



ORIGINAL ARTICLE

Multi-objective optimization and exergetic-sustainability of an irreversible nano scale Braysson cycle operating with Maxwell–Boltzmann gas



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Abstract Nano technology is developed in this decade and changes the way of life. Moreover, developing nano technology has effect on the performance of the materials and consequently improves the efficiency and robustness of them. So, nano scale thermal cycles will be probably engaged in the near future. In this paper, a nano scale irreversible Braysson cycle is studied thermodynamically for optimizing the performance of the Braysson cycle. In the aforementioned cycle an ideal Maxwell–Boltzmann gas is used as a working fluid. Furthermore, three different plans are used for optimizing with multi-objectives; though, the outputs of the abovementioned plans are assessed autonomously. Throughout the first plan, with the purpose of maximizing the ecological coefficient of performance and energy efficiency of the system, multi-objective optimization algorithms are used. Furthermore, in the second plan, two objective functions containing the ecological coefficient of performance and the dimensionless Maximum available work are maximized synchronously by utilizing multi-objective optimization approach. Finally, throughout the third plan, three objective functions involving the dimensionless Maximum available work, the ecological coefficient of performance and energy efficiency of the system are maximized synchronously by utilizing multi-objective optimization approach. The multi-objective evolutionary approach based on the non-dominated sorting genetic algorithm approach is used in this research. Making a decision is performed by three different decision makers comprising linear programming approaches for multidimensional analysis of preference and an approach for order of preference by comparison with

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Nomenclature

c_v	specific heat at constant volume ($\text{J K}^{-1} \text{kg}^{-1}$)	T	temperature (K)
c_p	specific heat at constant pressure ($\text{J K}^{-1} \text{kg}^{-1}$)	W	work output of the system (J)
Ex	exergy output (J)	Q	heat (J)
H	stroke length (m)	S_{gen}	entropy generation (J K^{-1})
h	the Planck constant (Js)	x	the pressure ratio
k	the Boltzmann constant (J)	η_E	expansion efficiency
L_c	half of the most probable Broglie's wave length ($\text{s (Kg J K)}^{-1/2}$)	η_C	compression efficiency
P	pressure (Pa)	η	energy efficiency
N	the number of particles (mol)	maw	the dimensionless Maximum available work
R	diameter (m)	ecf	the dimensionless ecological function

ideal answer and Bellman–Zadeh. Lastly, analysis of error is employed to determine deviation of the outcomes gained from each plan.

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1. Introduction

Performance optimization of heat engines and machines was continuously an interesting subject for all engineers and experts working in the area of thermal sciences. Sadi Carnot was the first scholar who presented the most effective thermal engine which was totally reversible (externally and internally). The maximum possible thermal efficiency within two temperatures is given in this engine with no other engine more efficient than that. Finite-time thermodynamics (FTT) was introduced then as a solution for better performance analysis of thermodynamic cycles. Curzon and Ahlborn investigated a Carnot engine and proposed the Efficiency of a Carnot engine at maximum power-output [1]. Moreover, Novikov (CAN) [2] studied the atomic power stations and suggested the efficiency of aforementioned system. This engine is internally reversible (endoreversible), and externally irreversible.

After that, new methods for performance evaluations were presented. Angulo-Brown [3] presented the ecological function (ECF) and Yan [4] improved it. This criterion is described as $ECF = W - T_o S_{gen}$ where W is defined as the work output, T_o stands for an environment temperature and S_{gen} represents entropy generation. There are a number of ecological functions based on the papers in the open literature [5–19] which consider the ecological functions for optimization procedure. For instance, $EPC = \frac{Ex}{T_o S_{gen}}$ where Ex stands for an exergy output of the system or $ECOP = \frac{W}{T_o S_{gen}}$ where W stands for the power output and S_{gen} denotes entropy generation. Chen and colleagues [5] performed optimization for generalized irreversible universal heat-engine cycles based on power, efficiency, entropy generation rate and ecological function. Also, with finite time thermodynamics, the performance analysis of the system consisting of two cooling branches, two heating branches and two adiabatic branches with losses of heat resistance, heat leak and internal irreversibility was done to present an improvement in the analysis of real heat engines. Chen et al. [6] considered a generalized irreversible heat engine with losses

due to heat resistance, leakage and internal irreversibility and optimized the engine employing an ecological objective function which takes into account the power and entropy production rate of the heat engine. Also, the effects of heat leakage and irreversibility were examined. Huang et al. [7] optimized an irreversible four-temperature-level absorption heat pump with considering losses of heat resistance and internal irreversibility. An ecological function consisting of heating load, coefficient of performance and entropy production rate was considered for optimization in study conducted by Huang et al. [7]. The optimization procedure led to a decrease in entropy production rate in cycle and an appropriate decrease in heating load. Yan and Lin [8] proposed an irreversible three-heat-source refrigerator and optimized the cycle with a compromise between cooling rate and entropy production rate. An ecological criterion was written as $E = R - \lambda T_o \sigma$ where R stands for the cooling rate of the refrigerator and σ represents the rate of entropy generation and λ denotes the dissipation coefficient of the cooling rate which was proved to be equal with coefficient of performance. Cheng and colleagues evolved a thermo-ecological approach for performance analysis of an irreversible Carnot heat-engine and optimized the performance of the aforementioned engine [9]. Xia and colleagues [10] investigated a universal ecological performance for endoreversible heat engine cycles. Zhang and colleagues [11] have explicated the exergy-based ecological optimum performance for a universal endoreversible thermodynamic cycle. Chen et al. [12] presented an exergy-based ecological function for a generalized irreversible Carnot-engine with heat resistance, heat leakage and internal irreversibility and optimized the engine based on a compromise between the power output and entropy-production rate of engine and an assumption of linear phenomenological heat transfer law. Zhu et al. [13] performed an optimization of ecological objective function for a generalized irreversible Carnot engine with considering losses of heat resistance, heat leakage and internal irreversibility. In their study, generalized heat transfer laws were assumed to be as $Q \propto (\Delta T)^n$. Moreover, Zhu et al. [14] performed an

exergy based optimization with ecological objective function as $E = P - T_o\sigma$ which consists of exergy-output rate and exergy-loss rate of a heat pump. Ecological coefficient of performance (*ECOP*) and exergetic performance coefficient are other criteria that were submitted by Ust et al. [20–26]. Ust et al. [20] presented a new thermo-ecological criterion based on coefficient of performance (*ECOP*) which is defined as the ratio of power output to the loss rate of availability. Results showed that optimized *ECOP* has advantage in terms of entropy-generation rate and thermal efficiency and fewer disadvantages on work output compared to objective functions in the literature. Furthermore, Ust et al. [21] applied their new thermo-ecological criterion on an irreversible refrigerator for optimizing the performance of the engine. It was defined as the ratio of the cooling load to the loss rate of availability (entropy generation) as $ECOP = \frac{\dot{Q}_L}{T_o\dot{\sigma}}$. They [22] also considered an irreversible regenerative-Brayton heat engine and optimized the cycle by employing ecological function defined as $\dot{E} = \dot{W} - T_o\dot{S}_g$ and $ECOP = \frac{\dot{W}}{T_o\dot{S}_{gen}}$. The results show that the optimization criterion is advantageous in terms of higher thermalefficiency and lower entropy-generation rate and lower investment cost but is disadvantageous in terms of power output compared to \dot{E}_{max} and \dot{W}_{max} . Sogut et al. [23] performed an analysis on irreversible closed Brayton heat engines with variable temperature of heat reservoirs. The effects of intercooling and regeneration were investigated on the mentioned engine with considering *ECOP*, \dot{E}_{max} and \dot{W}_{max} . Results show that the optical total isentropic temperature ratio and intercooling isentropic temperature ratio at $ECOP_{max}$ are less compared to \dot{E}_{max} and \dot{W}_{max} which contributes to cost savings. Ust et al. [24] investigated the effect of regeneration on irreversible air refrigerators having finite-rate heat transfer, heat leakage and internal irreversibilities based on thermo-ecological criteria including *ECOP*, η_{ex} and *COP*. Results show that optimal thermodynamic conditions are the same for all criteria, but *ECOP* gives information on entropy generation which includes loss rate of availability. Ust [25] optimized the air refrigeration cycles based on ecological coefficient of performance (*ECOP*). The cycle includes irreversibilities of finite-rate heat transfer, heat leakage and internal dissipations. The results show that the optimal conditions for *ECOP* and *COP* were the same. However, *COP* gives information about power needed for cooling load and *ECOP* gives information on entropy generation rate including loss rate of availability which is a great tool for evaluating the system. Açıkkalp and Yamık [26] presented criteria called maximum available work which is defined as $MAW = Q_H \left(1 - \frac{T_o}{T_H}\right) - T_oS_{gen}$. The FTT performance of the Brayton cycle [27–32] and the Ericsson cycle [33–35] were investigated for the power density, power output and the thermal efficiency.

Besides, nanotechnology has gained great attention during last decade and in the recent years this is entered through thermodynamic cycles. As a result, it can be said that nano-scale thermal cycles may be of great importance in near future. Because of this, quantum thermodynamics will gain attention in near future. In the open literature, there are studies about nano-scale thermodynamics or thermal cycles which use quantum gases [36–41]. Wu and colleagues [36] demonstrated

Quantum degeneracy effect on performance of irreversible Otto cycle with ideal Bose gas. Wang and colleagues [37] studied the Performance features of a quantum Diesel refrigeration cycle. Saygin and Şişman [38] applied an analysis on Brayton refrigeration cycles working under quantum degeneracy circumstances. He and colleagues [39] investigated the effect of quantum degeneracy on the performance of a Stirling refrigerator working with an ideal Fermi gas. Yang and colleagues [40] investigated the effect of regeneration on the performance of a Brayton refrigeration-cycle working with an ideal Bose-gas. Lin and colleagues [41] studied the effect of regeneration and quantum degeneracy on the performance of Bose–Stirling refrigeration-cycles operated in various temperature areas. Lucia [42–45] presented papers on entropy generation and quantum mechanics. Later 1993, by considering these last physical thoughts, a fully novel method to complicated systems is evolved [42,43]; the purpose was to gain a model associated with the natural behavior of complicated systems on the basis of the entropy owing to irreversibility, typically called entropy generation. Lucia [44] assessed k-exponential approach and Maximum entropy generation.

Some papers are published about power cycles, but there are a few papers on power cycles working with Maxwell–Boltzmann gas [46–49]. Lin and colleagues [46] studied finite time thermodynamic analysis for performance of Dual cycle. Wang and colleagues [47] studied the influences of friction on the performance of an air stand Dual cycle. Chen and colleagues [48] reflected the influence of variable specific heats of the working fluid on the cycle process and investigated the performance feature of irreversible Dual cycle when variable specific heats of working fluid are linear functions of its temperature and the maximum temperature of the cycle is not fixed. Ge and colleagues [49] evolved finite time thermodynamic approach for an irreversible Dual cycle.

Multi-objective optimization is a great asset for solving engineering problems [50–52]. Özyer and colleagues [50] evolved an intellectual model for prospect calculation by using of evolutionary algorithms. The multi-objective optimization is performed by various engineering issues such as vehicle routing problems with Time Windows [51]. Blečić and colleagues [52] illustrated a decision support system called Bay MODE on the basis of multi-objective optimization and Bayesian analysis.

Solving a multi-objective problem for the best performance is a hard task because it needs simultaneous satisfaction of various and occasionally conflicting objective functions. For solving such problems, various approaches including evolutionary algorithms (EA) were introduced in 20th century to help some multi-objective issues [53]. The aim of a multi-objective issue was to gain a category of answers, and each answer fulfills the objective functions at a relatively importance manner [54]. The result will be a series of solutions called Pareto frontier which shows feasible solutions throughout the objective area. Multi-objective optimization approach has been widely employed in energy systems engineering exponentially [55–84]. Ahmadi et al [55–57] developed an intelligent approach to figure power of solar Stirling heat engine by implementation of evolutionary algorithms. Ahmadi et al. [59] applied non-dominated sorting genetic algorithm for thermo-economic optimization of Stirling heat pump. Environmental emissions are included and performance indicators

evolved, providing valuable information about performance and possible improvements. Energy-system designs can be optimized by employing separate objectives linking to economics, energy and the environment [60].

Sayyaadi et al. [68] applied non-dominated sorting genetic algorithm for optimal design of a Solar-Driven Heat Engine.

In this work, three optimization scenarios are defined for the nano scale irreversible Braysson cycle. In the first scenario, in order to maximize the ecological coefficient of performance and energy efficiency of the system, a multi-objective optimization algorithm has been employed. Error analysis is performed to evaluate the precision of ultimate answers of various decision making methods.

In the second scenario, two objective functions comprising the dimensionless Maximum available work and the ecological coefficient of performance are maximized concurrently via employing multi-objective optimization algorithms.

In the third scenario, three objective functions including the dimensionless Maximum available work, the ecological coefficient of performance and energy efficiency of the system have been maximized simultaneously by employing multi-objective optimization algorithms. For making decision between Pareto frontiers (solutions) three fast and robust decision making methods are implemented comprising LINMAP, TOPSIS and Fuzzy techniques. Besides, an error analysis is done to specify the accuracy of these methods. More details of these approaches are explicated in the following sections.

2. Thermodynamic analysis

T - S diagram of the Braysson heat engine we consider can be seen in Fig. 1. It operates between infinite heat source and heat sink with temperatures T_H and T_L respectively. There are external irreversibilities in the cycle because of heat transfer at finite temperature difference. In addition, it has internal

irreversibilities that are represented by using isentropic efficiencies at the compressor and turbine. In the beginning, working fluid enters the compressor at point one and it is compressed to state point 2S point for ideal cycle or to state point 2 for the irreversible cycle. After the compression process, working fluid is given heat at constant pressure by contacting it with heat source and its reaches to state point 3 and then it is sent to turbine to be expanded. At the end of the expansion process, working fluid is expanded to state point 3S for ideal cycle and to state point 3 for irreversible cycle. Finally, heat is removed from the working fluid at constant temperature by contacting it with low temperature heat sink and cycle is completed, when working fluid reaches to state point 1 [85].

In this part, the thermodynamic analysis of a nano scale Braysson cycle is carried out. In the thermodynamic analysis, a nano scale cylinder is presumed. Its diameters are R and stroke length is represented by H as nanometer. Temperature—entropy diagram is depicted in Fig. 1. Subscript s denotes ideal conditions. Specific heats at constant volume and constant pressure (J/K) for ideal Maxwell–Boltzmann gas can be determined as follows [86–88]:

$$c_v = \frac{3}{2}Nk + Nk \frac{L_c(T)}{2\sqrt{\pi}} \left(\frac{1}{R} + \frac{1}{H} \right) \quad (1)$$

$$c_v = \frac{3}{2}Nk + Nk \frac{h}{8\sqrt{2m\pi kT}} \left(\frac{1}{R} + \frac{1}{H} \right) \quad (1a)$$

$$c_p = \frac{5}{2}Nk + Nk \frac{L_c(T)}{2\sqrt{\pi}} \left(\frac{1}{R} + \frac{1}{H} \right) \quad (2)$$

$$c_p = \frac{5}{2}Nk + Nk \frac{h}{8\sqrt{2m\pi kT}} \left(\frac{1}{R} + \frac{1}{H} \right) \quad (2a)$$

in which N stands for the number of particles, L_c denotes half of the most probable Broglie's wave length, h represents the

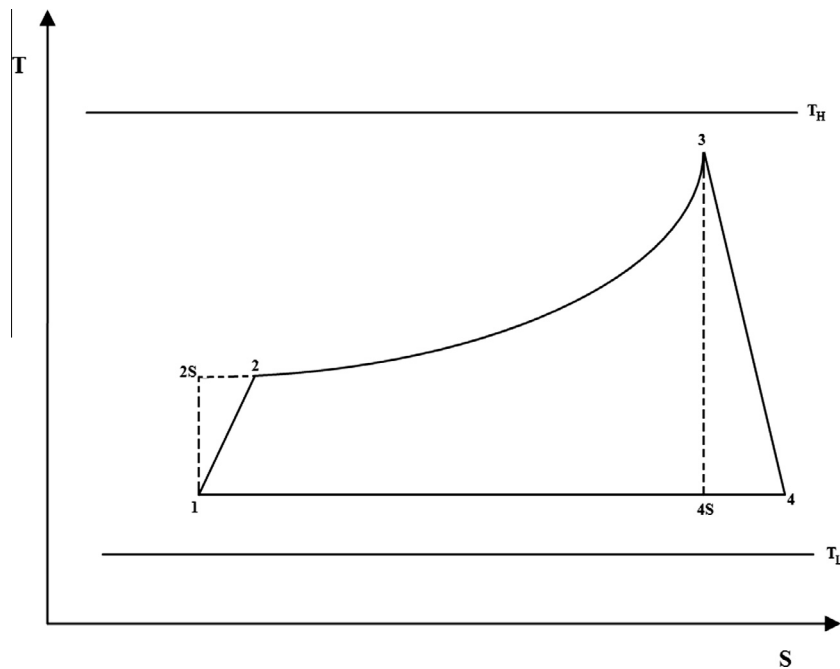


Figure 1 T - S diagram of an irreversible Braysson cycle model.

Planck constant and k stands for the Boltzmann constant. Heat addition (J) to the system can be calculated as follows [86–88]:

$$Q_H = \int_2^3 c_p dT \quad (3)$$

Heat rejection (J) from the system [88]:

$$Q_L = - \int_4^1 PdV = NkT_1 Ln \left(\frac{V_4}{V_1} \right) \quad (4)$$

Half of the most probable Broglie's wave length at temperature T can be determined as following as [66]:

$$L_c(T) = \frac{h}{\sqrt{8mkT}} \quad (5)$$

in which m represents the atomic mass of the gas. Work output of the system (J) calculated as follows:

$$W = Q_H - Q_L \quad (6)$$

Entropy generation (J/K) of the system can be described as follows:

$$S_{gen} = \frac{Q_L}{T_1} - \frac{Q_H}{T_3} \quad (7)$$

Energy efficiency of the system:

$$\eta = \frac{W}{Q_H} \quad (8)$$

Exergy output (J) is described as follows:

$$Ex = Q_H \left(1 - \frac{T_o}{T_3} \right) \quad (9)$$

where T_o is environment temperature. While pressure ratio of the Braysson cycle (x), temperature equation for this cycle is ($T_{2s} = T_1 x^{0.4}$). Irreversibility in the Braysson cycle can be defined by using compression efficiency. Efficiency of the compression process is as follows:

$$\eta_c = \frac{T_{2s} - T_1}{T_2 - T_1} \quad (10)$$

Employing this equation T_2 is specified as follows:

$$T_2 = \frac{(T_{2s} - T_1) + \eta_c T_1}{\eta_c} \quad (11)$$

Isobaric temperature ratio is described as follows:

$$z = \frac{T_3}{T_2} \quad (12)$$

Ecological function (J) is determined via following formula:

$$ECF = W - T_o S_{gen} \quad (13)$$

Ecological coefficient of performance is calculated as follows:

$$ECOP = \frac{W}{T_o S_{gen}} \quad (14)$$

Exergetic performance criteria are determined by below equation:

$$EPC = \frac{Ex}{T_o S_{gen}} \quad (15)$$

Maximum available work (J) is calculated as follows:

$$MAW = Ex - T_o S_{gen} \quad (16)$$

In this paper, dimensionless work output, ECF , MAW and entropy generation are introduced as follows:

$$w = \frac{W}{NkT_3} \quad (17)$$

$$ecf = \frac{ECF}{NkT_3} \quad (18)$$

$$maw = \frac{MAW}{NkT_3} \quad (19)$$

$$S_{gen}^* = \frac{S_{gen}}{Nk} \quad (20)$$

3. Multi-objective optimization

The multi-objective optimization approach evolved from evolutionary procedure is utilized to optimize Stirling heat pump system to specify the prior variables of system design. To assess this, Genetic algorithms (GA) perform stochastic and iterative search process to determine optimum solution and follow in a simplified behavior principle of biological evolution. The general concept of Genetic algorithms is depicted in Fig. 2 [53–59].

3.1. Objective functions, decision variables and constraints

The energy efficiency of the system (η) and the ecological coefficient of performance ($ECOP$) two objective functions for the first scenario, are evaluated via Eqs. (8) and (14).

The ecological coefficient of performance ($ECOP$) and the dimensionless Maximum available work (maw) two objective

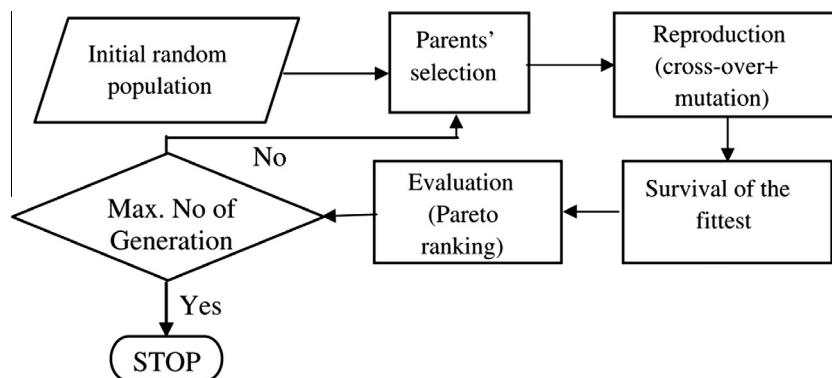


Figure 2 Scheme for the multi-objective evolutionary algorithm used in the present study [53–59].

functions for the second scenario, are evaluated via Eqs. (14) and (19).

The ecological coefficient of performance (*ECOP*), the dimensionless Maximum available work (*maw*) and energy efficiency of the system (η) three objective functions for the third scenario, are evaluated via Eqs. (8), (14) and (19).

Four decision variables have been chosen in our study as follows:

- η_c : compression efficiency
- x : the pressure ratio
- T_1 : Temperature of state point 1
- z : Isobaric temperature ratio

Even though the decision variables would be different in the optimization process, each should be in a proper interval. By assuming the following limits the objective functions are unraveled:

$$0.85 \leq \eta_c \leq 0.95 \quad (21)$$

$$2 \leq x \leq 6 \quad (22)$$

$$300 \leq T_1 \leq 350 \text{ K} \quad (23)$$

$$1.3 \leq z \leq 1.6 \quad (24)$$

3.2. Decision-making during the multi-objective optimization progress

Decision-making for gathering of the best answer from available answers via the multi-objective optimization method has a central role. There are a number of approaches for decision-making in the decision problems. These approaches could be employed for picking the improved optimum solution from the Pareto frontier.

3.2.1. Non-dimensionalization methods

3.2.1.1. Euclidean non-dimensionalization. F_{ij}^n stands for the matrix of objectives for various solutions of the Pareto frontier where i stands for the index of each solution on the Pareto frontier, and j represents the index of the objective in objective region. In this method, a non-dimensioned objective, F_{ij}^n , formulated as follows,

$$F_{ij}^n = \frac{F_{ij}}{\sqrt{\sum_{i=1}^m (F_{ij})^2}} \quad \text{for minimization and maximization goals} \quad (25)$$

3.2.1.2. Fuzzy non-dimensionalization. In this method, a non-dimensioned objective, F_{ij}^n , is calculated as follows,

$$F_{ij}^n = \frac{F_{ij} - \min(F_{ij})}{\max(F_{ij}) - \min(F_{ij})} \quad \text{for maximization objectives} \quad (26a)$$

$$F_{ij}^n = \frac{\max(F_{ij}) - F_{ij}}{\max(F_{ij}) - \min(F_{ij})} \quad \text{for minimization objectives} \quad (26b)$$

In this research the most well-known and standard type of decision-making methods such as the TOPSIS, LINMAP and fuzzy Bellman–Zadeh approaches is utilized concurrently while to obtain the optimum answer, the three aforesaid approaches are employed. The Bellman–Zadeh method carries out the

fuzzy non-dimensionalization whereas the two rest methods employ Euclidean non-dimensionalization. The further parts described these decision-making procedures.

3.3. Decision making methods

3.3.1. Bellman–Zadeh decision-making method

In the Bellman and Zadeh approach, the intersection of all fuzzy criteria and limits is defined as the final decision and meanwhile it is introduced via its relevant membership function. A matrix of membership function was introduced while the column of the addressed matrix contains the objective fuzzy membership function. The membership matrix rows represent values of the membership functions for gained route from the Pareto frontier. Detail for method of definition for the membership function is described in Refs. [55,56,66–70].

3.3.2. LINMAP decision-making approach

In the LINMAP method a definition called “ideal point” should be defined. Ideal point is introduced as the point on the Pareto frontier that each objective is optimized irrespective of the considering other objectives. A solution with a lowest distance in space from an ideal data point is chosen as a prior optimal answer. To gain more description about the LINMAP approach please refer to the following Refs. [55,56,66–70].

3.3.3. TOPSIS decision-making approach

In this method, furthermore a “non-ideal point” is also introduced. The non-ideal data point is defined as the latitude in the objective spatial that each objective includes its worst magnitude. Thus, another criterion for final solution selection is referred to distance in space from the non-ideal however; the distance in space from the ideal solution is also considered as another criteria. Final answer in the TOPSIS approach is selected based on the highest gap from the non-ideal point and lowest gap from the ideal point simultaneously. More description regarding this method can be found in refs [55,56,66–70].

4. Results and discussion

The sensitivity of the objective functions to the decision variables was examined. As illustrated in Fig. 3a, the ecological coefficient of performance of the system decreased considerably with increasing the compression efficiency (η_c) at various values of the temperature of state point 1 (T_1). As illustrated in Fig. 3b, the dimensionless Maximum available work (*maw*) decreased considerably with increasing the compression efficiency (η_c) at various values of the temperature of state point 1 (T_1). As shown in Fig. 3c, the energy efficiency decreases with the increase in the compression efficiency (η_c) at various values of the temperature of state point 1 (T_1).

As depicted in Fig. 4a, the ecological coefficient of performance of the system decreased significantly with increasing the compression efficiency (η_c) at various values of the isobaric temperature ratio (z). As illustrated in Fig. 4b, the dimensionless Maximum available work (*maw*) decreased considerably with increasing the compression efficiency (η_c) at various values of the isobaric temperature ratio (z). As shown in

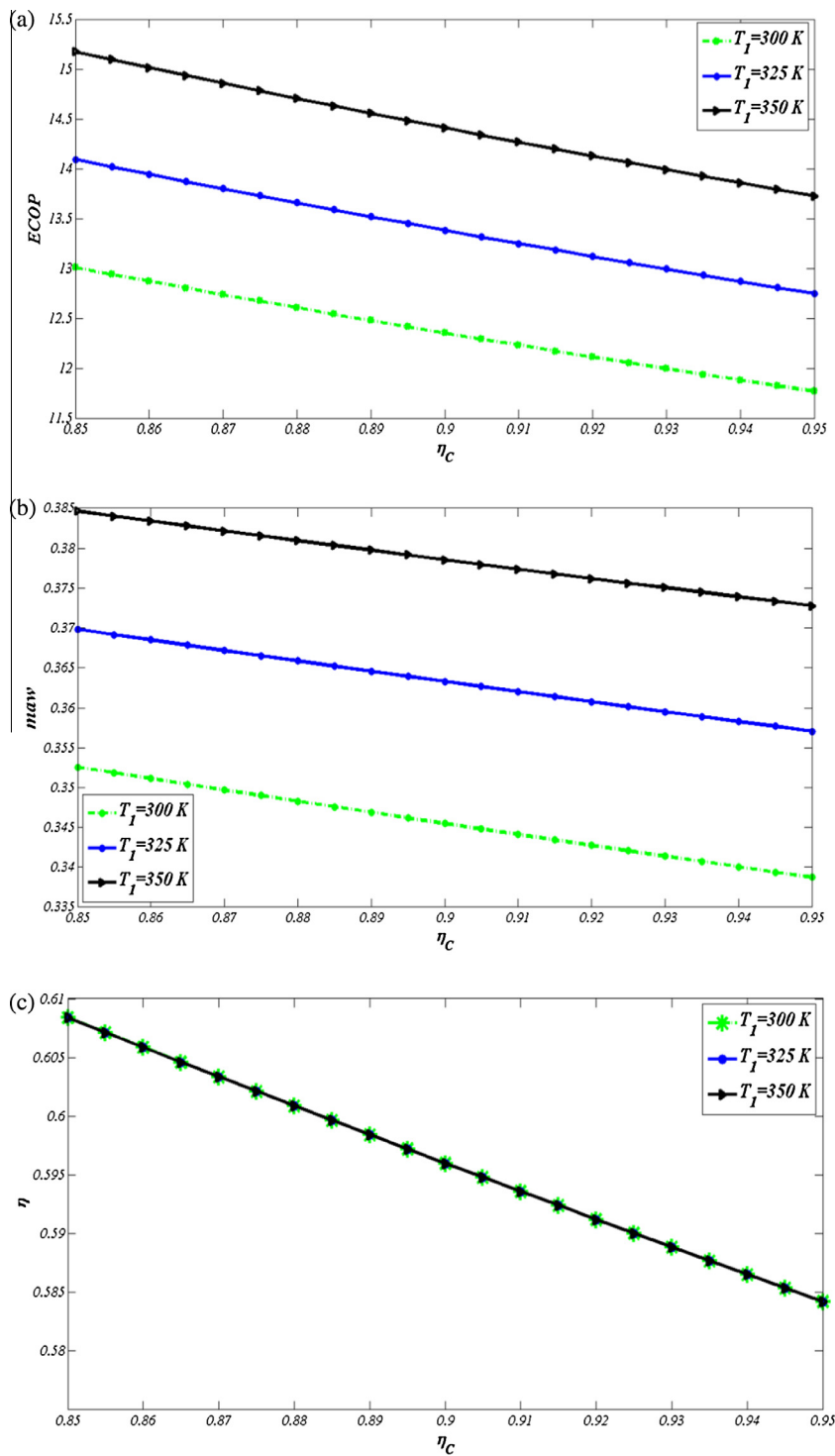


Figure 3 Effects of the compression efficiency (η_c) and the temperature of state point 1 (T_1) on (a) the ecological coefficient of performance, (b) dimensionless Maximum available work, and (c) energy efficiency in $x = 6$, $z = 1.3$.

Fig. 4c, the energy efficiency decreases with the increase in the compression efficiency (η_c) at various values of the isobaric temperature ratio (z).

As depicted in Fig. 5a, the ecological coefficient of performance of the system decreased significantly with increasing the compression efficiency (η_c) at various values of the

pressure ratio (x). As illustrated in Fig. 5b, the dimensionless Maximum available work (maw) decreased considerably with increasing the compression efficiency (η_c) at various values of the pressure ratio (x). As shown in Fig. 5c, the energy efficiency decreases with the increase in the compression efficiency (η_c) at various values of the pressure ratio (x).

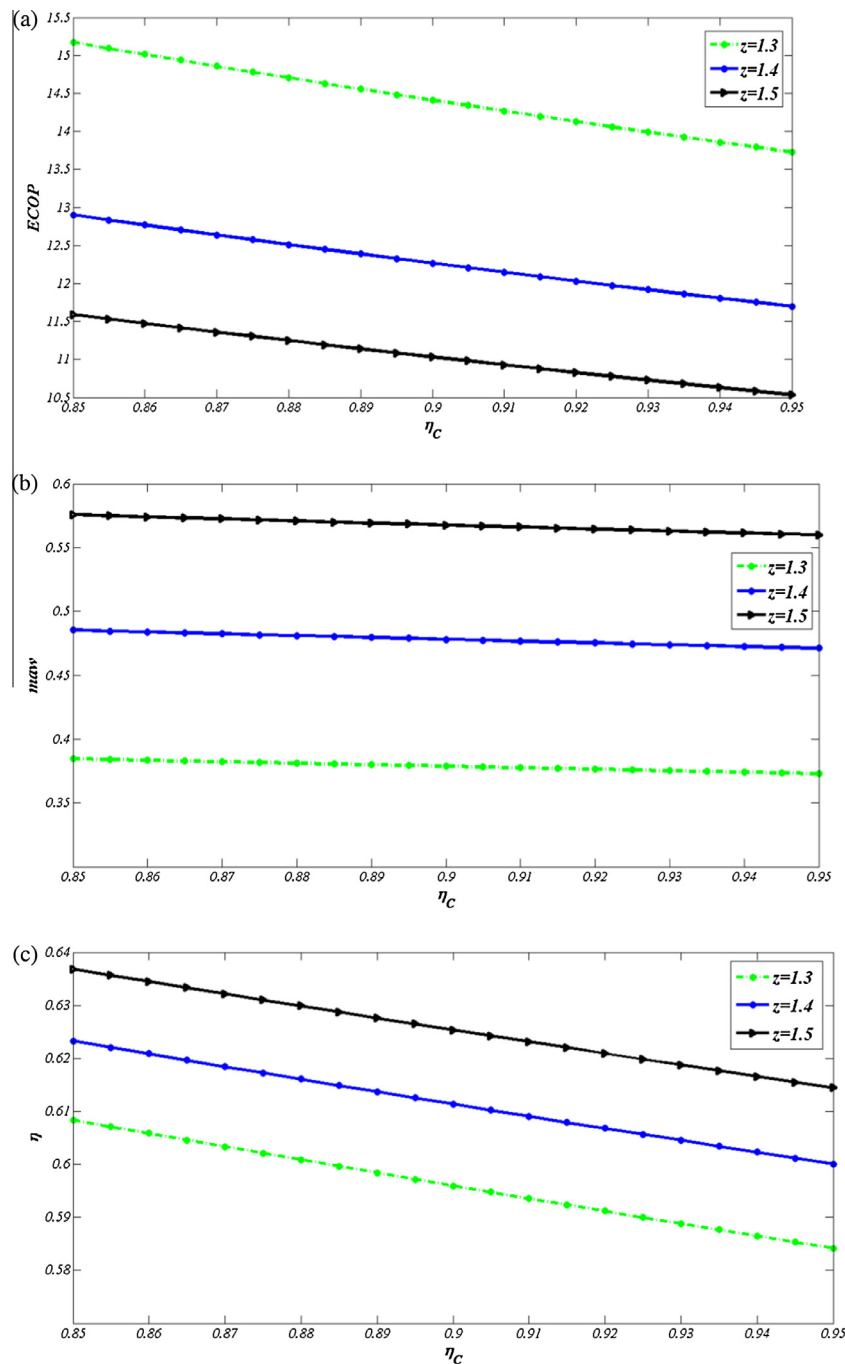


Figure 4 Effects of the compression efficiency (η_c) and the isobaric temperature ratio (z) on (a) the ecological coefficient of performance, (b) dimensionless Maximum available work, and (c) energy efficiency in $T_1 = 350$ K, $x = 6$.

4.1. Results of first scenario

Using multi-objective optimization on the basis of the NSGA-II method, the energy efficiency of the system (η) and the ecological coefficient of performance ($ECOP$) are maximized at the same time. The objective functions in the performed optimization, and the limitations that have been used, are identified by Eqs. (8) and (14) and (21)–(24) respectively. The compression efficiency, the isobaric temperature ratio, temperature of state point 1 and the pressure ratio are assumed as

design parameters throughout the optimization process. Due to agreement with appreciated literatures, following characteristics of the nano scale irreversible Braysson cycle system are presumed as below [87,88]:

$$R = 10^{-8} \text{ (m)}, H = 3 \times 10^{-8} \text{ (m)}, k = 1.0381 \times 10^{-23} \text{ (J)}, \\ h = 6.6262 \times 10^{-34} \text{ (Js)}, m = 6.6474 \times 10^{-27} \text{ (kg)}, T_o = 298 \text{ (K)}$$

Pareto optimal frontier for two objective functions, objective function associated with the energy efficiency of the system

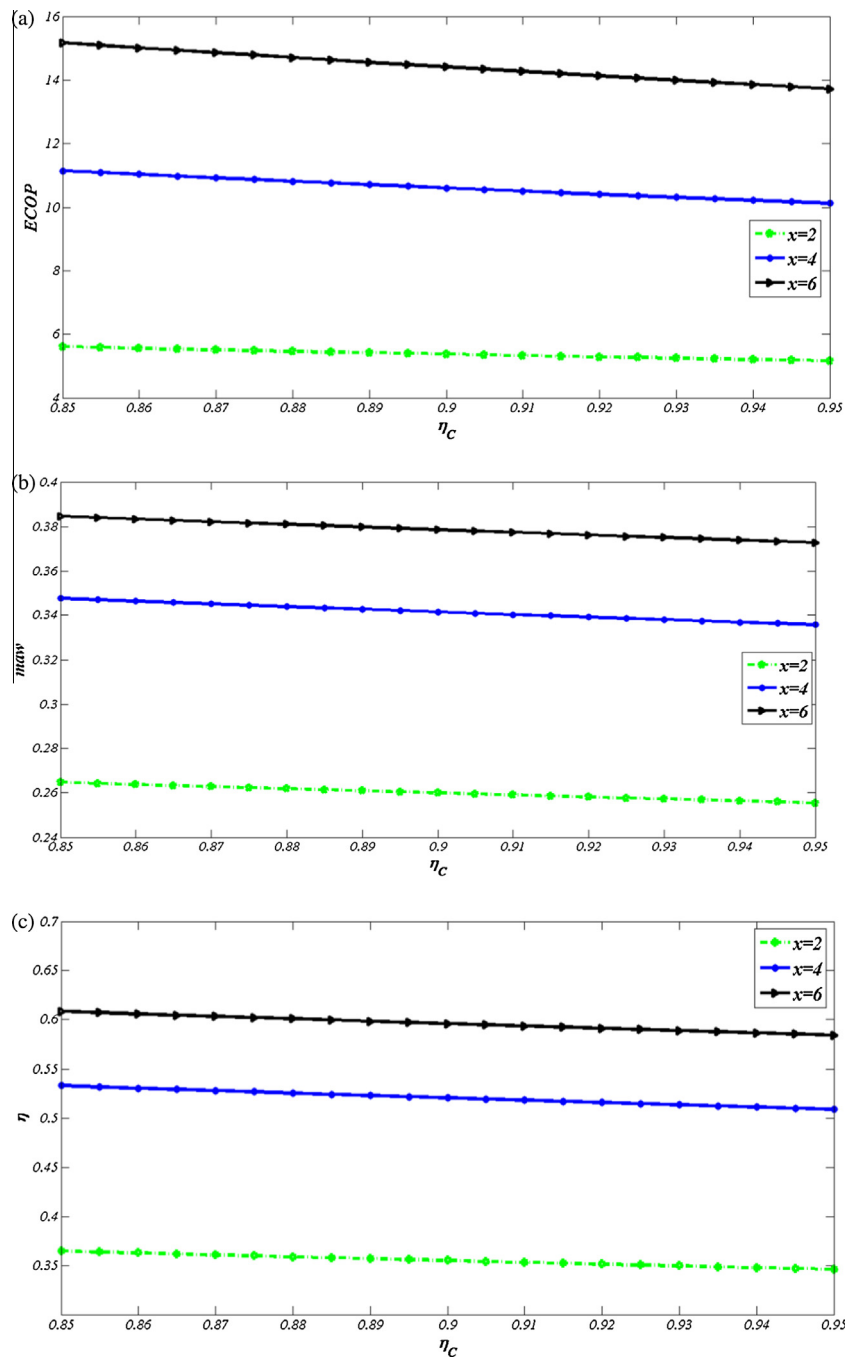


Figure 5 Effects of the compression efficiency (η_c) and the pressure ratio (x) on (a) the ecological coefficient of performance, (b) dimensionless Maximum available work, and (c) energy efficiency in $T_1 = 350$ K, $z = 1.3$.

(η) and the dimensionless Maximum available work (maw) of the nano scale irreversible Braysson cycle is represented in Fig. 6. The chosen points based on decision making methods are shown, too (See Tables 1 and 2).

4.2. Results of second scenario

Two strategic objective functions are considered for optimization which contain the ecological coefficient of performance and the dimensionless Maximum available work

(should be maximized) formulated via Eqs. (14) and (19), correspondingly.

Optimization is accomplished with objective functions which are illustrated by Eqs. (14) and (19) limitations which are formulated with Eqs. (21)–(24).

With the purpose of having uniformity with previous researches, characteristics of the nano scale irreversible Braysson cycle are reported as following as [87,88]

$$R = 10^{-8} \text{ (m)}, H = 3 \times 10^{-8} \text{ (m)}, k = 1.0381 \times 10^{-23} \text{ (J)},$$

$$h = 6.6262 \times 10^{-34} \text{ (Js)}, m = 6.6474 \times 10^{-27} \text{ (kg)}, T_o = 298 \text{ (K)}$$

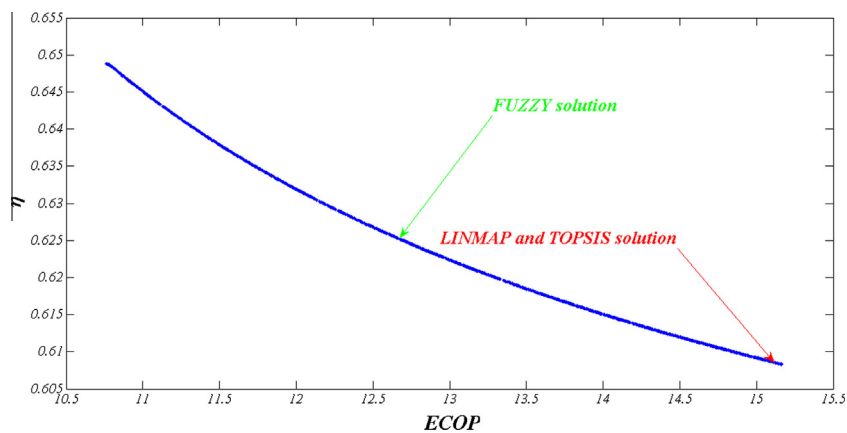


Figure 6 Pareto optimal frontier in the objectives' space for first scenario.

Table 1 Decision making of multi-objective optimal solutions for first scenario.

Decision making method	Decision variables				Objectives	
	η_C	z	x	T_1 (K)	$ECOP$	η
TOPSIS	0.850	1.300	6.000	349.812	15.161	0.608
LINMAP	0.850	1.300	6.000	349.812	15.161	0.608
Fuzzy	0.850	1.4158	6.000	349.822	12.638	0.625

Table 2 Error analysis based on the mean absolute percent error (MAPE) method for first scenario.

Decision making method	TOPSIS		LINMAP		Fuzzy	
	$ECOP$	η	$ECOP$	η	$ECOP$	η
Max error %	0.841	0.010	0.925	0.025	0.942	0.046
Average error %	0.599	0.007	0.654	0.014	0.645	0.022

Fig. 7 illustrates the Pareto frontier in the proposed objectives' space obtained in the optimization scenario. Three final solutions were selected by the Fuzzy Bellman-Zadeh, LINMAP and TOPSIS decision-making methods which are

indicated in this figure. According to Fig. 7, the obtained points by LINMAP and TOPSIS are approached toward each other. Also, it was shown that the optimal value of the dimensionless Maximum available work varied from 0.385 to 0.657 and the optimal value of the ecological coefficient of performance was between 10.760 and 15.170 (See Tables 3 and 4).

Table 3 Decision making of multi-objective optimal solutions for second scenario.

Decision making method	Decision variables				Objectives	
	η_C	z	x	T_1 (K)	maw	$ECOP$
TOPSIS	0.850	1.600	6.000	349.870	0.657	10.756
LINMAP	0.850	1.589	6.000	349.900	0.648	10.835
Fuzzy	0.850	1.416	6.000	349.875	0.500	12.630

Table 4 Error analysis based on the MAPE method for second scenario.

Decision making method	TOPSIS		LINMAP		Fuzzy	
	maw	$ECOP$	maw	$ECOP$	maw	$ECOP$
Max Error %	0.14	0.213	0.147	0.264	0.114	0.217
Average Error %	0.075	0.142	0.066	0.167	0.047	0.136

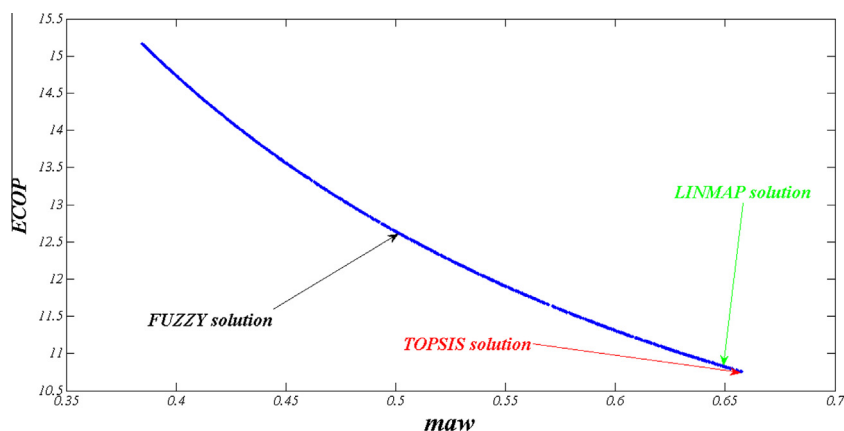


Figure 7 Pareto optimal frontier in the objectives' space for second scenario.

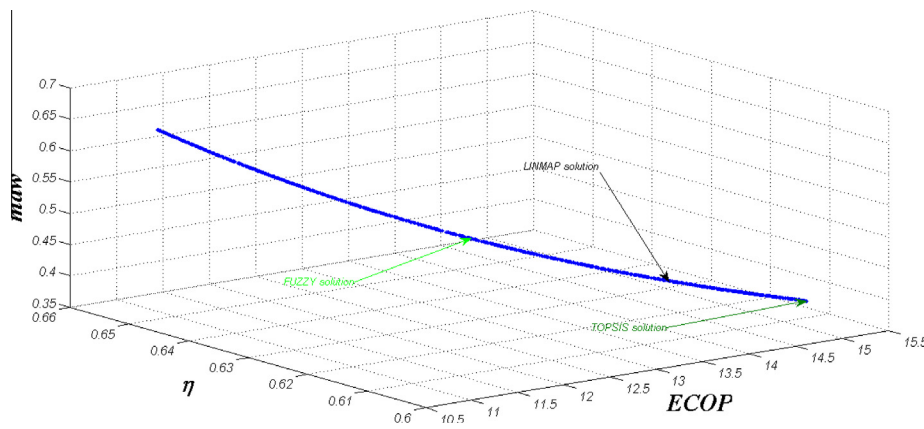


Figure 8 Pareto optimal frontier in the objectives' space for third scenario.

Table 5 Decision making of multi-objective optimal solutions for third scenario.

Decision making method	Decision variables				Objectives		
	η_c	z	x	T_1 (K)	$ECOP$	η	maw
TOPSIS	0.851	1.300	6.000	349.965	15.138	0.608	0.385
LINMAP	0.851	1.341	6.000	349.985	14.051	0.614	0.427
Fuzzy	0.851	1.417	6.000	349.974	12.614	0.625	0.500

Table 6 Error analysis based on the MAPE method for third scenario.

Decision making method	TOPSIS			LINMAP			Fuzzy		
	$ECOP$	η	maw	$ECOP$	η	maw	$ECOP$	η	maw
Max error %	0.618	0.043	0.363	0.403	0.054	0.644	0.668	0.053	0.244
Average error %	0.220	0.036	0.169	0.191	0.027	0.312	0.220	0.048	0.108

4.3. Results of third scenario

Three strategic objective functions are considered for optimization which contain the ecological coefficient of performance, the dimensionless Maximum available work and energy efficiency of the system (η) (should be maximized) formulated via Eqs. (8), (14), and (19), correspondingly.

By the way, optimization is accomplished with objective functions which are illustrated by Eqs. (8), (14), and (19) limitations which are formulated with Eqs. (21)–(24).

With the intention of having uniformity with preceding publications, qualifications of the nano scale irreversible Braysson cycle are comprised as following as [87,88]

$$R = 10^{-8} \text{ (m)}, H = 3 \times 10^{-8} \text{ (m)}, k = 1.0381 \times 10^{-23} \text{ (J)},$$

$$h = 6.6262 \times 10^{-34} \text{ (Js)}, m = 6.6474 \times 10^{-27} \text{ (kg)}, T_o = 298 \text{ (K)}$$

Fig. 8 illustrates the Pareto frontier in the proposed objectives' space obtained in the optimization scenario. Three final solutions were selected by the Fuzzy Bellman–Zadeh, LINMAP and TOPSIS decision-making methods which are indicated in this figure. Also, it was shown that the optimal

value of the dimensionless Maximum available work varied from 0.385 to 0.657 and the optimal value of the ecological coefficient of performance was between 10.748 and 15.140. Also, the optimal value of energy efficiency of system varied from 0.608 to 0.649 (see Tables 5 and 6).

5. Conclusions

Throughout this research the thermodynamic analysis is performed on the nano scale irreversible Braysson cycle. Further effects of the compression efficiency, the isobaric temperature ratio, the pressure ratio and T_1 are included in evaluation of the dimensionless Maximum available work, the ecological coefficient of performance and the energy efficiency of the nano scale irreversible Braysson cycle by employing thermodynamic analysis. Moreover, the optimum setups of the above-mentioned objective functions containing the dimensionless Maximum available work, the ecological coefficient of performance and the energy efficiency for the nano scale irreversible Braysson cycle are quantified.

In the multi-objective optimization approach, four discrete parameters, compression efficiency, the isobaric temperature ratio, the pressure ratio and temperature of state point 1, are assumed as the decision parameters. To designate an ultimate answer from the results gained by multi-objective optimization approach, three famous decision making methods are utilized and final answers are contrasted based on the error analysis.

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