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Research article

Using Monte Carlo method for evaporative cooling tower selection in an industrial company in Iran

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Abstract

The use of cooling towers in Iran's industries not only helps optimize energy consumption and increase equipment efficiency but also contributes to environmental preservation and reduces operational costs. Given the growing need for efficient cooling systems in industries, investment in this area can serve as an effective solution to address industrial challenges in Iran. In the present study, a cost comparison between two types of evaporative cooling towers, open and closed, is conducted for the first time using the Monte Carlo method. Initially, the effective parameters and their percentage tolerances were identified, and then the values of the effective parameters were calculated for 10000 iterations. The standard deviation, maximum, and minimum values for the total cost of cooling towers were evaluated. The results indicate that the open evaporative cooling tower has more consistent costs due to its standard deviation of 989815 compared to 2803948 for the closed type, leading to easier budgeting and financial planning. According to the results, the open evaporative cooling tower has lower risk analysis and better efficiency and productivity compared to the closed type, which is attributed to the lower maximum and minimum values of the open type. Additionally, the results showed that with the excess costs incurred for the closed evaporative cooling tower compared to the open type, an open evaporative cooling tower can be purchased after 6.38 years.

Keywords: Industrial processes, Steelmaking, Cooling tower, Operational costs, Monte Carlo Method.

1- Introduction

Cooling towers play a vital role in industrial processes by maintaining optimal thermal conditions and improving energy efficiency across a wide range of applications. As industries such as oil and gas, steel manufacturing, and power generation continue to expand, the need for efficient cooling solutions has become increasingly critical. In response to this demand, the global cooling tower market has experienced notable growth, supported by technological advancements and sustainability goals.

According to recent reports, the global cooling tower market size was estimated at $3.35 billion in 2023, and it is projected to grow from $3.49 billion in 2024 to $4.27 billion by 2028 (Fig. 1) [1]. This expansion is driven by several key factors: the rising demand for energy-efficient systems, the adoption of intelligent and automated technologies, and global initiatives aimed at reducing energy consumption and carbon emissions. Additionally, industrial investments in emerging markets—particularly in Asia-Pacific and Latin America—have further accelerated this growth trend.

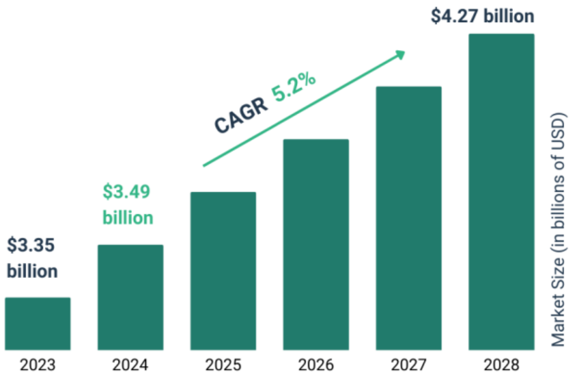

Fig. 1 Cooling Tower Market Size in 2024 and Growth Rate

The use of cooling towers in Iranian industries is crucial as an effective solution for temperature management and optimization of industrial processes. With the increasing demand for efficient and sustainable cooling systems in industries, cooling towers are recognized as key components in industrial facilities.

- Energy Consumption Reduction: Cooling towers can significantly reduce energy consumption in industrial processes. By optimizing temperatures in industrial equipment and machinery, the need for energy to achieve cooling is reduced. This is particularly important in large industries such as petrochemicals and steel manufacturing, which require continuous cooling [2].
- Increased Equipment Efficiency: Using cooling towers, temperatures in industrial systems are brought to desirable levels, which helps increase the efficiency and lifespan of equipment [3]. High temperatures can lead to reduced performance and early equipment failure. For instance, maintaining temperatures within an optimal range in manufacturing industries can improve the quality of final products.
- Pollution Reduction and Environmental Preservation: Cooling towers help reduce thermal pollution in the environment. These systems can lower temperatures sufficiently to prevent heat release into the environment. Given environmental crises and the need to reduce negative impacts of industries, this feature of cooling towers is very significant [4].
- Meeting Industrial Needs: With the rapid growth of industries in Iran and the need to supply cooling water for various processes, cooling towers are recognized as an effective solution for meeting these needs. These systems can continuously supply cooling water for use in industrial processes, thus optimizing water consumption [5].
- Reduction in Operational Costs: By optimizing energy consumption and increasing equipment efficiency, the use of cooling towers can lead to a reduction in operational costs for industries [6]. This is particularly important in the current economic conditions where industries face financial challenges. For example, reducing energy costs can help improve industrial profitability.

The choice of cooling tower technology significantly impacts the overall performance, economic, and environmental aspects of power plants and industrial processes. The studies in Table 1 compare the performance and costs of open and closed evaporative cooling towers in different applications.

Table 1: Recent studies on cooling towers

Paper	Abstract summary	Methodology	Main findings
Ivanyakov and Kryuchkov 2023 [7]	The paper optimizes operating parameters of open cooling towers in double-circuit cooling systems to minimize operating costs.	- Analysis of equipment operation in both open and closed cooling circuits, with certain parameters held constant - Use of previously developed models of pollution growth in heat exchangers - Consideration of control parameters to identify the main parameter for optimizing (minimizing) operating costs, which was the cooling water temperature - Analysis of the influence of ambient air parameters on the cooling water temperature in open cooling towers - Calculation of the economic efficiency of the cooling system operation considering seasonal changes in ambient air parameters	- The main parameter to optimize (minimize) the operating costs of the cooling system is the cooling water temperature. - The authors used models of pollution growth in the heat exchangers and control parameters to identify the cooling water temperature as the key optimization parameter. - The authors also analyzed the influence of ambient air parameters on the cooling water temperature and calculated the economic efficiency of the cooling system operation considering seasonal changes.
Liu et al. 2022 [8]	The paper compares the performance and costs of open and closed cooling towers, and proposes optimization methods to improve water savings and cost reduction.	- Evaluation of three different schemes to improve water savings and cost reduction of cooling water systems - Comparison of the performance of an open cooling system and a closed cooling system - Optimization of the heat load distribution between water cooling and air cooling - Use of multiperiod optimization to determine the optimal configuration and operation of the cooling water system	- Three schemes are proposed to improve water savings and cost reduction of cooling water systems. - The performance of an open cooling system and a closed cooling system are compared. - The optimal heat load matching between water cooling and air cooling is investigated.
Marazgioui and El-Fadar 2022 [9]	Wet and hybrid cooling technologies perform better and are more cost-effective than dry cooling for concentrated solar power plants.	- Selection of 7 CSP projects worldwide with distinct features - Simulation of the selected projects using the System Advisor Model software - Evaluation of the following performance metrics: Annual energy production, Capacity factor, Levelized cost of electricity - Assessment of the impact of cooling tower technologies in terms of: Discounted payback period, Savings-to-investment ratio, Greenhouse gas emissions, Water savings, Total cost savings - Comparison and ranking of wet, hybrid, and dry cooling tower technologies based on the performance findings	- Wet cooling technology had the highest performance, followed by hybrid and dry cooling technologies. - Wet cooling had lower greenhouse gas emissions, but dry and hybrid cooling were more water-efficient and profitable in water-scarce regions. - Wet and hybrid cooling technologies were the most cost-effective, with lower levelized cost of electricity and shorter payback periods compared to dry cooling.
Jiamei et al. 2021 [10]	The paper investigates the performance of closed wet cooling towers and proposes a new heat transfer strategy to improve their thermal performance.	- Proposing a new heat transfer strategy to improve the thermal performance of a closed wet cooling tower (CWCT) - Conducting both theoretical and experimental research to investigate the influence of fan frequency, spray density, and processing water flow on the thermal performance of the CWCT - Fitting the experimental data to obtain an empirical formula for the heat and mass transfer coefficient	- The study investigated how fan frequency, spray density, and processing water flow affect the thermal performance of a closed wet cooling tower. - The study derived an empirical formula for the heat and mass transfer coefficient based on experimental data. - The findings of the study can be used to improve the cooling efficiency and heat/mass transfer of closed wet cooling towers.

Bracho et al. 2020 [11]	The paper compares the performance and characteristics of two mechanical draft laboratory scale cooling towers in a recirculating water cooling system.	- Comparative analysis of two mechanical draft counterflow cooling towers - Direct contact heat transfer in a recirculating water cooling system - Studied the effects of tower height, water-air contact time, filling material, cooling range, approach to wet-bulb temperature, effectiveness, inlet water flow, and heat load - Used a high polyethylene mesh as the filling material in both towers	- Both mechanical draft cooling tower designs studied are suitable for laboratory scale applications. - The water flow rate should be shorter than the air flow rate for optimal performance. - The heating device should be placed outside the tower to avoid increasing the wet-bulb temperature.
Afshari and Dehghanpour, 2019 [12]	This paper reviews different types of cooling towers, their applications, performance, and working principles, but does not compare open and closed cooling towers.	- A review of existing literature on cooling towers, including their types, performance, applications, and working principles - A computational fluid dynamics simulation using the Fluent software to examine the flow field and major contours around a cooling tower	- The main function of cooling towers is to reject waste heat from hot water by using cooler and drier air. - The study reviewed different types of cooling towers and conducted a Fluent simulation to examine the flow field and contours around the cooling tower. - The overall aim of the study was to review different types of cooling towers, their applications, performance, and working principles, with potential usefulness in nuclear and other energy plants.
Jain et al. 2019 [13]	The paper compares the performance and costs of cooling tower assisted cascaded and hybrid refrigeration systems.	- Comparative analysis of two refrigeration system configurations: a cooling tower assisted cascaded refrigeration system (CRS) and a cooling tower assisted hybrid refrigeration system (HRS) - Evaluation of the performance, size, and cost of the two systems for a 100 kW cooling capacity - Optimization of the systems using four approaches: single-objective optimization of coefficient of performance (COP), single-objective optimization of operational cost, single-objective optimization of investment cost, and multi-objective optimization	- The CRS had a higher COP and second law efficiency compared to the HRS. - The CO_2 penalty cost of the CRS is almost half of the HRS. - Despite the higher efficiency of the CRS, the HRS has a 46.1% lower annual operational cost due to its more efficient energy utilization and lower CO_2 emissions. - The investment cost for the CRS is 10% lower than the HRS for the same cooling capacity.
Alhamid et al. 2019 [14]	This paper examines the effect of ozone on water quality in a closed-circuit cooling tower system, but does not compare performance or costs of open vs. closed cooling towers.	- Injecting ozone at a rate of 3 g/hour into the basin of a closed-circuit cooling tower system - Conducting laboratory tests using AAS, Titrimetric, Gravimetric and Spectrophotometric methods	- Ozone affected the water quality in the closed circuit cooling tower system basin, but did not affect the overall system performance for more than 10 days. - The range of evaporation loss values observed was 0.03 to 0.119 m^3/h.
Present work 2024	Comparison of short-term and long-term performance of two types of open and closed cooling towers	Using the Monte Carlo method and other numerical and statistical analysis methods	A closed-type evaporative cooling tower has a much higher cost in the medium term than an open-type.

Based on the aforementioned studies, it is observed that the Monte Carlo method has not been used for selecting between the two types of evaporative cooling towers, open and closed, until now. Moreover, previous analyses have primarily focused on the thermal performance and water consumption of the two types of towers, indicating that the objectives of these studies differ from the present work. Additionally, the studies conducted so far have been carried out in various climates and have not been comprehensive, failing to include all parameters influencing their performance. Therefore, in the present work, using the Monte Carlo method and based on 10,000 different scenarios, four parameters that have a direct impact on selection are evaluated. Ultimately, based on the results, a recommendation is made to either purchase a new open-circuit evaporative cooling tower or use the existing closed-circuit evaporative cooling tower as a substitute.

2- Location and Problem Statement

The "Rolling and Steel Parts Production Company" was established in 1968, making Iran one of the first steel producers in the Middle East. Currently, the company employs over 670 personnel and has a nominal production capacity of 150000 tons, of which approximately 55% was achieved in 2023.

The lower production capacity compared to similar companies allows the company to be more flexible in changing grades and sizes in the market, compensating for market shortages. Entering the alloy product market and ultimately transforming the company into a knowledge-based entity for producing alloy products have been notable achievements over the past five years.

Due to the need for cold water in various sections such as the descaling equipment, main rolling mill roller, scarfing machine, and hydraulic oil pumps, as shown in Figs. 2 to 5, an open-circuit evaporative cooling tower is currently in operation at the company, as depicted in Fig. 6. However, this tower needs replacement due to its worn-out condition. Considering the availability of three surplus closed-circuit evaporative cooling towers from the old workshop production line, as shown in Fig. 7, a follow-up was carried out to replace the worn-out open-circuit evaporative cooling tower with the closed-circuit ones. Therefore, feasibility studies from technical, economic, and environmental perspectives have been conducted to explore this replacement option.

Fig. 2 Cooling using water in the descaling section of the rolling process to remove oxide scales from the surface of rolled metals

Fig. 3 Use of water in the rolling stand section for cooling the rolling mill roller

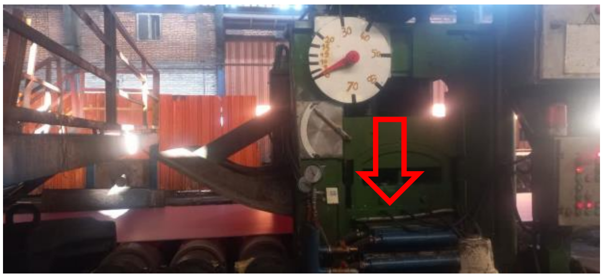

Fig. 4 Cooling the scarfing machine using water to remove waves, control thickness, and reduce defects

Fig. 5 Cooling hydraulic pack oil pumps to increase the lifespan and improve the efficiency of the pumps

Fig. 6 Current damages observed in the open-circuit evaporative cooling tower

Fig. 7 Closed-circuit evaporative cooling tower

3- Methodology

The Monte Carlo method was selected due to its strong analytical capability in simulating various conditions and assessing the impact of parameter changes in complex environments. This method can predict possible outcomes based on probability distributions and identify the risks associated with each option. For example, in evaluating the choice between open and closed cooling towers, parameters such as maintenance costs and energy consumption are examined under different scenarios. The final decision is then based on the analysis of simulated data, which enhances both the accuracy and reliability of the decision-making process.

The Monte Carlo method, as a powerful tool in choosing between two types of cooling towers, allows decision-makers to make an optimal and well-documented choice by considering uncertainties and varying conditions [15]. Uncertainties were managed using probability distributions and data modeling across a wide range of scenarios. This approach ensures that the results remain valid even under unpredictable conditions. In other words, the Monte Carlo method analyzes not only the average outcomes but also the range of variability, enabling users to make more informed and robust decisions. This method can especially help optimize costs and improve efficiency in large industries that require continuous cooling. The flowchart in Fig. 8 illustrates how this method operates in this context.

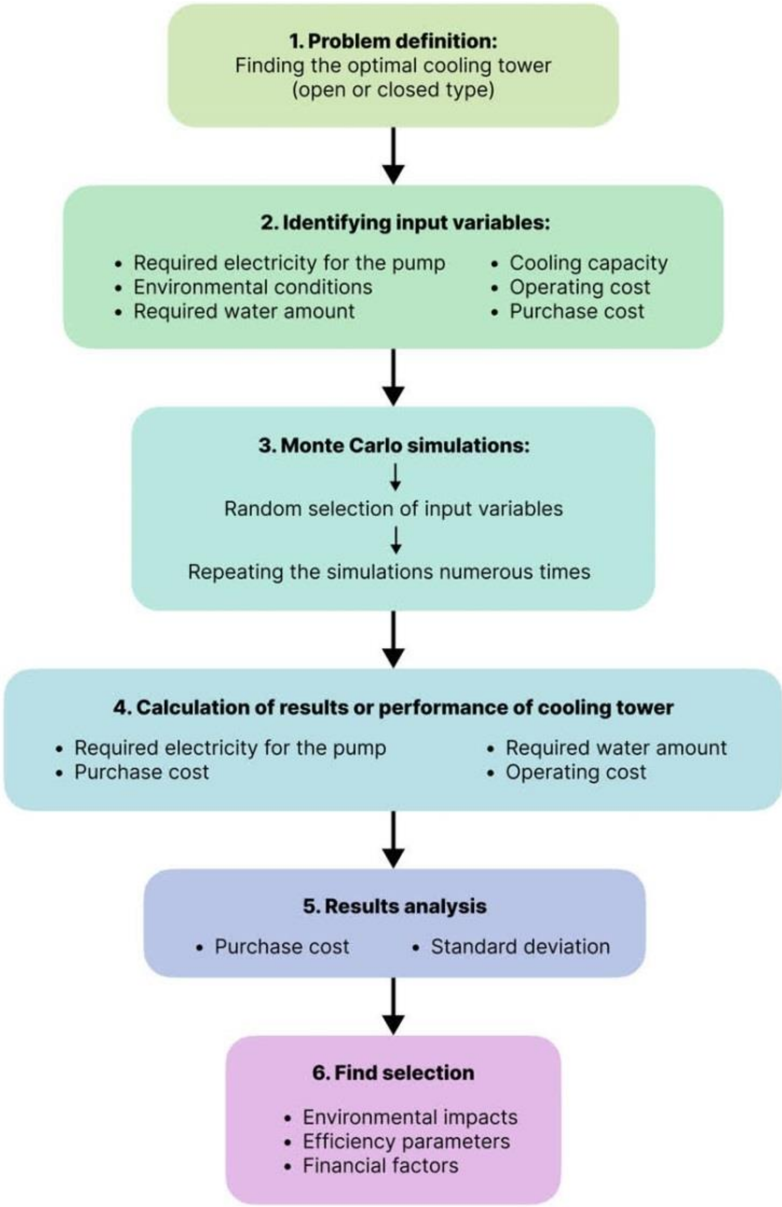

Fig. 8 Flowchart of optimal cooling tower selection using the Monte Carlo method

The governing equations for the Monte Carlo method are explained in the following steps [16-18]:

- Define the random variables in the model, which include purchase price, maintenance cost, water consumption cost, and electric motor power consumption cost, and select a normal probability distribution for each variable. The random variables are defined based on a normal distribution to ensure that the probability of each scenario aligns with real-world data. This modeling approach allows for the generation of numerous random values for each parameter and provides simulation results based on different scenarios.

- Generate random values for each random variable using probability distributions according to Equation 1:

$$X_i \sim N(\mu,\sigma^2) \tag{1}$$

where μ is the mean and σ^2 is the variance of the normal distribution.

- Compute the objective function or system performance according to Equation 2:

$$Y=f(X_1,X_2,\ldots,X_n) \tag{2}$$

where Y is the system output and f is a function dependent on input variables.

- Repeat the previous steps many times (usually thousands) to obtain a diverse range of results. For example, if N is the number of iterations, you can use Equation 3:

$$Y_i=f(X_{1,i},X_{2,i},\ldots,X_{n,i}) \quad for \quad i=1,2,\ldots,N \tag{3}$$

Use descriptive statistics to analyze the results:

$$\bar{Y}=\frac{1}{N}\sum_{i=1}^{N}Y_i \tag{4}$$

$$Var\,(Y)=\frac{1}{N-1}\sum_{i=1}^{N}(Y_i-\bar{Y})^2 \tag{5}$$

$$\sigma_y=\sqrt{Var\,(Y)} \tag{6}$$

where $\bar{Y}$ is the mean, Var(Y) is the variance, and σ_y is the standard deviation.

- Evaluate the probability of different outcomes according to the distribution of output Y.

4- Discussion and Results

The increasing use of cooling towers can be attributed to the upgrade of old infrastructures, stringent energy efficiency standards, data center expansion, economic development, evolution of chemical industries, and a focus on water treatment. As shown in Fig. 6, the reason for the present work is the upgrade of old infrastructures with a focus on economic issues.

Based on the flowchart in Fig. 8, four parameters are involved in selecting the appropriate cooling tower. These four parameters for the two types of cooling towers, open and closed, are presented in Table 2. The goal is to find the values of these parameters for the two types of cooling towers and make the final selection. Inquiries from Havarub Company regarding the purchase of a cooling tower with a 200-ton cooling capacity revealed that an open-type cooling tower would cost 100 million Tomans, while a closed-type cooling tower would cost 180 million Tomans [19]. Additionally, periodic maintenance costs, water consumption costs, and electric motor power consumption costs were obtained by consulting researchers and experts in this field and are presented as percentages of the purchase cost in Table 2.

The maintenance costs of closed cooling towers are significantly higher due to the complexity of the system and the need for more specialized repairs and components. While open cooling towers can be managed with lower maintenance costs—typically 5–7% of the purchase cost—this figure ranges between 6–10% for closed systems. In terms of water consumption, although closed towers use less water due to their closed-loop design, the overall costs increase due to water treatment requirements and the additional equipment needed to maintain water quality. Furthermore, electric motors in closed towers require higher power (4–7%) compared to those in open towers (3–5%), leading to greater energy consumption and thus higher operational costs. Altogether, these factors result in higher operational expenses for closed towers, making them a less practical choice in scenarios where cost reduction is a primary concern.

Table 2: Comparison of parameters between open and closed cooling towers

Cooling tower type	Purchase cost (Tomans)	Periodic maintenance cost (%)	Water consumption cost (%)	Electric motor power consumption cost (%)
Open	100000000	5-7	3-5	3-5
Closed	180000000	6-10	2-4	4-7

In Fig. 9, the final values for the parameters examined in Table 2 are presented, which are the results of averaging 10000 iterations using the Monte Carlo method. A total of 10,000 iterations was selected to generate a sufficient number of outcomes for accurate statistical analysis. This number of repetitions reduces the probability of error and enables a more precise comparison between the alternatives.

In Fig. 10, the standard deviation, maximum, and minimum parameters for 10,000 data points for each type of cooling tower, open and closed, are presented. According to the results of Fig. 10, the open-type cooling tower has a lower standard deviation, indicating more stable costs and fewer fluctuations. This means that costs are more predictable and there is less chance of significant changes.

Based on the maximum values, it is observed that under certain conditions, the costs of the closed evaporative cooling tower increase more compared to the open evaporative cooling tower. This is important for risk analysis and budget planning and should be considered by investors and industrial consumers. The minimum values, which indicate lower costs under optimal conditions, show that the open evaporative cooling tower is significantly less expensive. This indicates better efficiency and productivity compared to the closed type.

Furthermore, calculations show that the cost difference between maintenance, water consumption, and electric motor power consumption over a year is 15,681,829 tomans. Given the purchase price of 100,000,000 tomans for the open evaporative cooling tower, this means that after approximately 6.38 years, the cost difference is equivalent to the purchase of an open-type cooling tower. In other words, beyond the higher initial investment, the elevated operational expenses of the closed system over time effectively equal the cost of acquiring an additional open tower. This finding highlights that the selection of a closed cooling tower is justifiable only under specific conditions involving unique operational requirements. In most cases, opting for an open cooling tower proves to be a more cost-effective choice in the long term.

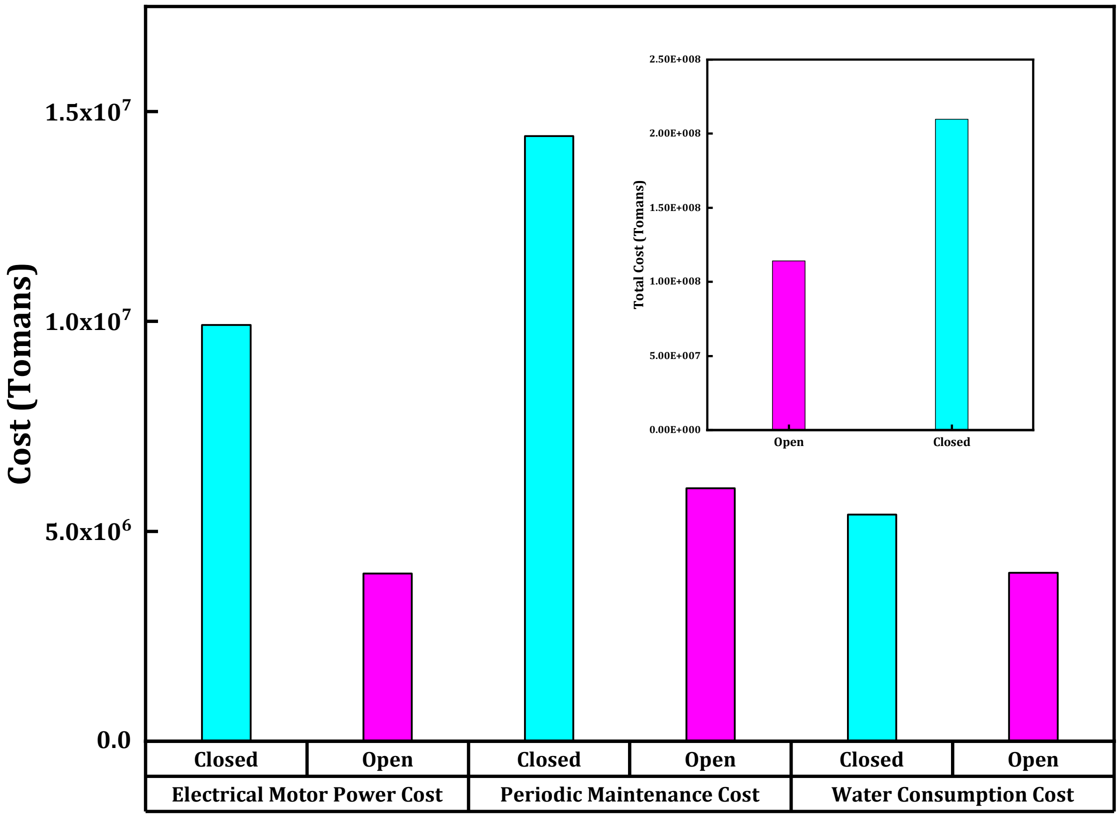

Fig. 9 Final results of the Monte Carlo method for incurred costs

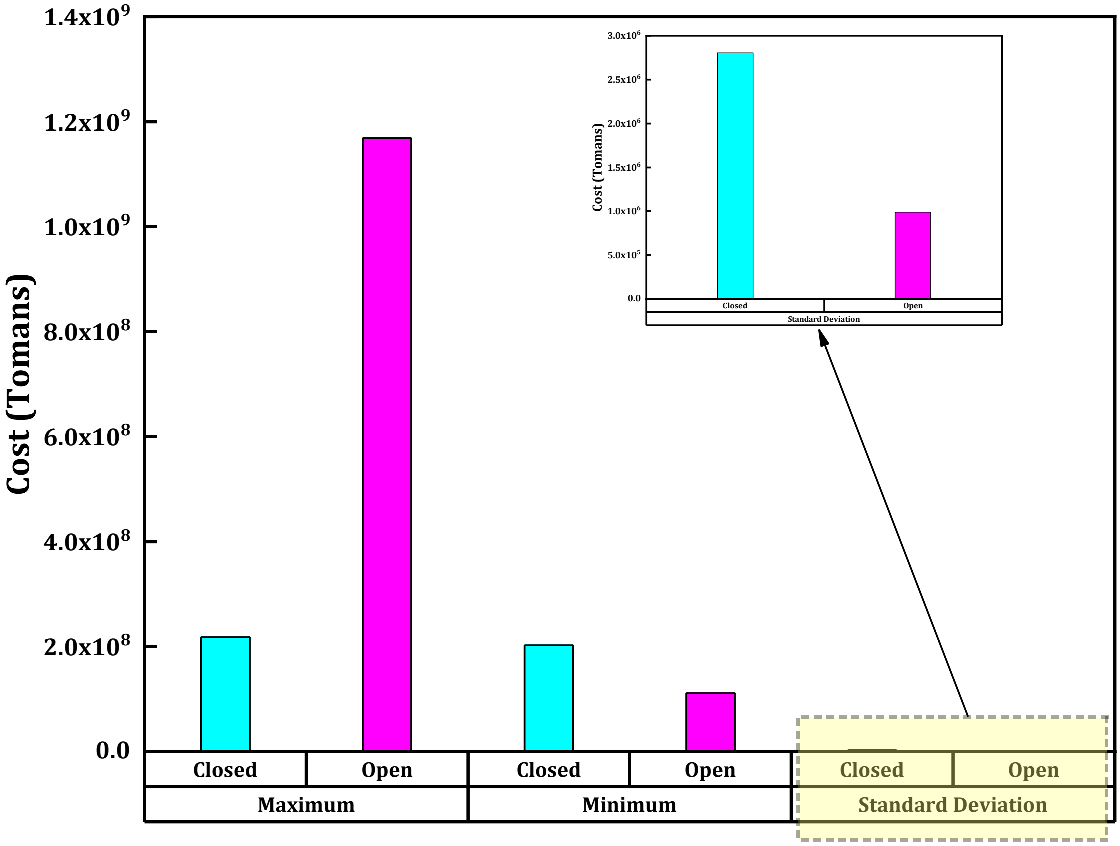

Fig. 10 Numerical Analysis of Monte Carlo Method Results

5- Discussion

Several factors influence the selection of a cooling tower type, including initial purchase cost, periodic maintenance expenses, energy consumption, water costs, environmental impact, and the specific operational requirements of the facility. For example, open cooling towers typically have lower initial capital costs, but in some cases, they consume more water, which can be a challenge in regions with limited water resources. In contrast, closed cooling towers require a higher upfront investment and more intensive maintenance, making their management more complex. Additionally, climatic conditions and the operational demands of the facility play a critical role. In regions where water quality and ambient temperature fluctuate, selecting a tower that aligns with these environmental factors can significantly affect overall system performance. Ultimately, these variables must be carefully evaluated using analytical tools such as the Monte Carlo method to ensure the most accurate and informed decision-making.

An open cooling tower incurs more stable and lower costs compared to a closed cooling tower. One of the main reasons is that the open cooling tower, due to its simpler design, involves lower costs in terms of maintenance, energy consumption, and water usage. This type of tower does not require additional equipment such as expensive pumps and heat exchangers, which are typically found in closed systems. Moreover, the operational costs of open towers are more predictable, as there are no significant fluctuations in energy or water consumption over time. Based on data analyzed using the Monte Carlo method, the standard deviation of costs for the open tower is lower (989,815 compared to 2,803,948 for the closed tower), indicating greater cost stability. Financially, this cost stability is highly valuable for companies, as it enables more accurate budget planning and reduces financial risks.

Risk analysis holds particular importance for closed cooling towers due to their higher costs and greater variability compared to open towers. As demonstrated in the Monte Carlo analysis, the higher standard deviation of costs in closed towers reflects greater fluctuations in operational expenses. This variability can lead to increased financial risk for investors and industrial users, as the unpredictability of costs may complicate budgeting and financial management. Moreover, the presence of high-cost scenarios—driven by the system's complex design and need for specialized maintenance—necessitates more meticulous planning. Risk analysis enables more accurate forecasting of such issues and supports more informed decision-making, which is especially critical in large-scale, capital-intensive projects.

The findings of this study, through comprehensive economic, environmental, and technical analyses, assist decision-makers in making more informed and intelligent choices. For instance, the assessment of maintenance costs, water usage, and energy consumption between the two types of cooling towers reveals that open cooling towers—due to their lower cost variability (i.e., lower standard deviation)—are better suited for reliable budgeting and more precise financial management. Moreover, the results indicate that open-loop systems offer greater efficiency in scenarios where lower operational costs and reduced financial risks are prioritized. This study enables decision-makers to adopt a more holistic perspective by considering long-term costs and environmental impacts, rather than focusing solely on initial capital expenditures.

6- Future directions

The findings of this study can be extended by examining the impacts of climate change on cooling tower performance and simulating diverse climatic conditions across different geographical regions.

Additionally, conducting more comprehensive sensitivity analyses to assess the influence of key parameters—such as energy costs and water consumption—on the final decision-making process could further enhance the proposed model. Moreover, integrating advanced technologies like artificial intelligence and machine learning models to predict tower performance under various scenarios can lead to more optimized design and operational strategies. For instance, collecting real operational data from existing towers and aligning it with simulation models enables the identification of performance patterns and system deficiencies. Subsequently, by integrating Internet of Things (IoT) technologies and smart control systems, a comprehensive management framework can be implemented—capable of autonomously adjusting system settings in response to environmental conditions and real-time performance metrics. This approach not only reduces operational costs but also enhances the efficiency and longevity of cooling systems, paving the way for more sustainable and adaptive thermal management solutions in industrial applications. Finally, a focused assessment of environmental impact and holistic sustainability analysis could pave the way for innovative solutions to promote the broader adoption of cooling towers.

Expanding cost and risk analysis under varying climatic conditions requires the implementation of multiple scenarios and the use of advanced statistical methods such as sensitivity analysis and Monte Carlo simulation. In this context, the first step involves collecting climate-related parameters—such as temperature, humidity, wind speed, and other meteorological indicators—and modeling them based on historical data and climate projections. Subsequently, by applying different variations to these parameters, system performance and related costs can be evaluated to determine the impact of climate change on operational, maintenance, and energy expenses. In addition, assessing risks and uncertainties resulting from seasonal fluctuations and extreme weather events—through probabilistic techniques and statistical distributions—can assist decision-makers in developing preventive strategies for unfavorable conditions. This approach allows for aligning the economic and risk models with diverse real-world scenarios, ultimately providing a comprehensive framework for cost and risk management in cooling systems.

examining the role of energy efficiency in reducing the environmental impacts of cooling towers can serve as a central focus in evaluating the performance of cooling systems. In fact, by improving energy efficiency, overall energy consumption is reduced, which in turn significantly lowers greenhouse gas emissions and other pollutants associated with energy production and use. This process can be assessed through a Life Cycle Assessment (LCA), in which energy consumption at each stage of the system’s life cycle—construction, operation, maintenance, and end-of-life—is considered, and the corresponding environmental impacts are quantified.

Moreover, a detailed analysis of energy efficiency enables the identification of performance shortcomings, which can guide future optimization and resource conservation efforts. Integrating real-world performance data with simulation models and sensitivity analyses can reveal optimal consumption patterns and support the development of effective management strategies to mitigate the environmental footprint of cooling towers.

The impact of climate change and varying ambient temperatures must be considered as one of the critical factors influencing the performance of cooling systems. As a continuation of the current work, it is recommended to incorporate historical climate data specific to the study region in order to capture temperature patterns and seasonal variations. However, to enhance the model's accuracy, it is further suggested that separate sensitivity analyses be conducted for different climatic conditions—such as temperature rise, changes in precipitation, and fluctuations in ambient humidity. This approach allows for a more precise assessment of climate change impacts on system performance and associated costs, and it facilitates the adaptation of the model to diverse geographical settings.

A LCA, which includes initial investment, maintenance, operational expenses, and end-of-life costs such as recycling or decommissioning, can provide a more comprehensive view of the economic efficiency of cooling towers. While this study primarily focused on analyzing operational and maintenance costs, incorporating a full LCA would more accurately capture hidden costs and long-term impacts. This approach enables decision-makers to consider not only ongoing expenses but also capital expenditures and the risks associated with each stage of the system's lifecycle, thereby facilitating the adoption of more economically optimized solutions.

7- Conclusions

The choice between an open or closed evaporative cooling tower depends on the specific needs of the factory, environmental conditions, and operational costs. Detailed analysis and comparison of various factors can help make the best decision to improve performance, reduce costs, and minimize environmental impacts. In this study, the feasibility of replacing a 200-ton capacity open evaporative cooling tower in an industrial plant in Iran with a closed evaporative cooling tower was assessed using the Monte Carlo method. Initially, the influential parameters were identified, and then, using 10000 iterations, the average values of the parameters were calculated. Finally, a technical-energy-environmental summary with an economic perspective was carried out. The main findings of this study are:

- Influential parameters such as periodic maintenance costs, water consumption costs, and electric motor fan power consumption costs were evaluated.
- For open and closed evaporative cooling towers, the periodic maintenance cost parameter as a percentage of the purchase price was assessed at 5-7% and 6-10%, respectively.
- For open and closed evaporative cooling towers, the water consumption cost parameter as a percentage of the purchase price was assessed at 3-5% and 2-4%, respectively.
- For open and closed evaporative cooling towers, the electric motor fan power consumption cost parameter as a percentage of the purchase price was assessed at 3-5% and 4-7%, respectively.
- The electric motor fan power consumption, water consumption, and periodic maintenance costs for the open evaporative cooling tower were estimated at 3993169 Tomans, 4013788 Tomans, and 6028513 Tomans, respectively, using the Monte Carlo method. These values for the closed evaporative cooling tower were estimated at 9911835 Tomans, 5394336 Tomans, and 14411129 Tomans, respectively.
- Due to having a lower standard deviation and lower maximum and minimum costs over 10000 generated data points by the Monte Carlo method, the open evaporative cooling tower is more stable, has lower risk, and also has better efficiency and productivity.
- If the periodic maintenance costs, electric motor power costs, and water consumption costs for the open and closed evaporative cooling towers are considered, the Monte Carlo method predicts that after approximately 6.4 years of using the closed evaporative cooling tower, the cost difference would be equivalent to purchasing an open evaporative cooling tower.

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