Simulation Project
Thermoelectric Plants Events System

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1 Abstract

This project focuses on simulating a system of thermoelectric plants that provide power to various circuits. Within this system, events can disrupt the optimal functioning of the thermoelectric plants, reducing their capacity to meet circuit demand. To manage these situations, the system includes a scheduler that can choose to either perform maintenance on the thermoelectric plants or shut down a circuit. The simulation aims to study the system's behavior over a specific period and analyze the results to optimize its operation.

2 Introduction

2.1 Brief project description

The system consists of a collection of thermoelectric plants that supply power to various circuits. Each thermoelectric plant has a specific energy generation capacity, which can be impacted by events occurring over time. These events can be categorized into two types: maintenance events and break events.

Break events occur when a thermoelectric plant is in a failure state, causing it to stop generating energy. In such cases, the thermoelectric plant needs repairs, which require a certain duration. Once the repairs are completed, the thermoelectric plant resumes its normal operational state.

A maintenance event occurs when the scheduler decides that a thermoelectric plant needs maintenance based on a specific criterion, such as the potential proximity of a break event. In this case, the thermoelectric plant is taken out of circulation and enters a state of repair, which should be shorter than when a break occurs. Once maintenance is completed, the thermoelectric plant resumes supplying the system with its energy generation capacity.

Each circuit has an energy demand that must be met by the thermoelectric plants. If the energy produced by the thermoelectric plants is insufficient to meet the circuits' demand, the system experiences an energy deficit. In such a scenario, the scheduler must decide under what criteria and in what proportion to shut down a circuit. Shutting down a circuit means the circuit will not receive energy for a certain period, resulting in a certain percentage reduction in its demand.

2.2 Objectives and goals

We want to compare different planning strategies for managing thermoelectric plants. Specifically, we want to determine which of the following heuristics is more effective in certain scenarios:

- Always waiting for breakdowns to occur before carrying out repairs.
- Scheduling systematic maintenance for the thermoelectric plants before a potential breakdown occurs.

We want to analyze this in two different scenarios:

- Electricity generation meets demand from the start because the system is sufficiently robust.
- The system fails to meet demand due to its initial characteristics and dimensions.

2.3 Variables describing the problem

To describe our problem, we need variables that allow us 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

According to the literature, $Weibull(\alpha, \lambda)$ is a distribution commonly used to model the distribution of failures (in systems) when the failure rate is proportional to a power of time, where 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 is a scale factor that stretches or compresses the distribution. It provides an estimate of the "characteristic life" of the product, which is the time at which 63.2% of the equipment will have failed.

Weibull analysis helps predict the future failure behavior of a component or system. This predictive capability assists in planning maintenance activities, reducing unplanned downtime, and increasing overall system efficiency.

Probability Cumulative Function: $F(x) = 1 - e^{(-\lambda x)^{\alpha}}$, for $x > 0$
To generate values with a Weibull distribution, we use its implementation from the Python **random** library.

2.3.2 Repair time of a thermoelectric plant

A log-normal distribution is a probability distribution of a random variable whose logarithm is normally distributed. In other words, if a variable X follows a log-normal distribution, then $\ln(X)$ follows a normal distribution. The log-normal distribution is useful for modeling positive data that are asymmetric and have a long right tail, meaning that high extreme values are more common.

Due to this characteristic, such a distribution fits well in this part of our problem, as repair times are more likely to be concentrated towards the right (higher) end of the data.

Properties of the Log-normal Distribution:
Mathematical Definition: If X is a log-normally distributed random variable, then:
$X \sim \text{Lognormal}(\mu, \sigma^2) \Rightarrow ln(X) \sim N(\mu, \sigma^2)$
Here, μ and σ are the parameters of the normal distribution of $\ln(X)$, where μ is the mean and σ^2 is the variance.

Probability Density Function (PDF):
The probability density function of a log-normal distribution is defined as: $f_X(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left(-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right)}$, for $x > 0$

2.3.3 Daily energy demand of a circuit

Similarly, the daily energy consumption of a circuit can be modeled with a log-normal distribution, as it is assumed that the consumption would be concentrated towards higher values.

To obtain values with a log-normal distribution, the generator implementation from Python's **random** library was used.

3 Implementation Details

Our investigation was made using Python. As external sources, we used the following libraries for data processing:

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

3.1 Implemented classes

- Weibull and LogNormal for each thermoelectric to keep track of their distribution parameters, each of these classes uses the corresponding distribution from rnd.
- ThermoElectric and Circuit were created to keep track of our entities' characteristics such as every thermoelectric's generation capacity and its previous and future events. Circuits are a similar case, they have their electric demand value, their history of deficit values, and the total deficit value.
- Event class name is self-representative, this class contains when each thermoelectric breaks and when it's repaired.
- In the Agent class, we store the different planning strategies for all different comparisons and posterior data analysis.
- Finally, RoundRobin enables the rotation of circuits when it is necessary to have power outages because the demand exceeds the generation capacity.

3.2 Jupyter Notebook

Thermoelectric generation

- Weibull class receives as α a random value between 40 and 70 and a λ value between 1 and 3. (Note: The implementation of Weibull in **random** receives the scale parameter as the first parameter (α), and the second one is the shape parameter (λ))
- LogNormal receives a random uniform between 2 and 2.5 as μ and another random value between 0.2 and 0.4 as σ^2.
- The electric generation has a random value between 200 and 1000.

We have auxiliary methods to obtain the next general event given the current day, to determine the average working time of all thermoelectric plants given their final state over time after running a single simulation. We also have a method to run a single simulation, in which the output is the state of all thermoelectric plants during the simulation, and a method to run k consecutive simulations with different parameters, the output of which is the average working days after the k-th simulation.

3.3 Simulation

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

It 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.

It then enters a loop that runs for a 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.

The function then calculates the total energy offered from the working thermoelectrics and the stored energy and calculates the energy deficit and stored energy for the day.

Finally, it 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: does nothing
- give_maintenance_heuristic: gives maintenance to a thermoelectric if it has been working for a number of days equal to the average break time calculated with a k-simulation
- disconnect_circuit_heuristic: turn off the next circuit clockwise 1/4 of the time until generation is above consume

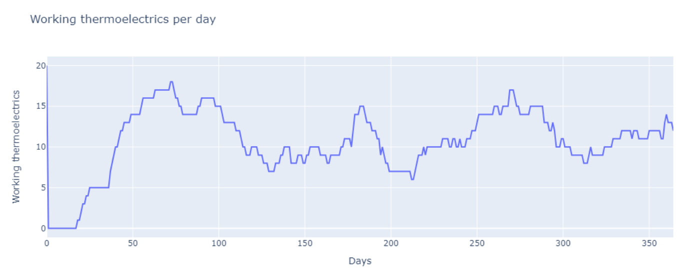
4 Results and Experiments

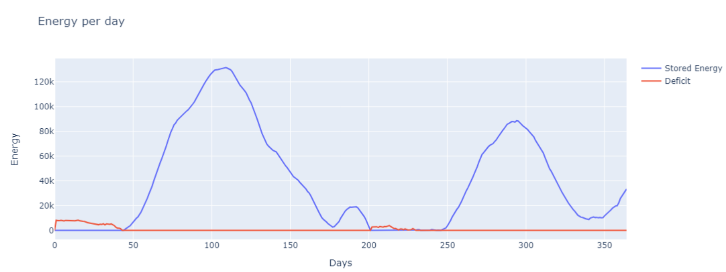
4.1 Simulation Findings

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

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

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





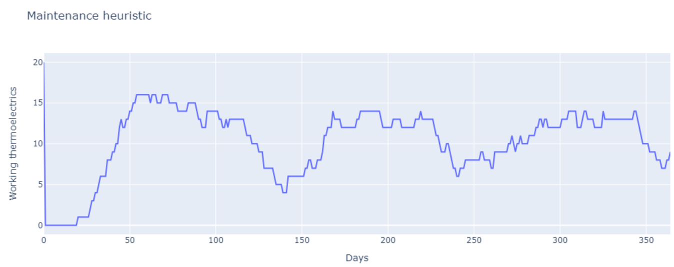
In this system, we observe that the demand from circuits associated with thermoelectric plants is largely met. However, between days 200 and 250, an energy deficit accumulates and then quickly recovers. Consequently, the number of operational thermoelectric plants during those days decreased significantly.

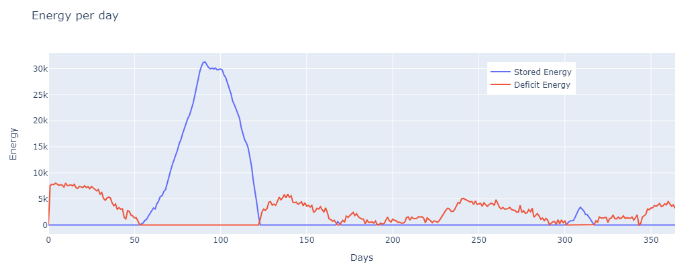
This leads us to consider the possibility of implementing preventive maintenance on thermoelectric plants as a strategy to prevent energy deficit accumulation.

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

Based on this average, we use an operator 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.

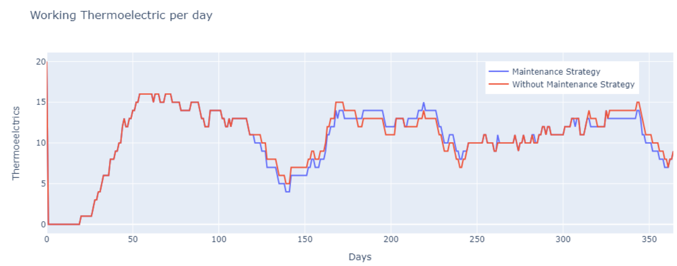
To avoid multiple thermoelectric plants undergoing maintenance simultaneously, we limit it to a maximum of one plant per day. Additionally, it is important to note that preventive maintenance is shorter in duration than a typical repair after a breakdown. We obtained the following results:

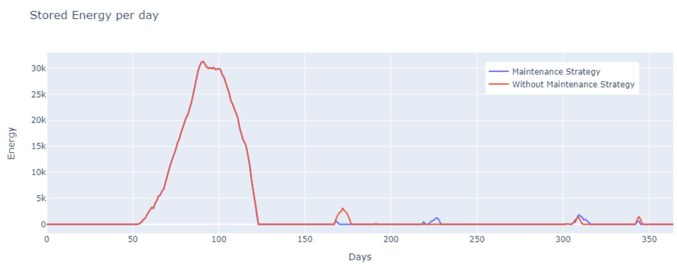


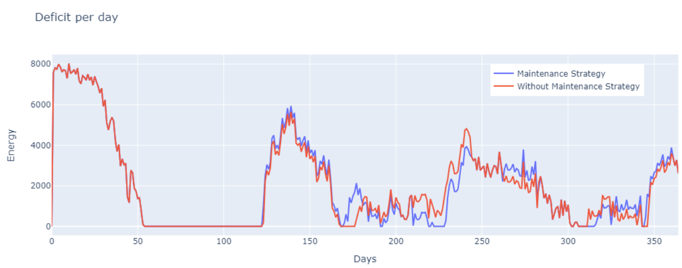


As can be seen, the energy deficit increased in the final days of the simulation.

Then we decided to simulate each case to better compare the results in the graphs, resulting in the following.







We really can't assure that this strategy is the best, so we will delve deeper into the topic later.

Another strategy, not influential in the previous analysis but that serves as a starting point for future ideas, was to decide to turn off the circuits evenly using RoundRobin, turning off a certain percentage of each circuit until the energy deficit for that day is met. This is to prevent the same circuit from always being affected

4.2 Interpretation of the results

From the simulation analysis, we could see that when we have a system that provides all necessary energy it is better to use the strategy of not providing maintenance and waiting for the breakdown to happen to repair, all this taking into account the parameters seen above. This result may be due to a poor fit of the parameters due to the lack of real data, the fact that the simulation is macroscopic, or because a better strategy is needed to obtain a better result. However, we can see that when demand is satisfied, applying this strategy allows us to obtain better results. This is because we can take them out of operation for maintenance without causing damage and reducing their repair time, allowing a better generation.

4.3 Hypotheses derived from the results

The results of the simulations led us to formulate the following hypotheses:

- In a scenario where the system fails to meet demand and a deficit is generated most of the time, the strategy of providing systematic maintenance is as effective or more effective than not providing it.
- In the opposite scenario, where the system comfortably meets demand, it is better not to provide maintenance to the thermoelectric plants, but rather to wait for breakdowns to occur before carrying out repairs.

4.4 Experiments conducted to validate the hypotheses

Given the hypothesis, the following experiment was designed to make comparisons:
Run a large number of simulations with the implementation of the strategy and an equal number without the implementation, to finally obtain the following statistics:

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

Each of the above statistics was calculated for each approach, and in the final comparison, we obtained the following results:

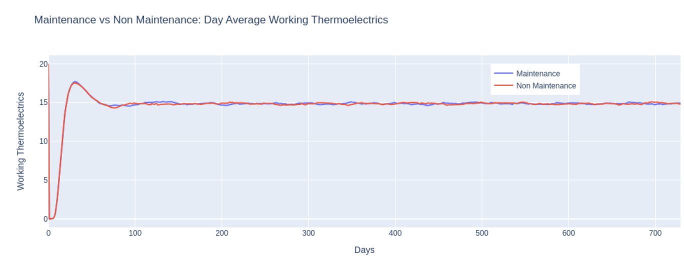
Deficit Scenario

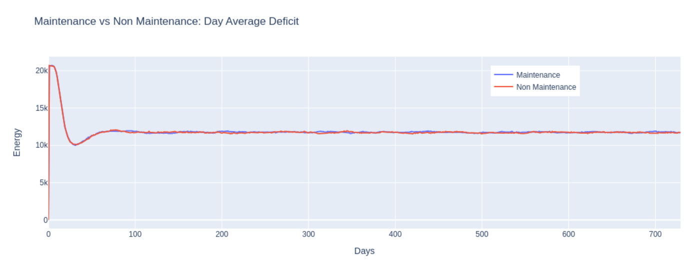
Non Maintenance
Average in 500 simulations:

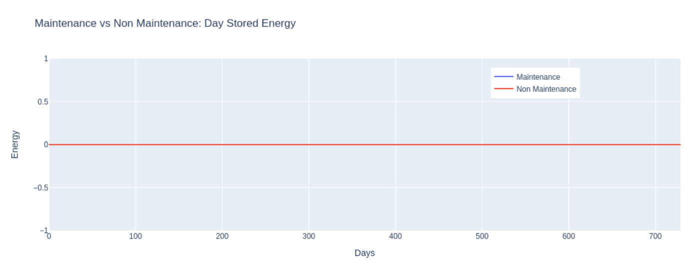
- Working Thermoelectrics: 14.691030136986301
- Deficit: 11839.281385171502
- Stored Energy: 0.0

Maintenance
Average in 500 simulations:

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







Scenario without Deficit

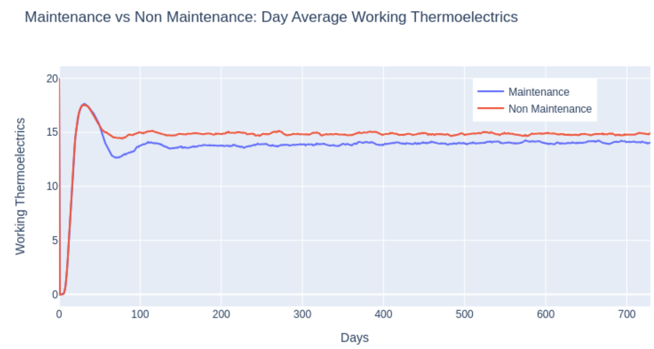
Non Maintenance
Average in 500 simulations:

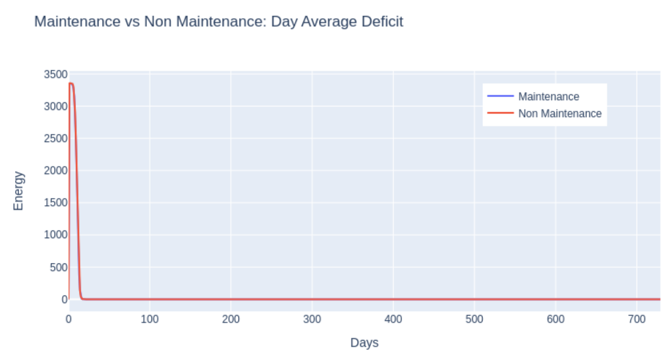
- Working Thermoelectrics: 14.687769863013699
- Deficit: 45.54689524173809
- Stored Energy: 1979794.462390682

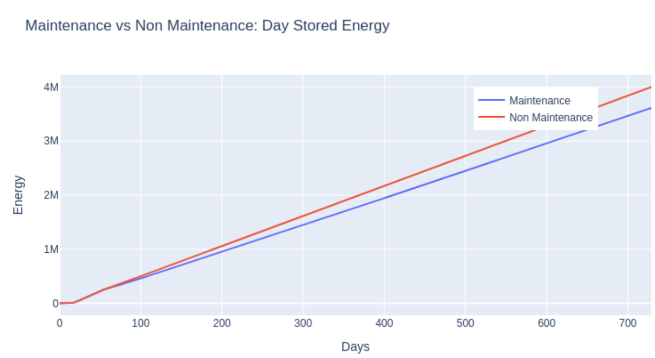
Maintenance
Average in 500 simulations:

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

As we can see from the graphs and results, the experiments are consistent with our hypotheses.


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


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


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