Research article

Exergoeconomic analysis of an industrial beverage mixer system

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ABSTRACT

Exergoeconomic analysis is a tool used to identify hidden costs associated with a machine or a system that cannot be identified using typical cost management techniques applied in the industry. While exergoeconomic analysis finds applications in power system innovations and optimization, it has not yet been harnessed by the manufacturing industry to reduce operating costs. The purpose of this study is to use exergoeconomic analysis to identify hidden costs in manufacturing processes, with a focus on the industrial beverage mixer system. The study proposes a methodology of identifying the hidden financial losses in the system and recommends modifying the systems operation and design as a measure to reduce costs and increase profitability. Thermodynamic and economic data for the study were obtained from manufacturing plants. An exergy cost analysis was performed using thermoeconomic analysis software. Exergoeconomic values and variables were obtained using equations based on extant literature. The results reveal that the mixer possesses a low exergoeconomic factor of 5.50% owing to the high irreversibility of the H2O reservoir, flow-mix reservoir, and carbonator. The total hidden cost of the system equaled 733.04 $/h, of which 99.0% is contributed by the mixer. Improvements to the deaeration technique for the H2O reservoir of the mixer component, as well as the H2O treatment procedure, can reduce the irreversibility of the H2O reservoir and the hidden costs.

1. Introduction

Increasing competition as well as energy and production costs in the manufacturing field have forced manufacturers to seek ways of delivering high quality and standardized products at low cost. Cost management has become essential as the growth and survival of any manufacturing organization depends on how well it can manage its economy [1]. However, existing cost management techniques are unable to identify the hidden costs associated with production [2,3]. Some of the cost management techniques being adopted by manufacturers include the total quality management system (TQM), Kaizen system, just-in-time production, line rationalization, budgetary control, cost volume analysis, standard cost analysis, and process automation [1,4]. None of these techniques focus on the identification of the thermodynamic limit of machines or equipment used in the manufacturing process, or the process itself. A machine or process will consume large amounts of energy and fuel if it has thermodynamic limitations [5], and subsequently operate at a high cost and low efficiency. Exergoeconomic analysis is a useful tool in identifying thermodynamic limitations of a machine, process, or system and the underlying cost implications.

Exergoeconomic analysis is an emerging tool that is used to identify the actual cost of a product, along with the hidden costs of a device, process, and system. It is based on the principle that the useful part of energy should be assigned a monetary value rather than an energy value. A manufacturing process cannot run without energy conversion, and in physics, anything that changes over time involves energy conversion [6]. According to the laws of thermodynamics, exergy is the part of energy that is available for conversion, i.e., it is the useful work potential of energy [6,7,8]. Unlike energy, exergy cannot be recovered once it is wasted [7,9]. Exergy analysis is a method of determining the exergy value of a system, process, or device, and is used to account for the thermodynamic imperfections of real processes and improve the efficiency of operations, devices, and systems [9]. Exergy has an economic value and is useful to society, and therefore worth addressing [9]. Exergy losses remain a major challenge in many industrial processes [10] and cannot be identified with conventional energy analysis. More recently, exergy analysis has been used to analyze manufacturing processes and equipment, including the evaluation of ultra-high-temperature milk pasteurization plants, assessment of the efficiency of industrial food chains, development of a more sustainable chemical industry advance-ment procedure, ethanol production process analysis, assessment of a
burner in cement production processes, analysis of a refrigeration system in a typical beverage manufacturing plant, vegetable oil production process analysis, cryogenic air separation plants, and steam boiler analysis [11,12,13,14,15,16,17,56,57]. Exergy analysis has been established as a tool commonly used to determine the quality of energy and resource of any system or process. The concept of exergy destruction is used to improve the efficiency of manufacturing processes and machines [18, 19], as opposed to energy analysis, whose concept of energy dissipation is not an indicator of irreversibility.

Exergoeconomic accounting is the determination and assignment of economic values to the exergy flows of a device, process, or system, while exergoeconomic analysis involves the estimation of the cost of product flow and the quantification of cost rate due to irreversibility, which is referred to as the hidden cost [20]. Various exergoeconomic analysis approaches have been developed [21,22,23] and applied in power system innovations and optimization [21,22,23,24,25,26,27,28,29,30,31, 32,33,34]. However, few published works in the literature focus on the application of exergoeconomics to manufacturing. The aim of this study is to evaluate the performance of an industrial beverage mixer system at a manufacturing plant using the thermoeconomic analysis of energy systems software (TAESS) to identify hidden costs in the manufacturing process. The specific objectives are to a) identify the most significant source of exergy destruction in the mixer and its location of occurrence, b) evaluate the exergoeconomic performance of the mixer by analyzing the exergetic cost parameters of each component of the mixer, and c) identify the hidden cost in the manufacturing process.

A beverage mixer is a machine used in the production of carbonated beverages, first developed by the Mojonier Brothers Corporation of Chicago in 1937 [35]. Although mixers are being continuously innovated and improved [36,37,38], there has not yet been any published works related to their exergoeconomics. This report identifies the most significant sources and locations of hidden costs in an industrial beverage mixer.

Singh et al. [12] applied the exergoeconomic analysis to the manufacturing ecosystem of a dairy food-processing plant. They reported that the heating coil underwent the highest exergy destruction (0.16 MW), followed by the homogenizer (0.055 MW). The highest cost consumption occurred in the pasteurizer because of its subunits. In another study, Atmaca [13] used energy, exergy, and exergoeconomic analysis to evaluate the performance of a dry-type rotary kiln in the cement industry. The exergoeconomic factor of the kiln was found to be 53%, which implied the need to improve exergy utilization in the rotary kiln system of cement plants. Fani et al. [39] adopted the pinch technology and exergoeconomic analysis to evaluate the complex manufacturing process of a pulp and paper mill. They demonstrated a 12% decrease in the energy consumption, while the amount of recoverable black liquor was increased by 7%. The industrial beverage mixer system, like the paper and pulp mill, is also complex. Therefore, we used TAESS and exergoeconomic analysis to evaluate the system. Developed by the Centre of Research for Energy Resources and Consumption in conjunction with the Department of Mechanical Engineering at the University of Zaragoza, Spain [40,41], TAESS has been used by various researchers for exergoeconomic applications [11,42,43]. It is based on the principle of exergetic cost theory (ECT) in the exergoeconomic analysis. The only limitation of TAESS is that it may not be adaptable to suit other exergoeconomic approaches such as the specific exergy cost method, modified productive structure analysis, Wonyer method, or Moran method. Compared with other frequently used exergoeconomic approaches by Haydargil and Abusoglu [22], the ECT approach is more detailed because it does not neglect any type of subsystem cost, such as the flow cost. It determines the unit exergoeconomic costs of all flows in the system, considering exergy destruction to be a product of the system. ECT combines the actual product cost of a subsystem with the cost of exergy destruction.

2. Materials and methods

The thermodynamic diagram of the material stream flow in the system is illustrated in Figure 1. The total exergy of the material stream was obtained based on published mathematical models, and the exergy cost was analyzed using TAESS. The mathematical models related to the exergy analysis, exergy values of the material streams inputted to TAESS, and the fuel-product definition of the system applied in TAESS and nomenclature are presented in “Exergoeconomic Analysis of an Industrial Beverage Mixer System” in the Supplementary file. Irreversibility, I, unit exergy consumption, κ, unit exergy cost of fuel, cf, and unit exergy cost of product, cp, were obtained from software simulations, as presented in “Exergoeconomic Analysis of an Industrial Beverage Mixer System” in the TAESS analysis and results file.

2.1. Description of industrial beverage mixer

The material streamflow shown in Figure 1 illustrates a typical industrial beverage mixer system. The mixer consists of the following major components: a H2O reservoir inlet valve, a H2O reservoir, a H2O orifice, a syrup reservoir inlet valve, a syrup reservoir, a syrup orifice, a flow mix reservoir, a flow mix pump, a node, a Carbo Trol, a carbonator inlet valve, a carbonator, a CO2 distribution valve, an air distribution valve, and a carbonator safety valve. The following utility equipment and systems work in line with the mixer: a treated H2O pump, a syrup pump, a refrigeration system, and an air compressor system.

The treated H2O from treatment plant flows into the H2O reservoir through a pneumatically controlled H2O reservoir inlet valve with the aid of a H2O treatment pump. Similarly, the syrups from the syrup tank flow into the syrup reservoir through the pneumatically controlled valve with the aid of the pump. Deaeration, a process in which the air molecules and other gases in the treated H2O are removed, occurs at the H2O reservoir. This process is achieved by the chemical reaction of CO2 from the carbonator safety valve and treated H2O. The product of the reaction is carbonated H2O. Based on the mixing ratio of the beverage and its Brix value, the H2O and syrup orifices are adjusted to achieve the required mass flow rate of syrup and carbonated H2O, respectively. In most cases, the syrup orifice is preset or predefined, while the H2O orifice is varied with the help of a micrometer screw gauge to achieve the required mixing ratio.

The proportioned flow of carbonated H2O and syrup to the flow mix reservoir, where the two are mixed, followed by the addition of more CO2 forms the carbonated beverage. Moreover, CO2 from the Carbo Trol is mixed with the beverage from the flow mix reservoir as it is transferred to the carbonator with the help of a flow mix pump through the carbonator inlet valve. The mixing point of the beverage and CO2 along the line of the beverage transport to the carbonator is referred to as the node, and it has a non-returnable valve to prevent any backpressure/flow into the flow mix pump.

At the carbonator, CO2 is dissolved into the beverage as it is chilled. The chilling of the beverage is achieved by the refrigeration system, which works using the heat exchange between the beverage and the NH3 refrigerant in a counter flow over the cooling plate inside the carbonator. The flow of the NH3 refrigerant through the cooling plate is powered by an NH3 compressor. The carbonated beverage is the product of the system-flow 30 in Figure 1. The dissolved CO2 is fed to the carbonator via a diaphragm valve, which is controlled by a pressure recorder–controller instrument, to maintain a constant preselected CO2 pressure in the carbonator. Excess pressure in the carbonator is used to deaerate the treated H2O, and some pressure is released into the environment by the carbonator safety valve. The air compressor system supplies compressed air for all pneumatic valves and level controls in the system. The CO2 used by the mixer comes from a CO2 storage tank.
2.2. Data

The primary and secondary thermodynamic data used in this study were obtained from the manufacturing plant presented in the Exer-
goeconomic analysis of an industrial beverage mixer system: process data article [44], and the economic data are presented in Table 1. Additional data required for the chemical exergy analysis are as follows—the chemical exergies of H₂O, CO₂, NH₃, and C₆H₁₂O₆ were assumed to be 0.9, 19.87, 337.9 [6], and 2,975.85 kg/kmol [45], respectively. The molar masses of H₂O, CO₂, NH₃, and C₆H₁₂O₆ were taken as 18, 44, 17.03 [6], and 180.16 g/mol [46], respectively. The syrup and beverage were modeled based on a C₆H₁₂O₆–H₂O mixture, and the treated H₂O was modeled based on H₂O.

2.3. Exergoeconomic analysis

According to Rocco, Colombo, and Sciubba [47], compared with energy-based methods, exergy-based methods provide valid information on any system in terms of its efficiency, resource utilization, and economic importance. Exergy-based methods can be classified into two types: exergy accounting (exergoeconomic analysis) and life-cycle exergy analysis. Based on the limitations of thermoeconomic cost analysis due to externalities, extended exergy accounting is developed. For this study, we adopted the exergoeconomic analysis approach because it is a single system among the numerous beverage manufacturing process systems being investigated.

The major steps that are involved in the exergoeconomic analysis, and which were adopted in this study, are listed below [48]:

i. Exergy analysis of the system
ii. Economic analysis of the system
iii. Exergoeconomic evaluation of the system
iv. Evaluate the exergoeconomic variables of the system.

2.3.1. Exergy analysis of the system

The exergy analysis monitors, identifies, and improves exergy efficiencies and reduces irreversibility of the system, process, or device, by applying exergy balance to a control volume. A simple and general procedure for performing exergy analysis has been highlighted in the literature [15,47,48]. For each control volume in the system, as shown in Figure 1, the mass and exergy balance are obtained from Eqs. (1) and (2), respectively [14].

\[
\sum m_i = \sum m_e \tag{1}
\]

\[
I = \sum E_{x_e} - W + \sum E_{x_i} - \sum E_{x_f} \tag{2}
\]

Exergy efficiency is the major outcome of exergy analysis, which is defined as Eq. (3) [49].

\[
\eta_{ex} = \frac{\sum E_{x_{product}}}{\sum E_{x_{source/fuel}}} \tag{3}
\]

where \(\sum E_{x_{product}}\) denotes the exergy of the part of the outgoing energy flow considered as the control-volume product, whereas \(\sum E_{x_{source/fuel}}\) denotes the exergy of the incoming energy flow necessary for product development in the present process.

Based on the product-fuel concept, the exergy balance of the control volume in Eq. (2) can be expressed as Eq. (4).

\[
I = \sum E_{x_{source/fuel}} - \sum E_{x_{product}} \tag{4}
\]

The definition of the product and fuel stream of each component in

| Parameters                      | Mixer       | NH₃ compressor | Air compressor | Treated H₂O pump | Syrup pump |
|---------------------------------|-------------|----------------|----------------|------------------|------------|
| Total cost of investment ($)    | 208,333.33  | 17,267.43      | 12,020.01      | 905.65           | 972.22     |
| Number of years operated        | 7.00        | 7.00           | 7.00           | 7.00             | 7.00       |
| Number of hours operated at full load in a year | 6,553.00 | 6,553.00 | 6,553.00 | 6,553.00 | 6,553.00 |
| Electricity tariff ($/kWh)      | 0.12        | 0.12           | 0.12           | 0.12             | 0.12       |
Figure 1 is presented in “Exergoeconomic Analysis of an Industrial Beverage Mixer System” in the Supplementary file.

2.3.2. Economic analysis of the system

The non-exergy-related cost comprises of expenditure associated with the investment, operation, and maintenance of a system. The total cost of investment (TCI) is the sum of costs related to equipment purchase, installation, and commissioning. For this study, the TCI of the equipment was obtained from the manufacturing plant, as shown in Table 1.

The operation-and-maintenance cost is the cost related to the daily running of the equipment. It includes parameters such as labor cost, spare parts cost, and equipment servicing cost. Based on the work of Querol, Gonzalez-Regueral, and Perez-Benedito [50], the concept of operation-and-maintenance cost factor, $f_{OM}$, was developed and defined as in Eq. (5) [50].

$$f_{OM} = \frac{\text{Total annual operation and maintenance cost} \ (\text{OM Tot})}{\text{Total cost of investment} \ (\text{TCI})} \quad (5)$$

For this study, $f_{OM}$ is 1.06 for each piece of equipment [25,50].

The cost rate due to investment, $Z_k$, is a levelized cost of the TCI, $Z_k^C$, of the equipment, and the operation-and-maintenance cost of the equipment, $Z_k^{OM}$, is defined by Eqs. (6) and (7) [13,20,50].

$$Z_k = Z_k^C + Z_k^{OM}, \quad (6)$$

$$Z_k^{OM} = f_{OM} \times TCI, \quad (7)$$

where [13,50]

$$CFR = \frac{i (1 + i)^n}{(1 + i)^n - 1}, \quad (8)$$

$$Z_k^{OM} = f_{OM} \times TCI, \quad (9)$$

$$Z_k = \left( \frac{i (1 + i)^n}{(1 + i)^n - 1} + f_{OM} \right) \times TCI, \quad (10)$$

and [50]

$$\dot{Z}_k (\$/h) = \frac{\left( \frac{i (1 + i)^n}{(1 + i)^n - 1} + f_{OM} \right) \times TCI}{N}. \quad (11)$$

The interest rate, $i$, for this study was taken to be 20% based on the manufacturing plant cost of capital.

The investment cost is a fixed cost independent of the magnitude of exergy stream entering and leaving the system.

2.3.3. Exergoeconomic evaluation of the system

The ECT approach was adopted to estimate the exergetic cost associated with each flow in the system and the exergetic costs of components in the system with the aid of TAESS. The appropriate productive structure and fuel-product table presented in “Exergoeconomic Analysis of an Industrial Beverage Mixer System” in the Supplementary file was applied for the TAESS application. The exergy cost of the productive structure flows, $E_{exj}$, is calculated by TAESS as follows [51]:

$$C_{in} = E_{exj} + \sum_{j \in F} E_{exj} \cdot v_j \in V \quad (12)$$

$$C_{in} = E_{exj} + \sum_{j \in F} E_{exj} \cdot v_j \in V. \quad (13)$$

A detailed explanation of the algorithm can be found in the work of Torres et al. [51]. For the monetary value, the fuel cost in kilowatts was related to the cost of electricity. According to Valdimarsson [52], each kilowatt of exergy entering and leaving a system carries a cost (or has value) that can be compared with the cost of electricity.

The cost rate of operating a system can be determined using Eq. (14) [13]:

$$C_0 = Cd + \dot{Z}_k \quad (14)$$

2.3.4. Evaluating the exergoeconomic variable of the system

The exergoeconomic factor applied in this study are

i. Hidden cost: The cost rate associated with exergy destruction within a system. The hidden cost of any system can be computed from Eq. (15) [13, 20, 50].

$$Cd = c_f \cdot \prod \quad (15)$$

The assumptions applied in this study are as follows.

1. All working fluids in the system were in the one-dimensional steady state flow.
2. The potential and kinetic energies of gases were assumed to be negligible.
3. The adiabatic state was assumed for expansion and compression processes.

3. Results and discussion

3.1. Exergy efficiency, irreversibility, and unit cost of the system

The location, degree, and causes of exergy depletion in an industrial beverage mixer were detected using the exergoeconomic analysis. The fuel and exergy consumed by each component were also reviewed, and the results of the system operating-cost analysis are summarized in Table 2.

The cumulative irreversibility in the system was 5,300 kW. The highest irreversibility occurred in the H2O reservoir, which represents 74.28% of the total irreversibility in the system, followed by the flow mix reservoir and carbonator, which represent 18.46% and 3.88%, respectively. The summation of irreversibility of the rest of the components in the system represents 3.38% of the total system irreversibility. There is a clear correlation between the exergy efficiency, unit exergy consumption, and unit exergy cost of the product. A unit's exergy consumption is directly proportional to its exergy cost of product and inversely proportional to the exergy efficiency, which implies that a component that consumes more exergy will incur a high cost of product and low exergy efficiency.

All pumps in the system had low exergy efficiencies, ranging from 0.63% to 4.04%, as shown in Figure 2. The cause of low exergy efficiency of the pumps could be over-sizing or the high-pressure head. According to Vuckovic et al. [53], however, circulation pumps of a steam boiler have the greatest potential for improvement because the exergy destruction is avoidable in the steam boiler. The air compressor has a high exergy efficiency of 73.55%, when compared with the other utility equipment that work in line with the mixer, such as the NH$_3$ compressor (52.08%), treated H$_2$O pump (0.63%), and syrup pump (0.83%).

All inlet valves of the industrial beverage mixer system have high exergy efficiencies within 99.9%, when compared with the carbonator safety valve, which has a low exergy efficiency of 35.63%. The low exergy efficiency of the valve could be due to the release of CO$_2$ into
the environment. The exergy efficiency of the syrup reservoir (99.8%) and flow mix reservoir (84.16%) is high compared to the H2O reservoir exergy efficiency of 26.13%. The low H2O reservoir exergy efficiency could be due to the deaeration process taking place in the H2O reservoir. Both syrup and H2O orifices have the same exergy efficiency of 100%, which indicates that there is no significant loss of energy from the orifices. Additionally, the exergy efficiency of the air distribution valve (72.62%) is high compared with the CO2 distribution valve (66.63%). The carbonator has a unique function in the mixer where the CO2 reaction/activity takes place, and it has an exergy efficiency of 96.14%, which is high compared with that of the H2O reservoir. Other components, including the node, Carbo Trol, and air receiver tank, have high exergy efficiencies of 99.75%, 89.59%, and 92.33%, respectively.

### 3.2. Cost flow within the system

Exergoeconomic analysis was performed to identify the manufacturing-cost flow at several system locations as shown in Figure 3. This was realized by relating economic resources to the operation flow
cost presented in “Exergoeconomic Analysis of an Industrial Beverage Mixer System” in the TAESS analysis and results file. The results obtained are beneficial for the product cost estimation because an accurate product-cost estimate will help businesses flourish, whereas an inaccurate cost estimate may cause them to collapse [54]. The cost flow rate of the “flow 30” product equaled 1,216.87 $/h.

### 3.3. Hidden costs in the mixer system

Hidden costs (cost rates of exergy destroyed) identified by exergoeconomics in the industrial beverage mixer system are listed in Table 3. The total hidden cost of the system was 733.04 $/h, of which 99% is of the mixer. The exergoeconomic factor of air compressor was found to be very high compared with other system equipment due to high cost rate of investment and maintenance, while that of the mixer was found to be low, due to high irreversibility [55]. The components of the mixer that have high irreversibility, and subsequently high hidden costs, are the H2O reservoir, flow mix reservoir, and carbonator (Figure 4).

As shown in Figure 4, the irreversibility and hidden cost of the H2O reservoir were high, which is due to the deaeration process. The stoppage of the deaeration process as a cost reduction step for the mixer system reveals that the irreversibility and hidden cost reduced in the H2O reservoir.

### Table 3. Results of exergoeconomic analysis of system equipment.

| Machine/Equipment       | Cost rate of exergy destroyed ($/h) | Cost rate of investment and maintenance ($/h) | Cost rate of operation ($/h) | Exergoeconomic factor (%) |
|--------------------------|-------------------------------------|-----------------------------------------------|----------------------------|---------------------------|
| Treated H2O pump         | 0.56                                | 0.19                                          | 0.74                       | 24.90                     |
| Syrup pump               | 0.58                                | 0.20                                          | 0.78                       | 25.60                     |
| NH3 compressor           | 4.85                                | 3.52                                          | 8.37                       | 42.10                     |
| Air compressor           | 1.45                                | 2.45                                          | 3.91                       | 62.80                     |
| Mixer                    | 725.61                              | 42.52                                         | 768.13                     | 5.50                      |

![Figure 3. Cost flow rate at all locations of the industrial beverage mixer.](image)

![Figure 4. Irreversibility and hidden cost from deaeration process of industrial beverage mixer subsystem.](image)
reservoir from 3,936.80 to 2.57 kW and 467.96 to 0.31 $/h, respectively. The flow mix reservoir then increases the irreversibility from 978.50 to 4,908.12 kW. This leads to a corresponding increase in the hidden cost from 190.34 to 954.77 $/h (Figure 5), thereby increasing the overall hidden cost of the mixer system by 40.97%. This improvement technique shows that the water treatment procedure would then need to be checked for finding methods to reduce the oxygen and other dissolved gas contents of the treated water.

A reduction in the mass flow rate of carbonated beverages from 2.82 to 2.00 kg/s causes a corresponding decrease in the hidden cost from 733.04 to 564.62 $/h. However, this will negatively impact the hourly production volume and consequently the organization’s projected profit. This article shows that the only cost-effective method to reduce the hidden costs in the mixer is to change the present deaeration technique and re-evaluate the H2O treatment procedure.

4. Conclusions

The benefit of using exergoeconomic tools to understand the efficiencies of an industrial beverage mixer system and improved methods to minimize hidden costs were demonstrated in this study. The results will be useful for engineering managers, investors, decision-makers, and policymakers in the beverage industry. Compared with the existing cost management techniques adopted by manufacturing organizations, no technique will be able to identify that the mixer system will consume more energy and incur invariably high cost of operation due to the high exergy destruction that occurred at H2O reservoir (3,936.80 kW), flow mix reservoir (978.50 kW) and carbonator (205.46 kW). The total hidden cost of operating an industrial beverage mixer, as identified by this study, is 733.04 $/h. The mixer has a low exergoeconomic factor of 5.50%, compared with the rest of the equipment in the system, which shows that the hidden cost of the mixer is related to exergy destruction rather than investment. The hidden cost can be minimized by reducing the irreversibility of the system. Based on this study, we conclude that improvements to the existing deaeration technique used in H2O reservoirs, as well as the H2O treatment procedure, can reduce irreversibility. There could be high concentrations of oxygen or other gases dissolved in the treated H2O.

Future studies should include a complete exergetic analysis of the beverage manufacturing process, including finding ways to reduce exergy destruction in the deaeration process and quantifying the gains of exergoeconomics in manufacturing applications, as a cost-control mechanism. A limitation of this study is that it could not compare the results with those of existing studies because there are no additional published results on the exergoeconomic analysis of industrial beverage mixers. Most researchers use exergoeconomics only to study power plants. In addition, process data from manufacturing plants are difficult to obtain, as a thorough understanding of the process flow and system operation is required.

Declarations

Author contribution statement

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

Olumuyiwa A. Lasode & Idehai O. Ohijeagbon: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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The authors declare no conflict of interest.
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References

[1] E. Ben-Caleb, A. Otekunrin, B. Rasak, S. Adewara, O. Oladipo, R. Eshua, Cost reduction strategies and the growth of selected manufacturing companies in Nigeria, Int. J. Mech. Eng. Technol. 10 (2019) 305–312.
[2] A. Jaiyeola, S. Alao, O. Akinpelu, Life cycle cost assessment of soybean oil extraction using steam distillation process, J. Supply Oper. Manag. 1 (2015) 489–506.
[3] S. Mahmood, N. Kureshi, A literature review of the quantification of hidden cost of quality in the historical perspective, J. Qual. Technol. Manag. 11 (2015) 1–24.
[4] T.G. Gutowski, D.P. Sekulic, Thermodynamic analysis of resources used in drilling, resource development and Power Plants, organized by UNU-GTP and CIRCE.http://www.energiauxiliaire.org/energieauxiliaire-en.html.
[5] C.J. Okereke, O.A. Lasode, I.O. Ohijeagbon, Exergoeconomic Analysis of an Integrated Solar Gas Turbine/Combined Cycle Plant with Desalination, Int. Energy J. 7 (2006) 35–41.
[6] D.J. Kim, A new thermoeconomic methodology for energy systems, Energy 35 (2010) 410–422.
[7] J. Xiong, H. Zhao, C. Zhang, C. Zheng, P. Luh, Thermoeconomic operation optimization of a coal-fired power plant, Energy 42 (2012) 486–496.
[8] J. Xu, B.J. Seo, P.B. Jung, Technical and economic analysis of transEpoch power plant Ughelli, Int. J. Energy Technol. 5 (2016) 36–44.
[9] A. Kojounek, The modified productive structure analysis of Afyon geothermal district in a system for economic optimization, Int. J. Renew. Energy Res. 3 (2010) 60–67.
[10] B. Hargitt, Introduction, in: D.P. Steen, P.R. Ashurst (Eds.), Carbonated Soft Drinks: Formulation and Manufacture, Oxford Blackwell Publishing Ltd., UK, 2006, pp. 1–15.
[11] M. Gorji-Bandpy, V. Ebrabimian, Exergoeconomic analysis of gas turbine power plants, Intern. J. Energy Technol. 3 (2018) 192–205.
[12] G.D. Vuckovic, M.V. Vukic, M.M. Stojiljkovic, D.D. Vuckovic, Avoidable and unavoidable exergy destruction and environmental evaluation of the thermal process in a real industrial plant, Therm. Sci. 16 (2012) S43–S446.
[13] G.D. Vuckovic, M.V. Vukic, M.M. Stojiljkovic, D.D. Vuckovic, Avoidable and unavoidable exergy destruction and environmental evaluation of the thermal process in a real industrial plant, Therm. Sci. 16 (2012) S43–S446.
[14] A. Musta, M.R. Okun, Optimization of steam temperature levels in a total site using a thermoeconomic method, Energies 5 (2010) 702–717.
[15] D. Haydargil, A. Abouagou, A comparative thermoeconomic cost accounting analysis and evaluation of biogas engine-powered cogeneration, Energies 15 (2018) 97–114.
[16] M. Górecki-Bandy, P. numbers, Exergetic analysis of gas turbine power plants, Int. J. Energy 7 (2006) 35–41.
[17] S.O. Oyedepo, R.O. Fagbene, S.S. Adeifa, M. Mahbub, Energy costing analysis and performance evaluation of selected gas turbine power plants, Cogent Eng. 2 (2015) 1101048.
[18] A. Smati, P. Jézéquel, Energy and exergy assessment of a reheat gas turbine engine, Am. J. Energy Res. 4 (2016) 1–10.
[19] G. Bonforte, J. Buchgeister, G. Manfrida, K. Petela, Exergoeconomic and exergoenvironmental analyses of a combined cycle power plant, in: Proceedings of ECOS 2017 - the 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 2017. San Diego, California, USA, 2017.
[20] M. Modesto, S.A. Neba, Exergoeconomic analysis of the power generation system using blast furnace and coke oven in a Brazilian steel mill, Appl. Therm. Eng. 29 (2009) 2127–2136.