum output is shown in Figure 7.7. It is assumed that there are negligible losses at the inlet and outlet points of the GT unit and between the GT and HRSG units. In a

\(^{10}\) This is higher than normal conventional plants as the "combustion POC" losses have already been factored into to the GT thermal efficiency.
cogeneration arrangement a HRSG should be able to extract around 60%, $\eta_{th}$, of energy from exhaust POC as useful thermal energy, likewise a "modern" GT is assumed to have a maximum load thermal efficiency for electricity recovery, $\eta_e$, of 35%.

![Diagram: Thermal Efficiency GT-HRSG Cogeneration](image)

**Figure 7.7:** Thermal Efficiency GT-HRSG Cogeneration

The plant's total thermal efficiency in this example would be 74%. Part of the 26% "waste" energy not recovered is attributed to latent energy trapped as POC steam range. Assuming HHV and LHV values of Natural Gas as 37 and 32 MJ/m³ respectively, POC steam losses are 13.5% of total energy released from combustion, i.e. $(37-32) / 37$. Additional losses would be due to NOx control and non-optimal steam recovery. The combined cycle steam expansion turbines of CCGT plant would not be able to utilise all of the "useful" thermal energy recovered, and total plant thermal efficiency in the range of 50-55% would be expected.

7.5.1 Power - Exhaust POC Trade Off

![Diagram: POC - Power Trade Off Curve for GT-HRSG Cogeneration](image)

**Figure 7.8:** POC - Power Trade Off Curve for GT-HRSG Cogeneration

Within the operational restrictions required to maintain the combustion flame, there is scope for variation in the proportions of the mechanical energy usage between the load and compressor shafts. In effect, it is possible trade off electrical output for greater compression, and hence greater volume of intake air. A relative increase in air supply
for a given fuel consumption creates a relatively greater volume of HRSG feed. However, the increased supply of air also lowers the average POC heat, hence average energy content; this decreases the possible electrical output of the generator set attached to the load shaft. A concept of the trade off curve is shown in Figure 7.8.

This POC - power trade off capability of multiple-shaft GT designs is greater than single, common-shaft GT but comes at the expense of compactness and increased maintenance. All GT-HRSG design can boost their trade-off capabilities by use of direct "bleeding" of superheated POC, bypassing the expansion turbine stage, directly into the flow of exhaust gas feeding the HRSG. Auxiliary firing of the HRSG incurs an additional fuel consumption cost, but is very effective in boosting the energy content of the exhaust POC as practically released additional energy can be recovered as steam.

7.5.2 Normal Operating Conditions

As mentioned in Subsection 7.4.1, IPP plant operators would not invest in a GT-HRSG plant unless they had a need, or sell-on market, for the full capacity power and steam outputs of the plant. As such, cogeneration feasibility studies and assessment algorithms have been a recurrent area of research since the early 1980s [8-14]. For both economic and plant maintenance reasons, cogeneration and combined cycle GT operators want to operate at maximum heat extraction levels. Additionally for CCGT plants, which are most commonly used in based load capacity, they want to operate at full power output; this ensures that GT exhaust POC is sufficiently hot to superheat steam in the HRSG.

For cogeneration users of GT-HRSG plant, low power outputs are undesirable. Though technically feasible, trading off power for additional exhaust POC for feeding the HRSG unit at the minimum fuel consumption exposes the GT to the danger of back-pressure flame out, which in turn leads compressor stall. Furthermore, due the low efficiencies for low power output from a GT, it is not economically viable to run a GT much below 60% power output (0.6 load factor) for significant periods.
As indicated in Figure 7.9, typically the minimum sustainable power output is about 40% of rated power, (0.4 load factor), but at these levels thermal efficiency of the GT is only around the mid 20s percentage range. The thermal efficiency of a GT typically will not exceed 32% (the "standard" conventional steam turbine plant efficiency) until around 0.6 load factor. Thermal efficiency continues to rise as load factor increases: the high simple-cycle efficiencies quoted for GT are those achieved at full load. The thermal efficiencies at over-rated power outputs are higher still, but possible turbine blade damage and not being able operate at maximum heat extraction makes this operating condition unattractive to cogeneration GT operators.

**7.6 Practical GT-HRSG FOR Modelling**

A two-segment FOR model for cogeneration units was used in the validation test system [18] used in Chapters 5 and 6. Using the above knowledge of the operating principles of gas turbines and heat recovery steam generators for cogeneration purposes, regions of interest in the full model will be identified and discussed. Following this, a more practical reduced area model will be suggested. The validation test case will then be re-
evaluated using the reduced FOR to demonstrate its implication to current CHPD research.

7.6.1 Full Two-Segment Model

Shown in Figure 7.10 is a generic example of the two-segment model published by Guo, Henwood, and van Ooijen [18]. Labelled in their publication were the minimum and maximum fuel consumption bounds as well as the maximum heat extraction bound.

This research introduces the additional concepts to the basic model. Minimum possible heat extraction and "free" useful heat are indicated by the left most of the two abutted quadrilaterals. On the electrical power output axis, "P", the percentage loads have been included to demonstrate over rated power output and the relationship between minimal fuel consumption and the danger of compressor stall. The capacity for trading GT power output for additional POC, for use as HRSG feed, is indicated in the downward sloping right hand quadrilateral. It is again noted the that actual MWe output of "100%" power load is dependent on the ambient air temperature and will change with the time of day and season.

![Full Two-Segment FOR Model for GT-HRSG Cogeneration](image)

*Figure 7.10: Full Two-Segment FOR Model for GT-HRSG Cogeneration*
The typical operating points for GT-HRSG plants FOR are shown along the right hand bound of the FOR model. Though it is technically feasible for CCGT plant to operate in the overrated region, it would be unattractive as the loss in HRSG feed through the trade off along the maximum fuel consumption bound would reduce the combined cycle output of the additional steam expansion turbine generator sets. The operating zone along the maximum heat extraction bound expected for cogeneration operators is not extended into the compressor stall danger zone.

7.6.2 Reduced Area Model

The reduced area FOR model, now only a single-segment, irregular-quadrilateral, is shown in Figure 7.11. With regard to plant maintenance and longevity, the "danger of compressor stall" zone has been removed from the model. The over rated power output has been left in; if an IPP operator is called upon to supply peak, which fetches the highest prices from utilities / network authorities, it would be safe for the GT to operate in this zone for a limited time.

![Reduced Area FOR Model for GT-HRSG Cogeneration](image)

**Figure 7.11:** Reduced Area FOR Model for GT-HRSG Cogeneration
In regard to economic operation factors, the "free" heat zone has been removed. As described in Subsection 7.4.1, to operate in the "free" steam production zone could actually incur additional operating costs.

The "power - POC" trade off zone has been split into "normal" and "uneconomic" operating zones. An IPP plant will not be viable if it costs more to produce its own electricity than to buy from a utility, and if it does not have a use or market for the full steam production capacity. In practice this means the cogeneration GT have to be producing power and steam at the equivalent or 60% power load or greater to be economic. "Normal" operation is the zone within the power-POC trade off zone that a typical GT-HRSG cogeneration plant can be assumed to be economic and in no danger of unplanned shutdown.

7.6.3 Validation Test Case Using Reduced Area Model

The full two-segment model of the validation test system, used in Chapter 5 and 6, was reduced accordance with Figure 7.11. The reduced FOR bounds are indicated by dashed lines in full cogeneration unit 2 FOR of Figure 7.12. The overrated power outputs and uneconomic operating zones limits were maintained in this model, with the "free" heat and compressor stall danger zone operating regions being barred. The research in this thesis looks at only static dispatch problems, so system feasible demand region have to be able to include all safe operating zones, therefore the system and cogeneration unit 2 should be allowed to operate up to its time-limited maximum output.

<table>
<thead>
<tr>
<th>Model</th>
<th>Cost ($)</th>
<th>Heat (MWth)</th>
<th>Power (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>Full</td>
<td>8073.13</td>
<td>85595.80</td>
<td>0.0</td>
</tr>
<tr>
<td>Reduced</td>
<td>8253.08</td>
<td>85463.82</td>
<td>15.9</td>
</tr>
</tbody>
</table>

Table 7.1: Test System Minimum and Maximum Values

The revised minimum and maximum fuel / operation costs and heat and power outputs of the "reduced" area system are compared to those of the original "full" system in Table 7.1: the differences are minimal. If CHPD optimisation algorithms are to be adapted to solve the unit commitment and economic scheduling problems, the time
spent in the uneconomic and overrated power output zones in preceding scheduling intervals would have to be factored into the FOR models. Time spent in the overrated zone would see the area of the overrated zone reduced, while more than two hours in the uneconomic zone would suggest that the GT-HRSG unit should be put off-line temporarily.

The demand in the validation test system is for 115 MWth of steam and 200 MWe of electricity. It has already been established in Section 5.2 that boiler and auxiliary power units do not feature in the solution. Indicated in Figure 7.12 are the following load settings: "Full" – optimal load settings of the original test system; "Reduced" – the optimal load settings of the reduced area test system; and "C1-Only" – the case where cogeneration unit 2 has been shut down.

The cogeneration unit outputs, "C1 (MWth, MWe)" and "C2 (MWth, MWe)", and total fuel cost for each of the three listed solutions, "Cost ($/hr)", are shown in Table 7.2.

![Figure 7.12: Optimal Solutions within Full and Reduced Area FOR Models](image)

<table>
<thead>
<tr>
<th>Model</th>
<th>Cost ($/hr)</th>
<th>C1 (h², p₂)</th>
<th>C2 (h³, p₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>9257.07</td>
<td>(40, 160)</td>
<td>(75, 40)</td>
</tr>
<tr>
<td>Reduced</td>
<td>9291.36</td>
<td>(36.55, 156)</td>
<td>(78.45, 44)</td>
</tr>
<tr>
<td>C1-Only</td>
<td>8522.75</td>
<td>(115, 200)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 7.2: Optimal Solutions using Full and Reduced Area FOR Models
Chapter 7: Cogeneration Feasible Operating Region Modelling

The principle of operating at maximum heat extraction holds true for the reduced area system, the GT-HRSG unit (cogeneration unit 2) is again operating in its lower right hand corner. The concurrent change of load points is seen in cogeneration unit 1. The hourly operating cost has risen by $34.29 by enforcing load zone restrictions, but is not in danger of compressor stall occurring.

Though not lying within the compressor stall danger zone, the loading of cogeneration unit 2 is still arguably uneconomic. It would be cheaper if the GT-HRSG unit 2 was shut down temporarily and cogeneration unit 1 left to meet the entire demand by itself, as demonstrated by the "C1-Only" solution shown in Figure 7.12 and Table 7.2. In an economic scheduling problem, the "uneconomic" operating zone restriction would be applied to heat and power demand cases that are very small in relation to their system's feasible demand region, such as 115 MWth, 200 MWe in this test system.

7.7 Conclusions

The suitability of the most common, single-segment, irregular-quadrilateral FOR model for conventional cogeneration plants has been demonstrated in terms of the steam cycle of top cycle power generation.

The operation factors concerning the continuous operation of gas turbines have been explained, as have the maintenance and environmental issues related to heat recovery steam generators energy recovery limitations. Economic factors affecting the viability of running a GT-HRSG cogeneration / CCGT plant have then been discussed.

The two-segment FOR model specific to GT-HRSG cogeneration has been examined with regard to the economic and operational factors. Within this "full" model various operating zones have been defined, some of which are undesirable for plant longevity and / or economic reasons. Typical operating points have also been shown. The area of the "full" GT-HRSG specific model has then been reduced to a more practical single-segment model.

To demonstrate the suggested area reduction scheme, the two-segment FOR model used in validation test system of Chapters 5 and 6 was reduced in accordance with the
principles described. The optimal results for the demand case in the "full" and "reduced" area test systems have been compared. The results were similar, as in both cases the GT-HRSG unit 2 operated in the lower right hand corner, seeking maximum heat extraction from minimal power generation. The effects of the area reduction total heat and power ranges of the feasible demand region, and hence possible total fuel costs, were minimal.

As previously discussed in Section 5.2, the very low output demand case used does not reflect a practical operating situation. The fact that the true optimal solution for this demand is achieved using only one of the four available generators highlights a shortcoming of the validation test case.
Chapter 8

Conclusion

The work reported in the thesis has made contributions to the resurgent field of cogeneration, or combined heat and power (CHP), dispatch (CHPD) problem solving. Developed in the course of this research have been: an evolutionary programming algorithm for solving CHPD problems; an input format for efficiently and accurately describing CHPD problems; a new CHP test system and; a set of corresponding demand case solutions. The cogeneration unit feasible operating region (FOR) models, that are integral to the CHPD problems, have been investigated and improved, and a reduced-area FOR model for gas turbine cogeneration units has been suggested.

The history, technology and importance of the independent power producers (IPP) and cogeneration in deregulated power markets, particularly the gas turbine and heat recovery steam generator (GT-HRSG) option, have been outlined. The objectives and constraints of the IPP-CHPD problem were mathematically formulated in Chapter 2.

The information required to describe cogeneration systems and demand cases has been specified in Chapter 3, various mathematical models available for modelling generator heat characteristics were also described. As part of the coding of the algorithm for testing and evaluation, an efficient input format for fully describing CHPD problems was developed; an example is shown in Appendix A.

The features and development of the CED-EP (Cogeneration Economic Dispatch – Evolutionary Program) algorithm have been detailed in Chapter 4. Specific knowledge of CHPD systems and the mathematical functions used have been incorporated into the gene mutation operation and constraint satisfaction routines to create an efficient and robust algorithm.
Since there are no standard test systems and demand cases for CHPD problems, the developed CED-EP algorithm has been validated against a published test system. The results from three stages of development of the algorithm have been presented in Chapter 5. However, the validation test case has a number of unrealistic and/or undesirable properties, so a new test system has been constructed and the CED-EP algorithm has been used to successfully determine the optimal solutions for an extensive set of demand cases.

In Chapter 6 an evolutionary acceleration technique, analytical solution acceleration (ASA), was incorporated into the CED-EP algorithm to assess its ability to improve solution time. The ASA technique was found to offer most benefit when applied periodically, rather than as a part of all iterations, and when only applied to the top few candidate solutions.

In Chapter 7 the existing single-segment and two-segment FOR modelling techniques have been examined in terms of thermodynamic properties and principles. From this examination, a more realistic, single-segment reduction of the two-segment for GT-HRSG FOR models has been suggested. The validation test case was used to compare results obtain using the reduced area FOR model with results from the original test system featuring the full two-segment model.

The developed CED-EP algorithm has been found to be a powerful tool for solving CHPD problems. Though capable of handling arbitrary, non-polynomial and discontinuous heat characteristics, the literature has not provided samples of these models for CHP systems to date. As these more accurate modelling techniques become more widely used and feature in the modelling of CHP systems, the CED-EP algorithm will be capable of using them.

The CED-EP algorithm has also been shown to be a suitable test bed for assessing evolution computation acceleration techniques. The ASA technique is currently valid because the test systems examined only use continuous polynomial heat characteristics. When more accurate models are readily available ASA may not be suitable, so other solution acceleration techniques for evolution computation approaches to CHPD problems should be investigated. It would be of interest to see if the findings regarding
the implementation of the ASA acceleration technique are applicable to other CHPD problems not currently in the literature. It would also be of interest to see if ASA implementation scheme findings hold true for other solution acceleration schemes on the test systems currently available.

The reduced area GT-HRSG cogeneration FOR model offers improvements in the accuracy and validity of solutions obtained from combined heat and power systems using them, both in terms of economic and operational considerations. It has been shown that existing FOR models can be reduced. Also, it is likely that greater accuracy would be achieved if the reduced FOR model were considered at the time of mathematically modelling heat characteristics.

The new test system developed in Chapter 5 is potentially more useful than the validation test system used, though its accuracy is still limited by the use of continuous polynomial heat characteristic models. Like the validation test system, it contains all three types of unit, but its boiler and generator heat / fuel characteristic models are more complex and realistic. Also like the validation system, it contains an example of both the single and two-region cogeneration unit FOR models. However, optimal solutions for 28 demand cases, covering the entire feasible demand region of the system have been provided, allowing the true robustness of CHPD optimisation techniques to be assessed.
References


Appendices

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Appendix A

CED-EP Input Files

A.1 "*. CED" and "*.CED2" Input Files

The CED input data file format was developed in parallel with the CED-EP algorithm. The final version of the input file used, given the postfix *.CED3, is much more compact than the earlier *.CED and *.CED2 versions.

The first version of the input file, *.CED, was designed for an emission and economic dispatch problem, and therefore contained information irrelevant to the "plain" economic dispatch problem. A feature of the *.CED format was that the dispatch order of the generation units was set by in the input file. This put high demands on the input file writer's understanding of how the algorithm works; inappropriate dispatch orders have negative affects on the performance of the algorithm.

The *.CED2 input format that was developed for use in the trials reported at the AUPEC conference [1]. In this format, emission dispatch input information (and emission dispatch related processes in the algorithm) was removed; this made considerable savings in running time. The risk of specifying an inappropriate dispatch order was partially solved by removing the dispatch order inputs and adding processes to the initialisation phase of the algorithm that determined a dispatch order based on "50%" loads of generation units [2].
A.2 "*.CED3" Input Files

The *.CED3 input format contributed to the great improvements in algorithm performance between the early and intermediate versions [1, 2] of the CED-EP algorithm and the final version described in Subsection 5.3.3. In the *.CED and *.CED2 input formats the cogeneration linear inequalities defining feasible operating region (FOR) bounds were inserted as part of the input data; the accuracy of these coefficients was limited to 3 significant figures. This created problems with FOR corner h-p load settings, as the FOR bound inequalities did not necessarily intersect at the corners.

The non-intersection problem was partially solved with the FOR corner acceleration described in Subsection 4.6.2. The *.CED3 input solved this problem completely by using the 10-parameter FOR modelling system described in Subsections 3.5.3 and 4.3.2. Using 10 parameters, additional processes in the initialisation phase, described in Subsection 4.4.3, generated inequality equations accurate to 8 decimal points that intersected correctly at corners.

Other performance-improving features were added to the final version of the CED-EP algorithm during the development of the *.CED3 input file. The first was to change the "50%" load settings used to determine for dispatch order during the "CED2 stage of development" to "%P" and "%H" load settings as described in Subsection 4.3.1.1. After implementing the "%P" and "%H" settings in the dispatch order, it was simple to develop the semi-deterministic initialisation process, described in Subsection 4.3.4, and the "tailored" off-zero search elements of the mutation operation, described in Subsection 4.4.2.

A.3 *.CED3 Text File Format

The *.CED3 input file format is shown below. Input files are text files and were created in the MS Notepad text editor. Lines that are in italics and bold contain "dummy" data that is not used by the algorithm. Comments [in italics and square brackets] are at the end of data lines. The program does not use line numbers list in the first "column", they
are shown as an aid to demonstrate how to construct an input file. A "Tab" separates each input coefficient.

Line

0  \textit{Case\_Name} \quad \textit{DD/MM/YYYY}

1 NCogen NBoiler NGen Tran\_V Tran\_R Tran\_Dist NInt

2 \textbf{Scheduling Interval Data}

3 Intvl\_Num Duration H\_Dem Int\_P\_Dem Ext\_P\_Dem

... Intvl\_Num etc [1 line per interval]

2 + NInt [Last line of interval data]

L \textbf{Cogeneration Units Data}

L+1 ID H\_Lo H\_Up P\_Lo P\_Up Fuel

L+2 NFOR U\_Drop U\_Run L\_Drop L\_Run R\_Rise R\_Run

L+3 F0 F1 F2 F3 F4 F5

... ID etc [3*NFOR lines per cogen]

L + 3*NCogen [Last line of Cogen data]

M \textbf{Boiler Data}

M+1 ID H\_Lo H\_Up Fuel

M+2 F0 F1 F2 F3

... ID etc [2 lines per boiler]

M + 2*NBoiler [Last line of boiler data]

N \textbf{Electricity Generators Data}

N+1 ID P\_Lo P\_Up Fuel\_Type Fuel P\_Rank

N+2 F0 F1 F2 F3

... ID etc [2 lines per generator]

N + 2*NGen [Last line of generator data]

O -999 [End data file flag]
### A.4 Test Problem Input File: "Lagrange.CED3"

The *.CED3 input file for the validation test system and demand case, used to generate the results of Subsection 5.3.3 and example output files of Appendix C, is shown below.

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<tr>
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<td>0.0 50.0 0.0 0.0</td>
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<td>999</td>
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</table>
**Appendix B**

**CED-EP Executable Program**

**B.1 The CED-EP Program**

An executable program was developed around the CED-EP algorithm in the C++ computer language. The final version of the program used was called "CED-EP-Final", and requires two files to compile the executable program: the header file "CED-EP-Final.h", and; the program code "CED-EP-Final.cpp". It is recommended that the code be compiled using a GNU based C/C++ compiler.

**B.2 CED-EP-Final Header File**

This file contains the structures and subroutine definitions used in the CED-EP-Final.cpp code. It also defines constants used by the code; the default value of these internal constants and where they are used are listed below.

**B.2.1 Evolution Programming Related Constants**

Evolutionary programming relies on two main inputs: the population size \( \mu \), and the maximum number of iterations each trials is allowed to run for. To save time during the validation studies, and because multiple runs of an EP are needed to be sure that the optimal solution has been found, the CED-EP program was developed so that multiple trials could be run in one execution of the program.
B.2 Economic Dispatch from Cogeneration

POP_MAX 100  Used to check input argument <a2>
IT_MAX  5000 Used to check input argument <a3>
TRIALS_MAX 50  Used to check input argument <a5>

B.2.2 IPP CHPD Related Constants

The independent power producer (IPP) combined heat and power dispatch (CHPD) problem is assumed to contain a small number of generation units due to the limited distance over which process steam can be transported efficiently. It was decided to limit the number of each type of generation unit (cogeneration, boiler and convention generator) used in CED-EP problems to three. As mention in Section 3.2, the short-line, lumped-parameter transmission line model assumptions are used; hence transmission distance is restricted to 80 km.

COGEN_MAX 3  Checked during read in from input file
BOIL_MAX  3 Checked during read in from input file
GEN_MAX   3 Checked during read in from input file
TRAN_D_MAX 80 Checked during read in from input file

B.2.3 Scheduling Interval Related Constant

The standard scheduling period is one day, and the minimum accepted interval duration for consideration is half an hour. The maximum number of intervals allowed in a daily, 24-hour period dispatch problem is 48 half-hour blocks.

INTVL_MAX 48  Checked during read in from input file
TIME_MAX  24 Checked during read in from input file

B.2.4 Acceleration Frequency Control

Chapter 6 describes the investigation of frequency of application of acceleration routine. This was controlled via the "FREQ" constant. In general the value of FREQ is left at 1, meaning that, when used, acceleration techniques are applied every iteration. In the frequency experiments described in Chapter 6 the CED-ASH program was compiled with FREQ = 2 and FREQ = 5 to obtain the reduced frequency results.

FREQ 1  Should be left as "1" (unless investigating frequency)
B.3 Executing the CED-EP Program

Compiling the C++ code and header file, allows the executable function "CED-EP-Final.exe" to be built. To run the program the following arguments needs to be inputted at a DOS-prompt command window:

CED-EP-Final  <a1>  <a2>  <a3>  <a4>  <a5>  <a6>  <a7>  <a8>

Where the input arguments are:

- `<a1>`  filename  Character string: 'filename'.CED3
  This input file needs to be in the same folder as the executable file
- `<a2>`  Pop_Size  Population size, "μ", used by EP: 3 - POP_MAX
- `<a3>`  Num_It  Maximum number of iterations of EP loop allowed: 1 - IT_MAX
- `<a4>`  ACC  Control % of population accelerated: 0, 1-6
  (0 = Acceleration bypassed, Approximately 16%-100%)
- `<a5>`  Num_Trials  Number of trials run: 1 – TRIALS_MAX
- `<a6>`  Sol_Form  8 options for data to be contained in solution file, *.SOL3:
  The 'filename'.SOL3 file will appear in the same folder as the *.CED3 file
  0 = Iteration-of-solution and cost for each trial (always produced)
  1 = System data also included
  2 = Settings of optimal solution data of each trial also included
  3 = Best solution cost after iteration also produced for each trial
  4 = Options 1 & 2  5 = 1 & 3  6 = 2 & 3  7 = 1 & 2 & 3
- `<a7>`  Convergence  0 = Convergence not used, 1 = Convergence used
- `<a8>`  Log  0 = No Log of screen messages kept, 1 = *.LOG file created.
  The 'filename'.LOG file will appear in the same folder as the *.CED3 file

To obtain the "Lagrange.SOL3" and "Lagrange.LOG" files, used as examples in Appendix C, the below set of input arguments was inputted at the command prompt. The directory folder being viewed contained the executable program, "CED-EP-Final.exe", and the "Lagrange.CED3" (argument `<A1>`) input file, as shown in Appendix A.
This set of inputs ran 3 trials ($a_5 = 3$) of the EP using a population size of 25 ($a_2 = 25$), for a maximum of 50 iterations each ($a_3 = 50$). For each trial 25% ("1/4" as, $a_4 = 4$) of candidates were accelerated as a part of all iterations (program compiled with FREQ = 1). The "Lagrange.SOL3" solution file contained all system information, solution data and lowest cost of all iterations ($a_6 = 7$), allowed early convergence stopping ($a_7 = 1$) and produced a log of all screen messages ($a_8 = 1$).
Appendix C

CED-EP Output Files

C.1 *.SOL3 Solution Output File

Options are listed in Appendix B for selecting the information to be included in solution text files, *.SOL3, generated by the CED-EP executable program. A complete "solution option 7" output file, "lagrange.SOL3", is shown below. [Comments appear in square brackets].

******************************************************************
* EVOLUTIONARY PROGRAMMING BASED ECONOMIC DISPATCH *
* FOR COGENERATING FACILITIES *
* *  
* Artificial Intelligence and Power Systems Research Group  *
* University of Western Australia  *
******************************************************************

Case Name: lagrange
Date: 13/9/2002
[takes name from *.CED3 input file]
[Date from computer]
[Solution "0", common to All ]
[Solution "1", "4", "5", & "7", System information ]
[generally option "1" data is only produced once during a validation study]

SYSTEM INFORMATION
No. Cogeneration Units : 2
No. Heat Only Units : 1
No. Electricity Units : 1
Transmission Voltage : 22.0 kV
Transmission Distance : 0.0 Km
Line Resistance : 0.03280 ohm/Km

CASE INFORMATION
No. Intervals : 1
Total Duration : 1 hrs

INTERVAL LOADINGS
<table>
<thead>
<tr>
<th>Interval</th>
<th>Active Power (MW)</th>
<th>Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>T</td>
<td>Internal</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>200.0</td>
</tr>
</tbody>
</table>
C-2

Appendix C: CED-EP Output Files

COGENERATION UNITS INFORMATION

Cogenerator Name: Cogenerator_1
Fuel Price : 1.00 $/MBtu
CHARACTERISTIC:
Heat MBtu/hr: 2650 + 14.5P + 0.0345PP + 4.200H + 0.030HH + 0.031HP
FEASIBLE OPERATING REGION DATA
Heat Range : 0.0 to 180.0 MWth
Power Range : 81.0 to 247.0 MW
No. FOR Regions: 1
Upper Bound : -32.0 MW over 180.0 MWth
Lower Bound : -17.8 MW over 104.8 MWth
Right Bound : +134.0 MW over 75.2 MWth

Cogenerator Name: Cogenerator_2
Fuel Price : 1.00 $/MBtu
CHARACTERISTIC:
Heat MBtu/hr: 1250 + 36.0P + 0.0435PP + 0.600H + 0.027HH + 0.011HP
FEASIBLE OPERATING REGION DATA
Heat Range : 0.0 to 135.6 MWth
Power Range : 40.0 to 125.8 MW
No. FOR Regions: 2
Upper Bound : -15.6 MW over 103.2 MWth
Lower Bound : -4.0 MW over 59.1 MWth
Right Bound : +70.2 MW over 60.6 MWth

HEAT ONLY UNITS INFORMATION

Boiler Name : Boiler_1
Fuel Price : 1.00 $/MBtu
CHARACTERISTIC:
Heat MBtu/hr: 0.0000 + 23.4000H + 0.0000HH + 0.0000HHH
FEASIBLE OPERATING REGION DATA
Heat Range : 0.0 to 2695.2 MWth

ELECTRICITY UNITS INFORMATION

Generator Name : Generator_1
Fuel Price : 1.00 $/MBtu
CHARACTERISTIC:
Heat MBtu/hr: 0.0000 + 50.0000P + 0.0000PP + 0.0000PPP
FEASIBLE OPERATING REGION DATA
Power Range : 0.0 to 150.0 MW

SYSTEM FDR INFORMATION [10-parameter data for system Feasible Demand Region]
Minimum Heat : 0.0 MWth
Maximum Heat : 3010.8 MWth
Minimum Power : 121.0 MW
Maximum Power : 522.8 MW
Upper Bound Drop: 47.6 MW
Upper Bound Run : 283.2 MW
Lower Bound Drop: 21.8 MW
Lower Bound Run : 163.9 MW
RH Bound Rise : 204.2 MW
RH Bound Run : 135.8 MW

MAX and MIN COSTS [Used in Fitness function]
Maximum Cost: $85562.52/hr
Minimum Cost: $8073.13/hr

DISPATCH ORDER
1. Cogenerator 1
2. Cogenerator 2
3. Generator 1
4. Boiler 1

EP SOLUTION DATA
Size of Population: 25
Maximum No. Iterations: 50
Rounds of Competition: 12
Number of Trials: 3
Program Run Time: 2.103s
Solution accelerated used, Top 0.25 of candidates
Acceleration applied every 1 iteration

Trial 1
Last Iteration: 29

!!! Solution Converged!!!

Lowest Operation Cost is $9257.07
found on iteration 19

CANDIDATE DATA:

<table>
<thead>
<tr>
<th>Intvl</th>
<th>Cogen1</th>
<th>Cogen2</th>
<th>Boil1</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.00</td>
<td>75.00</td>
<td>0.00</td>
<td>115.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intvl</th>
<th>Cogen1</th>
<th>Gen1</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>160.00</td>
<td>40.00</td>
<td>200.00</td>
</tr>
</tbody>
</table>

Best Result after Each Iteration

<table>
<thead>
<tr>
<th>It</th>
<th>Cost($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10315.00</td>
</tr>
<tr>
<td>1</td>
<td>10171.50</td>
</tr>
<tr>
<td>2</td>
<td>10171.50</td>
</tr>
<tr>
<td>3</td>
<td>10004.95</td>
</tr>
<tr>
<td>4</td>
<td>10004.95</td>
</tr>
<tr>
<td>5</td>
<td>9795.39</td>
</tr>
<tr>
<td>6</td>
<td>9674.79</td>
</tr>
<tr>
<td>7</td>
<td>9674.79</td>
</tr>
<tr>
<td>8</td>
<td>9607.67</td>
</tr>
<tr>
<td>9</td>
<td>9607.67</td>
</tr>
<tr>
<td>10</td>
<td>9449.00</td>
</tr>
<tr>
<td>11</td>
<td>9449.00</td>
</tr>
<tr>
<td>12</td>
<td>9449.00</td>
</tr>
<tr>
<td>13</td>
<td>9447.59</td>
</tr>
<tr>
<td>14</td>
<td>9257.61</td>
</tr>
<tr>
<td>15</td>
<td>9257.61</td>
</tr>
<tr>
<td>16</td>
<td>9257.61</td>
</tr>
<tr>
<td>17</td>
<td>9257.61</td>
</tr>
<tr>
<td>18</td>
<td>9257.61</td>
</tr>
</tbody>
</table>
C-4 Economic Dispatch from Cogeneration

Trial 2
Last Iteration: 25

!!! Solution Converged!!!

Lowest Operation Cost is $9257.07 found on iteration 15

CANDIDATE DATA:

<table>
<thead>
<tr>
<th>Intvl</th>
<th>Cogen1</th>
<th>Cogen2</th>
<th>Boil1</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.00</td>
<td>75.00</td>
<td>0.00</td>
<td>115.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intvl</th>
<th>Cogen1</th>
<th>Cogen2</th>
<th>Gen1</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>160.00</td>
<td>40.00</td>
<td>0.00</td>
<td>200.00</td>
</tr>
</tbody>
</table>

Trial 3
Last Iteration: 15

Lowest Operation Cost is $9257.07 found on iteration 5

[True optimum cost $9257.0757 \( \rightarrow \) first cost within $0.005 of optimum]

[\( \uparrow \) Solution "3", "5", "6" & "7" list of best cost \( \uparrow \)]

[for demonstration Trial 2, but option "3" data removed]
[This is the recommended solution output mode]

[for demonstration Trial 3 only has "0" option data shown]
[This can save time during validation study, however]
[option 2 is required for "real" problems to be solved]
C.2 *.LOG Screen Message Log Output File

Evaluation studies use evaluation scores as a measure of computational intensity for comparison. The CED-EP program can also keep a record of elapsed solution time as a measure of computational effort. In order to use solution time as a comparative measure fairly, all no background processes should be running on the test computer. The *.LOG file produced in conjunction with the above *.SOL3 file, "Lagrange.LOG", is shown below. Comments are [in square brackets].

Case : lagrange.ced3 [Case name and time and date when batch of trials was run]
Date : 13/9/2002
Start Time : 14:5:49
Population size : 25 [Summarises EP and acceleration conditions]
No. Iterations : 50
No. Rounds of Competition: 12
No. Trials : 3
Convergence Mechanisms enabled
Solution acceleration used, Top 0.25 of candidates
Acceleration applied every 1 iteration

Trial 1 is proceeding
On iteration 2, 1 pop1 interval settings reused. [if too many candidates are reused trial will terminate]
On iteration 3, 1 pop1 interval settings reused.
On iteration 6, 1 pop1 interval settings reused.
On iteration 7, 1 pop1 interval settings reused.
On iteration 14, 1 pop1 interval settings reused.
Trial completed in 0.701s [Elapsed time for each trial]

Trial 2 is proceeding
On iteration 1, 1 pop1 interval settings reused.
On iteration 2, 1 pop1 interval settings reused.
On iteration 3, 1 pop1 interval settings reused.
On iteration 5, 1 pop1 interval settings reused.
On iteration 6, 1 pop1 interval settings reused.
On iteration 7, 1 pop1 interval settings reused.
On iteration 8, 1 pop1 interval settings reused.
Trial completed in 0.901s

Trial 3 is proceeding
On iteration 2, 1 pop1 interval settings reused.
On iteration 3, 1 pop1 interval settings reused.
On iteration 4, 1 pop1 interval settings reused.
Trial completed in 0.481s