Combined heat and power plant using a multi-objective Henry gas solubility optimization algorithm: A thermodynamic investigation of energy, exergy, and economic (3E) analysis

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Research article

The principal context of this study was a combined heat and power plant (CHPP) system, with the aim of conducting the multi-objective optimization (MOO) of an energy, exergy, and economic (3E) analysis. To meet rising energy demands, optimal operational conditions for CHPPs are required. Enhancements to plant equipment and improvements in plant design are critical. CHPP design has its basis in the first law of thermodynamics; the losses from such systems are therefore most accurately determined via exergy analysis. Energy quality can also be assessed using exergy analysis. Consequently, it is possible for the designers of thermodynamic systems to apply the findings to achieve improved efficiencies. The economic aspect of CHPP optimization is also critical because the structure is highly complex. This study therefore makes use of a Henry gas solubility optimization (HGSO) algorithm in a CHPP base case situation to achieve MOO. In this particular CHPP system, the respective enthalpy and exergy efficiencies were increased in the case of the boiler (7.22% and 7.21%), the turbogenerator (4.52% and 6.84%), and the condenser (3.06% and 31.37%). In this study, four scenarios are proposed, whereby the design of a heat exchanger network (HEN) aims to optimize energy savings and economic performance through analysis of the profits generated through electricity and steam production. A payback period of around two to three years was reported, where the cost increase under optimal conditions was found to be 0.3824%. The results demonstrate clearly that the tested techniques may be appropriate in practical scenarios when enhancing CHPP performance in the context of the base case.

1. Introduction

Thailand’s current energy sector and its future development are constantly being examined. To decentralize the generation of power, all potential fuel sources are taken into consideration. Expectations about natural gas supply development will be studied up to 2025. Current predictions suggest that Thailand’s natural gas consumption levels would continue to rise. However, much of this increase will be associated with electricity generation, one of the principals use of natural gas. It has long been the case in countries worldwide that the implementation of the decentralized generation of power relies upon the creation of a suitable framework of rules to govern the process. Without such regulation, policy cannot be implemented effectively (Pepermans et al., 2005, Grecen, 2006, Nakawiro et al., 2008).

In contrast to other fossil fuel types, the environmental impact of natural gas consumption is significantly lower, with far lower carbon dioxide (CO₂) emissions. For this reason, natural gas is expected to serve as an essential potential factor in shifting to the use of fuels, allowing energy production without generating CO₂. Natural gas is widely employed to provide domestic heat and hot water for individual consumers. However, it would be important that natural gas be consumed using highly energy-efficient technologies in the future. Cogeneration has already been shown to be useful in medium and high-power applications and may have a vital role to play with residential, commercial, or industrial consumers. By generating power and heat simultaneously, the fuel is used more efficiently and generates less CO₂ than would generally be the case to achieve the same output (Alibadi et al., 2010, Yang et al., 2014, Liso et al., 2015, Wu et al., 2016, Valdés and Leon, 2019).
Combined heat and power plant (CHPP), also called a cogeneration power plant, produces both heat and electricity at the same time when using a single power source. It is possible to use this approach with a range of power plant types including steam power, gas turbines, internal combustion engines, or combined cycle power plants. The produced heat tends to differ widely in its temperature and entity, which vary according to the size, the technology used, and the parameters employed in operation (Gambini et al., 2019). Several different model types are currently used for integrated energy and economic and environmental analysis. Since the model structures and input assumptions vary, the details included and other factors can be challenging to compare. In many cases, the results would be different even when the input data changes and users would face unexpected difficulties (Fishbone and Abilock, 1981, Morris, 2002).

More recently, researchers have emphasized the 3E analysis of thermal power plants to optimize energy quality. Numerous research studies have focused on exergy analysis to gain insights into the associated issues (Scibba and Wall, 2007). In the context of power plants, studies have examined different energy and exergy efficiencies, and the findings have been useful for design engineers to implement where appropriate (Kanozlu et al., 2007). Combining economic and exergy analysis can help achieve better thermal performance for power plants and energy-consuming devices (Verkhivker and Kosoy, 2001). One particular novel method to support power plant development is optimization based on thermo-economic concepts (Manninen and Zhu, 1998). Further, an organic rankine cycle (ORC) was also powered by a sample of waste heat from a power plant. The most expensive components were the turbine, evaporator, and condenser (Mehrdad et al., 2020).

The use of exergy analysis also facilitates energy conversions at different stages, promotes efficiency in the system's different components, and reveals the situations where significant losses occur in addition to supporting the prevention of such losses (Dincer and Cengel, 2001, Rosen and Bulucea, 2009). The validity for exergy analysis areas has also been discussed (Szargut, 1980, Stanek and Budnik, 2010, Pavelka et al., 2015). It is a very effective means of assessing energy quality and improving efficiency in complex thermodynamic systems. A better understanding is achieved when it is possible to distinguish between these two loss types. When investigating systems that convert energy forms, operational performance can be determined through exergy loss and reduced second-law irreversibility. If the performance of those energy conversion systems is to be enhanced, it would help to examine the transport procedures relating to each of the different equipment types, focusing on local entropy generation. According to Nishida et al. (2002) techniques that emphasize reducing thermal device irreversibility have been of particular interest, while Beér (2007) developed electrical power generation systems focusing on plant efficiency.

In the context of the current study, pinch analysis refers to the study of the process as a whole, instead of taking a narrow view of a single unit (Rossiter, 2010). Stream process-to-stream process recovery of heat is maximized, allowing heat integration to occur through an approach initially pioneered by Townsend and Linhoff (1985a,b), Linhoff and Hindmarsh (1983).

Using a single objective optimization (SOO), the aim is to achieve the best mathematically since it should be a global minimum or maximum, depending on the type of optimization problem in question. If the optimization problem has several contradictory objectives, there would not be one single best solution (global maximum or minimum) that covers all objectives. For most multi-objective optimization (MOO) problems, a set of solutions can be found. These are referred to as Pareto-optimal solutions, or non-dominated solutions, which are superior to others within the same search space when all objectives are considered. However, such solutions may be inferior to others when only considering one of the objectives or a small proportion of the objectives (Hans, 1988). SOO and MOO are compared using the spotted hyena optimizer (SHO) algorithm on a cogeneration power plant. Based on the findings, the MOO employs a broader array of data to arrive at global solutions (Sukpancharoen, 2021).

It can broadly be stated that among the various metaheuristic optimization algorithms, particularly those based on populations, the search functions have a shared tendency to rely upon the phases of exploration and exploitation. The objective of metaheuristic algorithms is to make the search process more efficient by optimizing the balance of the activity in those two phases. The exploitation activity aims to produce similar solutions but improve upon the previous solutions, leading to good convergence. In contrast, exploration activity seeks new solutions across the search space to avoid becoming stuck on local optima (Olorunda and Engelbrecht, 2008, Lin and Gen, 2008).

Recently, there have been several metaheuristic optimization algorithms created to address real-world problems. For example, Hashim et al. (2019) offered a new metaheuristic algorithm in 2019, known as Henry gas solubility optimization (HGSO) algorithm. This method imitates the activity expected under Henry's law to find solutions to complex problems of optimization. Henry's law concerns gases and explains the quantity of a particular gas dissolved in a particular type of liquid when the liquid's quantities and temperature are predetermined. The HGSO algorithm mimics how gas behaves to balance the search space’s exploitation and exploration phases to avoid becoming trapped in local optima and suggested that multi-objective capabilities be used to solve other real-world optimization challenges. Furthermore, a multi-variable optimization of a power producing system's energy and exergy efficiency utilizing particle swarm optimization (PSO) was announced, ensuring that the algorithm is the optimal one for addressing this case study. It is blended by utilizing a supercritical brayton cycle and a Simple organic rankine cycle (SORC) with CO$_2$ (Ochoa et al., 2020).

This research study examined natural gas-fired power plants and CHPP through a thorough approach to assessing 3E analysis. Furthermore, the potential for energy conservation through the heat exchanger network (HEN) is explored, and the findings are calculated and explained. Thus, the system makes use of a MOO technique along with the HGSO algorithm. The last section considers the economic evaluation of cost-effectiveness for CHPP systems improvement and explains the payback period.

2. Literature review

Numerous studies in this field have been undertaken in recent years. For example, the work of Cavalcanti et al. (2020) investigated power plant sustainability, noting that the optimal outcomes would rely upon the analysis of many factors, including both environmental and thermodynamic parameters. The energy, exergy, and environmental evaluations are performed in the context of a cogeneration system based on sugarcane bagasse. Meanwhile, a novel cogeneration system was developed by Zhang et al. (2020) based on an ORC and absorption heat pump (AHP), which served to accomplish the twin goals of enhancing both heating capacity and power output in power plants fueled by coal.

In recent years, MOO has gained acceptance, having been used for cogeneration purposes in several works, including Awan et al. (2020) who sought to optimize and subsequently assess a solar tower power plant design for performance concerning full load thermal energy storage (TES) when applying a MOO approach. The TES system was employed with much greater efficacy by the optimized design and generated electricity after sunset for much more extended periods. MOO was also put forward by Naserbegi and Aghaie (2020) in the context of a nuclear cogeneration plant to determine the optimal net electrical efficiency, along with the best gain output ratio, and minimized freshwater cost. DEEP software was used to assess desalinated water cost, while the cogeneration plant’s overall optimization was achieved using the gravitational search algorithm (GSA). Meanwhile, (Kazda and Li, 2020) review of CHPP systems was notable in terms of enhancing both the economic performance and sustainability of the electrical generation
Table 1. Review the power plant’s 3E analysis with previous research.

| Citations            | Type             | Energy analysis | Exergy analysis | Economic analysis | HEN design | Capacity (MW) | Results                                                                 |
|----------------------|------------------|-----------------|-----------------|-------------------|------------|---------------|-------------------------------------------------------------------------|
| Sengupta et al., 2007 | Coal-fired       | ✗               | ✓               | ✗                 | ✗          | 210           | The boiler is the cause of the most exergy depletion, according to the data. |
| Ehyaei et al., 2011   | Gas-fired        | ✓               | ✓               | ✓                 | ✓          | 123           | The author investigates the effect of an inlet fogging system on the first and second laws of efficiency, and a unique function for traditional power plant improvement is proposed. |
| Bolatturk et al., 2015| Coal-fired       | ✓               | ✓               | ✗                 | ✗          | 150           | The boiler loses the most exergy, while the condenser loses the least. Expenses are carefully examined to evaluate if planned improvements would improve plant operations. |
| Boyaghi and Molaie, 2015 | Combined cycle | ✓               | ✓               | ✗                 | ✗          | 420           | The sensitivity of the various components of exergy loss was studied in a practical combined cycle power plant. |
| Li et al., 2020       | Combined cycle   | ✓               | ✓               | ✗                 | ✗          | 1989          | In cold climates, a CHPP system with turbine-driven fans and pumps is more efficient and effective in providing heat demand. |

process. Among the algorithms evaluated in operating CHPP systems, most were metaheuristic algorithms, which present various advantages and limitations that can be described further.

An assessment approach covering the environment, economics, and thermodynamics was put forward by Cao et al. (2019) in order to evaluate a CCHP system through the use of the improved emperor penguin optimizer (IEPO). The outcome of the test simulation revealed that IEPO provides a significant annual greenhouse gas (GHG) reduction, although at a high cost and with reduced exergy efficiency when comparisons are drawn with alternative approaches.

As seen in Table 1, several research papers previous founded on 3E analysis in thermal power plants have been assessed in this work.

3. Methodology

3.1. Multi-objective Henry gas solubility optimization (MOO-HGSO) algorithm via the weighted sum method (WSM)

MOO is a technique that involves determining optimal solutions for problems that have more than one objective. The advantage of MOO is that no complex equations are necessary, thus making the problem much more straightforward. Decision-making under MOO requires compromise when balancing some of the contradictory aspects of particular problems. Vilfredo Pareto first proposed the MOO approach. Within MOO, a vector represents the objective function; each objective function vector is then a function of the solution vector. There would be several solutions generated using MOO rather than a single best solution since one solution cannot be optimal for all objectives. Eq. (1) used in the MOO approach is expressed below (Ehrgott, 2005):

$$\min / \max F(x) = \sum_{k=1}^{l} w_k f_k(x)$$

Subject to: \( x \in U \)

In which \( f_k(x) \) denotes the \( k \)th objective function, while \( \min / \max \) indicates the combined object operations. Furthermore, \( k \) represents the number of criteria functions, serves as the decision vector, and \( U \) indicates a feasible set.

The MOO contains three objectives for the CHPP systems: one is to maximize average enthalpy efficiency, as in Eq. (2), two is to maximize average exergy efficiency, as in Eq. (3) and three is to minimize overall costs, as shown in Eq. (4). The weightings for these objectives are allocated equally, so each fitness can be assumed to have a weighting (\( w_k \)) of 0.33.

$$\max f_1 = \text{average} \left( \sum_{i=1}^{N} \eta_{\text{H,i}} \right)$$

$$\max f_2 = \text{average} \left( \sum_{i=1}^{N} \eta_{\text{E,i}} \right)$$

$$\min f_3 = \sum_{i=1}^{N} C_i$$

In which \( \eta_{\text{H}}, \eta_{\text{E}}, C \) indicate the enthalpy efficiency, exergy efficiency, and the overall cost, respectively, for the main equipment in CHPP including boiler (\( i = 1 \)), turbogenerator (\( i = 2 \)) and the condenser (\( i = 3 \)).

3.1.1. Decision variables

Ten variables affecting system performance are considered in light of the modeled system’s performance data and the design process of the system under inquiry. For the parameters listed above, Table 2 provides a suitable variation range.

3.2. HGSO algorithm theory and procedure

In 1800, J.W. Henry proposed the law that was to his name. It is based on solubility and precisely the maximum solute quantity, which dissolves in a given amount of the solvent at a specified pressure and temperature (Mohebbi et al., 2012). The HGSO is based upon the behavior of gases under Henry’s law. It is possible to apply Henry’s law
to establish how low-solubility gases would be soluble in specific liquids. Solubility is also strongly influenced by pressure and temperature. When temperatures are high, the solubility of solids increases but declines for gases. In the case of pressure, pressure increase causes gases to increase solubility (Brown, 2009). This study concerns gases and their solubility, which can be seen in Fig. 1. For that reason, Hashim et al. (2019) were inspired to propose the HGSO algorithm. A flowchart of the HGSO algorithm is presented in Fig. 2, and the calculation principle of the HGSO algorithm, where the equation used are Eq. (5) to Eq. (15). A detailed calculation procedure can be found in the reference for Hashim et al. (2019).

\[ x_i(t + 1) = x_{\text{min}} + (x_{\text{max}} - x_{\text{min}}) \times \text{rand}(0, 1) \]  
\[ H_j(t) = \text{rand}(0, 1) + \phi_1 \]  
\[ P_{i,j}(t) = \text{rand}(0, 1) + \phi_2 \]  
\[ C_j(t) = \text{rand}(0, 1) + \phi_3 \]  
\[ H_j(t + 1) = H_j(t) \times \exp \left( -C_j \times \left( \frac{T^0 - T(t)}{T(t) \times T^0} \right) \right) \]  
\[ T(t) = \exp \left( -\frac{T}{\tau} \right) \]  
\[ S_{i,j}(t) = H_j(t + 1) \times P_{i,j}(t) \]  
\[ x_{i,j}(t + 1) = x_{i,j}(t) + F \left\{ \left( x_{\text{best}}(t) - x_{i,j}(t) \right) \times \text{rand}(0, 1) \times \gamma \right\} \]  
\[ + \left( S_{j}(t) \times x_{\text{best}}(t) - x_{i,j}(t) \right) \times \text{rand}(0, 1) \times \eta \]  
\[ \gamma = \exp \left( \frac{F_{\text{best}}(t) + 0.05}{F_{j}(t) + 0.05} \right) \times \beta \]  
\[ \eta = N \times (c_1 + \text{rand}(0, 1)(c_2 - c_1)) \]  
\[ G_{i,j} = G_{\text{min}(i,j)} + \left( G_{\text{max}(i,j)} - G_{\text{min}(i,j)} \right) \times \text{rand}(0, 1) \]  

In which

- \( i, t \) refer to the total number of iterations and indicates the iteration time, respectively.
- \( x_{i,j}, x_{\text{min}}, x_{\text{max}} \) Show the position of the \( i \)th gas within the population \( N \) and indicate the problem bounds, respectively.
- \( x_{i,j,\text{best}} \) and \( x_{\text{best}} \) serve as the twin parameters offsetting the phases of exploration and exploitation.
- \( H_j \) is Henry’s coefficient concerning the cluster \( H_j \).
- \( P_{i,j} \) represents the partial pressure of the gas \( i \) in the cluster \( j \).
- \( C_j \) is a constant of type \( j \).
- \( S_{j}(t) \) represents the solubility of the gas \( i \) in the cluster \( j \).
- \( T, T^0 \) indicate temperature and constant and equal to 298.15 K, respectively.
- \( \gamma \) indicates the capability for interactions of gas \( j \) in the cluster \( i \) with other gases.

Fig. 2. The HGSO method is represented by a nine-step flowchart.

\( F, F_{\text{best}} \) are a flag of switching the search agent and the fitness of the best gas, respectively.
\( N, N_w \) are the total number of search agents and number of worst agents, respectively.
\( G_{i,j} \) indicates the position of the gas \( i \) in the cluster \( j \).
\( G_{\text{min}}, G_{\text{max}} \) serve as the problem bounds.
\( a, \beta, c_1, c_2, \phi_1, \phi_2, \phi_3 \) are constant parameters.

This study makes use of the following parameters: \( n_{\text{max}} \) is determined to be 500, the gas number is set to be 50, the cluster number is set to be 5, and \( \eta \) indicates a randomly generated number which lies in the range of 0-1, \( a = 1, \) and \( \beta = 1, \phi_1, \phi_2, \phi_3 \) serve as constants which have values that are respectively equal to 5E−03, 100, and 1E−02 (Hashim et al., 2019).

3.3. The CHPP system description

Fig. 3 presents the CHPP configuration, indicating a plant that comprises a boiler, turbogenerator, and condenser. During the process, water and natural gas flow into the boiler, which enters the turbine, which is linked to the electricity generator. After the steam has passed through the turbine, it enters the condenser, where it is duly condensed back into the water, which is therefore recovered for re-use. Fig. 3 shows that the power plant can generate between 40 to 45 Megawatts electric (MWe) and 2,570 kPA steam reaching 365 °C. The plant’s available data cover the steam production process, shown in Table 3, the natural gas composition, the natural gas heating value, and the air temperature of 25 °C. According to Chompuo (2016), the composition of natural gas is carbon (C: 66.03%), hydrogen (H: 19.63%), nitrogen (N: 2.98%), oxygen (O: 11.36%), and sulfur (S: 0%), the unit is in the form of
Table 3: Data on the production process of the CHPP base case scenario.

| Stream | m (kg/hr) | T (°C) | P (kPa) | State          |
|--------|-----------|--------|----------|----------------|
| Stream 1 | 160,000   | 206.65 | 12,100   | Compressed liquid water |
| Stream 2 | 15,000    | 510.98 | 11,220   | Superheated water   |
| Stream 3 | 140,000   | 586.57 | 11,220   | Superheated water   |
| Stream 4 | 140,000   | 599.22 | 11,000   | Superheated water   |
| Stream 5 | 26,000    | 365.25 | 2,570    | Superheated water   |
| Stream 6 | 12,500    | 304.82 | 740      | Superheated water   |
| Stream 7 | 24,500    | 436.77 | 6,500    | Superheated water   |
| Stream 8 | 68,000    | 53.89  | 6.8      | Superheated water   |
| Stream 9 | 4,000,000 | 34.64  | 360      | Compressed liquid water |
| Stream 10 | 4,000,000 | 43.87  | 300      | Compressed liquid water |
| Feed water to system | 92,000    | 195.00 | 12,100   | Compressed liquid water |
| Feed natural gas | 10,000    | 25.00  | 2,720    | Gas              |
| Blowdown water from boiler | 5,000     | 325.00 | 12,200   | Compressed liquid water |
| Flue gas from the boiler | 148,336   | 235.00 | 100      | Gas              |
| Condensate to the flash tank | 9,000    | 95.00  | 230      | Compressed liquid water |
| Condensate to boiler | 68,000    | 45.00  | 9.5      | Compressed liquid water |

Fig. 3. A CHPP system flow sheet.

kJ/kg natural gas. The high heating value (HHV) is 46,707 kJ/kg in the heating value for natural gas, while the low heating value (LHV) is 42,141 kJ/kg.

The specific sizing of the main equipment on CHPP includes a steam boiler at 150 ton/hr., a steam condenser absorbing 150 ton/hr., a steam turbogenerator 27 ton/hr., and a cooling capacity of water flow rate of about 8,000 m³/hr.

From this base case scenario, this is a case study for CHPP systems. The problems that arise with this plant are:

1. Losing exergy is wasteful, which mainly occurs at the condenser to allow the steam to condense and reuse the water.
2. Insufficient power consumption from improper temperature settings at each inlet.
3. High operational costs from the No. 1 and No. 2 reasons.

3.3.1. Conditions for operation of the CHPP system

- The annual operation of the plant amounts to 7,200 hours.
- The lifespan of the plant is 25 years.
- The unit selling price of electricity at peak is $USD 0.14 per kWh, while the off-peak price is $USD 0.09 per kWh. This paper uses the average price between peak and off-peak rates, equal to $USD 0.11 per kWh (Metropolitan Electricity Authority (MEA), 2020).
- The selling price of steam is $USD 0.043 per kg.
- An inflation rate of 5% is used.

3.4. Assumption for 3E analysis

Certain assumptions are made which have similarities to those applied by Avval and Ahmadi (2007), Ahmadi et al. (2008), Udomsri et al. (2010), and Dincer and Rosen (2012):

- All processes consider the steady-state and steady-flow conditions.
- The feeding fuel for the boiler is natural gas.
- Around 3% of LHV fuel is heat loss wastage from the combustion chamber.
- Other equipment used was considered to involve adiabatic processes.
- The thermodynamic statuses for reference are stated as $P_0 = 101.325$ kPa and $T_0 = 298$ K.
- The analysis does not take into account the mass and heat loss at the boiler.
• The input air and the products of the combustion unit are considered under conditions of ideal gas mixtures.
• The cost of operation and maintenance is 3% of the fixed capital investment in the first year, at which point the cost is then increased by 5% each year.
• To optimize the HEN design, Aspen Energy Analyzer software version 8.8 was employed. It is recommended that network designs use an embedded optimization algorithm.
• The Aspen Energy Analyzer software version 8.8 determined the total area of heat exchange, the hot and cold utility duty, capital investment, and results for annual operating costs.
• This study focused only on analyzing the operational processes rather than extending the investigation to cover the profitability of generating steam and electricity.
• In this study, three main costs of equipment included the boiler, turbogenerator, and condenser. Other equipment was not considered because the cost did not change.
• In calculating enthalpy and exergy efficiency, the following are considered: In terms of output, only the enthalpy and exergy quantities that benefit the system are taken into account. And in the input section, only the amount of enthalpy and exergy is taken into the system.

### 3.4.1. Energy analysis

There are many different energy forms, such as kinetic, electrical, chemical, thermal, mechanical, potential, magnetic, or nuclear. They collectively amount to the overall energy of a system, denoted by \( E \). The first law of thermodynamics has its basis in the energy balance, more formally known as energy conservation. It is possible for any given system undergoing any process to achieve a balance of energy and mass through the use of the Eq. (16) given below (Cengel and Boles, 2007):

\[
E_{in} - E_{out} = \Delta E_{system}
\]  

(16)

Mass flow rate refers to the total mass \( m \) recorded flowing through a particular cross-section during a specified period. It is linked to the volume flow rate \( \dot{v} \), defined as the fluid volume passing through a particular cross-section during a specified period, through the use of the Eq. (17) given as:

\[
m = \rho \dot{v} = \rho A \dot{v}_{avg}
\]  

(17)

Which is considered analogous to \( m = \rho \dot{v} \). This case represents fluid density and \( A \) indicates the cross-section area through which the flow is measured while \( \dot{v}_{avg} \) representing the average flow velocity \( A \). In the course of any process involving a steady flow, there is no variation in the overall mass in the control volume over time \( (m_{CV} = \text{constant}) \). Thus, the principle of the conservation of mass demands that the total mass going into the control volume should be the same as the total mass that leaves. In any process involving a steady flow, the mass flowing into or out of a device within a given period is not essential. It is the mass flow per unit of time that is significant, indicated by the \( m \) in Eq. (18), given as:

\[
\sum_{i} m_i = \sum_{out} m_i
\]  

(18)

It is essential to understand that the relationship described above relates to a closed system undergoing constant pressure processes. For this reason, it cannot be extended to cover those processes in which the pressure might change. The energy level necessary to increase the temperature of one unit of mass for any given substance by an amount of one degree is known as the specific heat at constant volume \( c_v \) for the process involving constant volume (Eq. 19) and specific heat at constant pressure \( c_p \) in a constant pressure process (Eq. 20) given by:

\[
c_v = \left( \frac{\partial h}{\partial T} \right)_p
\]  

(19)

\[
c_p = \left( \frac{\partial h}{\partial T} \right)_p
\]  

(20)

In the case of ideal gases, \( u \) it represents the internal energy, \( h \) indicates enthalpy \( c_v \), and \( c_p \) serves solely as temperature functions. The \( \Delta u \) (Eq. (21)) and \( \Delta h \) (Eq. (22)) values for ideal gases can be determined using the method outlined below:

\[
\Delta u = u_f - u_i = \int c_v(T)dT \equiv c_v,\text{avg}(T_f - T_i)
\]  

(21)

\[
\Delta h = h_f - h_i = \int c_p(T)dT \equiv c_p,\text{avg}(T_f - T_i)
\]  

(22)

For ideal gases \( c_v \), and \( c_p \) are formulated in Eq. (23):

\[
c_p = c_v + R
\]  

(23)

Which \( R \) denotes the gas constant, defined as \( R = 8.314 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \). The \( \Delta u \) (Eq. (21)) and \( \Delta h \) (Eq. (22)) values for substances that are incompressible are determined by (Eq. 24):

\[
\Delta h = \Delta u + \Delta P \nu
\]  

(24)

The temperature function is given by \( c_p \) (Eq. (25)), which is derived from Eq. (26), given as follows (Ganiev et al., 2019):

\[
c_p = A + BT + CT^2 + DT^3
\]  

(25)

\[
\int c_p(T)dT = AT + BT^2 + CT^3 + DT^4 + k
\]  

(26)

The constant parameters are indicated by \( A, B, C, \) and \( D \), and the temperature is represented by \( T \) in terms of \( k \) (which is a constant derived via integration) (Jarungthammachote and Dutta, 2007).

The first law of thermodynamics enables the calculation of enthalpy efficiency \( (\eta_E) \) through Eq. (27), given below as:

\[
\eta_E = \left( \frac{\text{Enthalpy output}}{\text{Enthalpy input}} \right) \times 100
\]  

(27)

This study allows the individual stream temperatures (°C) to be determined by interoperating, as can be seen in Eq. (28) below:

\[
T_i = T_{\text{upper_bound},i} - (h_{\text{upper_bound},i} - h_{\text{optimal}}) \times r_i
\]  

(28)

This study examines the upper and lower bounds of enthalpy and temperature for each stream represented as \( i \) (where \( i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 \)). The streams have their temperatures measured because they are suitable for pinch analysis to improve the CHPP examined in this base case. MATLAB software version R2020a was used to determine optimal enthalpy levels, along with the optimal operating parameters for the HGSO algorithm, while \( r_i \) denotes the ratio of the difference in temperatures at the upper and lower bounds divided by the difference in enthalpy between upper and lower bounds, which can be seen as follows in Eq. (29):

\[
r_i = \frac{T_{\text{upper_bound},i} - T_{\text{lower_bound},i}}{h_{\text{upper_bound},i} - h_{\text{lower_bound},i}}
\]  

(29)

To simulate optimal values for the system’s design variables, MOO-HGSO was performed to assess steam and gas profiles in the CHPP and establish the enthalpy and exergy for each plant line at both the input and output stages for each cost of equipment. The following section explains the energy balances along with the equations that govern each cost of equipment used.

- Boiler
Water at ambient pressure ($P_a$), which is 101.325 kPa, enters the heater at temperatures given as $T_1$. Moreover, after that the process allows steam to enter the boiler. The outlet boiler temperature would be strongly influenced by the boiler enthalpy efficiency ($\eta_{E, boiler}$). By applying Eq. (16) and Eq. (18) along with the first law of thermodynamics, the boiler input energy and output energy are equal according to Eq. (30) to Eq. (32):

$$E_1 + E_{natural\ gas} = E_2 + E_3$$ (30)

$$m_1h_1 + m_{natural\ gas}h_{natural\ gas} = m_2h_2 + m_1h_3$$

$$\eta_{E, boiler} = \left( \frac{m_2h_2 + m_1h_3}{m_1h_1 + m_{natural\ gas}h_{natural\ gas}} \right) \times 100$$ (32)

* Turbocharger

The turbocharger inlet temperature ($T_i$) and outlet temperatures ($T_s$, $T_o$) can be calculated using Eq. (28) by making use of the enthalpy efficiency ($\eta_{E, turbocharger}$). Eq. (16) and Eq. (18) are employed to establish the energy balance for the turbocharger, as shown in Eq. (33) and Eq. (34):

$$E_i = E_s + E_o + E_f$$ (33)

$$m_4h_4 = m_5h_5 + m_6h_6 + m_7h_7$$ (34)

The enthalpy efficiency of the turbocharger ($\eta_{E, turbocharger}$) is given as shown by Eq. (35) based on Eq. (27):

$$\eta_{E, turbocharger} = \left( \frac{m_4h_4}{m_5h_5 + m_6h_6 + m_7h_7} \right) \times 100$$ (35)

* Condenser

The condenser inlet temperatures ($T_s$, $T_o$) and outlet temperature ($T_{10}$) are based on Eq. (29). Eq. (16) and Eq. (18) can be employed to identify the energy balance of the condenser, as shown by Eq. (36) and Eq. (37):

$$E_o + E_s = E_{10}$$ (36)

$$m_9h_9 + m_8h_8 = m_{10}h_{10}$$ (37)

The enthalpy efficiency of the condenser ($\eta_{E, condenser}$) can be determined based on Eq. (27) as shown in Eq. (38):

$$\eta_{E, condenser} = \left( \frac{m_{10}h_{10}}{m_9h_9 + m_8h_8} \right) \times 100$$ (38)

### 3.4.2. Exergy analysis

This study assesses exergy to establish the exergy efficiency and evaluates the rate of exergy destruction for each equipment type, and the CHPP system as a whole. Furthermore, it is possible to define a new benchmark for exergy in terms of exergy loss per output unit power. It is usually possible to calculate the rate of exergy destruction for each equipment type within the power plant when steady-state thermodynamic conditions prevail by using Eq. (39) given below (Bejan, 1996, Kotas, 2013):

$$E_x = \sum (E_{x})_{in} - \sum (E_{x})_{out}$$

$$+ \sum \left( Q \left( 1 - \frac{T_o}{T} \right) \right)_{in} - \sum \left( Q \left( 1 - \frac{T_o}{T} \right) \right)_{out}$$

($E_{x}$)$_{in}$ and ($E_{x}$)$_{out}$ show the respective exergy flows going into and out of the control volume, while the pair of terms that follow in the equation contain items related to heat exergy. The reference temperature can be selected and $Q$ indicates the steady temperature for the heat transfer rate for the temperature ($T$) across system boundaries. The final term is used to show the work transfer rate ($W$) to or from the control volume for work done or given. In this case, the calculation only takes into account the physical exergy associated with the crossing mass flows over the control volume, in line with the work of Bejan (1996) and Kotas (2013), shown by Eq. (40):

$$E_x = m_i(h_i - h_{o2}) + T_o(s_{o2} - s_{o1})$$ (40)

For defining physical exergy, Eq. (40) contains the terms representing specific enthalpy and specific entropy. Analysis of exergy is carried out to determine the exergy efficiency to determine an indicator to represent the system as a whole or for each item of individual equipment’s performance. The calculation of exergy efficiency relies upon previously published methods under which the fuel exergy and product amounts are defined. Total consumption of the exergy resource can be represented through fuel exergy, but the plant’s commodity and the associated exergy can be explained by product exergy (Bejan, 1996). Meanwhile, Table 4 shows the necessary calculations to find the power plant’s critical device exergy efficiency. By taking the sum of the exergy destruction values arising for each item of equipment, it is possible to determine the total overall exergy destruction rate for the power plant as a whole, as shown in Eq. (41):

$$E_{Ex, total} = \sum E_{Ex} = E_{Ex, B} + E_{Ex, T} + E_{Ex, C}$$ (41)

The second law of thermodynamics allows the calculation of exergy efficiency ($\eta_{E}$) by using Eq. (42):

$$\eta_{E} = \frac{\text{Exergy output}}{\text{Exergy input}} \times 100$$ (42)

The following section explains the exergy efficiency and the governing equations for the various equipment types in the CHPP examined in the current base case.

* Boiler

Calculating the boiler’s exergy destruction rate is possible, as shown in Eq. (43):

$$E_{Ex, boiler} = E_x + E_{Ex, natural\ gas} - E_{Ex, 1} - E_{Ex, 2}$$ (43)

The exergy efficiency of the boiler is given by Eq. (44):

$$\eta_{E, boiler} = \left( \frac{m_{9}(h_7 - T_{o9} s_9) + m_{10}(h_8 - T_{o10} s_8)}{m_9(h_7 - T_{o9} s_9) + m_{10}(h_8 - T_{o10} s_8)} \right) \times 100$$ (44)

* Turbogenerator

The rate of exergy destruction for the turbogenerator is given by Eq. (45):

$$E_{Ex, turbogenerator} = E_x - E_{Ex, 1} - E_{Ex, 2}$$ (45)

It is possible to calculate the turbogenerator exergy efficiency as follows by Eq. (46):

$$\eta_{E, turbogenerator} = \left( \frac{m_{1}(h_1 - T_{o1} s_1) + m_{3}(h_3 - T_{o3} s_3)}{m_4(h_4 - T_{o4} s_4) + m_{5}(h_5 - T_{o5} s_5)} \right) \times 100$$ (46)

* Condenser

Eq. (47) is used to determine the rate of exergy destruction in the condenser:

$$E_{Ex, condenser} = E_{Ex} + E_{Ex, 3} - E_{Ex, 10}$$ (47)

The exergy efficiency of the condenser is given by Eq. (48):

$$\eta_{E, condenser} = \left( \frac{m_{10}(h_{10} - T_{o10} s_{10}) + m_{8}(h_8 - T_{o8} s_8) + m_{9}(h_9 - T_{o9} s_{9})}{m_8(h_8 - T_{o8} s_8) + m_9(h_9 - T_{o9} s_{9})} \right) \times 100$$ (48)
3.4.3. Economics evaluation

Economic evaluation investigates the equipment’s thermodynamic properties via exergy analysis, based on economic fundamentals. The literature review was used to provide the cost estimates for the CHPP’s critical components during this study. This enabled the boiler cost, turbogenerator cost, and condenser cost to be assessed using the equations given as:

- Cost of the boiler by Eq. (49) (Bamufleh et al., 2013)

\[
C_{\text{Boiler}} = 3 \times N_p \times N_T \times Q_b^{0.77} \quad (49)
\]

Where \( Q_b = (m_2 h_2 + m_1 h_1) - (m_1 h_1 + m_{\text{natural gas}} h_{\text{natural gas}}) \)

\( N_p = 7 \times 10^{-4} \times P_{St} \)

\( N_T = 1.5 \times 10^{-6} \times T_3^2 + 1.13 \times 10^{-3} \times T_3 + 1 \)

where, \( Q_b \) is the required boiler heat, (kJ/h)

\( N_p \) is the determining consideration in influencing the operation’s pressure

\( N_T \) is a variable that affects the superheat temperature

\( P_{St} \) is the boiler pressure, (kPa)

- Fuel cost (Bamufleh et al., 2013)

It is typically the dominant part, amounting to around 90% of the whole. It is calculated using Eq. (50):

\[
C_{\text{Fuel}} = a_T \times \left( \frac{h_2 - h_1}{1000} \right) / \eta_B \quad (50)
\]

where, \( a_T \) is fuel cost set to 2.45, ($USD/kJ)

\( \eta_B \) is overall boiler efficiency, (fractional)

- Cost of the turbogenerator by Eq. (51) (Bamufleh et al., 2013), Astolfi et al., 2014)

\[
C_{\text{turbogenerator}} = (475 \times P_f^{0.43}) + C_1 \times \frac{W_{el}}{W_{el,0}} \frac{0.67}{1.18} \quad (51)
\]

When \( P_f = m_1 h_4 - (m_3 h_5 + m_1 h_1 + m_{\text{Turb}} h_7) \),

where, \( P_f \) is the output of the turbine shaft, (kJ/h)

\( C_1 \) is the cost at the reference condition for the purpose of cost correlations, ($USD)

\( W_{el} \) is electrical power, (kW)

\( W_{el,0} \) is electrical power in its reference state, (kW)

- Cost of the condenser by Eq. (52) (Alus, 2017)

\[
C_{\text{condenser}} = 280 \times A_{\text{condenser}}^{1.04} \quad (52)
\]

When \( A_{\text{condenser}} = \frac{m_1 h_2 - (m_3 h_5 + m_1 h_1)}{U_{\text{condenser}} \times \text{LMFD}_{\text{condenser}}} \)

\[
\text{LMFD}_{\text{condenser}} = \frac{TR}{\ln \left( \frac{1}{\text{ITD}} \right)}
\]

where, \( A_{\text{condenser}} \) is the condenser heat transfer area, (m²)

\( U_{\text{condenser}} \) is the condenser’s heat transfer coefficient, (W/m².K)

\( \text{LMFD}_{\text{condenser}} \) is the logarithmic mean temperature difference for the condenser

\( TR \) is the temperature rise in the condenser, (K)

\( \text{ITD} \) is the initial temperature difference, (K)

3.4.4. Uncertainty analysis

The methodology described in Eq. (53) is used to analyze the uncertainty (\( U \)) of the data utilized in the system assessment (Li et al., 2020):

\[
U = \left[ \left( \frac{\partial F}{\partial z_1} u_1 \right)^2 + \left( \frac{\partial F}{\partial z_2} u_2 \right)^2 + \ldots + \left( \frac{\partial F}{\partial z_n} u_n \right)^2 \right]^{1/2} \quad (53)
\]

Uncertainties are permitted as long as their values fall within a ±5% range.
3.5. HEN design

In the CHPP, it can be observed that some stream temperatures are high, while other streams have lower temperatures. Therefore, we propose energy conservation using a heat exchanger network to save costs. We have analyzed the data necessary to create a heat exchanger network. For the convenience of analysis, this research uses Aspen Energy Analyzer software version 8.8 to design a heat exchanger network for the convenient calculation of confidential data from the companies under evaluation.

The heating and cooling utilities use the fired heat for sufficient to meet the unit’s heating load requirements, while the cooling water for sufficiently cold to meet the unit’s cooling load requirements. Therefore, fired heat and cooling water are the chosen utilities in this process. The software contains a default database of utilities that could generally be available at the process site. Cooling water has a temperature of 20 °C at the inlet, rising to 25 °C at the outlet. Fired heat reaches temperatures of 1,000 °C at the inlet and 400 °C at the outlet. From an economic perspective, cost data are also needed to make an evaluation. These data would include the cost of utilities and the time taken for an operation to estimate operational cost savings. In contrast, the cost of the heat exchanger is necessary to determine the probable investment cost.

The pinch analysis underpins the whole process of creating the HEN. Optimization primarily seeks to achieve the minimal annual cost while meeting the process energy targets, which serve as the constraints. The software can assist in designing the optimized HEN. The optimization approach can suggest several near-optimal designs for the heat exchanger by using an embedded algorithm. The various heat exchanger designs can be visualized graphically using a grid diagram that depicts the linkages between the hot and cold streams and the process-to-process heat exchange (Vural-Gürsel et al., 2015). These proposed options can then be compared in terms of annual costs, with the option that offers the minimum cost being the one that would be chosen (Wang and Chen, 2017).

3.6. CHPP optimization process

The MOO-HGSO process is significantly affected by the various operating temperature streams parameter because of the large thermodynamic and economic effects that these factors can exert upon system performance. The decision variables optimize the temperature stream for the units used in degrees celsius. In this study, it has been shown that when the temperature streams are optimized using MATLAB software version R2020a tool, this can significantly improve the base case of CHPP system performance. The CHPP system, which was used for optimization purposes, is shown in Fig. 4, which reveals how the system’s efficiency can be enhanced by applying the MOO-HGSO algorithm.

4. Results and discussion

4.1. Algorithm authentication

Validation of the HGSO algorithm is a prerequisite before it can be applied to the application. Therefore, three functions of the benchmark function problems (Jamal and Yang, 2013) that are well-known were tested: unimodal, multimodal, and fixed dimension, as shown in Table 5. The analysis used a population (number of gases, N) equal to 50 and a maximum of 1000 iterations.

From the results test of 30 times each of functions for the reliability of the HGSO algorithm, it can be concluded that the HGSO algorithm is advantageous for locating solutions and obtaining global or near-global optima in all formula types. The robustness of the test, as indicated by the standard deviation (st. dev.), can be summarized in Table 6 for the statistical data.

4.2. 3E optimization of CHPP system performance by MOO-HGSO algorithm

The test would be performed 30 times for each option, using the same fitness value as the initial iteration, as specified in the MOO-HGSO approach, the statistical data for which are given in Table 7. In this section, the values of enthalpy efficiency average ($\eta_{E_{\text{average}}}$), exergy efficiency average ($\eta_{E_{\text{average}}}$), and the overall costs $(\text{Cost}_{\text{overall}})$ are compared for both the MOO-HGSO algorithm and the CHPP base case scenario.

In general, the MOO-HGSO algorithm can enhance the values of enthalpy and exergy efficiency for each instrument in the CHPP system, with the economic cost between MOO-HGSO algorithm and CHPP base case scenario, as indicated in Table 8. The global solution is based on the solution vector obtained from the MOO-HGSO algorithm, which is given as: $\{T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_9, T_{10}\} = [179.01, 566.85, 572.24, 479.02, 427.83, 334.11, 417.57, 46.72, 34.55, 45.33]$

When examining the CHPP of the base case scenario, it is found that the value for overall cost of MOO-HGSO algorithm exceeds that of the base case scenario due to the system having an operating temperature such that most streams have improved operating temperatures for the MOO-HGSO algorithm, resulting in enthalpy efficiency and exergy efficiency of the base case being lower than MOO-HGSO algorithm. The stream of the boiler obtained from the MOO-HGSO algorithm is cooler at the inlet stream ($T_1$) and hotter at the outlet stream ($T_2$ and $T_3$) than is the case for the streams involved in the CHPP base case system. Thus, the values for the boiler’s enthalpy efficiency ($\eta_{E_{\text{boiler}}}$) and exergy efficiency ($\eta_{E_{\text{boiler}}}$) in the base case are lower than would be optimally seen in Table 7. This high boiler efficiency level results from the massive difference in values between the steam and the feed water’s enthalpies. As the steam in the isobaric process has a high temperature, this results in
Table 5. Benchmark functions and descriptions for the verification of the HGSO algorithm.

| Mathematical definition                                      | Type         | Dim (d) | Range                  | Global minimum |
|--------------------------------------------------------------|--------------|---------|------------------------|----------------|
| Griewank \( f(x) = 1 + \sum_{i=1}^{n} \frac{x_i^2}{4000} - \prod_{i=1}^{n} \cos \left( \frac{x_i}{\sqrt{i}} \right) \) | Unimodal     | 30      | \([-600,600]^d\)       | 0              |
| Rastrigin \( f(x) = 10d + \sum_{i=1}^{d} (x_i^2 - 10 \cos (2\pi x_i)) \) | Multimodal   | 30      | \([-5.12,5.12]^d\)     | 0              |
| Bohachevsky N1 \( f(x) = x_1^2 + 2x_2^2 - 0.3 \cos (3x_1) - 0.4 \cos (4x_2) + 0.7 \) | Fixed-dimension | 2       | \([-100,100]^d\)       | 0              |

Table 6. Statistical information obtained from benchmark function tests.

| Function   | Average | Best | Worst | St. dev. |
|------------|---------|------|-------|----------|
| Griewank   | 5.23E-34 | 0    | 1.57E-32 | 2.87E-33 |
| Rastrigin  | 1.08E-13 | 0    | 3.25E-12 | 5.93E-13 |
| Bohachevsky N1 | 0 | 0 | 0 | 0.00 |

Table 7. Statistical results obtained from the MOO-HGSO algorithm 30 times for the CHPP system.

|            | \( \eta_{\text{average}} \), % (Mean: St. dev.) | \( \eta_{\text{average}} \), % (Mean: St. dev.) | Cost\(_{\text{total}}\) (USD) (Mean: St. dev.) |
|------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 3E analysis| \( \eta_{\text{average}} \), % (Mean: St. dev.) | \( \eta_{\text{average}} \), % (Mean: St. dev.) | Cost\(_{\text{total}}\) (USD) (Mean: St. dev.) |
| MOO-HGSO   | 79.26-82.76 | 35.40-38.17 | 2.76-2.93 |
|            | (81.75±0.73) | (37.08±0.55) | (2.86±0.0436) |

Fig. 5. The convergence rate of iterations of each scenario in the CHPP system.

4.3. Four proposed scenarios for optimization of the CHPP system

This paper proposed four different scenarios under varied conditions, as shown in the results in Table 9. Scenario 1 provides the highest \( \eta_{\text{base}} \) at 94.22%, while the average enthalpy \( \left( \eta_{\text{average}} \right) \) and average exergy efficiencies \( \left( \eta_{\text{average}} \right) \) when considering the CHPP system stand at 82.76% and 38.07%, respectively. However, these results do not bring about the greatest cost-savings, as the overall cost \( \left( \text{Cost}_{\text{total}} \right) \) is USD28.9 million. The highest value for enthalpy efficiency of the turbogenerator \( \left( \eta_{\text{turbogenerator}} \right) \) is provided in scenario 2, at 54.57%, while, exergy efficiency of the turbogenerator \( \left( \eta_{\text{turbogenerator}} \right) \) is 49.16%, and the greatest cost-saving is for the turbogenerator, which has a cost \( \left( \text{Cost}_{\text{turbogenerator}} \right) \) of USD9,552 million. The highest value \( \eta_{\text{condenser}} \) is achieved by scenario 3 at 100%, while \( \eta_{\text{condenser}} \) is 18.48%. However, scenario 3 also has the highest condenser cost of USD11,064 million. The CHPP base case scenario overall cost offers the best cost savings, but the efficiency values are the worst, \( \eta_{\text{average}} \) equal to 78.66% and \( \eta_{\text{average}} \) equal to 33.95%.

The convergence rates for the iterations generated from MOO-HGSO in the CHPP system are shown in Fig. 5. As can be seen, each scenario has 500 iterations. To ensure equality, the solution vector at MOO-HGSO with value \( (F) \) is determined to be 170 for every scenario for the first iteration before testing. In Fig. 5, it can be seen that, for each iteration calculated, there are curves for the convergence trends in each scenario. The figure indicates that scenario 2, represented by the red line, offers rapid convergence but trapped a local optimum. However, scenario 1, represented by the violet line, does provide a global optimum, which indicates the solution vector of each stream’s temperatures in all scenarios, presented in Fig. 6.

Since the temperature resulting from the stream optimization can be higher and lower than the temperature for the CHPP system reported in the base case, it is possible to lower the utility consumption while optimizing investment, conserving energy, and achieving cost savings. For this reason, it can be put forward as a HEN design capable of achiev-
ing efficiency in the production process when the use of conservation energy is optimized.

4.4. Heat exchanger network (HEN) design of each scenario in the CHPP system

The HEN design options were created using the Aspen Energy Analyzer software version 8.8 to most closely achieve the given energy targets. This approach involves an embedded optimization that can find the minimum annual cost while respecting the given constraints. This starting network for this process includes the necessary heating and cooling components for the process streams satisfied by the utility streams. The grid diagram reveals the HEN based on the fundamental design, as shown in Fig. 7, which demonstrates how the utility streams and individual process streams comprising fired heat and cooling water can match the heat exchangers in each scenario.

The direction of flow for hot process streams is to the right, whereas the direction of flow for cold process streams is to the left. The use of red for the heat exchanger shows a heater indicating hot utility, while blue is used in the cold utility context.

The grid diagrams for the HEN scenarios 1-4 are shown in Fig. 7(a-d). The number of heat exchangers in each scenario differs; scenarios 1 and 3 have six external exchangers, while scenario 2 has two external exchangers and scenario 4 has three external exchangers. Thus, scenarios 1-4 have five, eight, six, and nine internal exchangers, respectively. The role of these exchangers is to perform the temperature stream-to-temperature stream of each line recovery of heat.

Table 8. Comparing the 3E analysis for the MOO-HGSO algorithm and the CHPP system's base case.

| Equipments | 3E analysis | MOO-HGSO (optimal) | Base case (before optimal) | Saving cost (%) |
|------------|-------------|---------------------|-----------------------------|-----------------|
| Boiler     | $\eta_{B boiler}$ (%) | 94.22            | 87.42                      | +7.22           |
|            | $\eta_{B boiler}$ (%) | 47.31            | 43.90                      | +3.41           |
|            | Cost $\times 10^5$ ($USD$) | 84.63           | 83.98                      | −0.77           |
| Turbogenerator | $\eta_{Turbogenerator}$ (%) | 54.46          | 52.00                      | +4.52           |
|            | $\eta_{Turbogenerator}$ (%) | 49.11           | 45.75                      | +6.36           |
|            | Cost $\times 10^5$ ($USD$) | 95.55           | 96.44                      | +0.99           |
| Condenser  | $\eta_{Condenser}$ (%) | 99.60           | 96.55                      | +3.05           |
|            | $\eta_{Condenser}$ (%) | 17.79           | 12.21                      | +31.37          |
|            | Cost $\times 10^5$ ($USD$) | 108.51          | 94.95                      | −12.50          |
| CHPP system | $\eta_{CHPP}$ (%) | 82.76           | 78.66                      | +4.95           |
|            | $\eta_{CHPP}$ (%) | 38.07           | 33.95                      | +10.82          |
|            | Cost $\times 10^5$ ($USD$) | 28.87           | 27.54                      | −4.61           |

Table 9. The MOO-HGSO algorithm produced 3E analysis results data for each scenario.

| Scenario | $\eta_i$ | $\eta_f$ | Cost $\times 10^5$ ($USD$) | $\eta_i$ | $\eta_f$ | Cost $\times 10^5$ ($USD$) | Overall $\eta_i$ | Overall $\eta_f$ | Cost $\times 10^5$ ($USD$) |
|----------|----------|----------|-----------------------------|----------|----------|-----------------------------|-----------------|-----------------|-----------------------------|
| 1        | 94.22    | 47.31    | 84.63                       | 95.55    | 96.55    | 108.51                      | 82.76           | 38.07           | 28.87                       |
| 2        | 84.16    | 49.46    | 54.46                       | 95.55    | 96.55    | 108.51                      | 78.66           | 33.95           | 27.54                       |
| 3        | 93.53    | 47.22    | 53.45                       | 95.54    | 96.55    | 108.51                      | 82.76           | 38.07           | 28.87                       |
| 4        | 94.10    | 47.43    | 54.51                       | 95.54    | 96.55    | 108.51                      | 82.76           | 38.07           | 28.87                       |
| Base case| 87.42    | 43.90    | 83.98                       | 94.95    | 96.55    | 108.51                      | 78.66           | 33.95           | 27.54                       |

Fig. 6. The stream temperature of the CHPP system is solved using the MOO-HGSO algorithm.
Fig. 7. Grid diagrams of the HEN design for each scenario in the CHPP system (a) scenario 1, (b) scenario 2, (c) scenario 3, and (d) scenario 4.

Table 10. Utility costs and consumption of the HEN design in the CHPP system.

| Scenario | The capital cost of heat exchanger ($USD) | Hot utility Cost ($USD/year) | Consumption (kJ/hr) | Cold utility Cost ($USD/year) | Consumption (kJ/hr) | Operating cost of utility ($USD/year) |
|----------|------------------------------------------|-----------------------------|---------------------|--------------------------------|---------------------|-------------------------------------|
| 1        | 110,393.24                               | 8.45E+01                    | 2,764.43            | 9.28E+00                        | 6,071.37            | 9.38E+01                           |
| 2        | 100,593.86                               | 4.90E+02                    | 10,938.59           | 9.33E+00                        | 6,097.79            | 5.00E+02                           |
| 3        | 120,381.33                               | 7.78E+01                    | 2,541.35            | 9.33E+00                        | 6,108.41            | 8.71E+01                           |
| 4        | 120,759.54                               | 6.51E+02                    | 17,576.80           | 9.31E+00                        | 6,090.69            | 6.61E+02                           |

Table 11. Increasing costs in each scenario.

| Scenario | Total cost, $USD | Increasing cost (%) |
|----------|------------------|---------------------|
| 1        | 28,979,353.80    | 0.3824%             |
| 2        | 27,964,554.00    | 0.3610%             |
| 3        | 29,295,461.30    | 0.4126%             |
| 4        | 27,714,313.80    | 0.4376%             |

scenario 4 being the least expensive, followed by scenarios 2, 1, and 3, respectively.

The total cost and average enthalpy and exergy efficiencies for the four different HEN for thermal management are shown in Fig. 8. Among the various scenario designs, it can be seen that scenario 1 has higher average enthalpy and exergy efficiencies than scenario 4, despite the fact that scenario 4 has the lowest total cost. Costs are high in scenario 1 due to the numerous shells and significantly increased cooling utility load. Costs are high in scenario 1 due to the numerous shells and significantly increased cooling utility load. As a result, in terms of total cost, scenario 1 is 4.56% more expensive than scenario 4.
4.5. Economic evaluation

The cost of water is considered to be $USD1.03 million in this analysis. The first year’s capital costs in scenarios 1-4 are shown in Fig. 9(a) to be $USD30.00 million, $USD28.99 million, $USD30.33 million, and $USD28.74 million, respectively. The relationship between operational and maintenance costs and the year for each of the four scenarios is depicted in Fig. 9(b). The first year’s cost of operation and maintenance was determined to be 3% of the capital cost, increasing by 5% each year thereafter.

4.5.1. Profits from the production of steam and electricity

As seen in Table 12, the fuel cost for each scenario is determined using Eq. (30), and the difference is due to the different enthalpies of steam into the boiler for each scenario. As a result, natural gas in scenario 2 was the highest, but scenario 1 had the lowest natural gas, and the fuel cost would eventually be combined with the operating cost. From Table 12, the electricity and steam produced per hour were compared among the 4 scenarios, and it was observed that scenario 2 was able to generate the most electricity per hour. On the other hand, scenario 3 could produce the lowest amount of electricity. The production of more or less electricity will depend on the exergy efficiency of the turbogenerator and each scenario’s entropy. When considering steam production, scenario 1 produced the most steam, but scenario 3 produced the least steam amount. The large amount of steam produced is from the high steam temperature. When considering all profits, it can be seen that scenario 1 is the most profitable, while scenario 3 is the least profitable.

According to the assumptions made previously, the payback period for a plant with a 25-year life can be calculated at the intersection of the operational cost and profit lines, where the payback periods for scenario 1 (Fig. 10(a)), scenario 2 (Fig. 10(b)), scenario 3 (Fig. 10(c)), and scenario 4 (Fig. 10(d)) are 2.11 years, 2.37 years, 2.41 years, and 2.17 years, respectively.

5. Conclusion

The first and second laws of thermodynamics are used to make recommendations for improving the CHPP base case scenario, which is supported by an analysis of the natural gas system’s economic characteristics for producing steam and electricity. To achieve the best results through MOO, the approach followed involved a metaheuristic known as the HGSO algorithm, which has the advantage of global search optima. As a result, the author uses this technique and MOO to address the CHPP system’s problem. 3E analysis was based on the maximization of enthalpy efficiency and the minimization of both irreversibility and cost; the boiler, condenser, and turbogenerator required to produce steam and electricity in the CHPP system. There are several advantages to using the MOO-HGSO algorithm for the CHPP base case, including optimizing the temperature streams, while there are increases in the average efficiencies of enthalpy and exergy of 4.95% and 10.82%, re-
Table 12. Detailed information about the total profits made by each scenario in the CHPP system.

| Cost details          | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|-----------------------|------------|------------|------------|------------|
| Fuel costs ($USD/kg)  | 0.9036     | 1.0529     | 0.9889     | 0.9440     |
| Natural gas ($USD/hr) | 9,036.04   | 10,529.14  | 9,889.10   | 9,439.90   |
| Electricity produced (kWh) | 43,897.13 | 44,278.42  | 42,290.06  | 44,049.82  |
| Electricity sale ($USD/hr) | 4,852.19  | 4,894.34   | 4,674.56   | 4,869.07   |
| Steam produced (kg/hr) | 28,948.81  | 27,449.46  | 26,234.27  | 27,862.40  |
| Steam sale ($USD/hr)  | 1,244.08   | 1,179.65   | 1,127.42   | 1,197.39   |
| All profit ($USD/hr)  | 6,096.27   | 6,073.99   | 5,801.98   | 6,066.46   |

Fig. 10. Payback period for each scenario: (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4.

respectively. At the same time, economic differences were minimal in comparison to the base case scenario.

The various components of the HEN design are also significant, with temperatures being a factor of the stream optimization in the CHPP based case while achieving lower costs and lower utility consumption in the long term. In this manner, the HEN design can minimize energy consumption during production. When heat recovery is most efficient, it may reduce utility consumption and promote energy conservation as the operating cost is reduced. This is why four different HEN designs are proposed to achieve an efficient production process for the base case. Among the scenarios, there are minimal differences in the cost of operation and maintenance. Profits from steam production and electrical power sales are estimated to be between $USD 5,800 and $USD 6,100 per hour in each scenario presented in this study. For the payback period, each scenario gives a payback period of approximately two years. Consequently, the authors propose the four scenarios, which will be appropriate choices for plant operators who wish to install their CHPP equipment and operate a plant in line with the required economic targets. Therefore, the MOO-HGSO solution has been demonstrated to provide suitable solutions that would be appropriate for various complex systems and larger power plants.

The HGSO algorithm could be used in future studies along with other approaches to achieve a rapid rate of convergence and an optimal solution. This involves the use of deep learning, a well-known approach in artificial neural network (ANN) modeling, which can predict the enthalpy efficiency, exergy efficiency, economic assessment, and HEN design of a CHPP system provided the ANN model is provided with sufficient data. Additionally, the ANN model simplifies the study of thermodynamic models for individuals who are unfamiliar with them.

Declarations

Author contribution statement

Somboon Sukpancharoen: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data;
Contributed reagents, materials, analysis tools or data; Wrote the paper.

Boonrit Prasartkaew: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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