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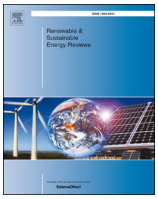

Computational tools and operational research for optimal design of co-generation systems

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ABSTRACT

Operational research (OR) methods have been successfully applied in many industrial process. The objective of this work is to discuss the application of computational tools and OR to the study and optimisation of industrial co-generation systems. After reviewing the literature a collection of technical data on co-generation systems is made and a complete OR model (objective function and constraints) for the co-generation problems is done. In order to find the optimal solutions for the co-generation systems a computer code that solves the resulting linear programming problem was developed. The first problem presented consists in a work production system, here considered as electrical power, and heat through multi-stage turbines and condenser, respectively. The second one is a simplified system of co-generation, which will be generated electrical power from a turbine in multi-stage and heat by two heat exchangers. Finally, it was possible to note that the computational tools combined with operational research have proven to be effective in solving industrial co-generation problems.

1. Introduction

The search for fast, secure, and reliable solutions intensifies the use of computational tools to support the decision-making process and, in many cases, operational research (OR) methods play a fundamental role. OR is a branch of engineering focused on solving real problems, focusing on decision-making, using mathematical, statistical features, and algorithms. The use of methods such as linear programming, network flow, integer programming, non-linear programming, mixed integer linear (and non-linear) programming, among others, is a reality in the search for optimal solutions mainly when the amount of data is huge and complex [1–3].

In industry, the operational research (OR) is used in many areas from control and production planning to logistics and product distribution. Various industrial processes may also be modelled and optimised using OR. In general, spreadsheets and specific computer programs are used.

Obtaining accurate solutions becomes impractical with increasing of the number of problem variables. In such cases, heuristics to specific OR problems have been formulated and implemented to search for good (but not always optimum) solutions. In the heuristic, it is desirable that computer programs are equally efficient.

OR methods have been successfully applied in co-generation problems, which is a complex process that depends on many variables and do not always operate optimally [4].

Co-generation is a process in which certain fuel generates heat and power, thus avoiding losses widespread. It has great potential both in the industrial (mainly in the sugar and alcohol, pulp and paper, chemical, and petrochemical facilities) and in the residential sectors [4–7].

Energy is a recurring and strategic issue for Brazil as well as for the world. In São Paulo state, this issue has become more evident with the water management crisis of recent years since the Brazilian electricity generation is largely dependent on hydro-power [8]. In this scenario, the co-generation presents a great alternative to increase the capacity and reliability of the electrical power system.

Reduction of uncertainties and risks in the long term planning of energy resources is the result of the multi-criterion ranking developed in, the model finds that the resources next to the demand side appear as lower full costs [9].

Biomass residues can be a potential sustainable source of energy. It is estimated that approximately one-third of the energy available from sugar-cane is contained in the tops and leaves (trash), which are generally either burnt prior to harvesting or are not recovered from the field. It is estimated that 1.353 million tons of trash is available annually for co-generation in South Africa, which could potentially produce 180.1 MW over a 200 day milling season [10]. Others examples are found around world such as Pakistan that has a potential to generate electricity from sugar cane bagasse estimated in 1598 GWh up to 2894 GWh [11]. Okello et al. [12] presented a review of the efforts and progress made by different organisations in promoting improved bio-

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energy technologies in Uganda.

The use of biomass residues for energy generation through co-generation has been increasingly adopted by many industries as it can reduce energy costs and even increase their profit by selling the energy excess in the market. The forestry industry has been increasingly investing in co-generation processes using the residue generated during the mechanical, physical and chemical processing of the wood logs [13,14]. Others promising bio-energy conversion technologies are also found in the literature, such as biomass conversion with anaerobic digestion [15].

Co-generation plays an important role in reducing of CO_2 emission to the atmosphere, fulfilling goals of the Kyoto Protocol, in which market-based mechanisms for buying and selling carbon credits are used [16–18]. These credits are certificates generated by reduction projects or absorption of greenhouse gases. They are also found other carbon markets outside the Kyoto Protocol [19].

The objective of this work is to discuss the application of computational tools and OR to the study and optimisation of industrial co-generation systems.

2. Literature review

In this section, fundamentals of a sort of topics inherent to this work are reviewed from specialised literature, preferable articles from periodic with high impact factor.

2.1. Thermodynamics

The *first law of thermodynamics* is a version of energy conservation law. Also known as Joule's principle, this law postulates that diverse forms of work can be converted into each other, corroborating that the *total energy transferred to a system is equal to the variation of its internal energy, that is, in every natural process, the energy of the universe is conserved* being that the system energy when isolated is constant. It is also observed the equivalence between work and heat, where it was verified that the variation $Q - W$ is the same for all thermodynamic processes [20–22].

$$\Delta U = Q - W \tag{1}$$

where, Q is the quantity of heat supplied to the system by its surroundings,

$$Q = m \cdot c \cdot (T_f - T_i) \tag{2}$$

where, c is the specific heat, m is the mass, and T is the temperature, and W is the work done by the system,

$$W = \int_{V_i}^{V_f} pdV \tag{3}$$

where, p is the pressure, and dV is the volume in infinitesimal form. This sign convention is implicit in Clausius' statement of the law given in Eq. (1). It originated with the study of heat engines that produce useful work by consumption of heat [20–22].

The *second law of thermodynamics* concisely expresses that *the amount of entropy of any thermodynamically isolated system tends to increase with time until it reaches a maximum value*. Most noticeably, when one part of a closed system interacts with another part, the energy tends to divide equally, until the system reaches a thermal equilibrium. While the first law of thermodynamics establishes the conservation of energy in any transformation, the second law establishes conditions for thermodynamic transformations to occur [20–22].

$$\frac{dS}{dt} \geq 0 \tag{4}$$

where S is the entropy, dt is the infinitesimal time, and the equality symbol only exists when the entropy is at its maximum value (in equilibrium).

The *third law of thermodynamics* was developed by Walther Nernst, between 1906 and 1912, and says that when a system approaches the temperature of absolute zero, all processes cease, and the entropy has a minimum value. The law, therefore, provides a reference point for the determination of the entropy value. The equation proposed by Nernst is $\lim_{T\to 0}\Delta S = 0$, where ΔS is the change in entropy and T is the temperature [20–22].

A process taking place in an insulated, constant-volume vessel, where $dU = 0$ and $dV = 0$, must be such that

$$dS]_{U,V} \geq 0, \tag{5}$$

which suggests that changes of state of a closed system at constant internal energy and volume can occur only in the direction of increasing entropy. The expression also implies that entropy approaches a maximum as a state of equilibrium is approached [20].

Let G be the Gibbs function defined as $G = U + pV - TS$. For any process taking place at a specified temperature and pressure ($dT = 0$ and $dp = 0$) must be such that

$$dG]_{T,p} \leq 0, \tag{6}$$

which indicates that the Gibbs function of a system at fixed T and p decreases during an irreversible process. Each step of such a process results in a decrease in the Gibbs function of the system and brings the system closer to equilibrium. The equilibrium state is the one having the minimum value of the Gibbs function [20].

2.2. Exergy analysis

Exergy analysis is a method that applies the conservation of mass and conservation of energy principles as well the second law of thermodynamics for the design and analysis of systems and processes. Exergy can be defined as the maximum amount of work that can be produced by a stream of matter or energy as it comes to equilibrium with a reference environment [21].

Exergy is consumed or destroyed because of irreversibilities in the process, and hence it is not subject to any conservation law. The exergetic balance allows one to calculate the irreversibilities or losses and identify their reasons [23–26]. Therefore, it might be possible to design more efficient energy systems by reducing the sources of inefficiency. Dincer and Rosen [21] compares energy and exergy from a thermodynamics point of view.

2.3. Heat and power systems optimisation

Optimisation in heat and power systems can be done in two different ways, the thermal and the economic, and the union of these factors is known as thermo-economics or exergo-economics [27]. Such optimisation is important because it can reduce losses in the system and consequently improve system efficiency by reducing their costs [28].

The thermoeconomics is an analysis method of a thermal system in which uses exergetic and economic concepts, whose objective is to assign costs to exergetic content of an energy carrier. Thus, the costs can be expressed in terms of exergy, or in monetary terms, taking into account the irreversibility (exergetic losses) of the mass flows through each of the components of the system [23,29]. This type of analysis applies mass, energy, and exergy balances, for each of the components of the system that allows the irreversibility and generated costs to be determined [28].

The contribution of exergy analysis to the system design, analysis, assessment, and improvement of energy systems was discussed by [30], also the influence of efficiencies into performance evaluation through case studies. Also the contribution of exergy analyses in chemical engineering was explained by [31], focusing the attention on two critical points of action: separation technologies (distillation and membrane technology) and CO_2 capture.

Five conventional liquefied natural gas processes were investigated