Simulation Project
Thermoelectric Plants Events System

Daniel Machado Pérez daniel.machado.0206@gmail.com

Daniel Toledo Martínez daniel.020126@gmail.com

Osvaldo R. Moreno P. osvaldo020213@gmail.com

Mathematics and Computer Science Faculty, University of Havana

June 2024

Contents

1 Abstract

This project focuses on simulating a system of thermoelectric plants that supply power to various circuits. Within this system, disruptions can occur, affecting the optimal functioning of the thermoelectric plants and reducing their capacity to meet circuit demand. To address these challenges, the system incorporates a scheduler capable of deciding between conducting maintenance on the thermoelectric plants or shutting down circuits. The simulation aims to investigate the system's performance over a defined period, conducting an analysis of the outcomes to enhance operational efficiency.

2 Introduction

2.1 Brief project description

The system under study comprises a collection of thermoelectric plants responsible for supplying power to various circuits. Each thermoelectric plant possesses a specific energy generation capacity, which can be affected by time-dependent events. These events are classified into two types: maintenance events and break events.

Break events occur when a thermoelectric plant enters a failure state, ceasing its energy generation. In such instances, the plant necessitates repairs, which require a defined duration. Upon the completion of these repairs, the thermoelectric plant returns to its normal operational state.

Maintenance events are initiated by the scheduler, which determines the necessity for maintenance based on specific criteria, such as the impending likelihood of a break event. During maintenance, the thermoelectric plant is temporarily removed from operation and enters a repair state. The duration of maintenance is intended to be shorter than that of a break event. Following maintenance, the thermoelectric plant resumes its energy generation capacity, contributing to the system.

Each circuit within the system has an energy demand that must be fulfilled by the thermoelectric plants. If the energy output from the thermoelectric plants falls short of the circuits' demands, the system experiences an energy deficit. In such scenarios, the scheduler must decide, based on specific criteria, which circuits to shut down and in what proportion. Shutting down a circuit implies that the circuit will not receive energy for a designated period, leading to a reduction in its demand by a certain percentage.

2.2 Objectives and goals

The study aims to compare different planning strategies for managing thermoelectric plants. Specifically, the effectiveness of the following heuristics in various scenarios will be evaluated:

- Waiting for breakdowns to occur before initiating repairs.
- Scheduling systematic maintenance for the thermoelectric plants preemptively, before potential breakdowns occur.

The analysis will be conducted across two distinct scenarios:

- Scenario 1: Electricity generation meets demand from the start because the system is sufficiently robust.
- Scenario 2: The system fails to meet demand initially due to its inherent characteristics and dimensions.

2.3 Variables describing the problem

To describe the problem, several variables are needed to represent the following phenomena:

- Time between breakdowns of a thermoelectric plant
- Repair time of a thermoelectric plant
- Daily energy demand of a circuit

2.3.1 Time between breakdowns of a thermoelectric plant

In the literature, the $Weibull(\alpha, \lambda)$ distribution is commonly used to model the distribution of failures in systems, where the failure rate is proportional to a power of time. Here, α is the shape parameter and λ is the scale parameter of the distribution.

- A value $\alpha < 1$ indicates that the failure rate decreases over time.
- When $\alpha = 1$, the failure rate is constant over time.
- A value $\alpha > 1$ indicates that the failure rate increases over time.

The parameter λ scales the distribution and estimates the "characteristic life" of the product, which is the time at which 63.2% of the equipment will have failed. Weibull analysis aids in predicting future failure behavior, facilitating maintenance planning, reducing unplanned downtime, and increasing overall system efficiency.

Probability Cumulative Function:

$$F(x) = 1 - e^{-(\lambda x)^{\alpha}}, \quad for x > 0$$

Values following a Weibull distribution can be generated using the implementation provided by Python's **random** library.

2.3.2 Repair time of a thermoelectric plant

The repair time of a thermoelectric plant can be modeled using a log-normal distribution, which is suitable for data that are positively skewed and have a long right tail, typical of repair times.

Properties of the Log-normal Distribution:

Mathematical Definition:
If X is log-normally distributed with parameters μ and σ^2, then $\ln(X) \sim N(\mu, \sigma^2)$.

Probability Density Function (PDF):

$$f_X(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left(-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)}, \quad for x > 0$$

Here, μ is the mean and σ^2 is the variance of the normal distribution of $\ln(X)$.

2.3.3 Daily energy demand of a circuit

The daily energy demand of a circuit can also be modeled using a log-normal distribution, as it typically exhibits similar characteristics to repair times, being concentrated towards higher values.

Values following a log-normal distribution can be generated using the implementation provided by Python's **random** library.

3 Implementation Details

The investigation was conducted using Python. The following libraries were utilized for data processing:

- `random` (`rnd`)
- `numpy` (`np`)
- `matplotlib.pyplot` (`plt`)

3.1 Implemented Classes

- **Weibull** and **LogNormal** classes were implemented for each thermoelectric plant to track their distribution parameters. Each of these classes uses the corresponding distribution from `rnd`.
- **ThermoElectric** and **Circuit** classes were created to track the characteristics of the entities, such as the generation capacity of each thermoelectric plant and its previous and future events. Circuits similarly track their electric demand value, their history of deficit values, and the total deficit value.
- The **Event** class is self-explanatory; this class contains information on when each thermoelectric plant breaks down and when it is repaired.
- The **Agent** class stores different planning strategies for various comparisons and subsequent data analysis.
- The **RoundRobin** class enables the rotation of circuits when power outages are necessary due to demand exceeding generation capacity.

3.2 Jupyter Notebook

Thermoelectric Generation

- The **Weibull** class receives a random value within a specified range in the notebook as α and a λ value also within a specified range in the implementation. (Note: The implementation of Weibull in `random` receives the scale parameter as the first parameter (α), and the shape parameter as the second parameter (λ)).
- The **LogNormal** class receives a random uniform value as μ and another random value between as σ^2.
- The electric generation has a random value between 200 and 1000.

Auxiliary methods are implemented to:

- Obtain the next general event given the current day.

- Determine the average working time of all thermoelectric plants given their final state over time after running a single simulation.
- Run a single simulation, with the output being the state of all thermoelectric plants during the simulation.
- Run k consecutive simulations with different parameters, with the output being the average working days after the k-th simulation.

3.3 Simulation

The **simulate** function models the operation of a set of thermoelectric devices over a specified number of days.

The function takes the following parameters:

- `thermoelectrics`: a list of thermoelectric devices to simulate.
- `days`: the number of days to run the simulation.
- `agent`: an optional agent that can manage the thermoelectrics and circuits.
- `circuits`: an optional list of circuits that the thermoelectrics are connected to.
- `stored_energy`: the initial amount of stored energy.
- `rotation`: the rotation strategy for the circuits.

The function initializes lists to keep track of the working state of the thermoelectrics, the energy deficit per day, and the stored energy per day.

The function then enters a loop that runs for the specified number of days. For each day, it calculates the total demand from the circuits, allows the agent to manage the thermoelectrics and circuits, and processes any events that occur on that day.

Subsequently, the function calculates the total energy supplied by the working thermoelectrics and the stored energy, and it computes the energy deficit and stored energy for the day.

Finally, the function returns lists representing the working state of the thermoelectrics, the energy deficit per day, the stored energy per day, and the circuits.

3.4 Agent Strategies

- `empty_strategy`: This strategy does not perform any actions.
- `give_maintenance_heuristic`: This strategy schedules maintenance for a thermoelectric plant if it has been operational for a number of days equal to the average break time, calculated using a k-simulation.

- `disconnect_circuit_heuristic`: This strategy disconnects the next circuit in a clockwise rotation for 1/4 of the time until the generation exceeds the consumption.

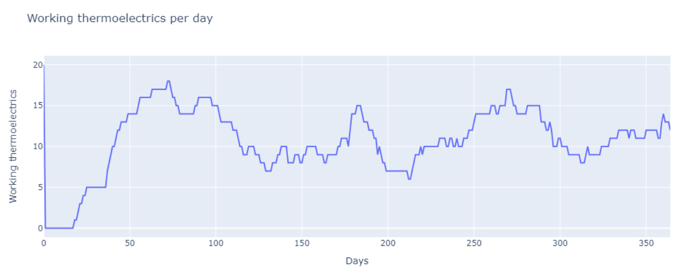
4 Results and Experiments

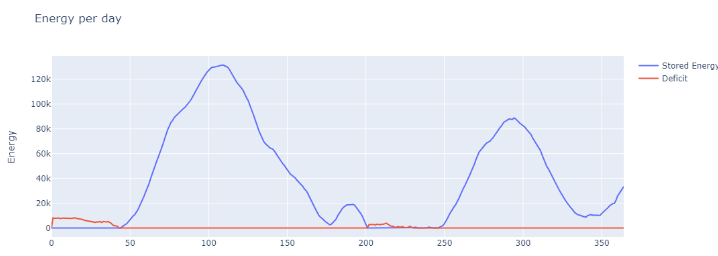
4.1 Simulation Findings

All experiments were conducted using 115 circuits associated with 20 thermoelectric plants, initially meeting the energy demand.

To better understand the system, a simple simulation was performed where daily statistics were collected on the number of operational thermoelectric plants, stored energy, and energy deficit.

The following graph illustrates the number of operational thermoelectric plants as a function of days. It also displays the amount of stored energy and the energy deficit as functions of days.





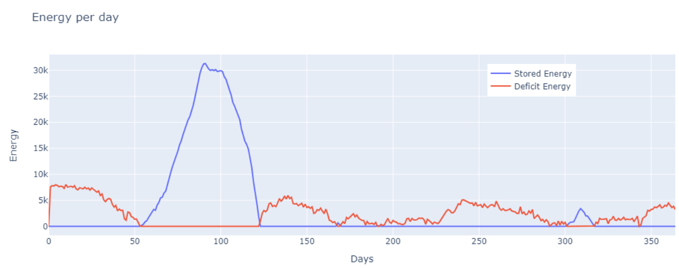
In this system, the demand from circuits associated with thermoelectric plants is largely met. However, between days 200 and 250, an energy deficit accumulates and then quickly recovers. Consequently, the number of operational thermoelectric plants during those days decreased significantly.

This observation leads to the consideration of implementing preventive maintenance on thermoelectric plants as a strategy to prevent the accumulation of energy deficits.

To develop this strategy, 10 simulations were performed with different independent variables to determine the expected day of a thermoelectric plant's outage due to breakage.

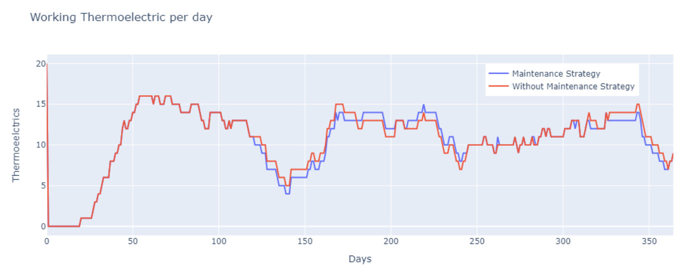
Based on this average, an operator was utilized that triggers maintenance for a thermoelectric plant when there is no energy deficit in the system and it has been operating for more days than the average expected days until breakage. To avoid multiple thermoelectric plants undergoing maintenance simultaneously, the maintenance is limited to a maximum of one plant per day. Additionally, it is important to note that preventive maintenance is shorter in duration than a typical repair after a breakdown.

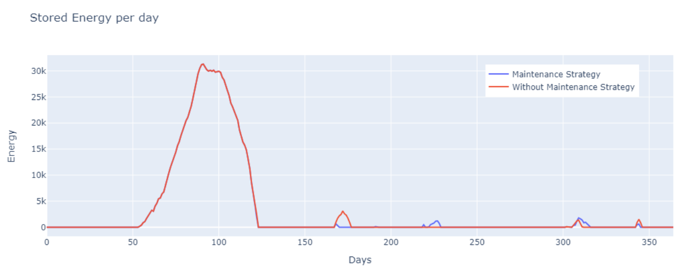
The following results were obtained:

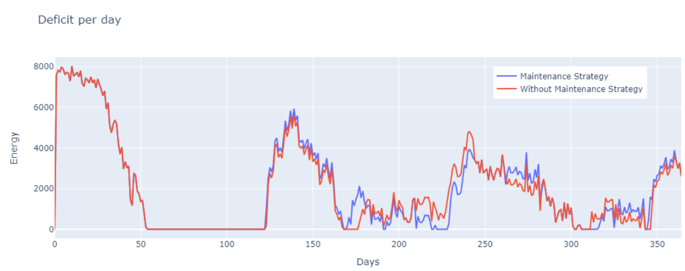


The effectiveness of the implemented preventive maintenance strategy remains inconclusive, prompting a need for deeper investigation.

Another strategy, although not significantly impactful in the previous analysis, serves as a preliminary approach for future exploration. This strategy involves employing RoundRobin to evenly distribute circuit shutdowns, thereby powering down a proportional segment of each circuit until the energy deficit for the day is resolved. The aim is to equitably distribute the operational impact across circuits and mitigate the recurring shutdowns of specific circuits.







4.2 Interpretation of the results

From the simulation analysis, it is observed that in systems where all necessary energy is provided, the strategy of refraining from proactive maintenance and instead waiting for breakdowns to occur before repair appears to yield better outcomes. This observation takes into consideration the aforementioned parameters. The reasons for this outcome could be attributed to imperfect parameter fitting due to the absence of real-world data, the limitations of macroscopic simulations, or the potential necessity for more refined strategies to achieve optimal results.

However, it is evident that when demand is satisfied, applying this strategy yields better results. This is because thermoelectric plants can undergo maintenance without causing operational disruptions or damage, thereby reducing repair times and enhancing energy generation efficiency.

4.3 Hypotheses Derived from the Results

The results of the simulations have led to the formulation of the following hypotheses:

- In scenarios where the system fails to meet demand and generates a deficit most of the time, the strategy of implementing systematic maintenance is as effective or more effective than refraining from maintenance until breakdowns occur.
- In contrast, in scenarios where the system comfortably meets demand, it is preferable not to conduct maintenance on the thermoelectric plants proactively but rather to wait for breakdowns to occur before initiating repairs.

4.4 Experiments Conducted to Validate the Hypotheses

Based on the hypotheses, the following experiment was designed to facilitate comparisons: Run a large number of simulations with the implementation of the strategy and an equal number without the implementation to gather the following statistics:

- The average number of operational thermoelectric plants on the i-th day across all simulations.
- The average energy deficit on the i-th day across all simulations.
- The average stored energy on the i-th day across all simulations.
- The average number of operational thermoelectric plants across all days of the simulations.
- The average energy deficit across all days of the simulations.
- The average stored energy across all days of the simulations.

Each statistic was calculated for each approach, and the final comparison yielded the following results:

Deficit Scenario

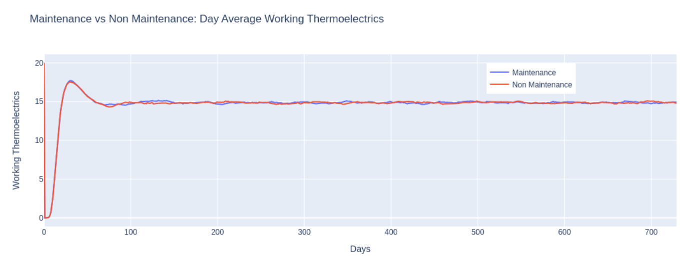
Non Maintenance
Average in 500 simulations:

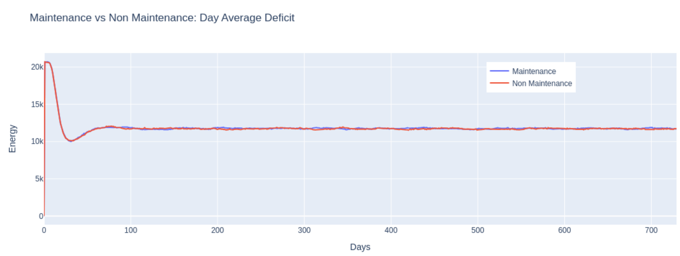
- Working Thermoelectrics: 14.691030136986301
- Deficit: 11839.281385171502
- Stored Energy: 0.0

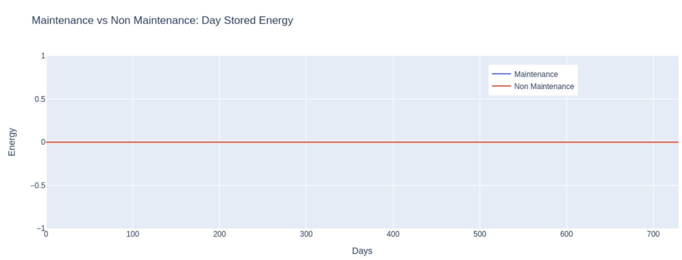
Maintenance

Average in 500 simulations:

- Working Thermoelectrics: 14.708687671232877
- Deficit: 11876.289282200563
- Stored Energy: 0.0







Scenario without Deficit

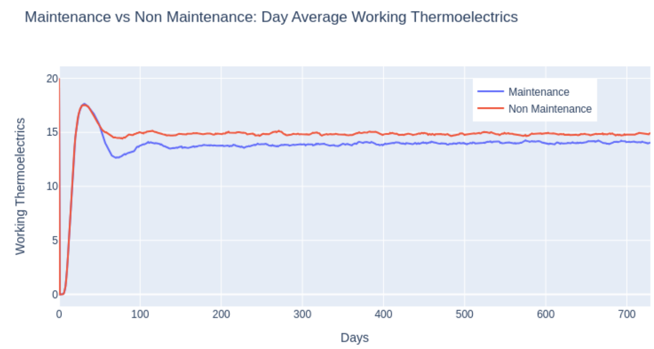
Non Maintenance
Average in 500 simulations:

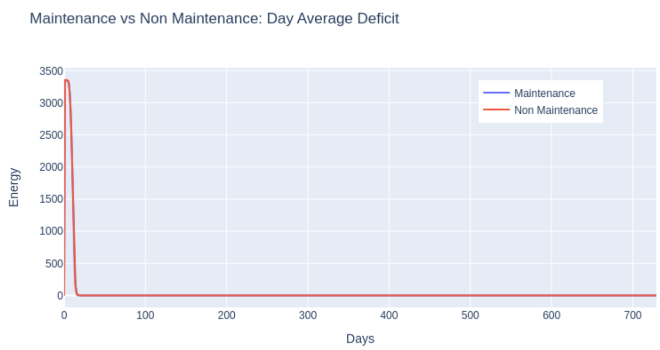
- Working Thermoelectrics: 14.687769863013699
- Deficit: 45.54689524173809
- Stored Energy: 1979794.462390682

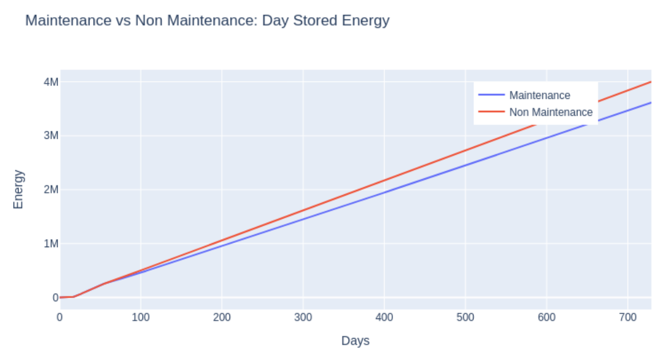
Maintenance
Average in 500 simulations:

- Working Thermoelectrics: 13.797731506849315
- Deficit: 45.47647307616969
- Stored Energy: 1782115.4892050272

As observed from the graphs and results, the experiments are consistent with the hypotheses.


Maintenance vs Non Maintenance: Day Average Working Thermoelectrics
Maintenance
Non Maintenance
Working Thermoelectrics
Days


Maintenance vs Non Maintenance: Day Average Deficit
Maintenance
Non Maintenance
Energy
Days


Maintenance vs Non Maintenance: Day Stored Energy
Maintenance
Non Maintenance
Energy
Days