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Congestion management: Human decision-making under forecast uncertainty

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Abstract

The integration of renewable energy sources (RES) into the electrical grid represents a significant stride towards a sustainable and low-carbon energy system. However, this integration also introduces a new source of uncertainty, as RES output depends on weather conditions and other variable factors. Forecast uncertainty arising from these fluctuations can profoundly impact grid stability and reliability. Therefore, effective communication of forecast uncertainty and risk becomes imperative, empowering decision-makers in electrical grid control rooms to make informed and resilient choices in the face of uncertainty.

In this thesis, is given an extensive review of the state-of-the-art in the domains of uncertainty forecasting, congestion management, and decision-making under forecast uncertainty within electrical grid control rooms. Throughout this review are identify critical challenges and opportunities concerning the communication of forecast uncertainty and risk.

Our analysis uncovers a pressing need for more robust communication strategies that facilitate the comprehension of forecast uncertainty and its associated risks in electrical grid control rooms. Additionally, the demand for more resilient decision-making frameworks capable of handling the dynamic and intricate nature of the grid becomes evident. By addressing these challenges, we envision a future where decision problems can be effectively formulated, and methodologies for evaluating decision quality and characterizing decision-maker's risk profiles are established.

Ultimately, this research seeks to enhance grid control strategies, foster greater grid stability, and ensure the continued integration of renewable energy sources to build a sustainable energy future.

Resumo

A integração das fontes de energia renováveis na rede eléctrica representa um passo significativo no sentido de um sistema energético sustentável e com baixas emissões de carbono. No entanto, esta integração também introduz uma nova fonte de incerteza, uma vez que a produção destas energias depende das condições meteorológicas e de outros factores variáveis. A incerteza das previsões decorrente destas flutuações pode ter um impacto profundo na estabilidade e fiabilidade da rede. Por conseguinte, a comunicação eficaz da incerteza e do risco das previsões torna-se imperativa, permitindo que os decisores nas salas de controlo da rede eléctrica façam escolhas informadas e resilientes face à incerteza.

Nesta tese, fazemos uma revisão exaustiva do estado da arte nos domínios da previsão da incerteza, da gestão de congestionamentos e da tomada de decisões sob incerteza de previsão nas salas de controlo da rede eléctrica. Ao longo desta revisão, identificamos desafios e oportunidades críticos relativos à comunicação da incerteza e do risco da previsão.

A nossa análise revela uma necessidade premente de estratégias de comunicação mais robustas que facilitem a compreensão da incerteza das previsões e dos riscos associados nas salas de controlo da rede eléctrica. Além disso, torna-se evidente a necessidade de estruturas de tomada de decisão mais resilientes, capazes de lidar com a natureza dinâmica e intrincada da rede. Ao abordar estes desafios, prevemos um futuro em que os problemas de decisão possam ser formulados de forma eficaz e em que sejam estabelecidas metodologias para avaliar a qualidade da decisão e caraterizar os perfis de risco dos decisores.

Em última análise, esta investigação procura melhorar as estratégias de controlo da rede, promover uma maior estabilidade da rede e assegurar a integração contínua de fontes de energia renováveis para construir um futuro energético sustentável.

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“ The greater danger for most of us is not that our aim is too high and we miss it, but that it is too low and we reach it ”

Michelangelo

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List of Abbreviations

RES	Renewable Energy Sources
ELF	Electric Load Forecasting
ESS	Energy Storage System
AI	Artificial Intelligence
SCADA	Separated Supervisory Control and Data Acquisition
EMS	Energy Management System
BMS	Business Management System
TSOs	Transmission System Operators
EERA	European Energy Research Alliance
WoC	WEB-of-Cells
HMI	Human-Machine Interface
OPF	Optimal Power Flow
MPC	Model Predictive Control
TP	True Positive
FN	False Negative
FP	False Positive
TN	True Negative
TC	Total Cost
L	Loss
HV	High Voltage
MV	Medium Voltage
WPP	Wind Power Plant
CHP	Combined Heat and Power Unit

Chapter 1

Introduction

The central focus of this dissertation is to understand the role of forecast uncertainty and risk in the operation of the electrical grid, and on identifying ways to improve the communication of this uncertainty and risk to enable more informed and effective decision-making in control rooms.

1.1 Problem Definition

As concerns about climate change continue to rise, there is an increasing demand for energy sources that are not dependent on limited resources and contribute to zero carbon emissions. Renewable energy sources such as hydro, solar, and wind have the potential to help address this need, but they are also subject to uncertainties that can impact their reliability as energy.

Variability is an inherent characteristic of renewable energy because they are dependent on the weather, which is unpredictable. As a result, the amount of energy that can be provided by these sources may change substantially, leading to significant uncertainty in power output. The grid operators who are in charge of balancing supply and demand may find this instability in power output a real challenge to deal with.

To address this uncertainty, grid operators rely on forecasts, which are based on weather models and historical data, to predict the amount of renewable energy that will be generated in a given period, and this information is used as the basis for grid management decisions. However, accurately forecasting renewable electricity generation can be difficult because weather patterns can change rapidly and renewable output does not always match expected output. Grid operators can face difficulties due to this forecast uncertainty, as they have to balance the need to integrate renewable energy sources against maintaining the stability and reliability of the grid.

In summary, the primary problem addressed in this thesis is how to effectively predict and define a set of actions like topology changes and flexibility activation that can proactively resolve power grid challenges arising from renewable energy forecast uncertainties

1.2 Motivation and objectives

Effective communication of forecast uncertainty and risk is a critical factor in the operation of the electrical grid and has the potential to improve the reliability, efficiency, and cost-effectiveness of the grid. However, there are still many challenges and opportunities related to the communication of forecast uncertainty and risk in control rooms, and there is a need for further research to better understand these challenges and opportunities. The motivation relies on this need to better understand the benefits and limitations of using probabilistic forecasting in different decision-making scenarios

The aim is to build a decision experiment based on these uncertainties in the electrical grid where various individuals will be presented with different and realistic use cases and when faced with a possible congestion they will have to decide how to manage it based on the information and actions provided. All the inputs provided by the user were stored in a database and will be used for conducting an experimental analysis of the users' answers and to analyze the outcomes of the experiment.

1.3 Document Structure

This thesis is organized into five chapters.

Chapter 1 sets the stage by presenting a clear problem definition, identifying the core challenges in dealing with uncertainty forecasts and congestion management in the context of electrical grids. The chapter also outlines the motivation and objectives of the research, providing a glimpse of the goals to be achieved. Moreover, the document structure is introduced, providing readers with an overview of what to expect in the subsequent chapters.

In Chapter 2, the state-of-the-art in uncertainty forecasts is explored. It covers the distinction between probabilistic forecasts and deterministic forecasts, emphasizing the importance of effectively communicating forecast uncertainty. Applications of uncertainty forecasts in various contexts are also discussed. Additionally, the chapter delves into the evolution of dispatch and control centers in the context of electrical grids, examining their visualization, present status, and future prospects. The chapter concludes by analyzing congestion management techniques, including optimal power flow and predictive voltage problem solutions.

Chapter 3 focuses on the development of the decision game, a framework designed to address uncertainty forecasts and congestion management challenges. It explains the decision game and its underlying function cost. Moreover, the chapter explores the study cases, distinguishing between deterministic and probabilistic information. The software and database components essential for implementing the decision game are also discussed, along with the limitations that should be taken into consideration.

Chapter 4 presents the outcomes and findings of the research. It analyzes the user feedback obtained through the decision game, comparing deterministic and probabilistic choices made within the framework. The chapter interprets the experiment outcomes for each scenario, drawing conclusions from the analysis. Furthermore, a comparison of the results is provided, shedding light on the strengths and weaknesses of each approach. Additionally, the chapter evaluates the decision game's performance using the Confusion Matrix and explores various performance metrics, providing a detailed analysis of the model's effectiveness.

In the final chapter, the thesis concludes by summarizing the main findings and contributions of the research. It revisits the problem definition and highlights the achievements in addressing uncertainty forecasts and congestion management challenges through the decision game. The chapter also offers insights into possible future research directions and applications of the framework. Ultimately, this chapter provides a comprehensive wrap-up, cementing the significance and impact of the research presented in the thesis.

Chapter 2

State-of-the-art

In this chapter, the aim is to provide a comprehensive review of the current state-of-the-art in the field of uncertainty forecasts and risk in electrical grid control rooms, including a analysis of the key research and development efforts that have been undertaken to date. By doing so, the analysis seeks to identify the main areas of progress and the remaining gaps in the literature and outline the potential avenues for future research in this exciting and rapidly-evolving field.

2.1 Uncertainty Forecasts

As the use of renewable energy sources becomes more widespread and extreme weather events become more common due to climate change, the uncertainty of weather and power production forecasts can no longer be oblivious to the operation of the grid and the electricity market [5].

Uncertainty forecasts are used in a range of scenarios, including risk management and weather forecasts, to predict or estimate the degree of uncertainty associated with a future event or outcome. It is a technique of expressing the level of certainty in a forecast or prediction while accounting for any variables that could increase uncertainty or variability. Uncertainty predictions, in general, are a crucial tool for assisting people and organizations in making wise decisions and managing risks in the face of uncertainty.

Following [6] the main sources of uncertainty weather forecasts are:

- the unpredictability of the atmosphere;
- uncertainty in interpreting data;
- uncertainty in creating forecasts;
- forecast interpretation.

As stated in [7] one important definition to retain is the difference between forecast error and forecast uncertainty. Forecast error is the difference between the value that was predicted and the actual value at a specific point in time, either in the past or present. On the other hand forecast uncertainty is the range of possible forecast errors that may occur in the future.

2.1.1 Probabilistic forecasts and Deterministic forecasts

Forecasts can be categorized into two categories: probabilistic forecasts and deterministic forecasts. It's crucial to remember that depending on the needs and objectives of the user, both probabilistic and deterministic forecasts can be helpful in certain circumstances. While deterministic forecasts may be more appropriate when the objective is to make a clear, confident conclusion, probabilistic forecasts are frequently more suited when there is a significant level of uncertainty or when numerous possibilities are possible.

The change from a deterministic to a probabilistic view is arguably the most significant development in the recent history of energy forecasting [8] because current deterministic methods have reached their limit due to the inherent inability to model and communicate forecast uncertainties, as renewable energy sources (RES) penetration levels rise and climatic changes produce more and more extreme weather conditions [5]. Uncertainty forecasts are gradually moving into the control rooms and trading floors as they fill the information void left by deterministic methods [9].

2.1.2 Communication of forecast uncertainty

The communication of forecast uncertainty and risk is a critical aspect of managing electrical grid control rooms, as it plays a key role in ensuring the safe and reliable operation of the grid. Weather, equipment breakdowns, and shifts in electricity demand are just a few of the factors that can cause a problem. Control room operators can make educated judgments and respond to potential dangers promptly with the aid of effective communication of these elements.

As demonstrated in [6] it is advantageous to communicate forecast uncertainty to end-users for a number of reasons:

- Optimize decision-making;
- Regulate user expectations;
- Increase user confidence;
- Reflect the state of the science.

In fact, it has been discovered in numerous studies that end users (experts and non-experts) who receive information on uncertainty along with probabilistic forecasts make noticeably better decisions than end users who don't [7].

To correctly communicate forecast uncertainty there are three main points to focus which are described in detail in [1]:

- Tailor the information to the audience;
- Understand how people interpret uncertainty;
- Use color wisely.

Understanding the advantages and effective communication of uncertainty forecasts requires delving into the methods of demonstrating this information to end-users. Several approaches can be employed, such as utilizing charts, graphs, tables, images, and written or oral narratives [7]. Examples of these methods include:

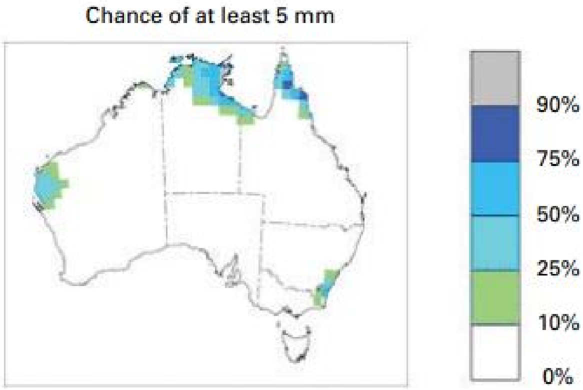


Figure 2.1: Graphical probability (source: [1])

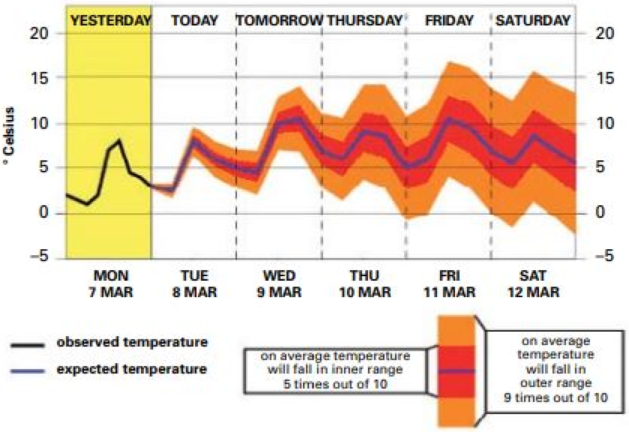


Figure 2.2: "Fan chart" showing the increase in uncertainty with time (source: [1])

A graphical probability, as shown in Figure 2.1, is a visual representation of the probability or likelihood of a particular outcome occurring. These forms of graphics can be used to display the range of uncertainty corresponding to each outcome as well as the distribution of potential outcomes.

In a "fan chart" (Figure 2.2) the most likely outcome is indicated by the central line, which is surrounded by a series of "fans" or lines that represent the range of potential possibilities. The probability of each occurrence is indicated by the width of each fan.

Overall both examples are valuable tools for helping to communicate uncertainty forecasts by providing clear and intuitive visual representations of the range of possible outcomes.

2.1.3 Applications for Uncertainty Forecasts

In this subsection the focus is on applications for congestion management in the power grid, others will be discussed in Section 2.2 and Section 2.3.

On one hand forecast uncertainty related to the power production from renewable energy sources (RES) frequently leads to significant changes between the scheduled and the actual power injections because of that larger and more frequent fluctuations in the power production require new approaches to handle congestion and ensure system security [10]. Additionally, uncertainty forecasts can be leveraged to predict the amount of energy that will be demanded by consumers at different times of the day or even in different seasons. This process, known as electric load forecasting (ELF), is an indispensable procedure for the planning of the power system industry, playing an essential role in the scheduling of electricity and the management of the power system [11].

Both approaches can help power grid operators to anticipate and prepare for changes in demand, and to allocate resources more efficiently.

In the article [2] is propose a reliability assessment and congestion relieving approach in power systems containing RES and energy storage system (ESS). This application can be described in Figure 2.3

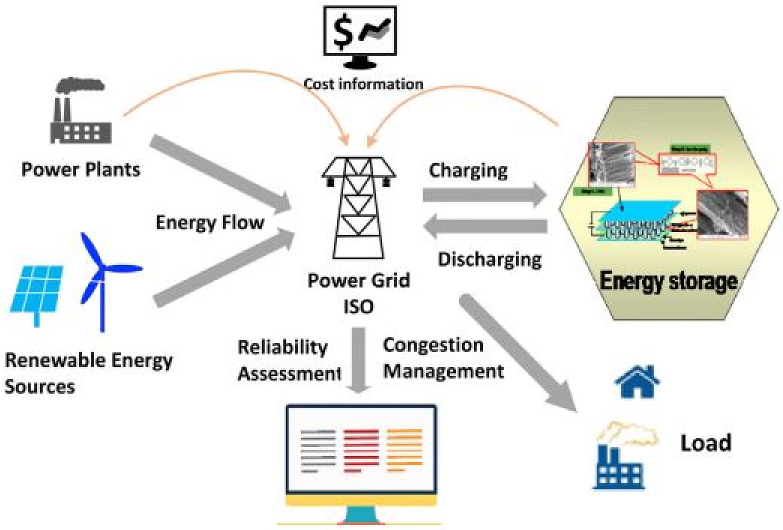


Figure 2.3: Schematic representation of proposed approach (source: [2])

Following what is described in [2] this approach shows that there are two types of generation i.e. RES and conventional generation to feed the load. RES are uncertain so they need to be modeled. ESS is installed in the system to mitigate uncertainties by optimal charging and discharging. The independent system operator (ISO) takes care of the smooth and healthy operation of the power system and coordinates the network to relieve congestion and assess reliability.

2.2 Dispatch and control center of the future

The dispatch and control center plays a critical part in the operation of the power grid by monitoring and regulating the flow of electricity to make sure that demand is fulfilled and the system is stable. In the future, the dispatch and control center of the electrical grid is expected to be more advanced and automated, with the use of advanced technologies such as artificial intelligence (AI) [12] and security features reviewed in [13].

2.2.1 Present of dispatch and control centers

Control centers of today play a crucial role in the operation of the electrical grid, using various technologies to monitor and control the flow of electricity to ensure a reliable supply of electricity to consumers. The trends of the present day are moving toward distributed control centers that are characterized by [14]:

- Separated supervisory control and data acquisition (SCADA);
- Energy management system (EMS);
- business management system (BMS);

SCADA systems use sensors and other equipment to gather data from various parts of the system, transmit that data back to a central control center, and allow operators to control the system remotely. One of its fundamental characteristics is that SCADA systems are isolated from the rest of the network. This indicates that they function on a distinct, exclusive network that is cut off from other networks, like the internet. By shielding the SCADA system from outside threats and interruptions, this separation contributes to ensuring the system's security and dependability. They are commonly utilized in crucial infrastructure systems including power grids, water treatment facilities, and transportation networks where downtime could have detrimental effects.

EMS is a computer-based system that is used to monitor, control, and optimize the operation of an electrical grid or other energy systems. A network of sensors and other devices that gather data from various system components are often included in EMS systems, along with a central control center where operators may monitor and regulate the energy system. This information is sent back to the control center, where it is examined and used to streamline the system's performance.

BMS systems can be used in control centers to oversee many facets of how the electrical grid or other energy systems operate. A BMS system can be used to track inventory and supplies, schedule maintenance and repairs, or monitor and analyze data from the energy system. BMS systems can be used to handle the control center's finances, including accounting, forecasting, and budgeting.

In 2008 to face the problem of the integration of renewable energy resources the "Réseau de Transport d'Electricité", French transmission system operators (TSOs), developed some methods and tools that were described in [15]. The main ones are:

- new EMS functionalities enabled [15]:
  - monitoring the system and the level of risk;
  - studying and ensuring security in anticipation;
  - submitting orders to the SCADA system;
  - optimizing the global system.
- a new concept of substation ("smart substation") with features like [15]:
  - fully digitalized protection and automation system;
  - extensive monitoring system.
  - advanced functions implemented using local computing resources.

2.2.2 The future of control centers

The growth of renewable energy resources (RES) in power networks is crucial as the need for electrification rises in response to the issue of decarbonizing the global energy system. The majority of these modifications have an immediate effect on their control centers, requiring them to manage weather-based energy resources, new interconnections with neighboring transmission networks, more markets, active distribution networks, micro-grids, and larger amounts of readily available data [3]. It is now necessary to reevaluate the architecture of the control center and the operator's position [3].

Since it is unlikely that flexibility cannot be provided via new infrastructure (due to visual and environmental impacts), the essential flexibility will instead come from smarter operations, devices, and resources, so operators will have to do more with the existing grid as summarized in Figure 2.4[3]:

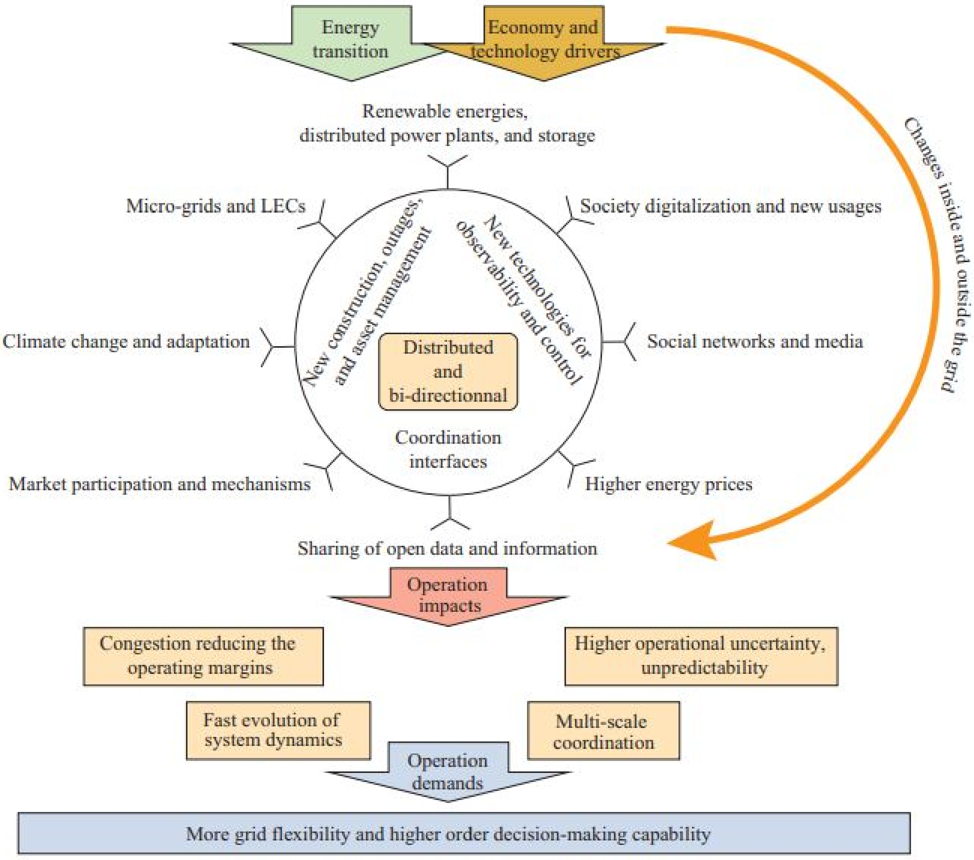


Figure 2.4: New operational needs under energy transition that is impacting operations along different dimensions (source: [3])

To address this problem the European Energy Research Alliance (EERA) developed the European Liaison on Electricity Committed Towards long-term Research Activities for Smart Grids (ELECTRA project) that focuses on analytics and visualization for the future control rooms of 2030 and beyond in the WEB-of-Cells (WoC) context [4]. According to the ELECTRA WoC idea, the operator's job is to monitor the operation of a highly automated power system and has the capability and choice to act if necessary [16], but as demonstrated in [17] the design of visualization and decision support systems for supervisory control of increasingly automated systems is challenging because increasing automation does not always result in a reduction in the cognitive effort required of operators, and more automated systems have been reported to put an increased strain on an operator's ability to make decisions, particularly in critical situations. In order to define detailed requirements for control room solutions, the designer thus has to understand what constitutes relevant information to be presented to the operator [18].

In order to define an effective visualization strategy for the arising concept has been located some main points [4]. There is a need to define how much information the cell operator needs to know so the recommendation is to show only the "need to know" information, providing straight guidance from the signaled problem to the root cause. In the high-level representation of the power system, the recommendation is to have the possibility of representing the power system as interconnected cells, which are represented with a traffic light approach (green if there are no issues, yellow if there are critical conditions, red if there are issues) as shown in Figure 2.5. The "need to know" information is presented in each cell and the operator can zoom in for further details. Connecting the cells is represented by a single line wiring following the same traffic light approach but for congestions like overcurrent or overvoltage.

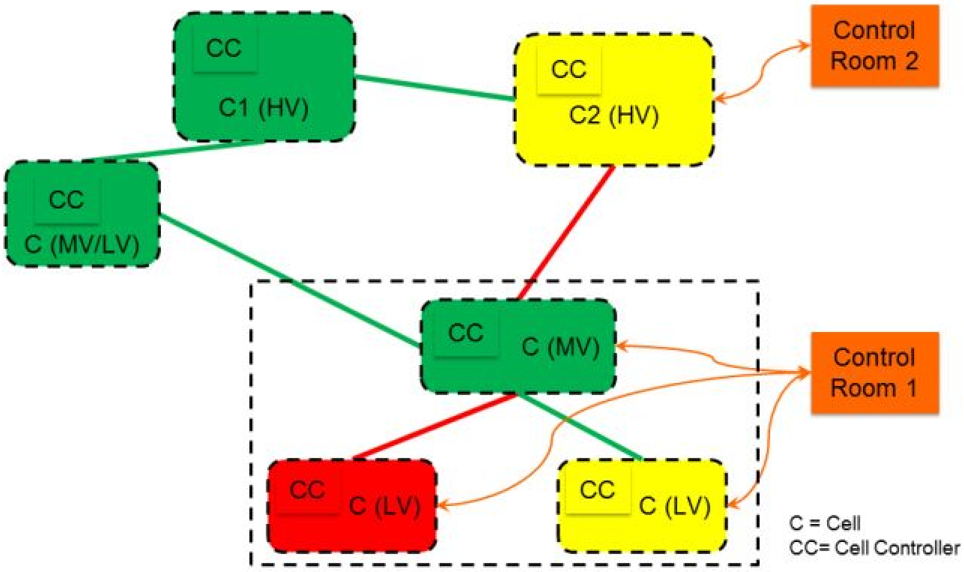


Figure 2.5: Traffic light approach for visualizing the WoC (source: [4])

Another approach is taking advantage of the latest developments in the Human-Machine Interface (HMI) and Artificial Intelligence (AI). The temptation to create a fully autonomous grid to handle the new operational needs may arise in the future, but for now, it is insufficient for such massive critical system operations [12].

In [12] is presented the future design of operator AI-infused assistant given the latest developments in HMI, AI, and decision-making science, featuring functions like:

- shows contextually relevant information at the right time;
- scope services and inform the user when in doubt;
- support efficient invocation and dismissal;
- take into account and learn from user behavior and feedback;
- conveys the consequences of user actions.

The dispatch and control center can utilize AI to examine a lot of data from the power grid and make judgments about how to run the grid more effectively. This may save costs and increase the grid's general effectiveness. AI is expected to play a significant role in the future of dispatch and control centers, helping optimize the electrical grid's operation and improve reliability for consumers.

2.3 Congestion management

In electricity transmission and distribution, congestion management involves balancing the demand for electricity with the available transmission capacity to ensure the reliability and stability of the power grid. Forecast uncertainty related to the power production from renewables frequently leads to significant changes between the scheduled and the actual power injections [19], this creates a challenge to accurately predict future electricity demand and the availability of generation resources, which can make it difficult to effectively manage congestion in the transmission system.

In this subsection are reviewed some solutions for congestion management.

2.3.1 Optimal Power Flow

The most effective power generation and transmission schedule for a power grid is found using the mathematical optimization process known as optimal power flow (OPF), given a set of restrictions. It is typically used by power grid operators to ensure that electricity is generated and transmitted in the most cost-effective and reliable manner possible. OPF aims to satisfy all system restrictions, such as power balance, transmission line capacity, and generator output limits, while minimising the overall cost of generation and transmission [20].

The formulation for the standard DC optimal power flow, including wind power generation, is [21]:

$$min C_G^T P_G \tag{2.1}$$

subject to:

$$P_G + P_W - B\theta = P_L \tag{2.2}$$

$$P_W = P_W^{fc} \tag{2.3}$$

$$P_G^{min} \leq P_G \leq P_G^{max} \tag{2.4}$$

$$-P_{ij}^{max} \leq \frac{1}{x_{ij}}(\theta_i - \theta_j) \leq P_{ij}^{max} \tag{2.5}$$

$$\theta_{slack} = 0 \tag{2.6}$$

Following [21] the objective is to minimize generation cost (2.1), the DC power equations are (2.2), with "B" being the bus admittance matrix. The wind power in-feed is set equal to the forecasted values in (2.3), (2.4) constrains generation to be within minimum and maximum levels. Constraints on the line flows are given by (2.5) and the angle of the slack bus is (2.6).

Based on this standard DC OPF a variety of formulations can be created to appropriate constraints like security and uncertainty such examples are shown in [21] and it's possible to conclude that incorporating uncertainty forecasts into OPF algorithms can help to improve the accuracy of the optimization results and ensure that the power system is operated in a reliable and efficient manner. By using OPF to optimize the communication of forecast uncertainty and risk, it can be ensured that the electrical grid is operated in the most efficient and effective manner possible.

2.3.2 Predictive voltage problems

Predictive voltage problems refer to issues that can occur in the power grid due to voltage deviations from the nominal or expected value. This can have serious consequences, such as power outages, equipment damage, and instability in the power grid. To address these problems, power grid operators use predictive voltage analysis tools to identify potential voltage issues and implement corrective measures to prevent or mitigate their impact on the power grid.

In [22] model predictive control (MPC) was proposed to deal with the massive introduction of renewable energy sources that leads to large amounts of distributed generation in the grid causing voltage variations. A standard MPC is a type of computer control algorithm that uses a mathematical model of the process to predict the system's future behavior, and then adjust control inputs to optimize performance based on those predictions. This paper demonstrated that MPC using an algorithm allowing online optimization to be applied to systems with higher dimensions produces good outcomes.

2.4 Decision experiments under forecast uncertainty

The literature review in this subsection is even more significant because the experiences mentioned are consistent with the goals of this dissertation. Through them, we may comprehend how to create decision problems with forecast uncertainty, comprehend what the expected outcomes are, and comprehend how to assess and make judgments regarding the outcomes. Let´s take a look at the different decision experiments and their results.

Decision-making plays a major role in all the topics described above. The traditional decision-making process, which relies heavily on the knowledge and awareness of the operators at the moment, will no longer be practical in the face of these developments instead, it will need to be adaptive and well-structured [3].

In the article [5] a study was conducted with 105 participants, mostly experts in the energy and meteorology fields, it was found that using probabilistic forecasts rather than deterministic forecasts resulted in better outcomes for 70% of participants and helped them make more accurate decisions with less risk. The study involved conducting experiments in which the participants were asked to decide whether to trade 100% or 50% of a wind farm's energy on a given day, using both types of forecasts in 12 different case studies. Additionally, 18% of participants changed all of their decisions and 90% changed at least one decision after being presented with probabilistic predictions, indicating that probabilistic forecasts have the potential to improve decision-making in complex situations.

In the research [23] participants were given a task in which they had to determine whether to apply salt to roadways in the winter to prevent icing or to withhold salt and risk a fine using single-value weather forecasts, either alone, with freeze probabilities, guidance, or both. Two studies were carried out and forecasts that included a numeric uncertainty estimate were superior to deterministic forecasts in all of the situations tested, same as in [5].

The capacity of power system operators to make decisions in extreme situations with and without the use of sophisticated power system technologies has been examined in relation to their estimated cognitive flexibility in the article [24]. Cognitive flexibility can be described in three points [24]:

- Cognitive Flexibility an ability which could imply a process of learning (could be acquired with experience);
- Cognitive Flexibility involves the adaptation of cognitive processing strategies;
- the adaptation will occur to new and unexpected environmental changes after a person has been performing a task for some time.

Each of the candidates were given to do the Iowa Gambling Task (IGT) and Situational Awareness of Risk Dynamics (SARD) followed by the Power System control action test. When the participants were provided with a second trial the time taken for making the correct decision decreased. In summary, results showed that with experience, the operator's performance improves when the participants were provided with a second trial. The time taken for making the correct decision decreases [24].

This article shows that decision-making can be improved with study and experience, so transmission system operators (TSOs) should always be synced and tested to improve their skills.

The research in [25] was to evaluate the impact of weather uncertainty information on decision-making in naturalistic settings (for nonexperts participants). Two studies were conducted to assess human decision-making with and without information about uncertainty. When uncertainty information is incorporated into the forecast, they demonstrate a noticeable improvement in decision quality, as shown in [5, 23]. Another significant finding of this study [25] is that by conducting the trials again, the participants came to understand the value of the uncertainty information, which motivated them to use it more effectively going accordingly with what is displayed in [24].

2.5 Summary

This chapter gives a deeper understanding of the challenges and opportunities related to the communication of forecast uncertainty and risk in electrical grid control rooms by reviewing the state-of-the-art in the areas of uncertainty forecasts, the dispatch and control center of the future, congestion management, and decision experiments under forecast uncertainty.

Effective communication of forecast uncertainty emerges as a critical factor in empowering decision-makers to make well-informed choices amid inherent uncertainties. However, this task can be challenging due to the intricacies of the power grid and the influence of renewable energy resources.

It becomes evident that the application of advanced technologies, such as visualization strategies and artificial intelligence, holds the potential to enhance forecasting accuracy and efficiency while enabling more effective communication of risks and uncertainties.

In summary, the reviewed literature underscores the necessity for further research on communicating forecast uncertainty and risk within electrical grid control rooms. A deeper understanding of the trade-offs and impacts associated with different approaches can pave the way for more effective decision-making processes.

Chapter 3

Development of the Decision Game

This chapter delves into the development and implementation of a web application designed to enhance decision-making in the context of uncertainties in the electrical grid. The primary objective was to create an interactive platform where users can experience different approaches when making choices and determine the quality of their decisions under various conditions. Through realistic simulation models incorporating diverse scenarios whilst capturing user feedback on our database system, we seek to gain insights into decision-making processes.

3.1 Decision Game

This section provides an overview of the decision game developed as part of this thesis on the communication of forecast uncertainty in electrical grid rooms. The objective of the game, key assumptions, the function cost, and how the game works are discussed, highlighting the significance and relevance of the decision game in addressing forecast uncertainty challenges in the energy sector.

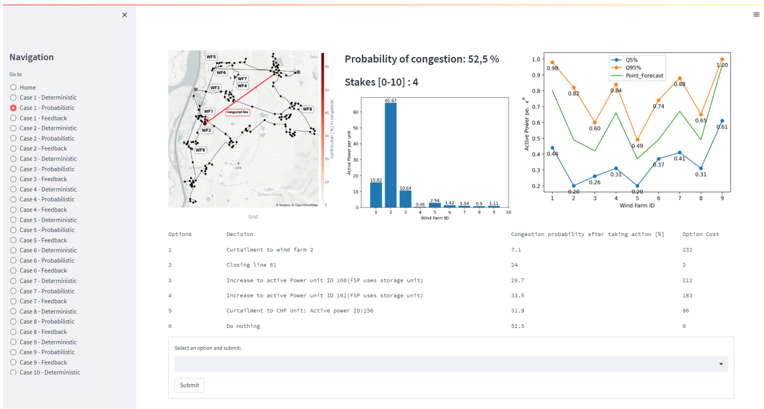
The primary objective of the decision game is to design an interactive and informative experience, allowing users to step into the role of system operators. Through this simulation, users can actively manage grid congestion while considering two types of critical information - deterministic and probabilistic data. By offering this hands-on approach, participants can gain valuable insights into the challenges of congestion management and the implications of incorporating different types of information in the decision-making process. By simulating realistic scenarios, the game aims to improve users' decision-making skills and their ability to effectively manage forecast uncertainties. Through the game, users can gain insights into the implications of their decisions and contribute to improve grid operation. Additionally, the collected data from the game will later enable to analyze the user's risk profile, preferences, and the effectiveness of different types of information i.e., deterministic and probabilistic, in decision-making processes.

During the development of our application, several key assumptions have been made in the design and implementation of the decision game. Firstly, it is assumed that users possess a basic understanding of electrical grid operations and the significance of forecast uncertainty in grid management. This assumption allows the game to focus on advanced decision-making aspects rather than providing introductory knowledge. Secondly, the decision game assumes that users can make informed decisions based on the provided information and the tools available within the game. While the game provides necessary context and guidance, it is designed to encourage users to apply their knowledge and judgment to address network congestion effectively. Lastly, the decision game assumes that the forecast data utilized within the game is representative of the actual uncertainty levels faced in real-world grid operations. This assumption allows users to experience and respond to realistic forecast uncertainty scenarios.

3.1.1 Understanding the Decision Game

This game consists of 12 diverse and realistic cases, each presenting a unique scenario involving forecasting uncertainty and each case is divided into three phases: deterministic phase, probabilistic phase, and feedback. The game interface was designed to present all the necessary information on a single page for each phase. This decision was made to ensure a seamless and user-friendly experience, allowing network operators to easily access and analyze the deterministic data without the need for navigating through multiple screens or sections. By having all the relevant information in one place, users can quickly assess the situation and make informed decisions based on the available data.

In each case, the user assumes the role of a network operator and is presented with deterministic information as the first step. This information is detailed in a separate chapter of the dissertation, where is outline the specifics of the data provided. Based on this deterministic information, the user is required to make a decision among six different options. Each decision carries distinct outcomes, including the potential to resolve the congestion or partial resolution, as well as the possibility of failure. Importantly, each decision is associated with a specific cost, which is added to the user's accumulated cost throughout the game. Below is an illustrative picture that demonstrates the layout of the game interface in this phase:



Navigation

Go to

○ Home
○ Case 1 - Deterministic
● Case 1 - Probabilistic
○ Case 1 - Feedback
○ Case 2 - Deterministic
○ Case 2 - Probabilistic
○ Case 2 - Feedback
○ Case 3 - Deterministic
○ Case 3 - Probabilistic
○ Case 3 - Feedback
○ Case 4 - Deterministic
○ Case 4 - Probabilistic
○ Case 4 - Feedback
○ Case 5 - Deterministic
○ Case 5 - Probabilistic
○ Case 5 - Feedback
○ Case 6 - Deterministic
○ Case 6 - Probabilistic
○ Case 6 - Feedback
○ Case 7 - Deterministic
○ Case 7 - Probabilistic
○ Case 7 - Feedback
○ Case 8 - Deterministic
○ Case 8 - Probabilistic
○ Case 8 - Feedback
○ Case 9 - Deterministic
○ Case 9 - Probabilistic
○ Case 9 - Feedback
○ Case 10 - Deterministic

Probability of congestion: 52,5 %

Stakes [0-10] : 4

Options	Decision	Congestion probability after taking action [%]	Option Cost
1	Curtailment to wind farm 2	7.1	232
2	Closing line 61	24	2
3	Increase to active Power unit ID 160(FSP uses storage unit)	29.7	212
4	Increase to active Power unit ID 161(FSP uses storage unit)	33.5	183
5	Curtailment to CHP Unit: Active power ID:156	31.9	86
6	Do nothing	52.5	0

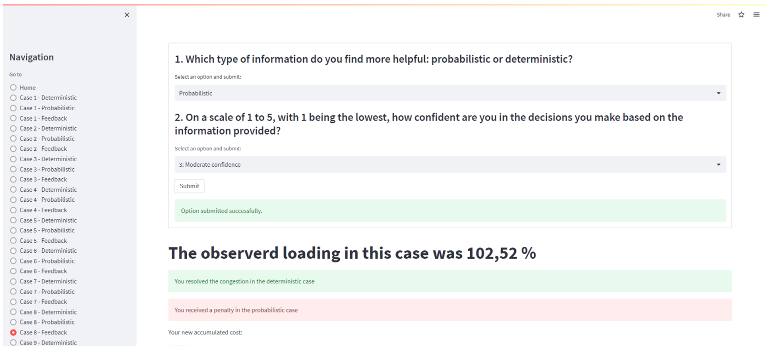
Select an option and submit:

Figure 3.1: Interface of Probabilistic phase

After the user has made a decision based on the deterministic information, the game progresses to the second phase. In this phase, the user encounters probabilistic information, which further adds to the complexity and uncertainty of the decision-making process. Similar to the deterministic phase, the probabilistic information is tailored to each case and explained in detail in a dedicated section of the dissertation. The user must analyze the presented probabilistic data and select a preferred decision from the available options.

Following the evaluation of both deterministic and probabilistic information, the game proceeds to the final phase. Here, the user is asked to reflect on their decision-making preferences. They are prompted to indicate whether they favored the deterministic or probabilistic information when making their choices. Additionally, users are requested to express their confidence levels regarding the decisions they made throughout the game.

Once the user has provided their decision preferences and confidence levels, the game reveals the outcomes of their decisions. Users are informed whether or not they successfully resolved the congestion. If the user's decision led to the congestion being resolved, no penalty is added to their accumulated cost. However, if the congestion persists due to an unsuccessful decision, a penalty is applied, increasing the user's accumulated cost. To provide a visual representation, here is an example screenshot illustrating the layout of the feedback page:



1. Which type of information do you find more helpful: probabilistic or deterministic?

Select an option and submit: Probabilistic

2. On a scale of 1 to 5, with 1 being the lowest, how confident are you in the decisions you make based on the information provided?

Select an option and submit: 3: Moderate confidence

Option submitted successfully.

The observerd loading in this case was 102,52 %

You resolved the congestion in the deterministic case

You received a penalty in the probabilistic case

Your new accumulated cost:

Figure 3.2: Interface of the Feedback page

In conclusion, the decision game offers an interactive and engaging platform for network operators to enhance their decision-making skills in the face of uncertainty and congestion management. By involving the users in realistic scenarios and incorporating both deterministic and probabilistic information, the game enables practitioners to gain practical experience and refine their decision-making strategies. Furthermore, the game encourages self-reflection, allowing users to assess their preferences and confidence levels, ultimately fostering continuous improvement in decision-making abilities. The cost associated with each decision and the penalties incurred for unsuccessful decisions contributes to the user's accumulated cost, adding an additional layer of realism and accountability to the game.

3.1.2 Cost Function

The decision game incorporates a function cost mechanism to evaluate the impact of users' decisions on network congestion management and it was an inspiration of the cost-loss matrix in [26]. Each decision made by the user to address network congestion carries a specific cost associated with it. The accumulated cost reflects the cumulative impact of the user's decisions throughout the game.

The cost calculation takes into account both pre-booking flexibility options and real-time management costs. If the selected flexibility options cannot fully resolve the congestion issue, additional real-time management may be required, potentially resulting in load or generation curtailment. Real-time management incurs higher costs compared to pre-booking flexibility.

The cost accumulation is based on the outcomes of the user's decisions:

- Outcome 1: Congestion still occurs despite the user's action. In this case, the user incurs the cost associated with the chosen option and a penalty cost for lost load. The penalty cost is calculated based on the lost load in megawatts (MW) multiplied by the penalty rate of 12 000€ per MW [27].

- Outcome 2: Congestion is successfully resolved, and the user incurs only the cost associated with the chosen option.

- Outcome 3: Congestion occurs because the user did not take any action. In this case, the user incurs a penalty cost for the lost load, calculated in the same manner as described earlier.

- Outcome 4: Congestion doesn't occur despite the user's inaction, resulting in no additional cost.

The objective of the game is to minimize the accumulated cost by making strategic decisions that effectively address network congestion. Users are encouraged to carefully consider the available options, their potential impact, and the associated costs to navigate the challenges and strive for efficient outcomes.

3.2 Study Cases

When choosing the study cases, the focus is on the selection and definition of relevant scenarios that capture the complexities and uncertainties inherent in the electrical grid. By carefully choosing these study cases, was created a diverse range of challenges that users will encounter during the decision game.

Throughout the development process, close collaboration took place with experts from INESC TEC that provided valuable input and guidance, particularly in providing the study cases that simulate real-life events. Their expertise contributed to the authenticity and relevance of the web application/decision game.

Each study case was provided with a real observed loading and different decisions that the user could choose alongside their cost and the line loading after taking the decision, for the deterministic case, and the congestion probability after taking action, for the probabilistic case, and if each decision resolved the congestion in the electrical grid.

In this study, we utilized the 20 kV Oberrhein MV network powered by two 25 MVA HV/MV substations as in [28]. To enhance the integration of RES and induce technical problems, certain modifications were made to the network. The grid elements are described in 3.1.

Network Specifications	**Details**
Voltage Level	20 kV
Supply Source	Two 25 MVA HV/MV Substations
MV/LV Substations	141
Peak Power Load	61.86 MW
MV Feeders	4
Grid Topology	Meshed, Operated as Radial Grid
Consumers	147
Wind Power Plants (WPP)	9
Combined Heat and Power Units (CHP)	4
Energy Storage Systems	3
Secondary Substation Load Data Source	Iowa Distribution Test System

Table 3.1: Elements of 20 kV Oberrhein MV Network

Each case also had a representation of this electrical grid with a visual portrayal of the congestion and the wind farms in the network as seen below.

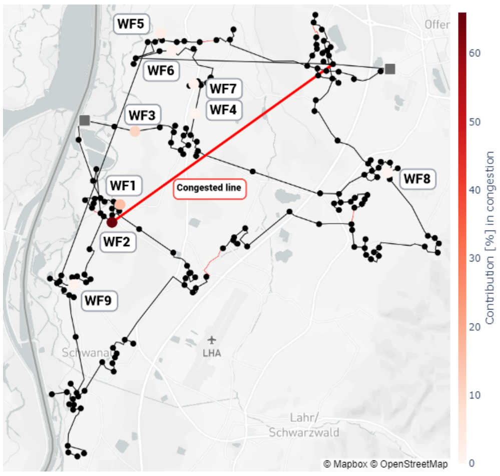


Figure 3.3: Visual representation of the electrical grid and congestion

3.2.1 Deterministic Information

In the deterministic information of each example is presented the line loading and the point forecast value. Line loading is a critical aspect in assessing the utilization and capacity of transmission lines within an electrical network. It provides essential information about the load carried by the lines and helps ensure their optimal performance and plays a significant role in evaluating forecast uncertainty in electrical grid rooms.

The evaluation of line loading based on deterministic information primarily focuses on comparing the actual load on the line with its maximum capacity. If the line loading exceeds the 100% limit, it indicates that the line is operating under stress and may be at risk of failure or reduced operational margin. It becomes crucial for grid operators to take appropriate actions, such as power re-routing or curtailment measures, to prevent overloading and ensure grid stability.

In the context of this research, effective communication of line-loading information based on deterministic forecasts is paramount. This communication enables decision-makers to comprehend the current state of transmission lines and make informed choices regarding network management. By considering deterministic values, grid operators estimates the line loading based on the point-forecast and proactively implement measures to mitigate potential problems.

The point forecast is a single value representing the forecast power production per unit from a wind farm.

In wind energy forecasting, the point forecast value provides a deterministic prediction of the anticipated power production per unit. It represents a specific point in the forecast range, indicating the most likely or central value. This single value is derived from various factors such as historical data, meteorological inputs, and mathematical models used in wind power forecasting.

The point forecast value is an essential tool for grid operators, energy traders, and other stakeholders involved in managing and optimizing wind farm operations. It enables them to make informed decisions regarding power allocation, grid integration, and resource scheduling based on the expected power production. By relying on this single forecast value, users can plan and adjust their operations accordingly, ensuring efficient utilization of wind resources and grid stability.

However, it is important to note that the point forecast value represents a deterministic forecast that does not account for the inherent uncertainties and variability associated with wind power generation. Factors such as weather conditions and wind patterns can introduce fluctuations in actual power production, deviating from the point forecast value. Therefore, it is essential to consider and communicate the associated forecast uncertainty to facilitate better decision-making and risk assessment.

The point forecast value was graphically represented using a chart as seen:

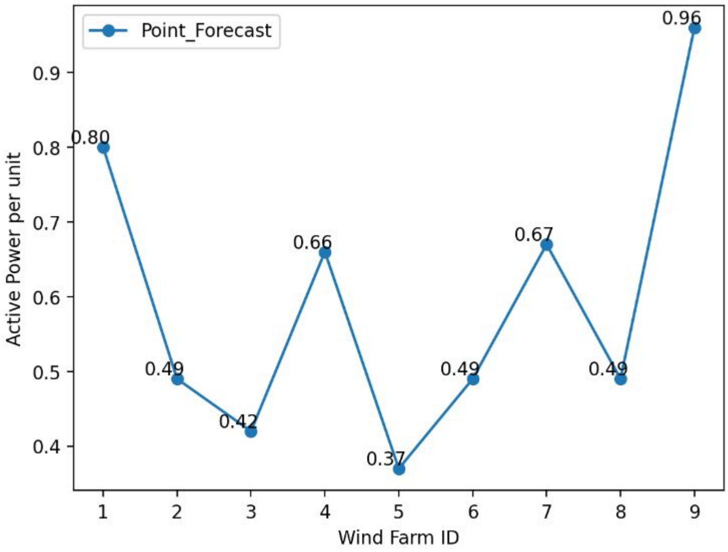


Figure 3.4: Point forecast value graph

By utilizing a graph, the point forecast values for different wind farms could be compared and analyzed in a clear and intuitive manner. The vertical axis represented the expected power output in units, allowing for a quick assessment of the forecast production levels. The horizontal axis, labeled with the wind farms IDs, facilitated easy identification and differentiation between the individual wind farm forecasts.

3.2.2 Probabilistic Information

For the probabilistic information of each case is provided different data like the probability of congestion, stakes, the forecast graph, and the wind farms contribution graph.

The probability of congestion refers to the likelihood or chance of network congestion occurring within an electrical grid or system. It represents a quantitative measure of the potential occurrence of congestion, taking into account various factors such as power generation, demand, and grid infrastructure.

In the context of grid management and operation, understanding the probability of congestion is crucial for grid operators and decision-makers. It provides valuable insights into the potential risks and challenges associated with the balance between power supply and demand. In this research, analyzing the probability of congestion serves as a fundamental component in evaluating the performance and resilience of the electrical grid. It enables the identification of critical periods or conditions when congestion is more likely to occur, allowing for targeted interventions and strategic decision-making.

In summary, the probability of congestion represents the likelihood of network congestion occurring within an electrical grid. It serves as a key metric for assessing and managing grid performance and resilience. By understanding and incorporating this probability into decision-making processes, grid operators can take proactive measures to ensure grid stability, reliability, and effective management of power supply and demand.

In the decision game, the stakes assigned to each line within the electrical grid serve as a crucial element in assessing the importance and potential consequences of line congestion. The stakes are represented on a scale ranging from 1 to 10, where higher values indicate a higher level of criticality for a particular line.

These stakes directly align with the risk of cascading failures that can occur as a result of a line failure. Cascading failures are a chain reaction of adverse events triggered by the initial failure of a single line. When a line fails, it can lead to an overload on neighboring lines, causing them to fail as well. This process continues, propagating through the grid and impacting other areas of the system, ultimately resulting in widespread disruptions and significant consequences.

By incorporating the stakes into the decision-making process, users can prioritize their actions based on the criticality of each line. Lines with higher stakes demand immediate attention and mitigation to prevent cascading failures and mitigate the risk of extensive system-wide impacts. Understanding the potential consequences of line congestion, as represented by the stakes, empowers users to make strategic decisions in managing the grid and ensuring its stability and reliability.

When managing line congestion, grid operators must prioritize their actions based on the assigned stakes. Lines with higher stakes require more immediate attention and mitigation measures to prevent cascading failures and minimize system-wide impacts. By incorporating the evaluation of stakes into decision-making processes, grid operators can effectively allocate resources, prioritize maintenance activities, and implement measures that mitigate the risks associated with line congestion.

The forecast graph provides a visual representation of the forecast power production per unit, incorporating both the quantiles and the point forecast as shown in 3.5. It offers a comprehensive overview of the anticipated range of outcomes and the most likely power production value.

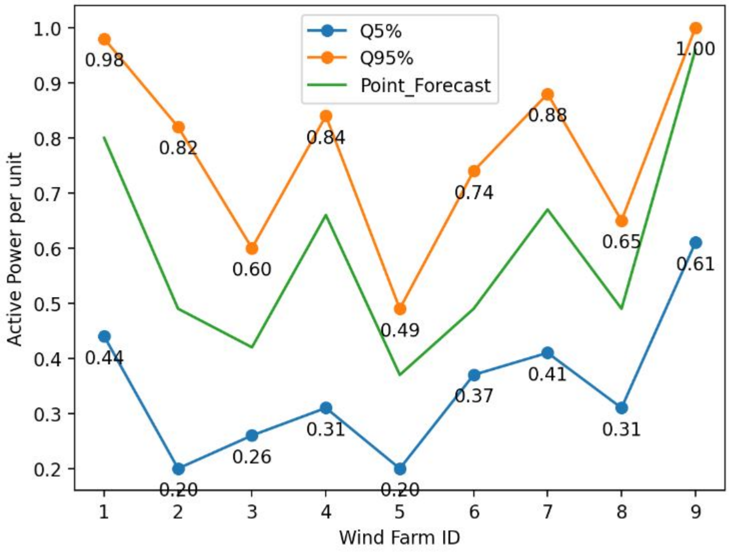


Figure 3.5: Forecast graph with quantiles and point forecast

In the forecast graph, two key elements are displayed: the quantiles and the point forecast. The quantiles, specifically the Q5% and Q95%, represent the lower and upper bounds of the forecast power production range. The Q5% quantile indicates the value below which there is a 5% chance that the actual power production per unit will fall, while the Q95% quantile represents the value below which there is a 95% chance of the actual power production per unit falling. As seen before the point forecast represents the central or most likely value of the forecast power production per unit. It serves as a single estimate within the range of possible outcomes, indicating the expected power output.

By combining the quantiles and the point forecast in the graph, stakeholders can gain a comprehensive understanding of the forecasted power production distribution and its associated uncertainties. The quantiles provide insights into the range of potential outcomes, allowing for risk assessment and decision-making based on different levels of confidence. The point forecast offers a specific value around which decisions can be made, considering the most likely scenario.

The contribution graph, a key feature in the decision game, provides users with valuable insights into the impact of individual wind farms on specific line congestion within the electrical grid. Through a visual representation in the form of a bar chart, users can grasp the relative extent of each wind farm's influence on causing congestion.

The calculation of each wind farm's contribution is based on a set of sensitivity indices. These indices are derived from intricate coefficients estimated using nodal power data and the grid topology. Nodal power refers to the power flow at different nodes within the grid, and the grid topology encompasses the interconnections between nodes and lines.

To determine the contribution of a wind farm to line congestion, the sensitivity indices analyze the correlation between nodal power variations at each wind farm and the resulting changes in line congestion levels. A higher contribution percentage indicates a more significant impact of a wind farm power output on causing congestion in a specific line. For instance, if a wind farm has a contribution of 60%, it means that it has a greater influence on line congestion compared to others with a 10% contribution. This difference in impact could arise from factors such as higher sensitivity to power deviations or greater power fluctuations.

As a result, the contribution graph visually displays the percentage of the impact that each wind farm has on causing congestion. The height of each bar in the graph represents the contribution percentage, with taller bars indicating wind farms that exert a more substantial influence on specific lines compared to those with lower contribution percentages.

By understanding the contribution of individual wind farms to line congestion, users can prioritize and strategize their actions to effectively manage grid operations. The contribution graph empowers decision-makers to identify wind farms with higher contributions and recognize their influence in specific congested lines and implement targeted measures to alleviate congestion and ensure optimal grid operation.

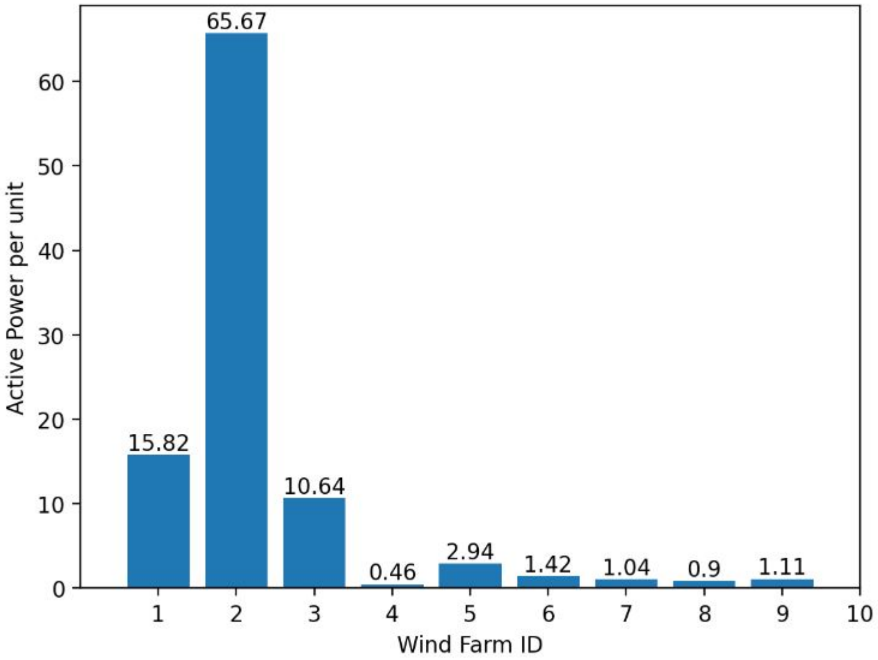


Figure 3.6: Contribution graph

3.3 Software and database

The successful implementation of the web application relies on robust software architecture and an efficient database structure. It’s provided a comprehensive overview of the software and database components, highlighting their crucial roles in ensuring a seamless user experience and enabling data storage for analysis.

To develop the decision game was used an open-source Python framework called Streamlit [29]. Because of its simplicity of use and power for creating data-driven web applications and visualizations, Streamlit was the ideal choice for our project. The user input widgets, data visualization tools, data storage, and analysis capabilities that were used to create our decision game are all covered in this chapter.

One of Streamlit's most valuable features is its capacity to create various user input widgets that enable seamless interaction with data and facilitate decision-making within online applications. These widgets, such as sliders, dropdown menus, and checkboxes, provide an intuitive and engaging interface for users to input their choices and preferences. Leveraging these widgets, the decision game empowers users to navigate through different scenarios and make informed decisions based on the available options.

Streamlit offers a wide range of data visualization tools that enhance the presentation and interpretation of information within the decision game. These tools enable the creation of interactive graphs, charts, and visual representations of the electrical grid network, forecast uncertainty, and congestion levels. By visualizing data intuitively and visually appealingly, the decision game enhances the user's understanding of complex grid scenarios and aids in the identification of potential congestion issues.

Effective data storage and analysis are critical components of the decision game's functionality. Streamlit provides seamless integration with various data storage technologies, allowing the game to store user inputs, decisions, and associated outcomes for further analysis. This enables the evaluation of user performance, identification of decision patterns, and characterization of risk profiles. The ability to analyze collected data assists in assessing the effectiveness of different decision strategies and contributes to improving the overall decision-making process in grid operations.

3.4 Limitations

In this subchapter, is explored the limitations associated with the developed experiment for analyzing forecast uncertainty in electrical grid operations. It is essential to acknowledge these limitations to provide a comprehensive understanding of the study's scope, potential deviations from real-world scenarios, and simplifications made throughout the development process. The limitations outlined here pertain to the conceptual and contextual aspects of the study.

One significant limitation of the decision game is its inherent deviation from real-world electrical grid operations. While the game aims to simulate realistic scenarios, it operates within a controlled environment that may not fully capture the complexity and nuances of actual grid operations. The simplified representation of the grid and the assumptions made during scenario creation contribute to this deviation. As such, the decisions and outcomes within the game should be interpreted with caution when considering their applicability to real-world situations.

To facilitate a manageable and focused decision-making experience, certain simplifications and assumptions were made during the development of the decision game. These simplifications aimed to strike a balance between providing a meaningful learning experience and maintaining a manageable scope. However, they may impact the accuracy and realism of the game. Some of the key simplifications and assumptions include:

- Simplified Forecast Models: The decision game utilizes simplified forecast models to generate power production forecasts. These models may not fully capture the intricacies and uncertainties present in actual forecasting processes, potentially leading to deviations between the game's forecasts and real-world predictions.
- Limited Input Variables: The game considers a limited set of input variables to simulate network congestion and decision-making. While efforts were made to include the most critical factors, certain variables that might have a substantial impact on congestion were omitted due to complexity or data availability constraints. This limitation may affect the game's ability to fully represent the range of factors influencing congestion in real-world scenarios.
- Absence of External Factors: The decision game focuses primarily on internal factors affecting network congestion, such as power production forecasts and strategic decision-making. External factors, such as extreme weather events, market dynamics, and unforeseen system failures, which can significantly impact grid operations, are not explicitly modeled within the game. Therefore, the game's outcomes may not account for the influence of these external factors on congestion management strategies.

This subchapter highlighted the limitations associated with the decision game used to analyze forecast uncertainty in electrical grid operations. The deviations from real-world scenarios, simplifications made, and assumptions utilized during development were discussed. It is crucial to recognize these limitations to ensure a nuanced interpretation of the game's outcomes and to understand the context in which the decision game operates. While efforts were made to simulate realistic scenarios, the limitations outlined here underscore the need for further research and refinement to bridge the gap between the decision game and real-world grid operations.

Chapter 4

Experimental Analysis and Performance Evaluation

In this chapter, we present a comprehensive experimental analysis and performance evaluation of the decision game framework under both deterministic and probabilistic scenarios. The decision game represents a crucial tool for managing congestion in the electrical grid and addressing forecast uncertainty. Through this analysis, we aim to gain valuable insights into the effectiveness and impact of user decisions within the decision game and explore the advantages of embracing probabilistic information in decision-making processes.

4.1 Analyzing User Feedback: Deterministic and Probabilistic Choices in the decision game

This subchapter examines and compares deterministic and probabilistic choices in the decision game. The aim is to analyze users' preferences and decision-making tendencies when presented with these two types of information.

The analysis of the user feedback provides valuable insights into the user's preferences and decision-making tendencies when presented with deterministic and probabilistic choices in the decision game. The graph displayed in Figure 4.1 illustrates the comparison of preferred information, namely the count of deterministic and probabilistic decisions, among the users participating in the study.

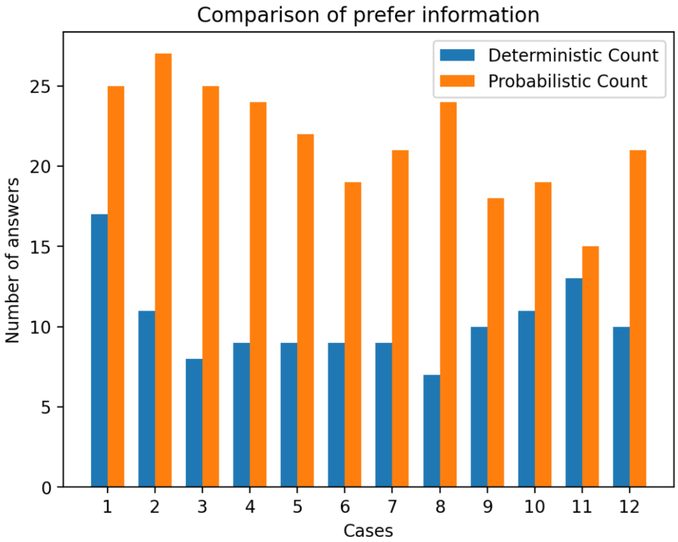


Figure 4.1: Preferred Information by the users

The graph displays the feedback answers provided by the users for both deterministic and probabilistic choices. The x-axis represents each case's feedback responses, while the y-axis represents the count of user responses. The graph allows us to visualize and compare the distribution of feedback answers between the two types of choices.

Upon analyzing the graph, can be observed variations in the decision preferences between deterministic and probabilistic information. These preferences were reported by the users, who had varying levels of experience in the field. It is important to note that the user's responses were collected from individuals with different levels of expertise, including both experienced professionals and those with limited experience.

Across the cases, there are noticeable fluctuations in the counts of deterministic and probabilistic decisions. These variations reflect the subjective nature of decision-making and the user's individual preferences. It is interesting to observe that a significant number of users prefer probabilistic information over deterministic information for making decisions in congestion management scenarios.

Upon analyzing the user feedback in the decision game, are observed intriguing patterns in the user's preferences for deterministic and probabilistic information. The graph (Figure 4.1), clearly illustrates that a significant number of users preferred probabilistic information over deterministic information when making decisions in congestion management scenarios. The comparison of preferred information among users reveals a strong inclination towards probabilistic data, suggesting its effectiveness in capturing uncertainties and influencing decision-making processes.

Additionally, probabilistic information offers users a broader perspective by considering multiple scenarios and potential outcomes. This allows for a more comprehensive evaluation of the possible impacts of congestion and facilitates the development of robust decision strategies.

Furthermore, users may prefer probabilistic information due to its ability to capture the dynamic nature of congestion scenarios. The unpredictable nature of network conditions and demand fluctuations necessitates the consideration of probabilistic information to account for potential variations and unforeseen events.

Despite the clear preference for probabilistic information, it is important to recognize that deterministic information still holds value in decision-making processes.

Deterministic information provides concrete and reliable data that serves as a strong foundation for decision-making processes. It allows users to make decisions based on known facts and historical patterns, offering a sense of certainty in otherwise uncertain scenarios. For certain users, deterministic information may be preferred when dealing with straightforward or well-defined cases, where probabilistic data might not offer substantial additional insights.

In summary, the results of this analysis demonstrate that a considerable number of users prefer probabilistic information over deterministic information in congestion management decision-making. This preference can be attributed to the ability of probabilistic information to capture uncertainties, provide a broader perspective, and accommodate the dynamic nature of congestion scenarios.

In addition to examining user preferences and decision-making tendencies, this subchapter also analyzes the user's confidence levels when presented with deterministic and probabilistic choices in the decision game. The table presented in Table 4.1 displays the average confidence values for each type of information across different cases.

	Deterministic	**Probabilistic**
Case 1	3.10	3.44
Case 2	4.00	2.96
Case 3	3.5	3.12
Case 4	2.56	2.88
Case 5	3.33	3.17
Case 6	3.11	3.25
Case 7	3.00	2.81
Case 8	2.71	3.00
Case 9	3.27	3.67
Case 10	2.83	3.00
Case 11	3.36	3.67
Case 12	3.18	3.45
Total Average	3.13	3.20

Table 4.1: Average Confidence

Upon analyzing the table, is observed interesting patterns in the average confidence levels. It is noteworthy that the average confidence levels for deterministic and probabilistic information are comparable, indicating a balanced perception of confidence among users. This finding is consistent across the different cases studied, suggesting that users, regardless of their level of experience, exhibit similar levels of confidence in both types of information.

The similarity in average confidence levels between deterministic and probabilistic information can be attributed to the diverse composition of users participating in the study. The mix of individuals with varying levels of experience and expertise in the field likely contributes to this balance. Users with extensive experience and knowledge may have higher confidence in interpreting and utilizing probabilistic information, while users with limited experience or a preference for deterministic approaches might exhibit similar confidence levels in deterministic information.

These results align with the previous analysis of user preferences, as they demonstrate that a significant number of users prefer probabilistic information over deterministic information for making decisions in congestion management scenarios. This preference can be attributed to several factors, including the inherent uncertainties and risks involved in congestion management, the broader perspective and comprehensive evaluation provided by probabilistic information, and its ability to capture the dynamic nature of congestion scenarios.

The balanced perception of confidence in both types of information highlights the importance of integrating deterministic and probabilistic approaches in decision-making processes. By leveraging the strengths of each approach, decision-makers can effectively manage uncertainties, evaluate potential risks, and develop more robust strategies. This finding underscores the need for adaptable decision-support tools in congestion management, which provide users with access to both types of information for a comprehensive evaluation of the congestion scenario.

In summary, the analysis of user confidence levels reveals a balanced perception of confidence in both deterministic and probabilistic information. This finding further supports the preference for probabilistic information in congestion management decision-making, indicating its value in capturing uncertainties and accommodating the dynamic nature of congestion scenarios. By combining both types of information, decision-makers can make well-informed and comprehensive decisions considering certainties and uncertainties.

4.2 Confusion matrix: Evaluating Forecast Detection Performance

Having previously examined user feedback and interpreted experiment outcomes, the confusion matrix serves as a powerful mechanism to assess the effectiveness and accuracy of each forecast in detection stage.

The confusion matrix enables us to analyze the decisions' classification into different outcomes and understand how well the model predicts these outcomes compared to actual occurrences. By providing a clear and concise representation of true positive (TP), false positive (FP), true negative (TN), and false negative (FN) results, valuable insights into the decision game's performance are gained under both deterministic and probabilistic scenarios.

- True Positive (TP): TP refers to the number of cases where the forecast method (i.e., deterministic or probabilistic) correctly predicted a line congestion case.

- False Negative (FN): FN indicates the number of cases where the forecast fails to identify the congestion.

- False Positive (FP): FP denotes the number of cases where the forecast incorrectly predicted congestion and led to a false alarm.
- True Negative (TN): TN represents the number of cases where the forecast correctly predicted a negative outcome. In simple terms, TN represents the number of correct negative classifications.

Taking this into account, the Confusion matrix for both cases was constructed, counting the number of occurrences for each indicator:

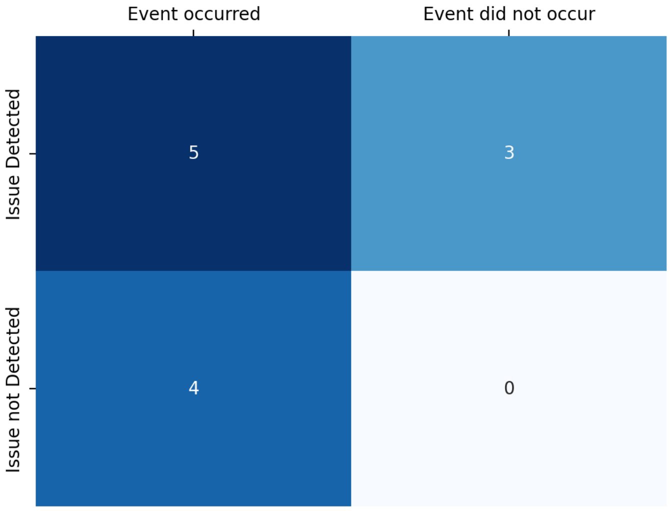


Figure 4.2: Confusion matrix for Deterministic Cases

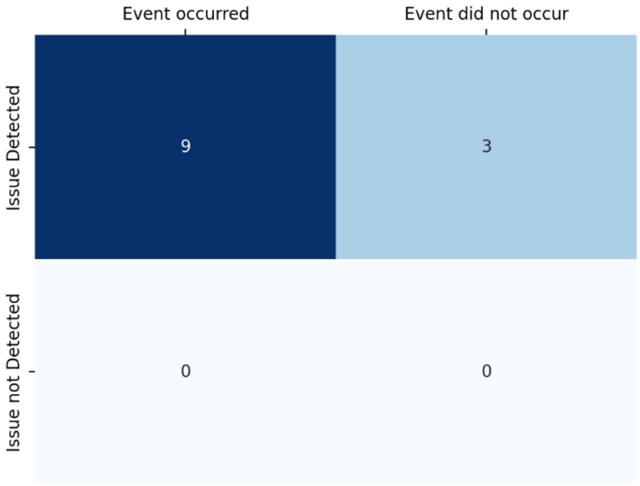


Figure 4.3: Confusion matrix for Probabilistic Cases

Two important metrics that aid in evaluating the decision game's performance are:

- Precision: Precision measures the proportion of true positive decisions among all positive predictions made by the model. It indicates the accuracy of positive predictions and is calculated as:

  $$Precision = \frac{TP}{TP+FP} \tag{4.1}$$

  A higher precision value signifies fewer false positive predictions, reflecting more reliable positive outcomes.

- Recall (Sensitivity): Recall, also known as sensitivity, calculates the proportion of true positive decisions among all actual positive occurrences. It indicates the model's ability to correctly identify positive outcomes and is computed as:

  $$Recall = \frac{TP}{TP+FN} \tag{4.2}$$

  A higher recall value indicates a higher ability to detect actual positive occurrences.

In addition we also have F1 and F3 scores:

- F1 Score: The F1 Score is a widely used metric in binary classification problems and represents the harmonic mean of precision and recall. It quantifies the balance between precision and recall, providing a single value that considers both metrics. The formula for the F1 Score is given by:

  $$F1Score = \frac{2 \times TP}{2 \times TP+FN+FP} \tag{4.3}$$

  A higher F1 Score indicates a better balance between precision and recall, signifying a more accurate and reliable decision game

- The F3 Score is an extension of the F1 Score that places more weight on recall than precision. This metric is useful when the emphasis is on minimizing false negatives, which can have significant consequences in grid management. The formula for the F3 Score is given by:

  $$F3Score = \frac{TP}{TP+0.1 \times FN+0.9 \times FP} \tag{4.4}$$

  By incorporating the weights for FP and FN, the F3 Score provides a metric that prioritizes recall while still considering precision.

4.2.1 Analysis of Decision Game Performance Metrics

The Confusion matrix and associated metrics provide valuable insights into the performance of the decision game framework in managing congestion, enabling us to assess its effectiveness and accuracy in making congestion management decisions under different scenarios.

In Table 4.2, the performance metrics for each indicator are presented, enabling us to evaluate the decision game's performance.

	rate(TP)	**rate(FN)**	**rate(FP)**	**rate(TN)**	**F1 score**	**F3 Score**	**Precision**	**Recall**
Deterministic	41.67%	33.33%	25.00%	0%	58.82%	56.18%	63%	56%
Probabilistic	75.00%	0%	25.00%	0%	85.71%	96.77%	75.00%	100%

Table 4.2: Confusion matrix Table

In the deterministic scenario, the decision game demonstrated a relatively high rate of True Positives (TP) at 41.67%, indicating its ability to correctly identify a congestion case. The model also exhibited a moderate rate of False Negatives (FN) at 33.33%, indicating instances where it failed to detect the congestion problem. Moreover, the rate of False Positives (FP) was relatively low at 25.00%, indicating that the model produced relatively few false alarms, leading to unnecessary costs or actions.

The F1 Score (58.82%) and F3 Score (56.18%) further highlight the overall accuracy and balance between precision and recall. The Precision value of 63.00% indicates a high proportion of correctly identified positive outcomes, while the Recall value of 56.00% signifies the model's ability to detect positive occurrences among all actual positive outcomes.

In the probabilistic scenario, the decision game demonstrated a considerably higher rate of TP at 75.00%, indicating an improved ability to correctly identify the congestion. Remarkably, there were no False Negatives (FN) in this scenario, meaning that the decision game successfully detected all congestions, resulting in more efficient congestion management. However, the rate of False Positives (FP) was 25.00%, indicating that the model produced more false alarms compared to the deterministic scenario.

The F1 Score (85.71%) and F3 Score (96.77%) in the probabilistic scenario show a superior balance between precision and recall compared to the deterministic scenario. The Precision value of 75.00% indicates that three-quarters of the positive predictions were correct, while the Recall value of 100.00% signifies the model's ability to detect all positive occurrences.

Comparing the performance metrics between the deterministic and probabilistic scenarios reveals distinct differences in decision-making effectiveness. The probabilistic scenario exhibits significantly higher rates of TP and overall accuracy (F1 Score and F3 Score), indicating that decisions based on probabilistic information lead to more successful outcomes in managing congestion. In contrast, the deterministic scenario struggles to capture all positive occurrences, resulting in lower F1 Score and F3 Score values.

The Precision and Recall values show that the probabilistic scenario has a higher proportion of correctly identified positive outcomes and a better ability to detect positive occurrences compared to the deterministic scenario. Furthermore, the probabilistic scenario's higher Precision value implies a lower rate of false positives, leading to more precise decision-making.

In conclusion, the analysis of the forecast detection performance metrics suggests that probabilistic information leads to more effective and accurate decisions in managing congestion. The decision game's performance significantly improved in the probabilistic scenario, capturing all positive occurrences and achieving higher overall accuracy. Leveraging probabilistic approaches offers valuable insights into uncertainties and enhances the decision game's performance and efficiency in congestion management strategies.

4.3 Interpreting Experiment Outcomes

In this section, is compared the outcomes obtained from the decision game using the cost-loss matrix as an analytical tool. The cost-loss matrix allows us to categorize and analyze the users' answers to identify patterns, trends, and successful approaches in handling congestion scenarios.

By dividing the users' responses into distinct outcomes, valuable insights into the effectiveness of their decision-making strategies. Each outcome in the cost-loss matrix represents a specific categorization for possible outcome of actions taken by users and the corresponding results in managing congestion within the electrical grid.

The cost-loss matrices capture the results of the decision game for both deterministic and probabilistic scenarios. Each matrix cell represents a unique outcome of actions taken and events that occurred during the congestion management process. The outcomes are divided into four categories, and their respective total costs and rates for each case are presented in Table 4.3.

	Outcome 1		**Outcome 2**		**Outcome 3**		**Outcome 4**	
	Total	Rate	Total	Rate	Total	Rate	Total	Rate
Deterministic	4 412 095	19.74%	28 104	57.40%	2 603 963	13.25%	0	9.61%
Probabilistic	1 615 967	14.70%	35 225	59.84%	1 435 528	13.65%	0	11.81%

Table 4.3: Table for cost-loss matrix

The outcomes are common for both the deterministic and probabilistic scenarios, and their calculation remains the same.

- Outcome 1: This outcome represents situations where flexibility was booked, but it was not sufficient to resolve the congestion issue. The total cost (C) includes both the cost of the booked flexibility and the loss (L) incurred due to unresolved congestion.

- Outcome 2: This outcome represents cases where flexibility was booked, and it was sufficient to resolve the congestion issue. The total cost (C) includes only the cost of the booked flexibility.

- Outcome 3: This outcome denotes situations where no flexibility was booked, and the congestion resulted in a Loss (L) due to a technical issue.

- Outcome 4: This outcome represents cases where no flexibility was booked, and there was no technical issue, resulting in no additional cost. It indicates successful decisions that avoided unnecessary costs.

The rates in Table 4.3 indicate the percentage of occurrences of each outcome. They are calculated as the total number of occurrences of a specific outcome divided by the total number of cases in the scenario. These rates provide insights into the frequency at which certain decisions and events lead to particular cost outcomes.

The V_indicator is a crucial metric that quantifies the overall cost incurred due to decision-making in congestion management. It takes into account both the rates (representing the likelihood of occurrence) and the total cost associated with each outcome.

For both deterministic and probabilistic scenarios, the V_indicator is calculated, as in [30] by summation of the matrix elements each weighed by the rate of occurrence as seen in 4.5. The V_indicator provides a valuable assessment of the efficiency and effectiveness of decision-making strategies.

$$Vindicator = (C+L) \times Rate_{Outcome1} + C \times Rate_{Outcome2} + L \times Rate_{Outcome3} + 0 \times Rate_{Outcome4} (€) \tag{4.5}$$

	V_indicator
Deterministic	1 232 032 €
Probabilistic	454 522 €

Table 4.4: V_indicator for both scenarios

Let us now proceed to present the cost-loss matrices for each scenario. Please note that the colors in the matrices correspond to the rates, whereas darker colors indicate higher rates.

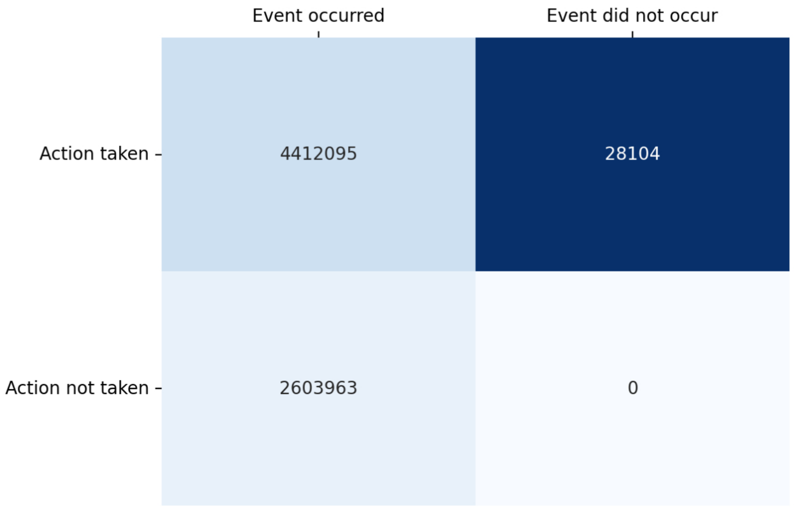


Figure 4.4: Cost-loss matrix for Deterministic Cases

- Probabilistic Cases

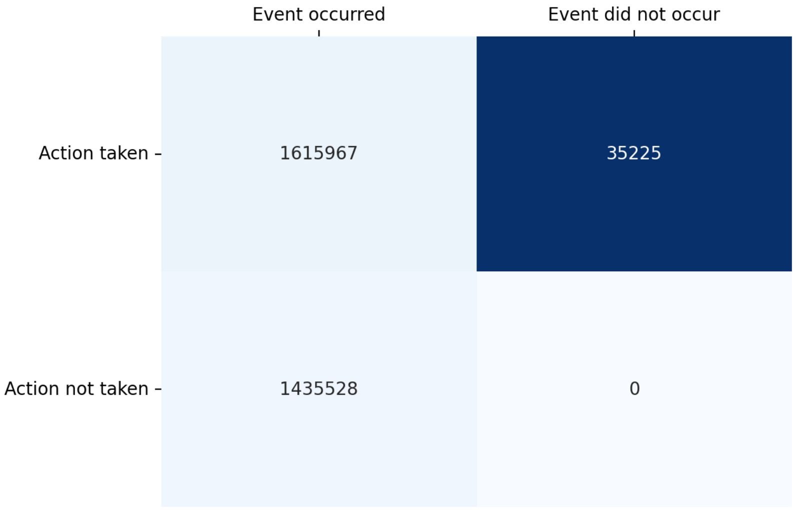


Figure 4.5: Cost-loss matrix for Probabilistic Cases

In the subsequent analysis, the values within each matrix will be thoroughly examined, with a specific focus on the total costs associated with each outcome and the corresponding rates linked to the decisions. Through a comprehensive comparison between the deterministic and probabilistic cases, the objective is to discern patterns and gain a deeper understanding of how distinct types of information influence decision-making strategies.

4.3.1 Outcome 1: Action Taken and Event Occurred

The cost analysis reveals notable distinctions between the deterministic and probabilistic cases. In the deterministic scenario, the total cost for this outcome is considerably higher compared to the probabilistic case. This suggests that decisions based on deterministic information may result in increased costs when the booked flexibility proves insufficient to fully resolve congestion issues. The higher rate in the deterministic scenario (19.74%) indicates that users frequently make decisions based on deterministic forecasts, even though they might lead to higher expenses. However, it is essential to note that this higher rate in the deterministic case is specific to this particular outcome, where partial solutions are obtained more frequently.

In the probabilistic case, the total cost for this outcome is lower, indicating that decisions made with probabilistic information are more effective in resolving congestion issues. The higher rate (14.70%) in this cell suggests that users are more inclined to take actions based on probabilistic forecasts, leading to more cost-efficient decisions. Furthermore, it highlights that decisions guided by probabilistic forecasts have a higher likelihood of achieving a full resolution to congestion.

4.3.2 Outcome 2: Action Taken and Event Did Not Occur

In the deterministic case, the total cost for this outcome is indeed lower compared to the probabilistic case. Users tend to avoid unnecessary costs effectively in the deterministic scenario, as reflected by the higher rate (57.40%). This suggests that deterministic decisions are good at preventing false alarms and booking flexibility, which is a positive aspect of this approach.

For the probabilistic case, the total cost is higher for this outcome and the rate (59.84%) indicates that users are still making effective decisions to avoid unnecessary costs based on probabilistic forecasts. However, it is essential to note that this higher rate in the probabilistic scenario is not solely attributed to the cost of false alarms but also includes cases where booked flexibility successfully resolved congestion. In other words, the higher cost in the probabilistic case is due to more instances of successful flexibility booking, which efficiently mitigates congestion issues. This highlights the advantage of leveraging probabilistic information to make more successful decisions in congestion management.

4.3.3 Outcome 3: Action Not Taken and Event Occurred

For the deterministic case, the total cost for this outcome is lower compared to the probabilistic case. The higher rate (57.40%) in the deterministic scenario suggests that users are more likely to make effective decisions to avoid unnecessary costs and false alarms. This indicates that deterministic decisions are more reliable in preventing false alarms, leading to cost savings and efficient utilization of resources.

For the probabilistic case, while the total cost is higher for this outcome, the rate (59.84%) indicates that users still make effective decisions to avoid unnecessary costs based on probabilistic forecasts. However, the slightly higher rate compared to the deterministic scenario may indicate that some users are more cautious when relying on probabilistic information

4.3.4 Outcome 4: Action Not Taken and Event Did Not Occur

The rates 9.61% and 11.81%, respectively, show that users tend to avoid unnecessary costs effectively in this scenario.

4.3.5 Comparasion and Conclusions

Comparing the outcomes between the deterministic and probabilistic scenarios reveals valuable insights into the strengths and weaknesses of each approach in congestion management. The analysis indicates that probabilistic information led to a reduction in total costs for Outcome 1 and an increase in successful bookings for Outcome 2. However, both scenarios had comparable total costs for Outcome 3 and were equally successful in avoiding unnecessary costs (Outcome 4).

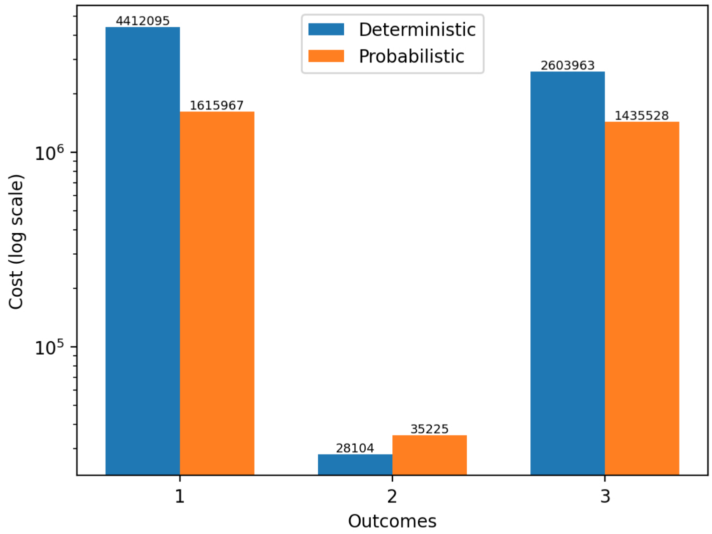


Figure 4.6: Outcomes Cost

The higher total cost in the deterministic scenario for Outcome 1 can be attributed to the lack of consideration of uncertainty, leading to less optimal decisions and potentially higher financial losses. On the other hand, the probabilistic approach provided a more comprehensive understanding of uncertainties, allowing for more informed decisions, particularly in successful bookings.

The rates for both cases were identical, as evident from 4.7 and goes along with what was previously said about in Table 4.1.

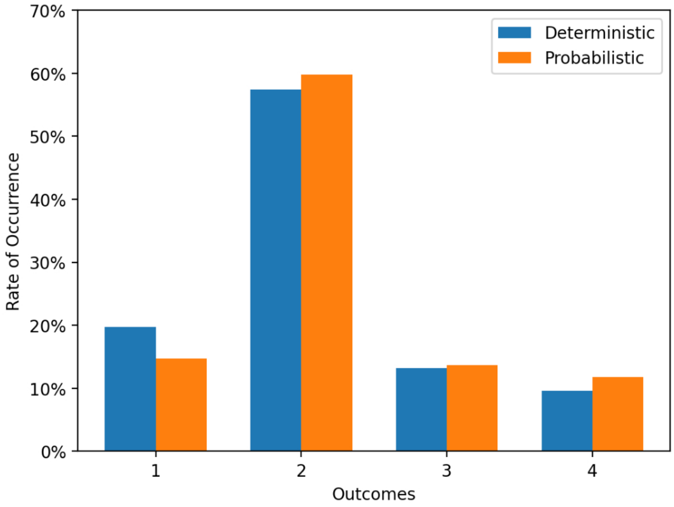


Figure 4.7: Outcomes Rates

The findings underscore the benefits of embracing probabilistic information in decision-making, leading to more cost-effective and efficient congestion management strategies. By incorporating probabilistic approaches, grid operators can better navigate uncertainties, optimize resource allocation, and enhance grid operation.

The V_indicator and average user confidence provide valuable insights into the effectiveness of decision-making strategies and the level of confidence associated with the outcomes. Interestingly, both the deterministic and probabilistic scenarios yield similar average user confidence levels. However, There is a noticeable difference in the V_indicator between the two scenarios, as illustrated in Table 4.5.

	V_indicator	**Average User Confidence**
Deterministic	1 232 032	3.13
Probabilistic	454 522	3.2

Table 4.5: Comparison between V_indicator and User Confidence

The comparison of the V_indicator between the two scenarios reveals that the probabilistic scenario yields a significantly lower V_indicator compared to the deterministic scenario, a 63% decrease to be exact. This further supports the notion that the probabilistic approach, which considers uncertainties and variability in power generation, leads to more cost-effective decision-making in congestion management.

When examining the analysis of the outcomes and comparing the V_indicator and average user confidence, it becomes evident that while both scenarios show similar average user confidence levels, the probabilistic approach's integration of probabilistic forecasts proves to be more effective in managing congestion and minimizing overall costs. The probabilistic scenario's consideration of uncertainties empowers users to anticipate potential outcomes and make informed decisions, leading to better outcomes and lower costs compared to the deterministic approach.

In conclusion, the analysis of the outcomes and the comparison of the V_indicator and average user confidence highlight the advantages of embracing probabilistic information in congestion management. The incorporation of probabilistic forecasts provides decision-makers with valuable insights into potential risks and uncertainties, leading to more efficient grid management and improved reliability. By understanding the impact of different types of information on decision-making, stakeholders can harness the full potential of probabilistic approaches to achieve cost savings and enhance overall grid performance.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this final chapter, the thesis culminates with a comprehensive conclusion, encompassing the key findings and contributions derived from the research conducted. The chapter revisits the initial problem definition, which pertains to the complex challenges of uncertainty forecasts and congestion management within electrical grids. It emphasizes the achievements attained through the implementation of the decision game framework as an innovative solution to address these challenges.

The research has successfully shed light on the intricacies of human decision-making under forecast uncertainty. Through the exploration of deterministic and probabilistic information within the decision game, valuable insights were gained into how individuals respond to uncertain conditions and make decisions that impact grid performance and reliability.

One of the notable contributions of this thesis lies in the detailed analysis of user feedback obtained from the decision game. By investigating the choices made by participants in response to varying information scenarios, the research has provided a comprehensive understanding of decision-making strategies under both deterministic and probabilistic contexts. This analysis has allowed us to identify patterns and draw conclusions on the effectiveness of each approach in managing congestion within the electrical grid.

Beyond the realm of electrical grids, the decision game framework may find application in other domains that deal with forecast uncertainty and decision-making. Its adaptability and effectiveness open up possibilities for implementation in diverse contexts, such as renewable energy integration, transportation networks, and financial systems.

In conclusion, "Congestion management: Human decision-making under forecast uncertainty" has contributed significant knowledge to the field of uncertainty forecasts and congestion management. The research findings and the innovative decision game framework pave the way for more informed decision-making in the face of forecast uncertainties, ensuring efficient grid operations, enhanced grid reliability, and sustainable energy management. As the thesis comes to an end, its impact resonates as a crucial stepping stone toward building a resilient and adaptive energy infrastructure for the future.

5.2 Future Work

The research conducted in this thesis has shed light on important aspects of uncertainty forecasts and congestion management within electrical grids. The findings have paved the way for potential future work that could further advance the understanding of decision-making processes and improve the management of forecast uncertainties in energy systems. Here are some potential avenues for future research:

Firstly, there is a need for continued efforts in enhancing the accuracy and reliability of probabilistic forecasts. Exploring advanced forecasting models and data assimilation techniques could lead to more precise probabilistic forecasts, enabling decision-makers to make well-informed choices in the face of uncertainties.

Understanding the cognitive and behavioral factors that influence decision-making in uncertain environments is another promising area of research. By considering human factors, such as risk perception and individual decision preferences, decision-making frameworks can be tailored to better support the decision-makers' needs.

To validate the effectiveness of the decision-making framework, future research could involve real-world implementations and pilot studies in grid control rooms or other relevant domains. This would provide valuable insights into the framework's performance and its practical applicability.

Scalability and generalizability are crucial considerations for the future development of decision-making frameworks. Research could focus on evaluating the framework's performance under different grid configurations and varying degrees of uncertainty, ensuring its adaptability to diverse energy management contexts.

Lastly, exploring the incorporation of multi-objective decision-making criteria, such as economic, environmental, and social factors, could enhance the decision-making process further. This would enable decision-makers to make more holistic and well-balanced choices that align with sustainability and long-term grid management goals.

In conclusion, the future work outlined above holds great potential for advancing the field of uncertainty forecasts and congestion management. By addressing these areas, researchers can work to create more effective and sustainable energy management strategies, ensuring the resilience and reliability of electrical grids in the face of uncertainty.

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