An Autonomous Serverless Fuzzy Logic-Based Decision Support System for Evaluating the Reliability of a Country's Electric Power System

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Abstract

In this article, we introduce an autonomous serverless fuzzy logic-based decision support system (DSS) designed to assess the reliability of an electric power system (EPS) at a country level and within its individual regions. Given this context, our work addresses the challenge of accurately assessing the reliability of an EPS on a large scale - a task that is complex due to the numerous interdependent variables at play. To resolve this issue, we propose building a system that leverages the capabilities of Microsoft Azure cloud computing services, including Azure Functions, Cosmos DB, Blob Storage, and message queue, while utilizing fuzzy logic as the foundation for its core operations. The DSS evaluates multiple input parameters, including power generation and consumption, air temperature, sunlight intensity, maintenance conditions, and meteorological factors, to derive a comprehensive assessment of EPS reliability. We provide an extensive overview of the system's high-level structural diagram, implementation specifics, and the methodology employed to configure the fuzzy logic components. The results obtained from the simulated test scenario demonstrate the potential of our proposed system to offer an assessment of EPS reliability. Furthermore, we discuss the outcome of the simulated test scenario that demonstrates the system's usability. In addition to these findings, we deliver a thorough analysis of the system's potential limitations and areas for its improvement.

Keywords

Decision support system, fuzzy logic, serverless architecture, web-based application, cloud computing.

1. Introduction

Modern society relies heavily on EPSs to power its infrastructure, residences, and businesses. It is vital to guarantee the dependability of such systems for the sake of sustained economic development, the security of the public, and a high standard of living. Numerous factors can influence the trustworthiness of energy provisioning systems, such as energy production, usage patterns, climatic conditions, upkeep levels, human errors, and constraints in the transmission network. A thorough evaluation method that considers each of these aspects is required to effectively assess the reliability of EPS. In this paper, we propose an autonomous serverless fuzzy logic-based DSS to assess the reliability of a country's electricity system and its separate regions.

Several studies have been conducted on evaluating the reliability of EPSs using various techniques. For instance, some studies presented new advanced intelligent strategies [1], while others created support vector machines for EPS stability analysis [2]. These studies underline the significance of establishing autonomous DSSs and reliability evaluation in EPSs.

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In recent years, fuzzy logic-based DSSs have gained significant popularity in addressing a broad spectrum of issues related to the decision-making process, owing to their ability to handle imprecision and uncertainty. Fuzzy logic offers a framework for knowledge representation and reasoning in circumstances where uncertainty and imprecision are mostly common. Fuzzy systems are capable of modeling complex systems without relying on a precise mathematical model and can incorporate human expert knowledge. As a result, they have been applied successfully in various fields, including control [3] and data mining. However, their replication and application require a high level of expertise.

Frequently, utilizing these systems necessitates substantial computational power and involves fluctuating workloads, which calls for resource augmentation as needed. In such instances, conventional server configurations can be rigid and costly to maintain. The growing appeal of serverless computing lies in its capacity to streamline the creation and implementation of applications. This approach eliminates server management responsibilities, enabling engineers to concentrate on devising effective solutions. Cloud service providers assume the task of administering and scaling the infrastructure according to the application's demands, offering benefits such as cost-effectiveness, adaptability, and diminished operational intricacy. Consequently, engineers can swiftly construct and deploy applications without concerning themselves with infrastructure oversight.

The main goal of this work is to develop and implement an innovative, autonomous serverless fuzzy logic-based (DSS) that can effectively evaluate the reliability of a country's EPS at both the country and regional levels. This goal stems from the increasing need to ensure the resilience and stability of power systems amidst the growing demand for electricity, the integration of renewable energy sources, challenges posed by climate change, and wars, where EPS infrastructure can be damaged. To achieve this aim, we have designed a system that harnesses the power of Microsoft Azure cloud computing services, specifically utilizing Azure Functions, Cosmos DB, Blob Storage, and message queue. By leveraging these advanced technologies, our proposed DSS offers a scalable, flexible, and cost-effective solution to assess EPS reliability, while maintaining the adaptability required to respond to the dynamic nature of power systems.

This paper is organized as follows: Section 2 provides reviews of existing solutions for assessing EPS reliability. Section 3 depicts the elements of the Microsoft Azure cloud infrastructure for the proposed DSS. Section 4 overviews the created relational databases in Cosmos DB, that aim to store data, referred to fuzzy logic and EPS reliability indexes. Section 5 explains the implementation of fuzzy logic. Section 6 outlines the process of generating, and processing test data as well as presents simulation results. Section 7 discusses future research directions. Finally, Section 8 concludes the paper.

2. State-of-the-art

Lately, there has been considerable advancement in the creation of DSSs for assessing the dependability of a nation's energy provisioning systems. Various methods have been investigated, encompassing fuzzy logic, machine learning, and artificial intelligence (AI) approaches.

The paper [4] proposes a DSS for managing flexibility in renewable energy source-operated power systems. The DSS aims to improve the efficiency and reliability of power systems by optimizing the use of flexibility resources, such as energy storage systems and demand response programs. The proposed DSS can help power system operators make informed decisions regarding the use of flexibility resources and improve the overall performance of renewable energy source-operated power systems.

The authors [5] propose a DSS for improving the energy efficiency of buildings in urban areas. The DSS employs remote sensing data, geographic information systems, and building energy simulation models to analyze the energy performance of buildings and identify opportunities for energy efficiency improvements. The article suggests a novel approach as one of the latest strategies for processing data, aimed at developing the most favorable energy scenarios in urban settings.

In this paper [6] the wind speed data collected and analyzed from 559 meteorological stations in Iran to evaluate the wind power potential of the regions. The study shows that the fuzzy logic-based approach is effective in evaluating the wind power potential and can provide valuable insights for investors in the renewable energy sector.

Another work [7] considers a comprehensive methodology for developing a fuzzy logic-based model that can accurately predict hourly power demand based on various factors. The authors claimed, that the suggested method can be used to model mechatronic or robotic plants.

This article [8] discusses a quantitative analysis of energy production methods in Chile, which aims to achieve a sustainable model of economic growth while respecting the environment and producing energy efficiently and reliably. The study uses the compromise ranking method to select the most sustainable energy production methods, considering nine major criteria prioritized using an analytical hierarchical process.

The authors of this paper [9] describe an innovative method for evaluating energy access in different regions of Mexico using fuzzy logic. The study ranks the regions according to their overall energy access, based on the country's political division into 32 states. The paper highlights the effectiveness and cost-efficiency of the proposed method, which can be used as an assessment tool to quantify the level of energy access in a particular region through qualitative data.

The paper [10] presents a fuzzy logic optimization method for the efficient location of voltage regulators and capacitors in radial distribution systems in developing countries, with a specific investigation of the Gondar power distribution system in Ethiopia. The paper describes the Gondar classification into different zones to ensure proper operation and supply of electricity. The voltage and power loss indices of the distribution system's nodes were modeled using fuzzy membership functions, and a fuzzy expert system was used to determine the voltage regulator and capacitor placement suitability index.

In this article [11] authors propose a new method for predicting electricity demand in the state of India. The proposed method is a modified k-means clustering for finding an optimal number of partitions on which fuzzy logic is applied. The study demonstrates that this method can provide accurate and efficient electricity demand forecasting.

The paper [12] focuses on the challenges of energy planning in cities characterized by high building intensity, where energy consumption is high. The article proposes a way to identify criteria that have the most significant impact on energy policy effects and the use of renewable energy in cities. The study analyses the results of tests that affect the energy potential of cities using various energy scenarios. The fuzzy logic and the geographic information system are used to assess them.

3. Microsoft Azure cloud infrastructure for the serverless fuzzy logic-based DSS

The motivation for selecting Azure as the foundation for the proposed DSS stems from the numerous benefits that this cloud computing platform offers, which are essential to achieve the primary objectives of our work. Azure's extensive range of services and features enable the seamless development and deployment of serverless applications. The suggested DSS benefits from a serverless strategy that offers a highly adaptable, elastic, and cost-efficient framework, seamlessly adjusting to the ever-changing demands of assessing electric power systems' dependability.

Additionally, leveraging Azure's cloud infrastructure eradicates the necessity for acquiring and preserving costly on-site equipment, consequently decreasing the overall cost of ownership, and simplifying the complexities typically linked to managing traditional infrastructure. Azure also guarantees excellent availability, resilience to faults, and rigorous security protocols, all of which are vital for protecting the data and procedures involved in evaluating the reliability of energy provisioning systems.

The proposed Microsoft Azure cloud infrastructure for the fuzzy logic-based DSS, the structural diagram of which is shown in Figure. 1, incorporates several critical components.

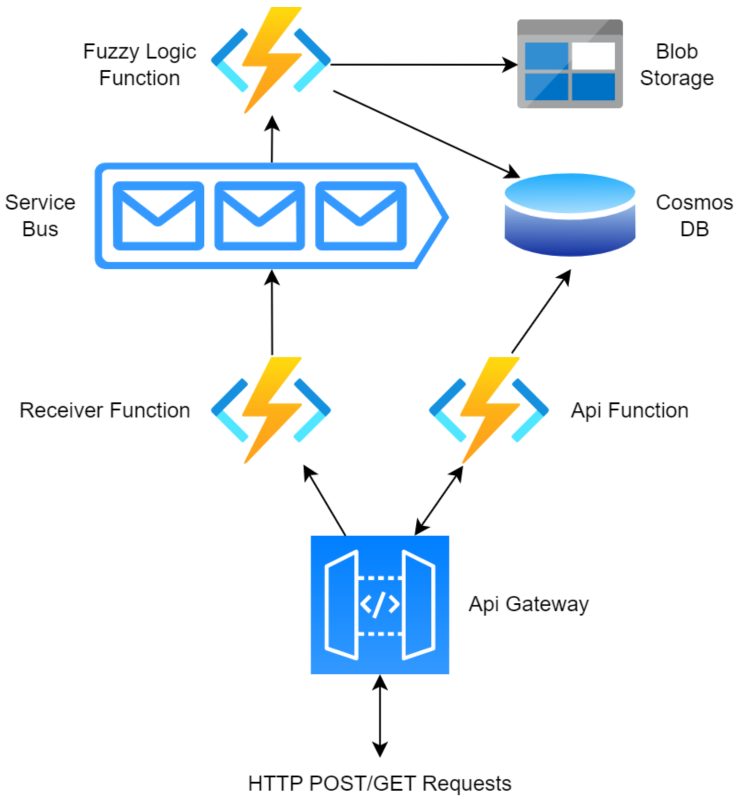

Figure 1: Microsoft Azure cloud infrastructure

The application programming interface (API) Gateway is the essential point of control for managing, securing, and monitoring API Functions. It provides access control by allowing only authorized users to obtain the reliability data while enforcing strict usage policies. This layer of protection ensures the prevention of unauthorized access and maintains data integrity within the system.

The Receiver Function, an HTTP-triggered Azure Function, oversees accepting and preprocessing incoming data. This function verifies the input data's validity, conducts required transformations, and subsequently deposits the preprocessed data into the Service Bus which is a message queue. The Receiver Function is activated by HTTP POST request.

The Service Bus serves as a message queue that separates the data reception process from the fuzzy logic processing. This decoupling allows for improved scalability and fault tolerance within the system. By segregating the processes, the system can efficiently manage high volumes of data without compromising reliability.

The Fuzzy Logic Function is also an Azure Function, that extracts data from the Service Bus (message queue) and processes it using fuzzy logic techniques. This processing calculates the reliability index of a country's EPS or specific regions. This function leverages the AForge.NET framework to implement fuzzy logic components such as linguistic variables, membership functions, fuzzy rules, and defuzzification methods. The Fuzzy Logic Function is triggered by the Service Bus.

Cosmos DB is a globally distributed, multi-model database service provided by Microsoft Azure. This database service stores the calculated reliability indices along with the associated input data and timestamps. The efficient storage and retrieval capabilities of Cosmos DB facilitate easy querying of the reliability data for further analysis and visualization. Additionally, Cosmos DB retains the information required to initialize the AForge.NET framework fuzzy inference module instance, including linguistic variables and fuzzy rules.

Microsoft Azure Blob Storage is employed to store the initialized AForge.NET fuzzy inference module instance. When the Fuzzy Logic Function is triggered, the stored instance is utilized, thus eliminating the need for reinitialization each time. This approach improves the system's efficiency and reduces resource consumption.

The API Function is an HTTP-triggered Azure Function designed to fetch the most recent reliability data from Cosmos DB and provide an API for external access. This function facilitates the querying of reliability data for the entire country or specific regions, allowing users to obtain insights into EPS reliability with ease. The API Function is triggered by a GET request.

The infrastructure presented forms the backbone of the serverless fuzzy logic-based DSS for evaluating the reliability of a country's EPS. Each component of the infrastructure plays a crucial role in achieving the desired scalability, fault tolerance, and efficiency. This infrastructure allows the DSS to provide valuable insights into the reliability of EPSs, empowering human experts to make informed decisions.

4. Relational databases in Azure Cosmos DB

Microsoft offers Azure Cosmos DB, a fully managed, globally distributed, multi-model database service. It is a NoSQL database that can support several data models, including document, key-value, graph, and column family, and can handle substantial amounts of unstructured data. For this work, only the column-family model was used, and Cosmos DB with its variety of proposed models was chosen for the future, as the system expansion may require the use of other models. Within one account, we decided to make two separate databases, each of which has its limited area of use.

The relational database named FuzzyDB contains interdependent tables that contain the necessary information for initializing the fuzzy module inside the Fuzzy Logic Function. Its diagram is shown in Figure 2.

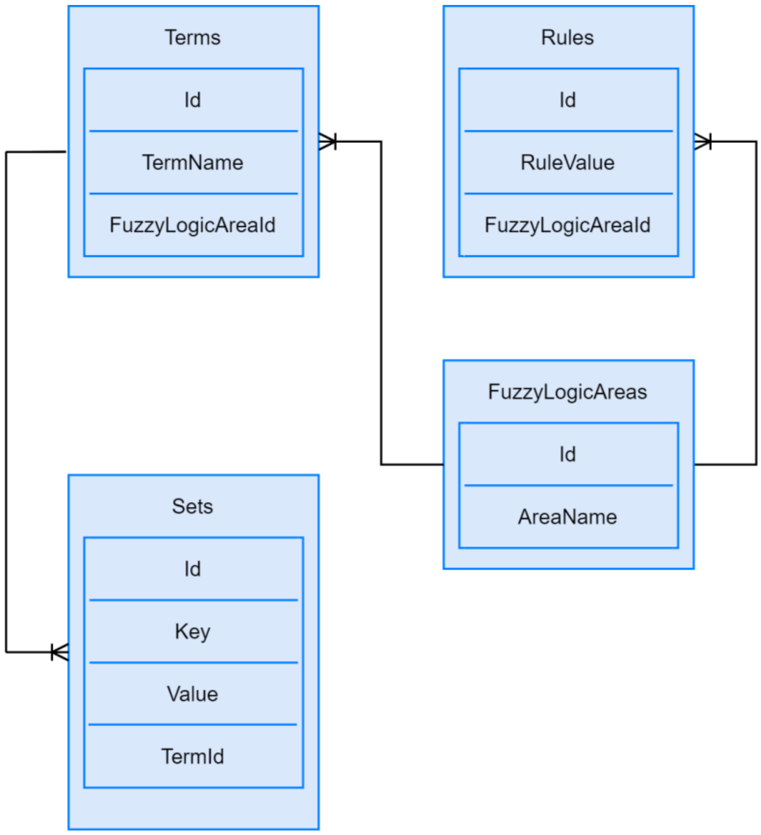

Figure 2: Relational FuzzyDB database diagram

The FuzzyLogicAreas table record has an AreaName property that corresponds to the topic area it solves. This table can contain many records because even a basic problem can be decomposed into parts and the separation of data and rules into categories can be performed.

It has a one-to-many relationship with Rules and Terms. A Term table record has a TermName String property that represents a linguistic variable. A term table stores a set of linguistic variables for a particular subject. This table has a one-to-many relationship with the Sets table.

The Sets table record has a key string property, which is the linguistic value that can be applied to the corresponding linguistic variable, and its numeric value, which is the Value double property.

A rule table record has a RuleValue String property that represents a rule in a specified format using a linguistic variable and its corresponding linguistic value. Rules are defined as IF-THEN constructs.

The relational database named EPS_Reliability contains interdependent tables that are used to store countries, regions, and EPS reliability values. Its diagram is shown in Figure 3.

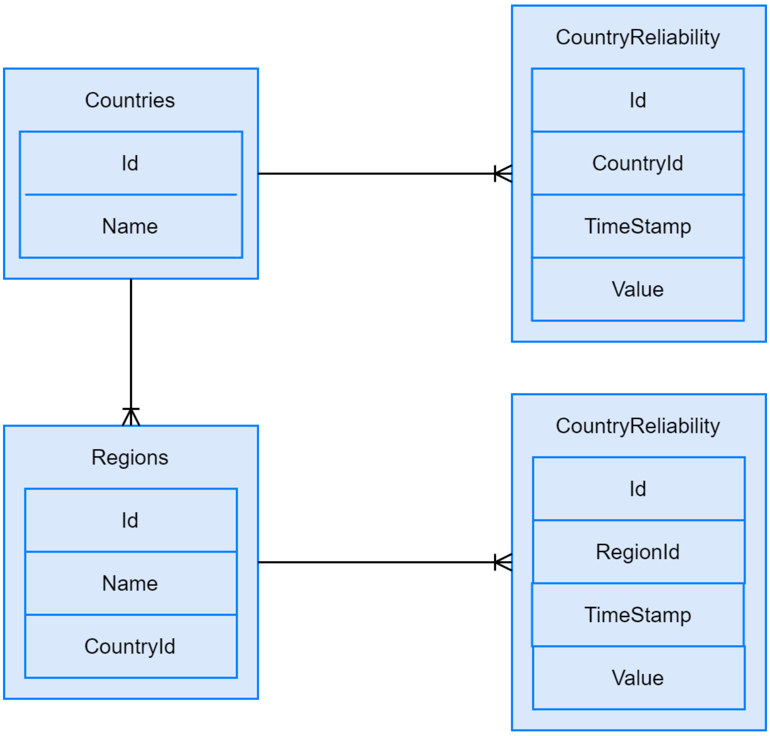

Figure 3: Relational EPS_Reliability database diagram

The system can process information from many regions of the same country, or different countries, and store the result – EPS reliability value, including the evaluation time.

5. Fuzzy logic implementation

Fuzzy logic is a mathematical technique that simulates ambiguity and imprecision using fuzzy set concepts. In contrast to traditional set theory, which stipulates that an element either belongs or does not belong to a set, fuzzy sets permit partial membership, with values spanning from 0 to 1. Fuzzy logic has found extensive applications in diverse areas, including control systems, decision-making processes, and expert systems, owing to its capacity to manage inexact and uncertain information.

A fuzzy set $A^{\sim}$ in the universe of information U can be defined as a set of ordered pairs and it can be represented mathematically as

$$A^{\sim} = \{ (y, \mu A^{\sim}(y)) \mid y \in \mathrm{U} \}, \quad (1)$$

where $\mu A^{\sim}(y)$ is the degree of membership of y in $A^{\sim}$ and assumes values in the range from zero to one, so that:

$$\mu A^{\sim}(y) \in [0,1]. \quad (2)$$

The first step in implementing fuzzy logic is to define linguistic variables and their associated membership functions. Linguistic variables represent input and output parameters in a fuzzy logic system, and membership functions describe the degree to which an element belongs to a fuzzy set. The process of defining linguistic variables as well as their linguistic and numeric values should involve a human expert. All this data is stored in the database and is used later for initializing fuzzy inference module instance.

For our system, we defined the following linguistic variables for input and output as shown in Table 1.

Table 1
Linguistic variables for fuzzy logic

Linguistic Variable	Type	Value 1	Value 2	Value 3
Power generation	Input	Low	Medium	High
Power consumption	Input	Low	Medium	High
Air temperature	Input	Cold	Mild	Hot
Sunlight intensity	Input	Low	Medium	High
Maintenance status	Input	Poor	Fair	Good
Weather status	Input	Bad	Normal	Good
Reliability index	Output	Low	Medium	High

The membership functions for these linguistic variables can be triangular, trapezoidal, Gaussian, or other shapes, depending on the specific application and domain knowledge. We have chosen the triangular membership function and Figure 5 shows an example of it for the Air temperature linguistic variable.

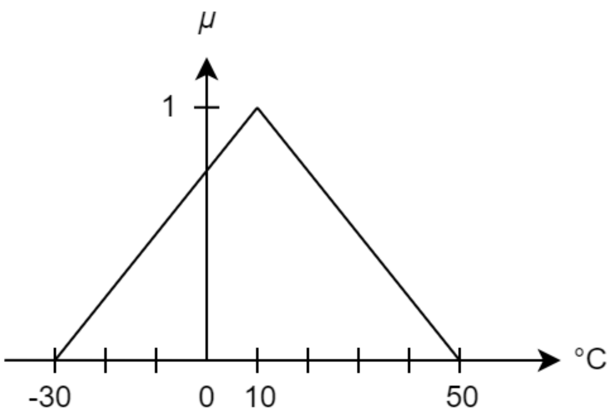

Figure 5: Triangular membership function for the Air Temperature linguistic variable

After defining linguistic variables and membership functions, there should be created a fuzzy rule base. The fuzzy rule base is a set of IF-THEN rules that describe the relationships between input and output linguistic variables. These rules are usually derived from domain knowledge or expert opinions. Rules are also stored in the database.

The fuzzy inference mechanism (Fig.6), which is implemented in the AForge.NET framework, that is used by the Fuzzy Logic Function, processes input data by evaluating the rules in the fuzzy rule base and determining the degree of fulfillment for each rule. The resulting values are combined to produce a fuzzy output set. For the purpose of our work, the fuzzy inference mechanism computes the fuzzy output set for the Reliability index linguistic variable.

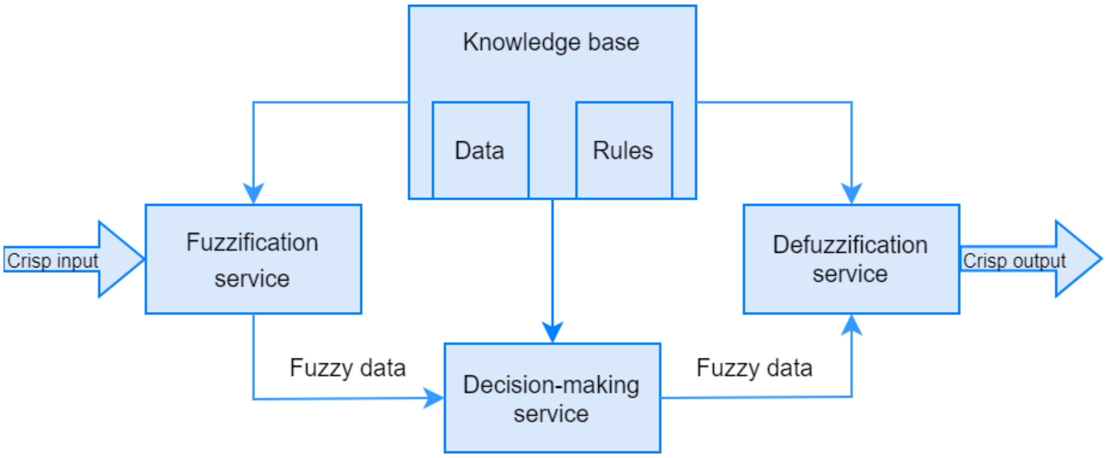

Figure 6: Fuzzy inference mechanism

The final step in the fuzzy logic process is defuzzification, which converts the fuzzy output set into a crisp value. Various defuzzification methods can be employed, such as the centroid method, the maximum membership method, or the weighted average method. We use the centroid method, which calculates the crisp output value as the center of gravity of the fuzzy output set. This method provides a good balance between computational complexity and accuracy.

6. Results

To evaluate the performance and effectiveness of the proposed system, we generated simulated test data that closely resembles real-world data. The test data includes power generation, power consumption, air temperature, sunlight intensity, maintenance status, and weather status for various regions within Ukraine. To generate the test data, we use the following approach (Fig.7): collect historical data for each input parameter from public datasets, industry reports, and governmental sources, analyze the collected data to identify trends, patterns, and correlations between variables, create statistical models based on the analysis to simulate realistic data for each input parameter, combine the simulated data for each input parameter to create a complete dataset representing various regions within the country.

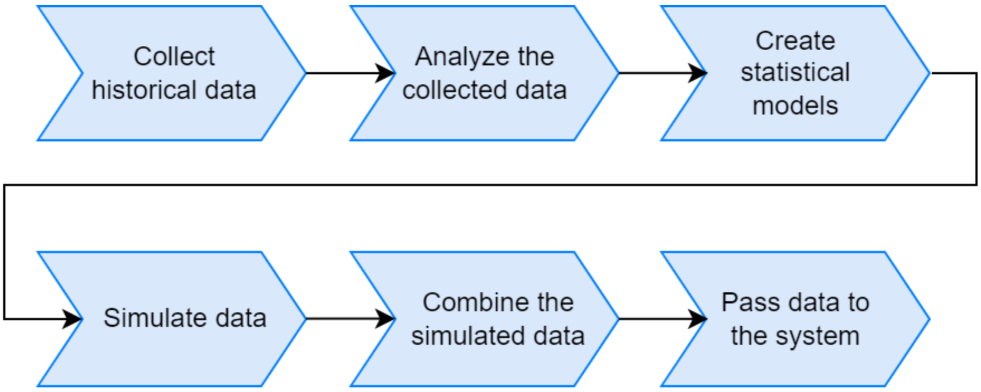

Figure 7: The process of generating test data

Once the test data is generated, it is sent to the Data Receiver Function for preprocessing. The Data Receiver Function validates the received data, performs necessary transformations, and stores the preprocessed data in the message queue. The Fuzzy Logic Function retrieves the data from the message queue and processes it using fuzzy logic to compute the reliability index for the country and individual regions. The computed reliability indices are stored in Cosmos DB.

The latest reliability data can be accessed through the API Function. The API supports querying reliability data for the entire country or specific regions, enabling users to easily obtain insights into the electrical system's reliability.

To analyze the results, we generated a heatmap diagram that displays the EPS reliability rating for 5 regions during the day with a time interval of 4 hours. As depicted in Figure 8, the heatmap diagram can aid a human expert in pinpointing trends, patterns, and possible concerns related to the reliability of the EPS.

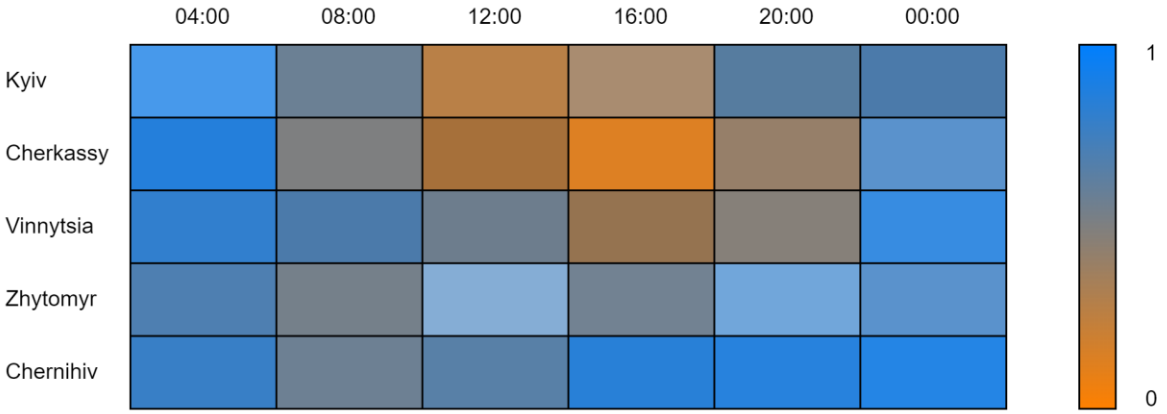

Figure 8: Regions' EPS reliability heatmap

7. Future work

One of the main tasks in the near future is refining the fuzzy logic model to improve the accuracy and comprehensiveness of the reliability assessment. It would be valuable to incorporate additional input parameters into the fuzzy logic model, such as grid topology, load profiles, and network congestion. This extension would facilitate a more holistic understanding of the factors affecting EPS reliability.

Another important task is exploring deeply machine learning techniques. Investigating the potential application of machine learning techniques, such as neural networks or support vector machines, could provide valuable insights into their efficacy in predicting the reliability of electrical systems. This research may lead to the development of a complementary or alternative model to the fuzzy logic approach, offering improved predictive capabilities.

Another challenge that must be tackled is the creation of hybrid architecture. To address data privacy, security, and latency concerns, it is advisable to consider developing a hybrid structure that merges the advantages of serverless computing and edge computing. This method enables localized data processing, diminishing the constant data transmission to the cloud while preserving the scalability and adaptability inherent to the serverless model.

And, finally, a crucial step in validating the proposed system is to evaluate its performance using real-world data and compare the results with traditional approaches to electrical system reliability assessment. This analysis will provide a more robust understanding of the system's capabilities and potential for practical deployment in monitoring and evaluating EPS reliability.

8. Conclusion

The proposed autonomous serverless fuzzy logic-based DSS offers several advantages for evaluating the reliability of a country's EPS. Utilizing Microsoft Azure cloud computing services, the DSS provides scalability, flexibility, and cost-effectiveness while eliminating the need for on-premises hardware. The incorporation of fuzzy logic allows for robust decision-making, accommodating uncertain and imprecise input parameters to deliver accurate reliability assessments. By evaluating a diverse range of inputs, the system offers a comprehensive analysis and valuable insights for human experts. The cloud-based architecture enables seamless integration with existing infrastructure and promotes interoperability. Azure's security measures protect data integrity and confidentiality, while the modular design of the DSS supports continuous improvement through the integration of future enhancements, such as machine learning techniques or hybrid architectures, further boosting the system's performance and capabilities.

Our research findings demonstrate the potential of the proposed serverless framework for evaluating the reliability of EPSs, showcasing its capacity to function as intended. A visual representation using a heatmap of the reliability metric offers a comprehensive understanding of the EPS stability throughout distinct regions, allowing human experts to effortlessly pinpoint areas in need of attention.

The novelty aspect of our work lies in the seamless integration of autonomous serverless architecture with the fuzzy logic model, creating a new framework for evaluating the reliability of a country's EPS. This synthesis is, to the best of our knowledge, the first to use cloud-based serverless technology alongside fuzzy logic in this specific context. This research pushes the boundaries of conventional EPS reliability assessment methods, offering a new direction in this crucial field.

Although our research yields encouraging outcomes, it is crucial to recognize the limitations linked to the suggested system. Primarily, the precision of the fuzzy logic model is contingent upon the input data's quality, the choice of suitable membership functions, and the formulation of fuzzy regulations. Ensuring the optimal configuration of these components requires domain knowledge and expert input. Additionally, the test data used in our simulation is artificial, potentially not wholly reflecting actual-world situations. The system's efficacy in real-world contexts might differ based on the input data's quality and characteristics. The serverless structure and dependence on cloud-based services could give rise to issues surrounding data privacy, security, and adherence to regulations. Addressing these concerns requires careful planning and adherence to best practices in cloud security.

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