

ENC-2020-0296
EXERGOECONOMIC ANALYSIS OF A CHILLED WATER SYSTEM IN A SHOPPING MALL

Renata Portela de Abreu

Victor Hugo Lobo Correia

Federal University of Paraíba, João Pessoa - PB, Brazil
re.portela96@gmail.com, victorloboc@gmail.com

Adriano da Silva Marques

Federal Rural University of Pernambuco, Cabo de Santo Agostinho – PE, Brazil.
adriano.marques@ufrpe.br

Monica Carvalho

Federal University of Paraíba, João Pessoa - PB, Brazil
monica@cear.ufpb.br

Abstract. *The use of air conditioning in large commercial buildings represents a considerable portion of electricity consumption in many countries, and the increase in refrigeration demands is deeply related to climate change. Meanwhile, there is growing awareness about reducing the environmental impact of energy systems, leading to searches for more efficient and eco-friendlier equipment. This work employs the SPECO method to perform an exergoeconomic analysis of the chilled water system in a shopping mall located in João Pessoa, Northeast Brazil. The analysis aims to identify improvement points for energy efficiency in the system, from an exergoeconomic perspective, considering all the costs involved in the productive process. Each control volume was analyzed in terms of the First and Second Law of Thermodynamics, followed by the exergoeconomic analysis. The results of the analyses conducted herein enabled the quantification of exergy streams and the irreversibility of each equipment. Exergoeconomic data and variables were calculated for each component. The thermodynamic analysis revealed that the equipment with the highest exergy destruction rate is the compressor. However, from an exergoeconomic perspective, the evaporator is the most important equipment, as it is second in the order of cost importance, and presents a high relative cost difference value. The exergoeconomic factor values of all equipment are very low, suggesting that the associated costs are almost exclusively due to exergy destruction. Essential considerations can be made from the thermodynamic analysis of an energy system, given that the main points of inefficiencies are highlighted. Nevertheless, it is indispensable to consider the economic factors related to possible changes and optimizations in the system, so that the results do not entail excessive expenses.*

Keywords: *Energy efficiency, SPECO method, thermoeconomics, refrigeration system.*

1. INTRODUCTION

The use of air conditioning in large commercial buildings represents a considerable portion of electricity consumption in many countries (LIN et al., 2014). According to the International Energy Agency – IEA (2018), the energy demand for space cooling is increasing faster than any other application in buildings, both in warmer emerging countries where revenues are rising and in developed economies with high consumer expectations for thermal comfort. Thereby, it is worrying that this demand, especially in warmer countries, can more than triple by 2050, considering economic and demographic growth (IEA, 2018).

This widespread increase in refrigeration demands is also profoundly related to climate change, creating a vicious cycle. The rising atmospheric temperatures caused by global warming increase the need for cooling, resulting in additional exploitation of natural resources to meet the increased electricity load, and causing environmental degradation, worsening climate change (IEA, 2018). Attention must be paid to this fact once the climate change represents a severe threat to the Earth, by causing irreversible damage to society and the environment (INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC, 2018; OWUSU; ASUMADU-SARKODIE, 2016).

There is growing awareness about the need to reduce the environmental impact of energy systems (CARVALHO; SERRA; LOZANO, 2011), which motivates searches for more efficient and eco-friendlier equipment. Zhang *et al.* (2020) affirmed that sustainable alternatives for refrigeration and air conditioning systems must be investigated, otherwise the

greenhouse gas (GHG) emissions will rise significantly. The refrigeration industry has been working to produce more efficient equipment, as these efforts are justified by economic, social, and environmental positive effects.

Thermoeconomics can play a vital role in the analysis and optimization of thermal systems as it associates Thermodynamic and Economic principles to understand how energy and resources degrade, identifying which systems operate better, to minimize the energy consumption of thermal systems, and avoid environmental damages by reducing waste disposal (VALERO *et al.*, 2001). Several thermoeconomic methodologies and approaches have been proposed to carry out these analyses, such as the Theory of Exergy Cost (LOZANO and VALERO, 1993) and the Specific Exergy Costing (SPECOC, LAZZARETTO and TSATSARONIS, 2006).

According to Lazzaretto and Tsatsaronis (2001), SPECOC is a methodology for the assessment of component efficiencies and costs involved with each matter or energy stream in thermal systems. SPECOC employs exergy as the only rational basis for allocating costs to the interactions between a component, group of components, or overall thermal system and its surroundings (LAZZARETTO and TSATSARONIS, 2001).

This work employs the SPECOC method to perform an exergoeconomic analysis of a chilled water system in a shopping mall located in João Pessoa, Northeast Brazil. The analysis aims to identify margins of improvement for energy efficiency, considering all the costs involved in the productive process.

2. METHODOLOGY

The chilled water system is responsible for cooling and storing water to serve the air conditioning system of the shopping mall. The study object consists of seven chillers, seven cooling towers, and one chilled-water storage tank. Additionally, there is a recirculation water pump for each chiller and a set of seven pumps to drive the cold water into the mall. Figure 1 depicts the chilled water system.

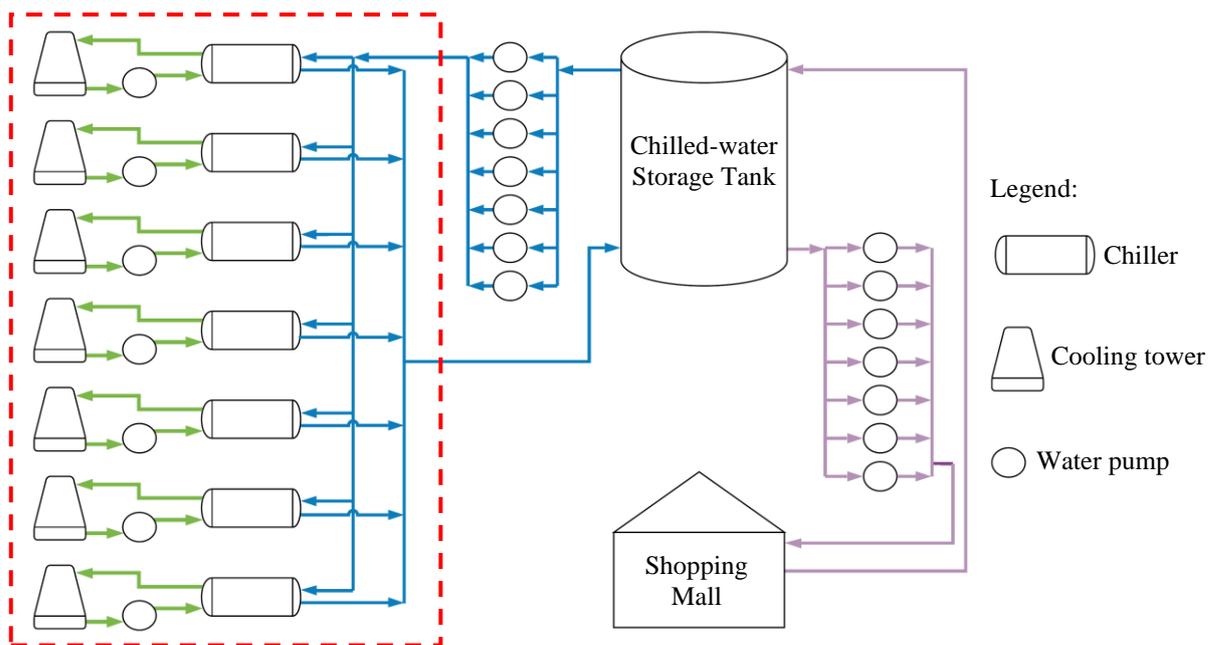


Figure 1. Refrigeration plant scheme.

Figure 1 shows that there are three water cycles: the primary (blue lines) corresponds to the water that leaves the tank at about 16°C, is cooled in the chillers, and then returns at approximately 7.5°C; the secondary cycle (purple lines) refers to the water that supplies the mall's air conditioning system; and the condensing circuit (green lines), which corresponds to the water that exchanges heat with the refrigerant in the condenser. The chillers are turned on at night (approximately from 10 pm to 7 am), wherefore in the morning, there is chilled water in the storage tank. During the day, when the mall is open, the chilled water is pumped to the mall's air conditioning system.

Figure 2 depicts the study object and its internal streams. Streams of refrigerant (in red), chilled water (in blue), condensing water (in green), air (in purple), and recovery water (in orange) are enumerated from 1 to 12. \dot{W}_{COMP} , \dot{W}_{TOWER} and \dot{W}_{PUMP} represent the power for the compressor, cooling tower, and pump, respectively.

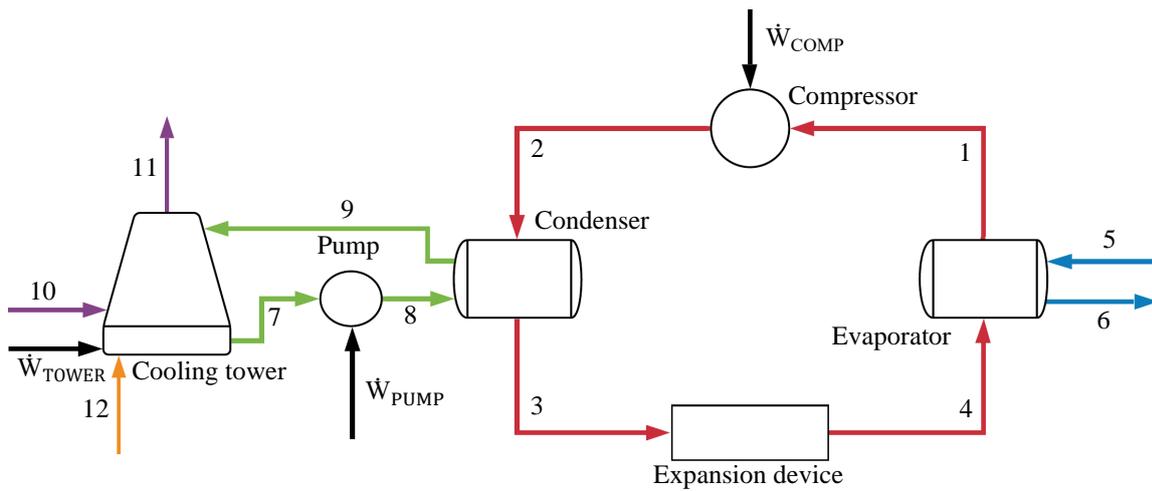


Figure 2. Internal streams of a chiller and cooling tower group.

The thermodynamic study was carried out based on the following considerations: all equipment operate in steady-state conditions; the effects of gravity and kinetic energy were neglected; the expansion device is isenthalpic; there is no pressure drop inside the heat exchangers; and there is no heat transfer between the components and the surroundings. Four sets of chiller, cooling tower and pump were evaluated considering the following control volumes: compressor, condenser, expansion device, evaporator, cooling tower, and pump.

Each control volume was analyzed in terms of the First and Second Law of Thermodynamics. By implementing the aforementioned considerations in the energy balance given by Eq. (1), the thermodynamic state of each single stream was defined, as well as the heat transfers. The specific exergy for each stream was calculated by Eq. (2), and the exergy balance (Eq. 3) was implemented to determine the exergy destruction rates.

$$\dot{Q} - \dot{W} + \sum_{inlet} \dot{m}(h+ec+ek) - \sum_{outlet} \dot{m}(h+ec+ek) = \left(\frac{dE}{dt}\right) \quad (1)$$

$$\psi = (h - h_0) - T_0(s - s_0) \quad (2)$$

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q} - \left(\dot{W} - P_0 \frac{dV_{VC}}{dt}\right) + \sum_{inlet} \dot{m}\psi - \sum_{outlet} \dot{m}\psi - \dot{E}_D = \frac{dX_{VC}}{dt} \quad (3)$$

The terms used in the equations are: heat transfer (\dot{Q}), work transfer (\dot{W}), mass flow (\dot{m}), specific enthalpy (h), kinetic (ec) and gravity energy (ek), energy variation (dE), specific exergy (ψ), specific entropy (s), and exergy destruction rate (\dot{E}_D). For the dead state (subscript 0), pressure (P_0) and temperature are 101,325 kPa and 28°C ($T_0 = 301,15$ K), respectively. T_k and dV_{VC} refers to heat source temperature and volume differential, respectively.

The next step is the exergoeconomic analysis by the SPECOC method. According to Lazzaretto and Tsatsaronis (2006), the method can be summarized in three stages: identify and calculate all the exergy streams; define products (\dot{E}_P) and fuels (\dot{E}_F); and obtain the cost equations (Eq. 4).

$$\dot{C}_y = c_y \cdot \dot{E}_y \quad (4)$$

\dot{C}_y is a cost rate associated with the correspondent exergy stream (\dot{E}_y) and c_y refers to the average cost per unit of exergy. The key to this analysis is to obtain the values of c_y for each stream of the overall system, so the cost balance given by Eq. (5) must be applied to each component.

$$\sum_{i=1}^n \dot{C}_{i,out} = \sum_{i=1}^n \dot{C}_{i,in} + \sum_{k=1}^n \dot{Z}_k \quad (5)$$

According to Penkuhn and Tsatsaronis (2019), Eq. (5) expresses that the total cost rate related to the output exergy streams ($\dot{C}_{i,out}$) must be equal to the total cost rate related to the input exergy streams ($\dot{C}_{i,in}$) plus the appropriate monetary expenses due to capital investment, operating, and maintenance, denoted by \dot{Z}_k , given by Eq. (6) and (7).

$$\dot{Z}_k = \varphi \cdot CRF \cdot Z_k^{CI} \quad (6)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \cdot \frac{1}{n \cdot op \cdot 3600} \quad (7)$$

Where φ is the maintenance factor, Z_k^{CI} is the acquisition cost, i is the interest rate, n represents the lifespan, and op is the annual plant operation hours. However, cost balances are not sufficient to calculate all the specific costs, requiring the formulation of auxiliary equations. This is achieved by applying the F and P principles (LAZZARETTO and TSATSARONIS, 2006).

Bejan, Tsatsaronis, and Moran (1996) summarized these general principles as follows: for a component that generates more than one product, in the lack of details about the production process of each product, it may be presumed that each unit of exergy is provided to each product stream at the same average cost; and when the variation between the entering and exiting states of the same stream of matter goes into the fuel definition for a component, the average cost per exergy unit remains constant for this stream.

There are components in which exergy is destroyed without generating thermodynamically useful streams. A product cannot be defined when this type of equipment is isolated because its operation seems meaningless from a thermodynamic viewpoint (LAZZARETTO and TSATSARONIS, 2006). In this case, all the costs associated with owning and operating a dissipative component must be charged to the component(s) served by it. Then, by applying the cost balance, a fictitious cost ($\dot{C}_{dif,dc}$) is calculated, given by Eq. (8).

$$\dot{C}_{dif,dc} = c_{in} \cdot (E_{in} - E_{out}) + \dot{C}_{aux} + \dot{Z}_{dc} \quad (8)$$

c_{in} is the cost per exergy unit of the main working fluid in the inlet (which according to F Principle remains constant between the inlet and outlet), \dot{C}_{aux} is the cost rate associated with the use of the auxiliary working fluid, \dot{Z}_{dc} is the total cost of investment, operating, and maintenance of the dissipative component, and E_{in} and E_{out} are the exergy of the main working fluid in the inlet and outlet, respectively. As stated by Lazzaretto and Tsatsaronis (2006), $\dot{C}_{dif,dc}$ needs to be allocated to the system equipment(s) served by the dissipative component, charged to the productive component(s) associated with the use of the dissipative component, or apportioned to the final product(s) of the system.

Table 1 provides the cost balances and auxiliary equations for each equipment of the chilled water system.

Table 1. Monetary cost balances and auxiliary equations.

Compressor	$c_2 E_2 = c_1 E_1 + c_w \dot{W}_{COMP} + \dot{Z}_{COMP} + \dot{C}_{dif,disp}$
Condenser	$c_3 E_3 + c_9 E_9 = c_2 E_2 + c_8 E_8 + \dot{Z}_{COND}$ $c_2 = c_3$
Expansion device	$\dot{C}_{dif,disp} = c_3 (E_3 - E_4) + \dot{Z}_{DISP}$ $c_3 = c_4$
Evaporator	$c_1 E_1 + c_5 E_{Q_{evap}} = c_4 E_4 + \dot{Z}_{EVAP} + \dot{C}_{dif,tower}$ $c_1 = c_4$
Cooling tower	$\dot{C}_{dif,tower} = c_9 (E_9 - E_7) + c_{10} (E_{10} - E_{11}) + c_w \dot{W}_{TOWER} + \dot{Z}_{TOWER}$ $c_9 = c_7$ $c_{10} = 0$ $c_{11} = 0$
Water pump	$c_8 E_8 = c_7 E_7 + c_w \dot{W}_{PUMP} + \dot{Z}_{PUMP}$

Once cost balances and auxiliary equations are defined, it is possible to calculate c_y for all streams, followed by the calculation of the cost rate of exergy destruction (\dot{C}_D), relative cost difference (r_k), and exergoeconomic factor (f_k).

According to Bejan, Tsatsaronis, and Moran (1996), cost rate of exergy destruction for a k_{th} component is given by Eq. (9) and represents a hidden but significant cost within the study as it accounts for the effect of exergy destruction ($\dot{E}_{D,k}$) in the total fuel cost rate. Herein $c_{F,k}$ denotes the average cost per unit of fuel of the k_{th} component.

$$\dot{C}_{D,k} = c_{F,k} \cdot \dot{E}_{D,k} \quad (9)$$

The relative cost difference, r_k , is calculated by Eq. (10) and represents “the relative increase in the average cost per exergy unit between fuel and product of the component” (BEJAN, TSATSARONIS, and MORAN, 1996).

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \quad (10)$$

The exergoeconomic factor (f_k) relates two categories of costs: non-exergy-related costs and costs associated with exergy destruction and exergy loss ($\dot{E}_{L,k}$). The point of this factor, given by Eq. (11), is to understand the contribution of the non-exergy-related cost to the total cost increase.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}(\dot{E}_{D,k} + \dot{E}_{L,k})} \quad (11)$$

Also, from the definition of product and fuel is possible to define the exergy efficiency (ϵ_k) displayed in Eq. (12) and to compare with the same indicator obtained through the exergy analysis in order to validate the results.

$$\epsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \quad (12)$$

Finally, after calculating these parameters for each component, it will be possible to carry out an interpretation of the exergoeconomic variables based on Bejan, Tsatsaronis, and Moran's (1996) methodology.

3. RESULTS AND DISCUSSION

During the procedure of data acquisition, only four sets of the chiller, cooling tower, and pump (Fig. 2) operated, identified herein as I, II, III, and IX. Table 2 depicts the exergy flows of each equipment of all four sets, and Tab. 3 shows the exergy destruction rates.

Table 2. Exergy streams, \dot{E}_y [kW], of each set of chiller, cooling tower, and pump.

Stream	I	II	III	IX
1	378.20	344.90	343.90	351.80
2	592.20	546.50	540.80	554.60
3	547.20	502.40	491.10	505.90
4	504.50	465.00	465.30	479.50
5	59.73	63.58	56.76	58.97
6	154.60	153.20	146.40	154.60
7	0.65	1.10	2.11	0.65
8	13.59	14.04	15.05	13.59
9	32.56	32.56	38.16	32.56
10	0	0	0	0.00
11	38.61	36.26	40.15	38.61
12	0	0	0	0.00

Table 3. Exergy destruction rate, $\dot{E}_{D,k}$ [kW], of the equipment under analysis.

Component	I	II	III	IX
Compressor	51.05	56.18	65.99	40.31
Condenser	26.07	25.6	26.64	29.71
Expansion device	42.64	37.4	25.79	26.41
Evaporator	31.42	30.49	31.7	32.06
Cooling tower	0.65	2.55	3.25	0.65
Water pump	17.06	17.06	17.06	17.06

In Tab. 3, it is observed that the total exergy destruction rates are similar for all chillers. In particular, the heat exchangers (evaporator and condenser) of the four chillers presented equivalent results, as well as the cooling towers. Regarding the compressors, the discrepancy in results is mainly because of the difference in electricity consumption.

The exergy efficiencies calculated from exergy and exergoeconomic analyses were compared and provided satisfactory correspondence.

The cost rates of acquisition, operation, and maintenance of each equipment are shown in Tab.4. These values were used for the calculations of the monetary costs.

Table 4. Total cost rates, \dot{Z}_k [R\$/s], for each equipment.

\dot{Z}_{COMP}	$2,48 \cdot 10^{-4}$
\dot{Z}_{COND}	$1,55 \cdot 10^{-4}$
\dot{Z}_{DISP}	$6,20 \cdot 10^{-6}$
\dot{Z}_{EVAP}	$1,55 \cdot 10^{-4}$
\dot{Z}_{TOWER}	$6,36 \cdot 10^{-5}$
\dot{Z}_{PUMP}	$9,94 \cdot 10^{-6}$

Applying the definitions of fuel and product, and solving the equations system presented in Tab. 1 for each set, exergoeconomic data is obtained, as shown in Tab. 5. Only productive equipment are under consideration as fuel and product cannot be defined for the dissipative components.

Table 5. Exergoeconomic data of productive equipment.

Equip.	I				II			
	\dot{E}_F [kW]	\dot{E}_P [kW]	c_F [R\$/MJ]	c_P [R\$/MJ]	\dot{E}_F [kW]	\dot{E}_P [kW]	c_F [R\$/MJ]	c_P [R\$/MJ]
COMP	265.00	214.00	0.06872	0.1081	257.80	201.60	0.06872	0.1098
COND	45.04	18.97	0.10810	0.2649	44.12	18.52	0.10980	0.2699
EVAP	126.30	94.86	0.10810	0.2264	120.10	89.62	0.10980	0.2341
PUMP	30.00	12.94	0.06872	0.1601	30.00	12.94	0.06872	0.1601
Equip.	III				IX			
	\dot{E}_F [kW]	\dot{E}_P [kW]	c_F [R\$/MJ]	c_P [R\$/MJ]	\dot{E}_F [kW]	\dot{E}_P [kW]	c_F [R\$/MJ]	c_P [R\$/MJ]
COMP	262.90	196.90	0.06872	0.1074	243.10	202.80	0.06872	0.09648
COND	49.75	23.11	0.10740	0.2379	48.68	18.97	0.09648	0.25580
EVAP	121.30	89.63	0.10740	0.2379	127.70	95.61	0.09648	0.20880
PUMP	30.00	12.94	0.06872	0.1601	30.00	12.94	0.06872	0.16010

The pieces of equipment presented a minor variation in the values of Tab. 5. For all components, the values of the fuel (\dot{E}_F) are higher than the product (\dot{E}_P), indicating consistency in the results. Furthermore, the values for the pumps are the same - this occurs because the values of exergy flows 7 and 8 (Fig. 2) are considered the same for all the sets.

Table 6 shows the exergoeconomic variables for each set, were calculated from the values shown in Tab. 3, 4, and 5.

Table 6. Exergoeconomic variables for productive equipment.

Equip.	I				II			
	$\dot{C}_{D,k}$ [R\$/s]	r_k [%]	f_k [%]	ϵ_k [%]	$\dot{C}_{D,k}$ [R\$/s]	r_k [%]	f_k [%]	ϵ_k [%]
COMP	0.003508	57.32	7.3660	80.74	0.003861	59.73	6.7380	78.21
COND	0.002819	145.00	5.2110	42.12	0.002810	145.80	5.2270	41.98
EVAP	0.003397	109.40	4.3630	75.12	0.003347	113.20	4.4260	74.62
PUMP	0.001172	133.00	0.8405	43.13	0.001172	133.00	0.8405	43.13
Equip.	III				IX			
	$\dot{C}_{D,k}$ [R\$/s]	r_k [%]	f_k [%]	ϵ_k [%]	$\dot{C}_{D,k}$ [R\$/s]	r_k [%]	f_k [%]	ϵ_k [%]
COMP	0.004535	56.29	5.7940	74.90	0.002770	40.39	9.1490	83.42
COND	0.002861	121.50	5.1390	46.46	0.002867	165.10	5.1280	38.96
EVAP	0.003405	121.50	4.3530	73.87	0.003093	116.40	4.7710	74.89
PUMP	0.001172	133.00	0.8405	43.13	0.001172	133.00	0.8405	43.13

The exergoeconomic variables are instrumental both in the design and performance evaluation of a thermal system. In the first case, considering the design stage, these variables are vital to improve the cost effectiveness of the system. On the other hand, exergoeconomic variables are applied to identify and understand possible malfunctions in a component and verify if the system is working correctly. The methodology proposed by Bejan, Tsatsaronis, and Moran (1996) provides guidelines for the analysis, illustrated as follows.

Considering the design stage, initially, the components are placed in order of cost importance ($\dot{Z}_k + \dot{C}_{D,k}$). The order of components for the sets I, II and III is the same: compressor first, then evaporator, condenser, and water pump. This means that, firstly, design changes must be considered for the compressor, to reduce its costs. For the set IX, there is a small difference in the order: the first equipment is the evaporator, followed by the compressor, condenser, and water pump. This difference is due to the smaller exergy destruction rate of the compressor, compared to the other sets. Table 7 shows the sums of \dot{Z}_k and $\dot{C}_{D,k}$ for each set.

Table 7. Sums of \dot{Z}_k and $\dot{C}_{D,k}$ for each set under analysis.

Equipment	I	II	III	IX
COMP	0.003787	0.004140	0.004814	0.003049
COND	0.002974	0.002965	0.003016	0.003022
EVAP	0.003552	0.003502	0.00356	0.003248
PUMP	0.001182	0.001182	0.001182	0.001182

Componentes are then evaluated considering the relative cost difference (r_k), which indicates how much the product cost increased in relation to the fuel. Bejan, Tsatsaronis, and Moran (1996) stated that attention must be paid to high r_k values, especially when $\dot{Z}_k + \dot{C}_{D,k}$ is high. Tab. 7 indicates that the $\dot{Z}_k + \dot{C}_{D,k}$ values for evaporators are high, and Tab. 6 also indicates high values for r_k , so it can be concluded that these pieces of equipment should be prioritized if any interventions are to be implemented.

The exergoeconomic factor (f_k) identifies the major cost source: capital investment or exergy destruction. High values of f_k indicates that it might be reasonable to reduce capital investment for the component. However, if the f_k value is low, improvements in the component efficiency should be considered by increasing the capital investment. From Tab. 6, the f_k values of all the components are low. (typical values for compressors are between 35% and 75%, for heat exchangers under than 55%, and above 70% for pumps, according to Bejan, Tsatsaronis, and Moran, 1996). The low value of f_k for all pieces of equipment indicates that the costs associated are almost exclusively due to exergy destruction.

Because of the low values of f_k for all components, it is recommended to focus improvement efforts on the evaporators, which presented a high combination of the $\dot{Z}_k + \dot{C}_{D,k}$ value and also for r_k . Design changes must be considered initially for reducing the exergy destruction rate of this component, such as a reduction of the evaporator pressure (P_4).

When developing a performance evaluation of the system, Bejan, Tsatsaronis, and Moran (1996) stated that only fuel-related costs are considered, as the capital investments (\dot{Z}_k) are sunk costs, and for simplicity, the operation and maintenance costs are neglected. Exergoeconomic variables can be applied as a diagnostic tool for the system.

With the aid of a performance assessment software, the exergoeconomic variables can be confronted with the design values obtained from a simulation with manufacturer data. The comparison of actual and target specific exergy costs allows early detection of component malfunctions and rapid identification of the malfunction source. Moreover, exergy stream cost data can be used to decide whether a malfunctioning component should be replaced (BEJAN, TSATSARONIS, and MORAN, 1996).

4. CONCLUSION

Attention should be given to the widespread and increasing deployment of refrigeration systems throughout the world, considering the economic and environmental impacts associated with the high electricity consumption of this type of equipment. In this context, the work presented herein describes the exergoeconomic analysis of a refrigeration system in a shopping mall by the SPECO method, which is a very useful tool to evaluate the system's performance and can be replicated in other applications of the tertiary sector, such as hotel complexes, hospitals, and supermarkets.

The thermodynamic analysis revealed that the equipment with the highest exergy destruction rate is the compressor, followed by the expansion device, evaporator, condenser, cooling tower and pump. However, the exergoeconomic analysis indicated that the compressor presented a high $\dot{Z}_k + \dot{C}_{D,k}$ value, but the lowest r_k value among the analyzed equipment. Thus, from an exergoeconomic perspective, the evaporator is the most important equipment, as it presents the second highest $\dot{Z}_k + \dot{C}_{D,k}$ value, and a high r_k value, indicating that its irreversibilities generate the most significant economic impacts. The f_k values of all equipment are very low, suggesting that the costs associated are almost exclusively due to exergy destruction.

Essential considerations can be made from the results of the thermodynamic analysis of an energy system, given that the main points of inefficiencies are highlighted. Nevertheless, it is indispensable to consider the economic and environmental factors related to possible changes and optimizations in an object of study, so that the results do not become excessively expensive or harmful to the environment. Thereby, the importance of developing integrated and comprehensive analyzes is remarkable, because it is possible to obtain a broad overview of the system.

5. ACKNOWLEDGMENTS

The authors acknowledge the support of the Coordination for the Improvement of Higher Education Personnel (CAPES) for the MSc. Scholarship and the National Council for Scientific and Technological Development (CNPq) for the Research Productivity Grant, n° 307394/2018-2 and MSc. Scholarship n° 132407/2019-1. Also, the authors thank Eng. Germano Pordeus for the essential support and valuable contributions to this work.

6. REFERENCES

- Bejan, A., Tsatsaronis, G., and Moran, M., 1996. *Thermal design and optimization*. New York: Wiley.
- Carvalho, M., Serra, L. M. and Lozano, M. A, 2011. "Geographic evaluation of trigeneration systems in the tertiary sector. Effect of climatic and electricity supply conditions". *Energy (Oxford)*, v. 36, p. 1931-1939.
- IEA - International Energy Agency, 2018. *The Future of Cooling: Opportunities for energy-efficient air conditioning*. OECD/IEA.
- Lazzaretto, A. and Tsatsaronis, G., 2001. "Comparison between SPECO and functional exergoeconomic approaches," In: *Proceedings of ASME international mechanical engineering congress and exposition*. IMECE/AES-23656, New York, ASME, November 11– 16.
- Lazzaretto, A. and Tsatsaronis, G., 2006. "SPECO: a systematic and general methodology for calculating efficiencies and costs in thermal systems". *Energy*, v. 31, p. 1257–1286.
- Lin, H., Li, X., Cheng, P. and Xu, B, 2014. "Thermoeconomic evaluation of air conditioning system with chilled water storage". *Energy Conversion and Management*, v. 85, p. 328-332.
- Lozano, M. A and Valero, A., 1993. "Theory of the exergetic cost". *Energy*, v. 18, p. 939-960.
- Owusu, P.A. and Asumadu-Sarkodie, S., 2016. "A review of renewable energy sources, sustainability issues and climate change mitigation". *Cogent Engineering*, v. 3, p. 1–14.
- Penkuhn, M. and Tsatsaronis, G., 2019. "Thermoeconomic modeling and analysis of sCO₂ Brayton cycles." In: *Proceedings of 3rd European supercritical CO₂ Conference*, Paris, September 19-20.
- V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, , and T. Waterfield (eds.), 2018. Global warming of 1.5°C. an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Technical report, Intergovernmental Panel on Climate Change (IPCC).
- Valero, A., Serra, L. and Uche, J., 2001. "Fundamentals of thermoeconomics". *EURO Summer Course on Sustainable Assessment of Clean Air Technologies*.
- Zhang, N. *et al.*, 2020. "A dynamic analysis of the global warming potential associated with air conditioning at a city scale: an empirical study in Shenzhen, China". *Environmental Impact Assessment Review*, v. 81, p. 106354.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.