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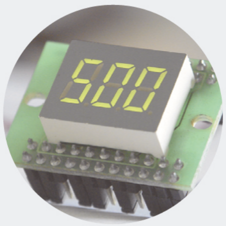

Análise geoespacial para mapeamento e visualização da infraestrutura da rede elétrica de média tensão no apoio à sua expansão

PEDRO FILIPE RIBEIRO GONÇALVES
outubro de 2025

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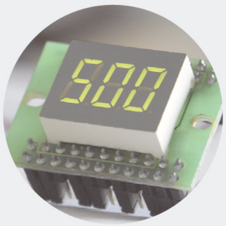

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Setembro de 2025

POLITÉCNICO
DO PORTO

ISEP INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

MAPPING AND VISUALIZATION OF A MEDIUM VOLTAGE DISTRIBUTION NETWORK IN SUPPORT OF ITS EXPANSION USING GEOSPATIAL ANALYSIS

Pedro Filipe Ribeiro Gonçalves

Dissertação para obtenção do Grau de Mestre em Engenharia Eletrotécnica - Sistemas Elétricos de Energia

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Porto, September 2025

Resumo

Estudos recentes têm destacado a crescente importância da integração da análise geoespacial no planeamento das redes de distribuição de média tensão. Para esta análise, é fundamental incorporar a utilização do solo, as restrições de declive e os fatores regulamentares nos modelos de custo, garantindo soluções que sejam simultaneamente tecnicamente viáveis e economicamente sustentáveis. Com base nestes fundamentos, esta dissertação explora a integração dos sistemas de informação geográfica para apoiar a expansão das redes de distribuição de eletricidade de média tensão. Através da análise da função do *Least Cost Path* no *software* QGIS, foram geradas múltiplas rotas candidatas em oito estudos de caso que cobrem diferentes regiões, de sul a norte, do território continental português. Cada área de estudo apresentou desafios específicos, tais como zonas urbanizadas, áreas industriais, aeródromos, terrenos agrícolas e restrições de declive, que foram incorporados em superfícies de custo espacial. Estes resultados geoespaciais foram posteriormente processados com um modelo de otimização desenvolvido em *Python*, permitindo calcular um número ótimo de postes e os custos associados para cada tipo de percurso gerado, utilizando a biblioteca *Pyomo* e a ferramenta de otimização *Gurobi*, para avaliar a viabilidade técnica e a eficiência económica. O modelo considerou parâmetros como o espaçamento entre postes, o número de ângulos e curvas, os materiais, os custos de instalação e de licenciamento, garantindo resultados realistas. As conclusões demonstram que a integração dos sistemas de informação Geográfica e da otimização constitui uma ferramenta poderosa para o planeamento das redes de média tensão, permitindo identificar percursos simultaneamente económicos e tecnicamente viáveis. Os resultados evidenciam a variabilidade dos custos em diferentes condições, mostrando que pequenas alterações no traçado podem originar poupanças significativas. De forma geral, esta metodologia estabelece uma ponte entre a análise espacial e o processo de decisão, contribuindo para um planeamento mais sustentável e eficiente das infraestruturas energéticas.

Palavras-chave: Análise Geoespacial, *Least Cost Path*, Média tensão, Planeamento Ótimo, *Python*, Sistemas de Informação Geográfica

Abstract

Recent studies have highlighted the growing importance of integrating geospatial analysis into the planning of Medium Voltage distribution networks. For this analysis, it is important to incorporate land use, slope constraints, and regulatory factors into cost models, ensuring solutions that are both technically feasible and economically sustainable. Building upon these foundations, this thesis explores the integration of Geographic Information Systems to support the expansion of Medium Voltage electricity distribution networks. Using Least Cost Path analysis in QGIS, multiple candidate routes were generated across eight case studies covering different regions, from south to north, of the Portuguese mainland. Each study area presented unique challenges, such as urbanized zones, industrial areas, aerodromes, agricultural land, and slope constraints, which were incorporated into spatial cost surfaces. These geospatial outputs were then processed with an optimization model built in Python, using Pyomo library and the optimization solver Gurobi, to evaluate engineering feasibility and economic efficiency. The model accounted for an optimal pole spacing and evaluated the cost related to each pathway generated. The findings demonstrate that the integration of Geographic Information Systems and optimization offers a powerful tool for Medium Voltage grid planning, enabling the identification of cost-effective and technically feasible routes. Results highlight the variability of costs across different conditions, showing that minor routing changes can lead to significant savings. Overall, this methodology bridges spatial analysis and decision-making, contributing to more sustainable and efficient energy infrastructure planning.

Keywords: Geographic Information Systems, Geospatial Analysis, Least Cost Path, Medium Voltage, Optimal Planning, Python

Acknowledgments

I would like to express my gratitude to my parents and family for their support throughout this journey. Even during challenging times, they managed to keep me motivated and focused on my goals.

I extend my sincere thanks to Dr. Fernando Lezama and MSc. Fábio Castro for their guidance and availability throughout the development of this work. I would also like to express my appreciation for the guidance provided by Dr. Bruno Canizes throughout the first semester of this work.

I am also grateful to Dr. Luís Aires and Dr. Sandra Mourato from the Polytechnic Institute of Leiria for their invaluable support and guidance in the use of QGIS for geospatial analysis.

Last but not least, I would like to offer a special tribute to my grandfather, Bernardino Mendonça Gonçalves, whose strength and determination were a constant source of inspiration in my life and studies. His values have guided me through this journey, and I dedicate this achievement to his memory.

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Acronyms and Symbols

Index of Acronyms

ALOS	Advanced Land Observing Satellite
DEM	Digital Elevation Models
DERs	Distributed Energy Resources
DESS	Distributed Energy Storage Systems
DG	Distributed Generation
ERSE	*Entidade Reguladora dos Serviços Energéticos*
ESRI	Environmental Systems Research Institute
GDAL	Geospatial Data Abstraction Library
GHG	Greenhouse Gas
GIS	Geographic Information System
MILP	Mixed integer linear programming
MIP	Mixed-integer programming
LV	Low Voltage
MV	Medium Voltage
OnSSET	Open-Source Spatial Electrification Tool
OSM	OpenStreetMap
SOPs	Soft Open Points
SotA	State of the Art
SRTM	Shuttle Radar Topography Mission

Index of Variables

$C_{equipment}$	Cost of Equipment
C_{inst}	Cost of Installation Labor

C_{lines}	Cost of Lines
CO_2	Carbon Dioxide
C_{pole}	Cost of Poles
C_{TL}	Cost of Taxes and Licenses
$C_{terrain}$	Cost of Terrain

Index of Units

V	Volt
$	Dollar
kV	kilovolt
m	meter
M$	Million Dollar

1 Introduction

1.1 Contextualization / Study Necessity

This study was selected due to a personal interest in geospatial analysis and the processing of geographic data to support the planning and development of essential infrastructure for modern demands. The initial work on applying this method to the mapping and planning of the medium voltage (MV) network was carried out with the guidance of Dr. Bruno Canizes and MSc. Fábio Castro, whose work has focused on the complexities of managing MV networks and adapting them to evolving energy needs. Given the increasing pressures on distribution networks, the professors have identified geospatial analysis as a critical tool for mapping and visualizing MV network infrastructure. This approach not only supports strategic expansion planning but also provides valuable insights into the current state of the network, helping to identify areas in need of improvement, maintenance, or expansion.

The motivation for this research topic stems from urgent needs within the energy sector, as the world moves towards cleaner, more flexible power systems. Integrating large-scale renewable energy sources, expanding the infrastructure for electric vehicles, and enhancing energy efficiency are all essential strategies for achieving significant reductions in greenhouse gas (GHG) emissions. Additionally, empowering citizens to engage in energy-saving practices and improving the system's adaptability to fluctuating demands are fundamental goals. Together, these factors necessitate a distribution network that can manage the complexities of modern energy consumption and production. Such advancements are essential for establishing a robust, reliable, and efficient power grid that aligns with global sustainability goals.

The scientific purpose of this study is to evaluate how geospatial analysis can directly influence the planning and optimization of MV grid expansion. Specifically, it seeks to determine whether the application of geospatial methodologies truly enhances cost efficiency, accuracy, and overall effectiveness in mapping and expanding MV lines. The research focuses on identifying and analyzing key spatial parameters such as terrain slope, land use, and existing infrastructures, and assessing their relative influence within a multi-criteria decision-making framework. Through a series of case studies, the study aims to examine how these parameters affect the selection of optimal expansion pathways under varying geographic conditions. By comparing planning scenarios characterized by different land uses and terrain slopes, the research seeks to provide insights into how geospatial approaches can guide more efficient, cost-effective, and sustainable MV network expansion strategies.

1.2 Objectives

To efficiently study the expansion of the MV grid by analysing the geospatial characteristics of the terrain to be applied, there are some tasks and objectives that must be fulfilled. These chores begin with a study of the state of the art (SotA) on the topic under discussion and existing case studies, until the practical simulations using the appropriate software and conclusions. During this process the main goals established to ensure the success of the main objective of the thesis are the following:

- Analyse the most current case studies like the subject in debate, by writing a SotA and reflect on the challenges and benefits establishing a solid theoretical foundation and identify existing methodologies, helping to highlight current gaps and guide the development of an improved geospatial approach for MV grid expansion.

- Gather enough data about geospatial from the MV network infrastructure including power generations plants, transmission lines and electrical substations, using public repositories, ensuring a comprehensive, to understand the current energy distribution framework, enabling accurate spatial modelling.

- Understand the current public laws and obligations regarding electrical and environmental requirements, guaranteeing that the proposed solutions comply with national regulations and environmental standards, ensuring that all expansion strategies are technically viable and legally sustainable.

- Collection of other relevant data, such as land use, population density, and meteorological conditions, in order to integrate socio-environmental and climatic factors, this task allows for a more realistic analysis of how external conditions influence network planning and operational efficiency.

- Manage to filter, pre-process and integrate the same data into a database using the open-source Geographic Information System (GIS) software, such as QGIS, allowing the creation of a structured geospatial database that supports efficient analysis.

- Create an interface to visualize the results of the spatial analysis using open-source tools, in this case the software Plotly, providing an interactive and intuitive visualization platform that facilitates interpretation of results and supports transparent communication of spatial insights.

- Once gather the data and the certain tools, simulate the scenarios, analyse the results and take conclusions about the outcomes, to finally do an assessment of how different parameters such as terrain slope and land use affect expansion pathways, helping to identify optimal planning strategies.

- Write a scientific article, as well as the thesis, contributing to the scientific community and advancing the application of geospatial analysis in power grid planning.

1.3 Thesis Structure

This thesis is structured to comprehensively address the topic of geospatial analysis for mapping and supporting the expansion of MV distribution networks. It begins with an Introduction that establishes the study's background, contextual relevance, and research objectives, including the primary question guiding the research. Following this, the section 2 reviews existing literature on MV network planning and geospatial analysis, identifying key gaps that this study aims to fill. The subsection 2.3 details the methods and tools used, including relevant legislation that informs network expansion practices, ensuring that the research aligns with current standards. Next, on subsection 2.4 offers a practical application of the methods through selected examples, discussing the data, results, and insights derived from each case. In the Results Analysis section, the findings from the case studies are critically analysed, exploring their implications for MV network planning and resilience.

The thesis concludes with subsection 2.6 summarizing the main findings, discusses potential future applications, and evaluates the advantages and limitations of the methods used. This structure provides a coherent progression from theoretical foundations to practical applications, offering a thorough exploration of MV distribution network planning through geospatial analysis.

After concluding the SotA, section 3 presents the methodology proposed for each stage of this study. subsection 3.1 justifies the selection of the case studies by defining them and explaining the reasons for their inclusion. It also describes the main characteristics of each scenario, including its objectives and the principal challenges identified. subsection 3.2 introduces the parameters required to conduct the GIS analysis and, subsequently, the economic study. The relevance and influence of these parameters are discussed, along with the sources of the databases used. In subsection 3.3, the treatment and processing of the collected data are described, explaining how the data were prepared for use in the GIS simulations, for example, the conversion of height rasters into slope rasters. subsection 3.4 presents the mathematical formulation employed to determine the optimal number of poles and to select the most cost-effective pathway among different alternatives. The simulations that generate these pathways are described in subsection 3.5, where the procedures performed in QGIS are outlined, including the integration of all data within a given area and the generation of alternative pathways from the MV grid to a specific point. This subsection consolidates the outcomes of the two preceding subsections and introduces the Python code developed to adapt the mathematical formulation. This code receives the outputs from the GIS analysis as inputs and returns the optimal pathway along with the best possible configuration of poles. Finally, subsection 3.7 provides a brief reflection on the potential limitations of the results, considering both the adopted framework and the available data.

After outlining the project framework, section 4 presents the results of each case study. Each subsection displays the pathways generated for the corresponding area, together with the economic analysis performed using the Python code, which calculates and presents the cost associated with each pathway. A brief discussion is also provided to explain why the conditions associated with the LCP proved to be the most favourable. The final subsection offers an overview of the results obtained and highlights which conditions were most suitable across the different scenarios.

Subsection 5 presents the conclusions of this thesis. It reflects the results obtained, their significance, and the methodology that proved most favourable in general cases. It also discusses how the framework applied in this study addressed the main objectives of the project and how it could be improved considering the limitations identified, particularly when compared with the initial expectations. Finally, the references used throughout this study are presented.

1.4 Publications

As part of the main objectives defined by the thesis supervisors, and with the additional goal of enhancing personal recognition within the scientific community, a scientific paper was prepared based on the research conducted in this study. This work aims to demonstrate the relevance and potential of geospatial analysis in the planning and optimization of medium voltage networks. Although the paper has not yet been published, it is intended for submission to the IEEE Transactions on Smart Grid.

2 Literature Review

This section will provide a comprehensive review of the current SotA regarding the expansion of MV distribution infrastructures. It will focus on the role of geospatial analysis in the mapping and planning of these systems, while considering the legal frameworks specific to Portugal, the integration of renewable energy production, and the evolving local energy demands. The analysis will include an in-depth examination of existing literature, as well as case studies of grid expansion projects implemented in other countries, offering valuable insights and comparisons.

2.1 Overall in MV Network Infrastructure

Nowadays, MV distribution grids are a fundamental component for power distribution systems, operating between high voltage transmission grids and low voltage (LV) networks that serve end consumers. These networks typically operate at voltages between 1 kV and 50 kV, balancing efficiency and cost-effectiveness while ensuring reliable energy distribution over moderate distances. They are essential for integrating renewable energy sources, enabling electrification initiatives, for example in e-mobility, and maintaining grid stability under varying power demands [1], [2].

Figure 1 illustrates a typical MV distribution network that integrates renewable energy sources to deliver electricity to final consumers. The process begins with renewable energy generation from sources such as wind turbines, hydropower plants, and solar panels. These sources contribute to a centralized substation (60/30/15 kV) where the energy is aggregated and prepared for distribution. At the substation, voltage levels are transformed to suit the MV distribution grid, typically operating at around 15 kV, enabling efficient energy transport over medium distances. The MV distribution grid then delivers electricity to transformers that reduce the voltage from MV to LV levels (400/230 V), making it suitable for direct consumption by residential, commercial, and industrial users. This structure ensures efficient energy flow while maintaining voltage stability and minimizing losses.

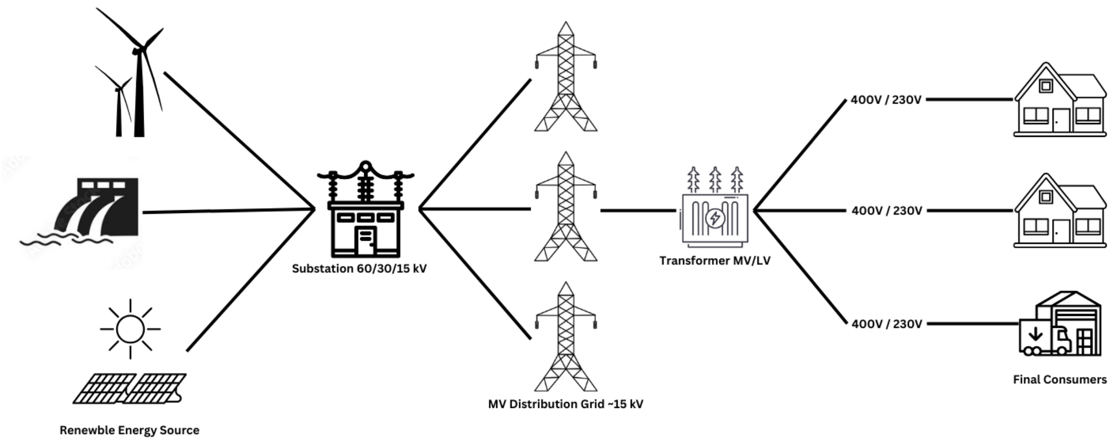


Figure 1 - Scheme of the MV Distribution Grid's role in the electrical energy transmission, from the renewable energy source to the final energy consumer (Adapted from: [3])

Several studies, such as the one by Soroudi et al. [3], emphasize the importance of optimizing the placement of distributed energy resources (DERs) within the MV grid to enhance eco-environmental sustainability. Similarly, El-Khattam et al. [4] highlight the need for integrating distributed generation (DG) units into MV network planning to improve reliability and reduce operational costs. The incorporation of advanced grid reconfiguration strategies, as suggested by Dai [5], [6], also enables real-time adaptability, ensuring voltage stability and energy efficiency in diverse operational scenarios. These methodologies underscore the evolving strategies for enhancing MV grid design, particularly in scenarios involving renewable energy integration.

In Portugal, MV infrastructure is a mixture of overhead and underground systems. Overhead lines dominate in rural areas due to lower costs and simpler installation processes, while underground systems are preferred in urban settings to preserve aesthetics and minimize spatial impact [6]. Key components of the MV network include concrete or galvanized steel poles, insulated conductors, transformers, and protective devices designed to maintain safety and operational efficiency. Advanced technologies, such as GIS, are increasingly employed to map these networks and support efficient management [7]. Figure 2 demonstrates different structural designs of towers used for MV distribution lines. These designs serve specific purposes based on load capacity, terrain, and environmental constraints. From left to right, the variations include single-pole and multi-pole configurations, with differences in cross-arm arrangements and insulator placements to support multiple conductors. As discussed in Chaitanya Tendolkar's Thesis [8], the selection of tower designs is influenced by geospatial considerations like land use, wind loads, and accessibility, ensuring the reliability and efficiency of the MV grid.

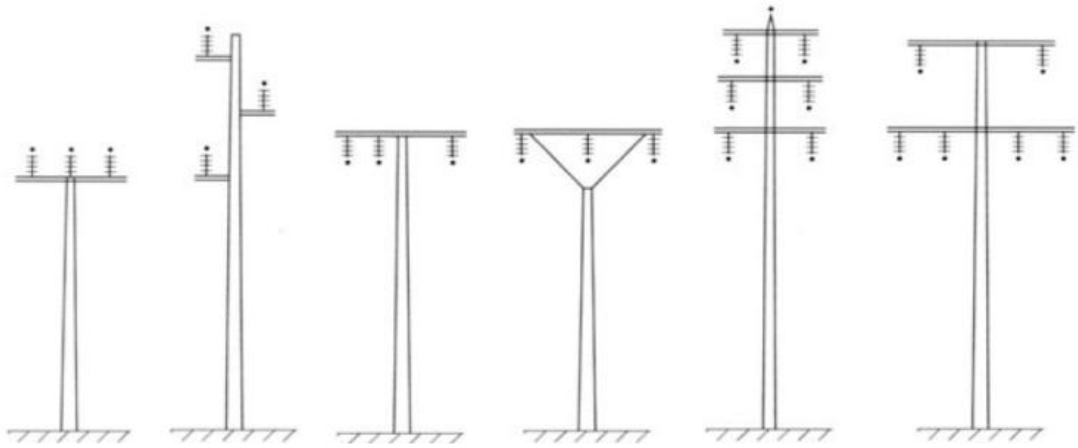


Figure 2 - Towers for MV distribution lines (Source: [8])

In Portugal, MV networks are adapting to modern challenges, including the rise of DG and the need for smarter grid solutions. Active distribution networks leverage advanced technologies such as sensors, IoT devices, and dynamic control systems to enable more efficient grid operation and significantly improve fault detection and response times. For example, as highlighted in [7], expansion planning of active networks with energy storage systems demonstrates the value of integrating dynamic and responsive components into modern grids. Similarly, the optimization models discussed in [4] and the geospatial analysis presented in [8] underscore how advanced planning and real-time monitoring tools enhance the adaptability and reliability of distribution systems. This shift aligns with global trends toward decentralization and the integration of DERs, which require innovative solutions to manage intermittency and ensure reliability.

2.2 Expansion of MV Distribution Infrastructure

Expanding MV networks is crucial to address increasing electricity demand, support renewable energy integration, and facilitate emerging technologies like electric vehicles and distributed storage. This process requires detailed planning that considers future energy needs, geographical constraints, and technological innovations [1],. For example, studies like Carvalho et al. [1] highlight the role of distributed energy storage systems (DESS) in enhancing grid flexibility, enabling the storage and redistribution of surplus energy to balance supply and demand [1]. Planning for MV network expansion involves advanced tools and methods, such as GIS for mapping existing infrastructure and identifying optimal expansion routes [9]. Predictive analytics and machine learning are increasingly used to anticipate load growth and determine the most cost-effective deployment strategies. Ponce de Leao [9] introduced fuzzy load allocation as a method to address uncertainties in load forecasting, providing a robust framework for expansion planning [9]. Case studies demonstrate the diverse challenges and solutions in expanding MV infrastructure. For example, research on integrating wind power into MV networks in Portugal emphasizes the importance of robust planning frameworks to manage variability in renewable energy generation [10]. These frameworks often incorporate smart grid technologies, enabling real-time monitoring, dynamic control, and improved fault management [11]. The use of GIS-based systems further ensures that environmental and community impacts are minimized, while optimal siting of infrastructure can reduce costs and improve operational efficiency [7], [12], [13].

Furthermore, expansion projects must adhere to stringent regulatory requirements. Environmental assessments and compliance with safety standards are integral to the approval process. These requirements ensure that expansion initiatives not only meet technical needs but also align with broader sustainability and community objectives [2], [9]. With careful planning and the adoption of innovative technologies, MV networks can effectively support the energy transition and meet growing demands for a reliable and sustainable electricity supply [3]. The development, maintenance, and expansion of MV networks in Portugal are regulated by a framework that ensures compliance with national and European Union standards. The *Entidade Reguladora dos Serviços Energéticos* (ERSE) is critical in setting technical and operational guidelines for MV systems, encompassing safety requirements, environmental considerations, and system reliability. These regulations specify standards for equipment installation, safety clearances, and environmental protections, ensuring that infrastructure projects align with technical needs and societal goals [7], [10]. Environmental impact assessments are mandated for most new installations, particularly overhead lines in ecologically sensitive or populated areas. Portugal also adheres to EU directives such as the Renewable Energy Directive, which influences the planning of MV infrastructure by promoting renewable integration and grid modernization. Local authorities further contribute by approving infrastructure projects in alignment with municipal zoning and urban planning requirements [2]. In terms of expansion, legislative frameworks emphasize sustainability and innovation. For instance, policies incentivize the adoption of technologies like energy storage systems and smart grid solutions, which can optimize the performance of MV networks while reducing the environmental footprint of new installations [1], [13].

Specifically, regulations such as ERSE Regulation No. 4/2023 [14] and the E-REDES Public Service Grid Connection Guide focus on the technical and commercial conditions for accessing and expanding MV networks, ensuring a streamlined integration of new connections. Additionally, Regulation No. 5/2023 [15] focuses on the operational management of these networks, ensuring their efficiency and reliability. Furthermore, Regulation No. 817/2023 [16] encourages the adoption of smart grid technologies, which are essential for creating modern, flexible, and resilient infrastructures. On the legislative side, Decree-Law No. 15/2022 [17] establishes the organizational responsibilities for network planning and expansion, while Decree-Regulatory No. 1/92 [18] defines safety standards for constructing and operating MV lines. This regulatory and technical foundation is crucial for addressing the challenges posed by the energy transition, including the growing demand for electrical power, the integration of DERs, and the need for enhanced grid flexibility. Entities like EDP Distribution also contribute through technical manuals, such as the Public Service Grid Connection Guide [19], which details procedures for connecting and expanding MV networks. By adhering to these standards, Portugal ensures the sustainable expansion of its MV distribution networks, supporting a more reliable and efficient electrical system. Table 1 represents a summary of the measurements responsible for developing robust MV networks, addressing growing energy demands, integrating renewable energy sources, and ensuring the safe and efficient operation of Portugal's distribution grid.

Table 1 - Key regulations and directives related to the expansion and planning of MV distribution networks in Portugal

Entity	Regulation	Description
ERSE	Regulation No. 4/2023 - Network Access [14]	Defines the technical and commercial conditions for accessing electrical networks, facilitating the integration of new MV lines.
ERSE	Regulation No. 5/2023 - Network Operation [15]	Establishes standards for the efficient operational management of networks, essential for MV expansion planning.
Portuguese Government	Regulation No. 817/2023 - Smart Grids [16]	Promotes the integration of advanced technologies in distribution networks, supporting efficient MV infrastructure expansion.
Portuguese Government	Decree-Law No. 15/2022 [17]	Regulates the organization and responsibilities in the electricity sector, including guidelines for MV network planning and expansion.
E-REDES	Public Service Grid Connection Guide [19]	A technical guide outlining procedures for connecting and expanding electrical networks, including MV lines.
Portuguese Government	Decree-Regulatory No. 1/92 [18]	Regulates safety standards in the construction and operation of high and MV power lines.

2.3 General Optimal Grid Planning and Mapping

The planning and expansion of MV distribution networks require innovative approaches that integrate geospatial analysis, optimization methods, and advanced computational tools. With the increasing penetration of renewable energy sources and the growing complexity of energy systems, it has become critical to address the technical and economic challenges of network design. The selected studies demonstrate a range of methodologies, from optimization-based models and fuzzy logic frameworks to GIS-based tools, each focusing on improving the reliability, cost-efficiency, and sustainability of MV grid expansion. By examining these methods, it is easier to understand the evolving landscape of distribution network planning and its alignment with global energy goals. Table 2 summarizes various methodologies for optimal energy planning, highlighting key features and tools used in each approach. Techniques range from deterministic and stochastic optimization to fuzzy logic and multi-objective models, addressing challenges like renewable energy integration, cost-efficiency, and system reliability. These approaches leverage advanced tools such as Mixed-Integer Linear Programming (MILP), renewable simulation models, and Monte Carlo simulations to improve grid expansion and flexibility.

Table 2 - General Optimal Grid Planning - Reviewed Literature

Reference	Primary Objective	Methodology/Approach	Challenges Addressed	Key Statistics/Outcomes
[1]	Integrate DESS flexibility into grid expansion planning	MILP model to optimize grid expansion scenarios leveraging DESS	Uncertainty in renewable energy production and load demand	Reduces investment costs by optimizing storage use, delays grid reinforcement
[3]	Eco-environmental planning with DERs and fuel cells	Hybrid optimization combining probabilistic modelling and MIP	Balancing environmental impact with cost efficiency	Achieves lower emissions and reduced operational costs
[4]	Integration of DG into MV grid planning	MILP-based optimization for DG placement and sizing	Voltage stability, load demand, network constraints	Improves reliability, reduces network losses, minimizes expansion costs
[5]	Multi-objective network reconfiguration using SOPs	Genetic algorithms and particle swarm optimization	Stability under varying load and generation conditions	Enhances grid controllability, reduces power losses, improves voltage profiles
[10]	Planning under uncertainty with DER remuneration	Monte Carlo simulations with probabilistic modelling	High scenario variability, financial incentive integration	Optimized network configuration balancing resource remuneration, emissions, and risk
[9]	Fuzzy logic-based load allocation	Fuzzy sets for dealing with forecast uncertainties	Incomplete data, rapidly changing demand patterns	Enables flexible and adaptive grid expansion planning
[12]	Stochastic optimization for wind power integration	Scenario-based optimization evaluating multiple wind generation profiles	Variability in wind power generation, grid reliability	Minimizes overall costs while maintaining grid stability and reliability

[13]	Deterministic planning for active MV networks	Load-flow analysis with deterministic optimization	Managing high penetration of renewable energy	Ensures voltage stability, minimizes power losses, validates on test systems
[20]	Develop an optimisation framework for integrating DG into long MV networks.	MILP combined with load-flow analysis.	Managing voltage stability, minimising losses, and improving network efficiency.	Achieved optimised DG placement and sizing; reduced losses and voltage deviations along extended MV feeders.
[21]	Enhance coordination between MV networks and interconnected microgrids.	Aggregate flexibility region modelling and network optimisation.	Integration of variable renewable sources; maintaining flexibility and system stability.	Improved grid flexibility and operational coordination; reduced curtailment and balancing costs.
[22]	Enhance coordination between MV networks and interconnected microgrids.	MIP for expansion cost minimisation.	Balancing investment and operational costs; ensuring reliability in growing demand scenarios.	Provided cost-effective substation placement and transmission routing; improved long-term reliability planning.

S. Carvalho et al. [1] introduces a planning approach that integrates the flexibility provided by DESS. The method emphasizes optimizing grid expansion while considering the uncertainties in renewable energy production and load demand. A MILP model is used to evaluate various expansion scenarios, leveraging the flexibility of DESS to reduce investment costs in grid reinforcement. By simulating different configurations, the study demonstrates how storage systems can delay or eliminate the need for costly upgrades, optimizing the grid's economic and technical performance.

The study by Soroudi, Ehsan, and Zareipour [3] proposes a practical model for eco-environmental planning in distribution networks, incorporating renewable and non-renewable DERs, including fuel cells. The methodology optimizes the placement and sizing of DERs within the network by considering environmental constraints, such as CO_2 emissions, and economic factors, such as operational costs. A hybrid optimization approach combines probabilistic modelling and mixed-integer programming (MIP) techniques to address uncertainties in energy generation and load demand. This ensures the network can achieve its environmental objectives without compromising reliability and cost-efficiency. The model emphasizes the integration of DERs into the MV network to support sustainable energy transitions. The framework also evaluates the trade-offs between environmental impact and economic cost, making it a comprehensive tool for utility planners. By including probabilistic load forecasts and weather data, the model effectively accounts for uncertainties associated with renewable energy sources. The study demonstrates how such an approach can lead to optimized grid expansion plans that balance ecological sustainability with practical network requirements. Figure 3 illustrates the trade-offs between total CO_2 emissions and economic costs. The proposed dynamic model outperforms static models by achieving lower emissions, particularly at reduced cost levels, showcasing its ability to balance ecological and financial objectives. This highlights the model's effectiveness in optimizing grid expansion while supporting sustainability goals by integrating renewable energy resources.

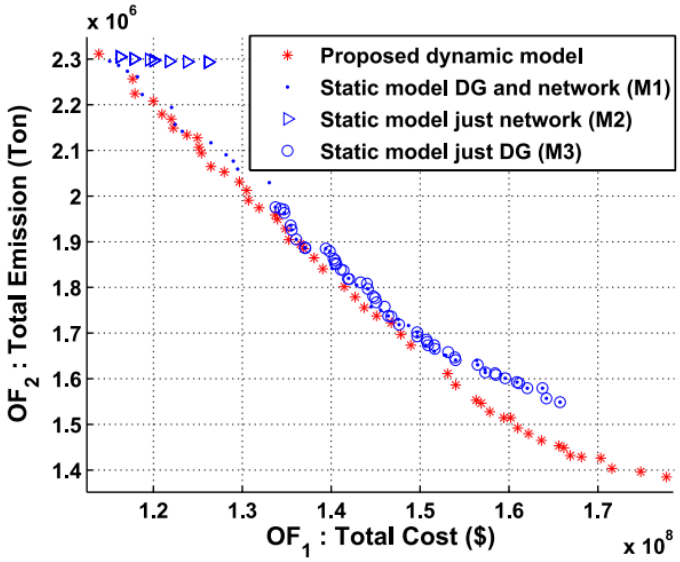


Figure 3 - Comparison of Pareto optimal front found by proposed model to other static (Source: [3])

El-Khattam, Hegazy, and Salama's [4] research focuses on integrating DG into distribution network planning. The proposed optimization model aims to minimize the overall cost of system expansion while improving reliability and reducing network losses. The methodology leverages MILP to determine the optimal locations and capacities of DG units. Factors like voltage stability, load demand, and network constraints are integrated into the model to ensure that the MV grid can meet future energy requirements effectively. The model's novelty lies in its ability to balance economic and technical considerations, such as investment costs and power quality. It introduces a comprehensive approach to grid expansion planning, considering the synergies between DG and traditional network components. The inclusion of DG in the planning process enhances the resilience and flexibility of the MV network, making it better suited to accommodate increasing energy demands and renewable energy penetration. Table 3 provides a comparative analysis of various planning scenarios, showcasing that incorporating DG alongside substation expansion results in lower overall expansion costs, reduced network losses, and improved demand satisfaction. This highlights the model's effectiveness in optimizing the distribution network by leveraging the synergies between DG and traditional infrastructure.

Table 3 - Analysis of the results regarding the DG and substation expansion (Source: [4])

Stat	Substation Expansion	DG & Substation Expansion	DG & Substation Expansion (Planner Decision)
Total Expansion Cost (M$)	29.47	25.81	26.37
Total Expansion Cost ($/MWh)	78.74	74.01	74.43
Additional Substation Purchased Power (MVA)	4.33; 10	0.73; 0	0.00; 0.00
Total Losses (MVA)	3.23	1.63	1.50
Total System Demand (MVA)	54.33	52.73	52.60
Expanding Substation Cost (M$)	0.40	0.20	0.00
DG Capacity (MVA) & Location	0.00	3 (4 & 1 MVA) buses: 2, 6, 8	2 (4 & 1 MVA) buses: 2, 8 2 (3 & 1 MVA) buses: 4, 6
DG Investment Cost	0.00	7.50	9.00
Losses Cost (M$)	5.35	2.70	2.48
Additional Substation Purchased Power Cost (M$)	23.72	1.21	0.00
DG O&M Costs (M$)	0.00	14.19	14.89

Dai's work [5] introduces a multi-objective optimization framework for distribution network reconfiguration, with a specific focus on incorporating Soft Open Points (SOPs). SOPs are flexible network elements that enhance grid controllability and allow for real-time reconfiguration. The model addresses conflicting objectives, such as minimizing power losses, improving voltage profiles, and reducing operational costs. A weighted sum method is used to balance these objectives, and the model is solved using advanced optimization algorithms like genetic algorithms and particle swarm optimization. This approach is particularly beneficial for MV networks, where maintaining stability under varying load and generation conditions is critical. The study highlights how SOPs can enable adaptive grid reconfiguration, allowing the network to respond dynamically to changes in demand and renewable energy generation. The findings underline the importance of integrating advanced technologies, such as SOPs, into MV grid expansion strategies to achieve a more resilient and efficient distribution system.

In reference Castro et al. [10], the study emphasizes planning under uncertainty by incorporating probabilistic models for load demand and DG. It also introduces a novel remuneration framework for DERs, encouraging their integration into the planning process. A combination of Monte Carlo simulations and optimization techniques is employed to evaluate different expansion scenarios. This approach ensures a robust and adaptable MV distribution network design that accounts for the financial incentives of DERs deployment.

The case study represents diverse energy sources and technologies, including photovoltaic, wind, and biomass generation, electric vehicle's charging stations, and energy storage systems. The case studies aim to optimize network planning by incorporating factors such as resource remuneration, carbon emissions, and risk aversion, while evaluating the economic implications of these considerations. The challenges include managing computational complexity due to high scenario variability and ensuring the network's adaptability to uncertainties in energy generation and demand. The diagram illustrates the allocation of lines to feeders, new lines added to accommodate the expanded infrastructure, and potential lines not selected for implementation. The scheme was adapted from Canizes et al. [2]. Further Castro et al. [23] developed a more extensive risk-based focused approach, in which doubled the scenarios, complemented the conclusions of Canizes et al. [2].

As for M. T. Ponce de Leao [9], it proposes a fuzzy logic-based approach for load allocation in MV distribution network expansion planning. The method uses fuzzy sets to deal with the uncertainty and imprecision inherent in future load forecasts. By applying fuzzy logic, the study ensures that the planning process can accommodate a range of possible scenarios, providing more flexible and adaptable grid expansion strategies. This approach is particularly effective for planning in areas with incomplete data or rapidly changing demand patterns.

In R. Saberi et al. [12], the case explores planning methods for MV distribution networks that integrate wind power generation. A stochastic optimization framework is employed to handle the uncertainties associated with wind power variability. The method involves creating multiple scenarios for wind generation profiles, which are then used to evaluate grid expansion options. The optimization process minimizes overall costs while ensuring reliability and stability, addressing operational and infrastructural challenges posed by the intermittent nature of renewable energy sources.

G. Mokryani et al. [13], present a deterministic planning approach tailored for active distribution networks with high levels of renewable energy integration. The methodology focuses on optimizing the placement and sizing of renewable energy sources and grid reinforcement measures. Using a load-flow analysis combined with deterministic optimization techniques, the study ensures voltage stability and minimizes power losses. The approach is validated on test systems, demonstrating its capability to manage the operational challenges posed by high renewable penetration.

Serrano-Guerrero et al. [20] proposed an optimisation framework for the strategic integration of DG in long MV networks. By applying MILP in combination with load-flow analysis, the authors achieved a well-balanced model that considers technical, economic, and spatial aspects of grid operation. The approach effectively reduced energy losses and maintained voltage levels within operational limits, demonstrating strong practical relevance for MV grid enhancement. From a planning perspective, the work is technically sound, yet it could be extended by incorporating geospatial constraints or land-use considerations, which would provide greater realism in siting DG units. Introducing spatial cost surfaces or GIS-based routing layers could strengthen its applicability for geographically explicit grid expansion strategies.

Zhou et al. [21] introduced an aggregate flexibility region approach to coordinate MV networks with embedded microgrids, aiming to optimise operational flexibility and renewable integration. The methodology stands out for its analytical sophistication, capturing dynamic interactions between decentralised resources and central network operations. It represents a valuable step towards resilient and adaptive MV systems capable of managing renewable variability. However, the framework remains largely conceptual in spatial terms, as it does not fully integrate geographic or locational parameters influencing microgrid interconnections. Future research could enhance this by embedding spatial network topology and regional demand patterns within the aggregate flexibility region model, allowing planners to visualise and optimise physical connectivity alongside flexibility performance.

Eren et al. [22] presented an early yet influential study employing Mixed Integer Programming for transmission and substation expansion planning. Their work effectively minimised investment and operational costs while ensuring system reliability under demand growth scenarios. The optimisation logic remains robust and forms the foundation for many modern expansion models. Nonetheless, the study reflects the methodological constraints of its time: it treated the network as a largely abstract system without spatial integration or environmental context. Incorporating geospatial modelling techniques, such as terrain analysis, land-use constraints, and accessibility mapping, could substantially improve planning precision. Embedding GIS layers would transform the model from a purely mathematical construct into a spatially grounded planning framework, better suited to contemporary MV expansion challenges.

The reviewed methodologies underscore the critical role of advanced tools and approaches in optimizing the planning and expansion of MV distribution networks. By integrating geospatial analysis, incorporating DERs, and utilizing optimization models that address uncertainties, these methods provide comprehensive solutions to the complex challenges faced by modern power systems. Approaches such as probabilistic modelling, scenario-based optimization, and load-flow analysis ensure cost-effective, reliable, and adaptive grid designs. As the global energy transition accelerates, adopting these innovative strategies will be vital for creating resilient and sustainable distribution networks capable of supporting the increasing penetration of renewable energy sources and meeting future energy demands efficiently.

2.4 Geospatial Analysis for the Expansion of MV Distribution Infrastructure

Geospatial analysis has emerged as a critical tool in the planning and expansion of MV distribution networks. With the increasing integration of renewable energy sources and the electrification of society, grid planning must adapt to complex challenges, including data scarcity, terrain variability, and population density considerations. By leveraging advanced tools such as GIS, open-source frameworks like OpenStreetMap (OSM), and specialized optimization algorithms, researchers and practitioners are developing innovative methods to optimize grid expansion. These tools enable detailed spatial modelling, allowing for the integration of environmental, economic, and demographic factors to create cost-efficient and scalable network designs. Table 4 highlights key case studies showcasing the role of geospatial tools and their outcomes in addressing modern energy distribution challenges.

Table 4 - Geospatial Analysis for the Expansion of MV Distribution Infrastructure - Reviewed Literature

Case Study	Primary Objective	Geospatial Tools/Software	Challenges Addressed	Key Statistics/Outcomes
[8]	Use open data for predictive mapping of power systems globally.	GIS, machine learning algorithms, and open-source mapping tools.	Lack of comprehensive global datasets.	Created scalable global power system predictions, aiding renewable energy integration.
[11]	Optimize electricity distribution network design for developing regions.	GIS software, spatial modelling frameworks.	High geospatial tool costs, incomplete terrain data.	Enhanced grid planning efficiency by integrating multi-layered spatial analyses.
[24]	Optimize MV grid expansion models using open data and software.	OSM, OSMnx, NetworkX, DIgSILENT PowerFactory, Gurobi.	Data scarcity, scalability of large-scale models.	Generated grid models reflect realistic configurations; accuracy validated with OSM data.
[25]	Evaluate the role of geospatial factors in grid expansion in Sub-Saharan Africa.	OnSSET (Open-Source Spatial Electrification Tool), GIS tools, population and terrain datasets.	Data limitations, terrain challenges, investment risks.	Identified cost-efficient routes integrating terrain and population density.
[26]	Develop a multi-objective framework for optimizing MV distribution network investments.	GIS-based tools, investment simulation platforms.	Balancing investment costs with demand growth and renewable integration.	Provided a comprehensive strategy for efficient multi-investment planning for MV networks.
[27]	Evaluate MV distribution network expansion using geospatial data analysis and optimization techniques.	GIS-based tools, geospatial data analysis frameworks.	Optimal route planning, renewable energy integration, and demographic expansion.	Achieved precise identification of optimal expansion routes, minimizing environmental and economic impacts.

[28]	To develop and demonstrate a GIS-based tool for MV network analysis.	Custom GIS-based tools	Optimization of grid layout and analysis under constraints.	Demonstrated an advanced GIS tool for improving MV network design.
[29]	To plan high-level distribution network expansions using GIS while accounting for reliability.	GIS tools	Handling reliability under normal and contingency scenarios.	Showed how GIS can help improve reliability in MV network planning.
[30]	To review GIS applications for renewable energy planning and future research directions.	GIS tools, including QGIS	Challenges of integrating renewable energy in spatial planning.	Identified research gaps and proposed avenues for GIS in renewable energy planning.
[31]	Develop a GIS-based intelligent platform to assess bird-related risks for power grid infrastructure.	GIS mapping tools, remote sensing data, risk assessment algorithms.	Identification of spatial risk zones; lack of dynamic environmental data.	Created spatial risk maps highlighting vulnerable grid sections; improved predictive maintenance planning.
[32]	Apply spatial analysis techniques to improve energy transition strategies within distribution grids.	GIS, spatial analytics, grid modelling software.	Integration of renewable energy sources and spatial data interoperability.	Enhanced planning of distribution networks through spatially informed transition models.
[33]	Design an integrated GIS-based approach for siting and sizing photovoltaic DGA in semi-arid environments.	GIS, multi-criteria decision analysis, solar potential mapping.	Environmental variability, limited infrastructure data.	Achieved optimised photovoltaic deployment layouts; improved spatial efficiency and energy accessibility.

Tendolkar thesis [8] explores the influence of geospatial factors on MV network planning. The study employs GIS tools, including ArcGIS, to incorporate geographic constraints such as terrain, land use, and infrastructure into network design. By considering spatial elements in the planning process, the primary goal is to improve cost optimization and reliability. Key challenges addressed include modelling the complex interaction between geographic factors and technical requirements for MV networks. The results highlight the critical role that terrain and spatial constraints play in determining network configuration, leading to more informed decision-making for planning engineers.

A. Rastgou research [11] provides a comprehensive review of existing methods for distribution network expansion planning, focusing on integrating geospatial considerations. Although it does not use specific GIS tools, it addresses challenges such as incorporating renewable energy, spatial data, and uncertainties into network expansion models. The study identifies gaps in the current literature, such as insufficient frameworks for handling real-time geospatial data and complex scenarios involving DERs. It offers recommendations for future research, emphasizing the importance of integrating GIS-based tools to tackle these challenges effectively.

In I. Hebbeln et al. [24], the study focuses on automating the generation of large-scale distribution grid models using open data and open-source tools. It utilizes OSM and Python-based optimization software to create scalable and accurate grid models. The primary goal is to address the challenges of scalability, data accuracy, and efficiency in grid modelling. The research successfully demonstrates the feasibility of automated grid modelling with open-source tools, achieving high scalability and flexibility. This approach has significant implications for expanding MV networks cost-effectively and transparently, especially in regions with limited proprietary data availability. It highlights the segmentation and layout of grid components, addressing challenges like data scarcity and enabling realistic network simulations. This visualization supports planning for grid expansion and integration of renewable energy and E-Mobility.

C. Ardene et al. [25], presents a method for predictive mapping of global power systems using open data, such as OSM and OnSSET. Geospatial software creates predictive maps that visualize power system infrastructure, including transmission and distribution lines. The objective is to provide a comprehensive and publicly accessible dataset for power systems worldwide. The main challenge is the lack of detailed, high-quality data in underserved regions. Despite these limitations, the research successfully produces accurate and detailed predictive maps responsible for supporting MV network planning. In Figure 4, the methodology for predictive mapping of global power systems using open data. The workflow starts with data inputs, including OSM data, night-time lights, land cover, elevation, and population data. These inputs are filtered and processed to estimate electrified targets, access rates, and cost, which are essential for generating MV and LV line models. The outputs include MV and LV networks validated using additional data, such as energy use, economic data, and geographical constraints like ocean buffers. This streamlined process provides a comprehensive geospatial approach to modelling power distribution networks globally.

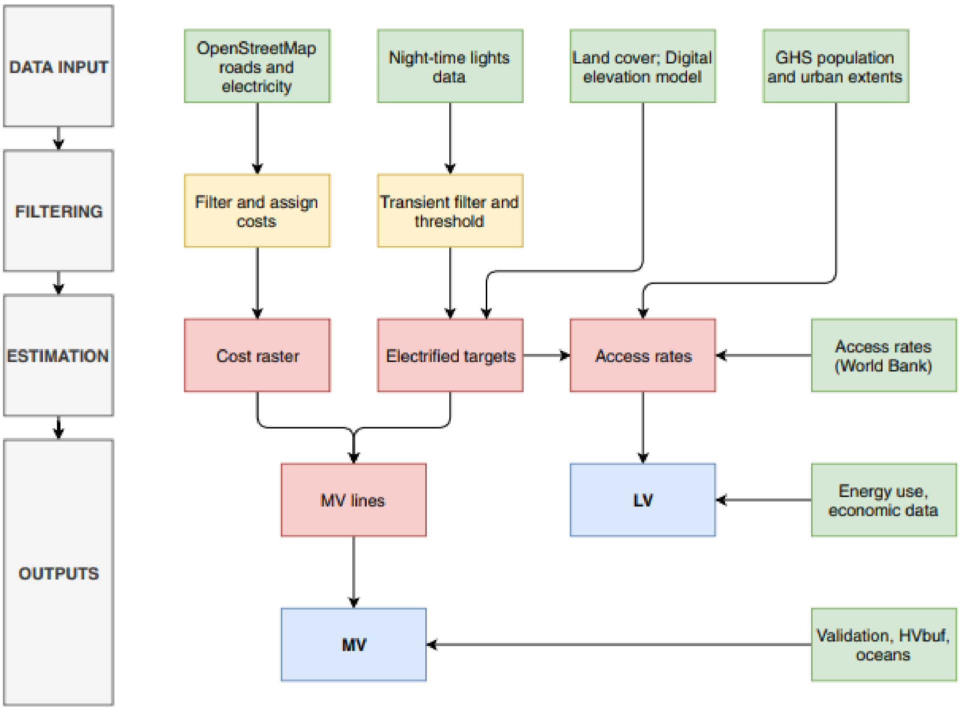


Figure 4 - Simplified overview of methodology. Data inputs in green, filtering steps in yellow, intermediate results (Source: [25])

The paper regarding the comprehensive framework for distribution network multi-investment [26] proposes a framework for optimizing multi-investments in MV distribution networks, integrating geospatial data with multi-objective optimization techniques. GIS tools are used to account for spatial constraints and opportunities in planning network expansions. The study addresses the challenge of coordinating multiple investment streams, such as DERs and network reinforcement, in a spatially informed manner. The framework demonstrates significant improvements in optimizing investment costs and operational efficiency while considering geospatial data.

The research related to geospatial analysis of an MV distribution network expansion [27] integrates geospatial analysis into the expansion planning of MV networks. Tools such as QGIS are used to analyse spatial data and optimize network expansion strategies. The main goal is to incorporate geographic and infrastructure constraints into planning processes. The study effectively addresses the challenge of including spatial data in planning models and demonstrates a GIS-based framework for optimizing MV network expansions. The methodology illustrated in the Figure 5 further highlights this approach, starting with selecting a general location needing power line infrastructure. Initial pathway selection criteria consider environmental, technical, and social constraints, using data from sources like NASA's SRTM, ASTER, and ALOS. GIS processing, employing raster layers for factors such as slope and proximity to infrastructure, refines possible path options. Restrictions, including protected areas, agricultural land, or private properties, are factored into the GIS constraints to ensure compliance with environmental and legal requirements.

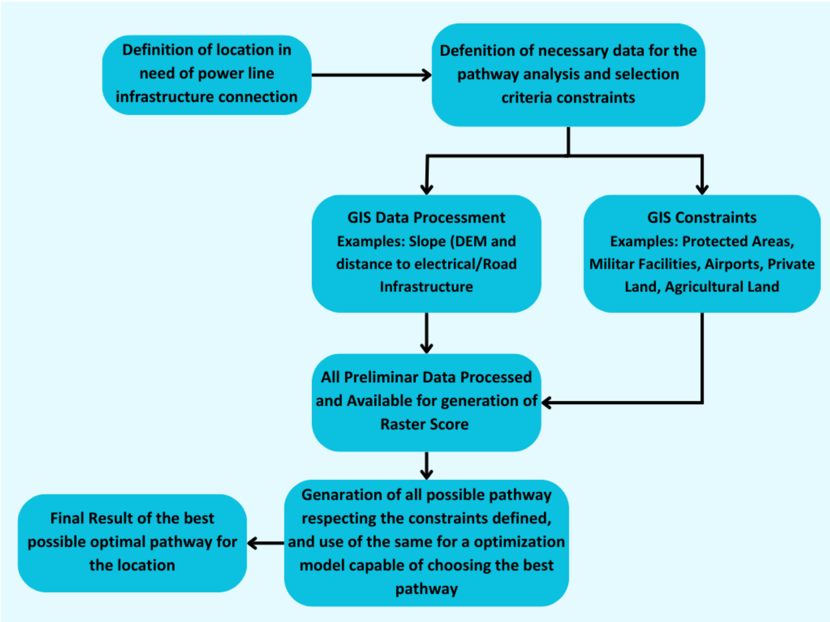


Figure 5 - Flowchart of the methodology used for the case study in [27] (Adapted from: [27])

Figure 6 - Line expansion location and start points (Source: [27])

Figure 7 - Example of a result of the optimal line expansion path from a substation to a specific location (Source: [27])

This approach ensures more precise and efficient planning, reducing both costs and environmental impact. The model selected one of 12 possible pathways for the expansion, in which Figure 6 shows the start points and the location of the expansion, while Figure 7 demonstrates the result of the optimal line expansion path. This result accounts challenges like a steep slope and dense trees, which required a direction change. The red dots indicate the pathway and the placement of support poles, with only one direction change necessary despite the obstacles.

The work of Guilherme Custodio and Fernanda Trindade [28] introduces an advanced GIS-based tool designed for analysing and optimizing MV distribution network expansion. Custom GIS tools are employed to model and analyse spatial constraints in network design. The main challenge tackled by the study is the optimization of network planning under geographic and infrastructure constraints. The tool demonstrates improved efficiency and accuracy in planning decisions, showcasing the advantages of integrating GIS technologies into MV network design processes.

The study made by Bernd Resch et al. [29], proposes a GIS-based approach for high-level MV network expansion planning, with a focus on reliability under normal and contingency scenarios. GIS tools and reliability modelling software are used to evaluate and optimize network performance. The research addresses the challenge of balancing reliability and efficiency in network planning. The outcomes demonstrate the effectiveness of GIS tools in identifying optimal network configurations and improving system reliability while minimizing costs.

A. Bosisio et al. [30], review GIS applications in renewable energy integration and distribution network planning. Tools such as QGIS are highlighted for their role in modelling spatial data and optimizing energy systems. The study identifies key challenges, including the integration of renewable energy sources into geospatial planning and addressing gaps in data availability. It offers future research directions, emphasizing the potential of GIS to revolutionize MV network planning and renewable energy deployment.

H. Pan et al. [31] introduced a GIS-based intelligent platform to assess and predict bird-related risks to power grid components. The study's strength lies in its integration of spatial and ecological data to identify high-risk areas for outages, demonstrating how geospatial tools can enhance grid reliability and maintenance scheduling. From a geospatial standpoint, the mapping of environmental interactions with infrastructure was particularly well executed, offering practical insight into spatial risk management. Nevertheless, the system could evolve further by incorporating temporal environmental dynamics, such as migration patterns and seasonal variations, as well as real-time spatial data feeds. This would enable a more adaptive and continuously updated risk model, rather than a static spatial snapshot.

L. Sandrini et al. [32] explored the application of spatial analysis in supporting the energy transition within distribution networks, focusing on how GIS tools can guide network adaptation and renewable integration. The study successfully demonstrated the strategic use of spatial analytics to align grid infrastructure with regional energy transition goals, highlighting GIS's value in visualising and managing complex energy systems. While the spatial integration was robust, the analysis could benefit from deeper topological modelling of MV networks, allowing planners to assess how spatially DG and consumption patterns affect network resilience. Expanding the GIS workflow to include network connectivity metrics and spatial simulation of grid reinforcement would enhance its practical utility for MV grid expansion planning.

Y. Guehrar et al. [33] developed a comprehensive GIS-based multi-criteria framework to optimise the siting and sizing of photovoltaic generation in semi-arid regions, using Ouargla as a case study. The research stands out for its detailed spatial consideration of environmental and technical constraints, effectively applying GIS for solar potential mapping and network integration. The methodology demonstrates strong spatial coherence and clear adaptability to other regions with similar climatic conditions. Still, the work could be strengthened by extending the geospatial linkage between photovoltaic siting and MV grid capacity, since the current analysis primarily focuses on generation locations rather than network expansion. Integrating spatial network routing and grid connection cost layers would bridge this gap and deliver a more complete geospatial framework for distributed energy planning.

In conclusion, geospatial analysis plays a pivotal role in the sustainable and efficient expansion of MV distribution networks by providing critical insights into spatial, environmental, and socioeconomic factors that shape grid design and planning. Through the integration of advanced tools and methodologies, planners can optimize infrastructure placement, such as substations and transmission lines, while addressing challenges like cost minimization, terrain complexity, population distribution, and environmental impacts. Recent advances have transformed GIS into a powerful analytical and predictive platform capable of modelling future network scenarios. This approach enhances grid reliability, scalability, and adaptability to emerging needs, including renewable energy integration and energy storage systems key components for transitioning to a sustainable energy future. Furthermore, the growing availability of high-resolution spatial datasets and automation techniques offers new opportunities for data-driven decision-making, paving the way for smarter and more resilient MV grid planning.

The Figure 8, shows the impact of each challenge discussed, in which the challenges faced in MV network planning reveal the multifaceted nature of grid expansion, ranging from environmental constraints like steep terrain and dense vegetation to data-related issues, including availability and accuracy. These obstacles emphasize the need for adaptable and robust methodologies to balance costs, environmental impacts, and technical feasibility. By addressing these challenges through predictive modelling, terrain analysis, and data validation, planners can ensure reliable and sustainable energy systems. Despite these complexities, the advancements showcased in various case studies highlight the potential to overcome barriers and achieve more resilient and optimized grid infrastructures.

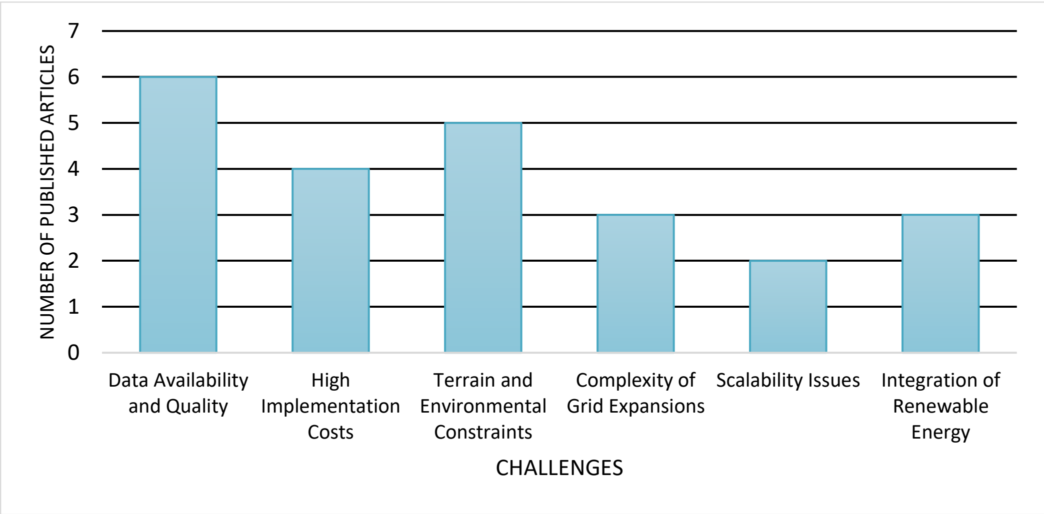


Figure 8 - Results of the challenges with most impact in the Case studies used for this review

As Figure 9 demonstrates, the predominant use of GIS platforms, open-source frameworks like QGIS and Python, and specialized modelling tools reflects the industry's shift toward data-driven planning and optimization. These tools facilitate complex analyses, including cost optimization, spatial routing, and renewable energy integration, making them indispensable for modern grid design. The widespread reliance on these technologies underscores their effectiveness in addressing key aspects such as scalability, environmental impact, and efficiency in planning MV networks.

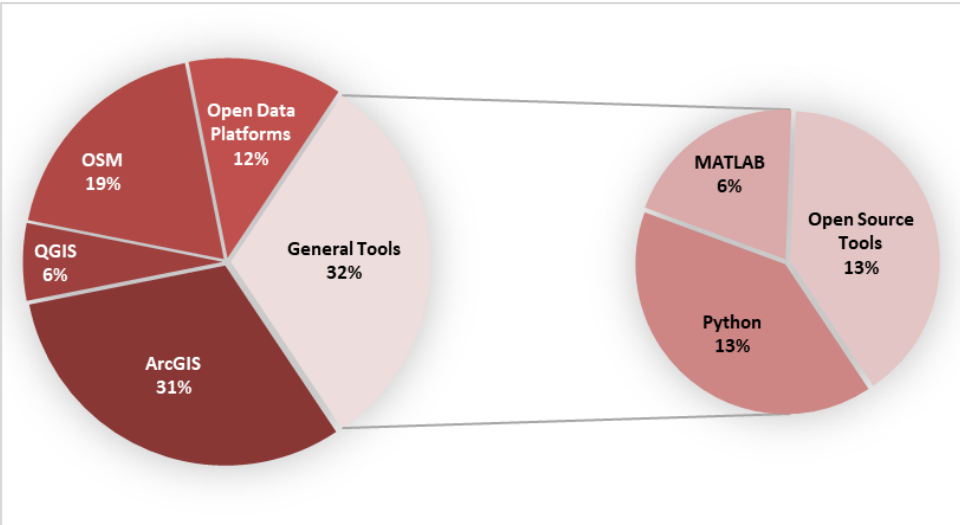


Figure 9 - Percentage of usage of each tool/software in the case studies

The reviewed case studies highlight the transformative potential of geospatial technologies in MV network planning. From leveraging open data to generate detailed grid models to applying GIS-based frameworks for cost-effective network design, these methodologies have demonstrated marked improvements in efficiency, scalability, and environmental sustainability. While challenges such as data accessibility and implementation costs remain, the findings underscore the value of predictive modelling and geospatial tools in overcoming these barriers. By addressing these limitations, geospatial analysis fosters the development of resilient, future-ready energy systems that support universal electricity access, renewable energy integration, and the broader goals of sustainable development.

2.5 Cost-Based Land Use Analysis

Lima et al. [34] embrace a complete methodology for connecting transmission lines by merging a cost surface approach with a structured decision-making method capable of obtaining derived numerical weights for multiple criteria through pairwise comparison (Analytical Hierarchy Process), in order to choose the best alternative. In their framework, each cost surface is represented as a raster, where each pixel is assigned, a value reflecting its constraints and influence on the construction. These weights can be influenced by parameters such as monetary cost, slope steepness, land use restrictions, or environmental sensitivity. This work emphasizes that cost assignments should mirror real-world constraints, with urban areas, water bodies, and infrastructure corridors typically receiving prohibitively high costs to discourage route passage. Their weighting of slope and land-use costs is consistent with the approach in which undesired areas are assigned a prohibitive value (999). This ensures that steep slopes and sensitive land-use categories serve as robust spatial barriers, thereby strengthening the integrity of the routing framework. Furthermore, the authors demonstrate the usefulness of normalized slope factors in balancing land use and terrain effects.

La Riccia et al. [35] applied a LCP approach where different land use types are assigned constraint values that reflect their resistance to movement, for a study of ecological corridor planning within Sardinian cork oak forests. These resistance maps are derived from ecosystem service valuation combined with categorical land use descriptors. Although focused on ecological processes, the principle transfers directly, in which impermeable areas such as urban zones and water bodies are given high resistance, while more permeable areas like open forests and pastures receive lower values. The framework used a cost scale, where flat, open zones are given low costs (10–50) and restricted zones receive a prohibitive 999, mirrors this logic of resistance layering, similar to Lima et al [34]. The paper also highlights the absence of universal standards in resistance assignment by tailoring cost values to the heterogeneity of the landscape.

DImovski et al. [36] developed a GIS-based framework for modelling and analysing the electricity grid of small islands, using Isola del Giglio in Italy as a pilot case. By integrating open-source geospatial and electrical data, the authors built a digital representation of the island’s grid to support network planning and energy management decisions. The main strength of the work lies in its extensive use of open and spatially detailed datasets, demonstrating that accurate grid modelling is possible even in data-scarce environments.

From a geospatial perspective, the approach is well executed, offering strong spatial resolution and interoperability between datasets. Future developments could involve expanding the GIS analysis to include terrain-based constraints or spatial optimization for renewable siting, which would make the model even more comprehensive for island energy planning.

Zambrano-Asanza et al. [37] presented a GIS-based multi-criteria decision-making model to identify optimal locations for photovoltaic power plants. The framework combined environmental, technical, and socio-economic layers with spatial overlays of electricity demand to identify high-priority sites for solar deployment. The study's use of GIS is a clear highlight, since it demonstrates a sophisticated integration of spatial data and decision-making processes, effectively bridging technical and geographic domains. The spatial analysis is both methodically rigorous and transparent, allowing the model to be replicated or adapted in different regions. A potential next step could be the inclusion of dynamic geospatial factors such as land-use change, grid expansion forecasts, or temporal solar resource mapping, which would enrich the spatial dimension of the analysis and enhance its long-term applicability.

Finally, in I. Suryawati et al. [38] introduced an online power flow management system that incorporates GIS technology to support the operation of active distribution networks. The system enables spatial visualization of network components, facilitates real-time monitoring, and improves coordination of DG sources. The integration of GIS was one of the study's most valuable aspects, as it allowed for intuitive spatial representation and enhanced decision-making within complex grid environments. While the use of GIS was effective for visualization and monitoring, the geospatial component could be further developed by embedding spatial analytics. Such enhancements would leverage the full analytical potential of GIS beyond visualization purposes.

The examination of how LCP outcomes are highly sensitive to input cost parameters in ecological connectivity models is made in Sawyer et al. [39] analysis. Their work demonstrates that varying cost assignments can substantially alter predicted routes, where cost functions incorporate both land cover and topographic characteristics. For example, the authors compare models where slope thresholds above 15% are treated with high resistance, while urban or wooded zones are assigned elevated costs that reshape corridor predictions. This reinforces the use of extreme costs to prevent infrastructure crossing restricted zones, showing that such decisions critically shape routing logic, common with Lima et al. [34] and La Riccia et al. [35]. This study ensures an iterative modelling to test multiple resistance schemes. This approach ensures systematic testing and strengthens the defensibility of the modelling process.

GIS has become an important tool for modelling and managing electrical networks, yet its application to MV grid expansion remains relatively underexplored. Most studies still use GIS mainly for mapping and visualisation rather than for advanced spatial analysis or optimisation. Future research could make better use of geospatial methods by integrating network topology analysis, spatial optimisation, and multi-criteria decision tools directly within GIS platforms. Combining these with high-resolution spatial data and machine learning techniques would allow for more accurate, automated, and realistic planning of MV grid extensions. Overall, the field shows strong potential but still lacks the analytical depth needed to fully support spatially informed grid expansion strategies.

2.6 Section Conclusions

This last section provides a comprehensive examination of the existing knowledge surrounding MV network infrastructure and its expansion. It highlights the critical importance of understanding current practices and challenges in MV distribution systems, particularly in the context of geospatial analysis. By analysing various case studies, the review identifies gaps in the literature that this thesis aims to address, emphasizing the need for innovative approaches to optimize grid planning and mapping. This foundational understanding sets the stage for the subsequent research, ensuring that the study is grounded in established theories and practices.

Furthermore, the literature review underscores the significance of integrating geospatial data into MV network planning. It discusses the various methodologies employed in previous studies, including using GIS to analyse spatial data related to energy production, transmission lines, and substations. The review also examines the implications of public laws and environmental requirements on network expansion, illustrating the complex interplay between regulatory frameworks and technical considerations. This analysis not only informs the methodological choices made in this thesis but also highlights the necessity of a multidisciplinary approach to address the challenges faced in MV distribution infrastructure effectively.

In addition, particular attention is given to the treatment of land use data and its transformation into cost surfaces for LCP analysis. As reviewed, several studies have adopted different strategies to assign cost values to various land cover types, with inaccessible or prohibited zones such as protected areas or densely urbanized regions typically receiving maximum penalty values to steer routing algorithms away from these zones. The literature validates the use of discrete cost levels (e.g., 10 to 999) based on ecological, logistical, and regulatory constraints, which helps translate real-world feasibility into GIS-based planning models.

Slope also emerged as a critical physical constraint, with many studies advocating the integration of terrain steepness into cost models to ensure technical feasibility and structural stability for MV lines. This thesis builds upon those practices by implementing conditional raster expressions that penalize areas exceeding slope thresholds and incrementally increase cost in moderately sloped areas to reflect additional construction and maintenance difficulties. These strategies ensure that the resulting paths are not only cost-effective in abstract terms but also pragmatically executable in real terrain conditions.

In conclusion, this section serves as a critical foundation for the thesis, providing insights into the current state of MV network planning and the role of geospatial analysis. It establishes a clear rationale for the research objectives and methodologies employed in the study, ensuring that the work is relevant and impactful. By synthesizing existing knowledge and identifying key areas for further exploration, the literature review not only contributes to the academic discourse but also lays the groundwork for practical applications that can enhance the resilience and efficiency of MV distribution networks in the future. In particular, the integration of land use-based cost attribution and slope-informed constraints into GIS-based LCP analysis offers a powerful decision-making framework, one that this thesis further develops and validates through multiple scenario simulations and case studies across diverse Portuguese landscapes.

3 Proposal Methodology

This section presents the methodology and tools applied throughout the study. Subsection 3.1 describes the definition of the case studies considered for the analysis, detailing the criteria used to establish them. Subsection 3.2 addresses the identification and selection of the necessary GIS input parameters required to conduct a comprehensive geospatial analysis. In Subsection 3.3, the procedures adopted to process, organize, and prepare the shapefile data for analysis are outlined. Subsection 3.4 explains the formulation of the objective function and the definition of the mathematical restrictions applied in the study. Furthermore, Subsection 3.5 details the structure of the GIS algorithm developed, highlighting how it integrates with the mathematical model previously defined. Lastly, Subsection 3.6 focuses on evaluating the results, encompassing both economic and environmental perspectives based on the outcomes of the geospatial and mathematical analyses.

3.1 Case Study Creation

Additionally, the selection of substations located in different geographic regions across Portugal enables the study to capture a wide variety of physical, environmental, and urban conditions. By incorporating sites from distinct contexts, the analysis accounts for the diversity of challenges that can influence MV grid expansion. This geographical spread ensures that the study reflects the real heterogeneity of the Portuguese territory, providing a more comprehensive understanding of how local factors affect planning and network development. This spatial variability is crucial to demonstrate how geospatial factors can significantly influence the technical and economic criteria associated with MV grid expansion. The inclusion of different regions guarantees that the analysis is not limited to specific geographic conditions but rather reflects the heterogeneity of the Portuguese territory, reinforcing the practical relevance and applicability of the study's conclusions. As demonstrated in Table 5, the selected areas were chosen not only for their different locations but as well for the variant obstacles and distances between the expansion points.

As Table 5 demonstrates, the selected areas were chosen not only for their geographic diversity but also based on the specific obstacles and distances between the potential expansion points. The locations were carefully selected according to their proximity to possible MV consumers and areas where new MV sources could provide significant benefits. The final points were defined as potential consumers in need of improved MV supply, ensuring that the proposed expansions would address real or anticipated energy needs. Additionally, certain intermediate areas along the possible expansion paths were considered as potential additional consumers, allowing the analysis to evaluate how a single expansion could benefit multiple users. The origin points, on the other hand, were defined in locations where MV infrastructure already exists, such as existing poles or substations, to ensure technical feasibility and realistic network integration. Consequently, the main selection criteria for each scenario were based on the identification of potential MV consumers located within a reasonable distance (between 1,000 and 5,000 meters) from an existing MV line or substation. In each case study, a primary origin point was defined, and in two conditions, alternative origin points were introduced on the opposite side of the MV grid relative to the primary origin. The only exception was Case Study 7, where the expansion originated directly from the substation.

Table 5 - Definition of each Case Study details

ID	Main Obstacle	Localization	District	Expansion Point	Final Point	Direct Distance (m)
1	Water Park	Loulé	Faro	MV Pole	Service Area	1 680
						1 678
						1 585
2	Reservoir	Beringel	Beja	MV Pole	Village	4 100
						4 160
						4 240
3	Industrial Park	Santarém	Santarém	MV Pole	Event Park	1 705
						1 605
						1 950
4	Buildings	Monte Real	Leiria	MV Pole	Military Facility	3 205
						3 160
						3 115
5	Terrain Slope	Cernache do Bonjardim	Castelo Branco	MV Pole	Village	2 045
						2 100
						2 060
6	Terrain Slope	Penafiel	Porto	MV Pole	Leisure Park	2 650
						2 640
						2 645
7	Terrain Slope	Vila Real	Vila Real	Substation	Airport	1 900

8	Buildings	Aboim da Nóbrega	Braga	MV Pole	Village	1 740
						1 800
						2 000

The creation of scenarios, which is the definition of a local with a possible origin and final point described above, is the first step to start this study, as it defines where and how the analysis will be done. In this case, the scenarios are based on selected MV substations, which will be used as reference points for the grid expansion. These substations were chosen because they represent key locations in the MV network and allow for realistic planning of new grid paths. The scenarios were also defined in different geographic areas to consider various territory characteristics since this is a geospatial analysis. At this stage, the inputs needed for the GIS simulations were also identified. These include information such as the location of water bodies, roads, urban areas, slopes, and protected zones, which will later be used to analyse the best path options for the MV grid expansion. Figure 10 explains the chain of events following the definition of the scenarios and GIS parameters.

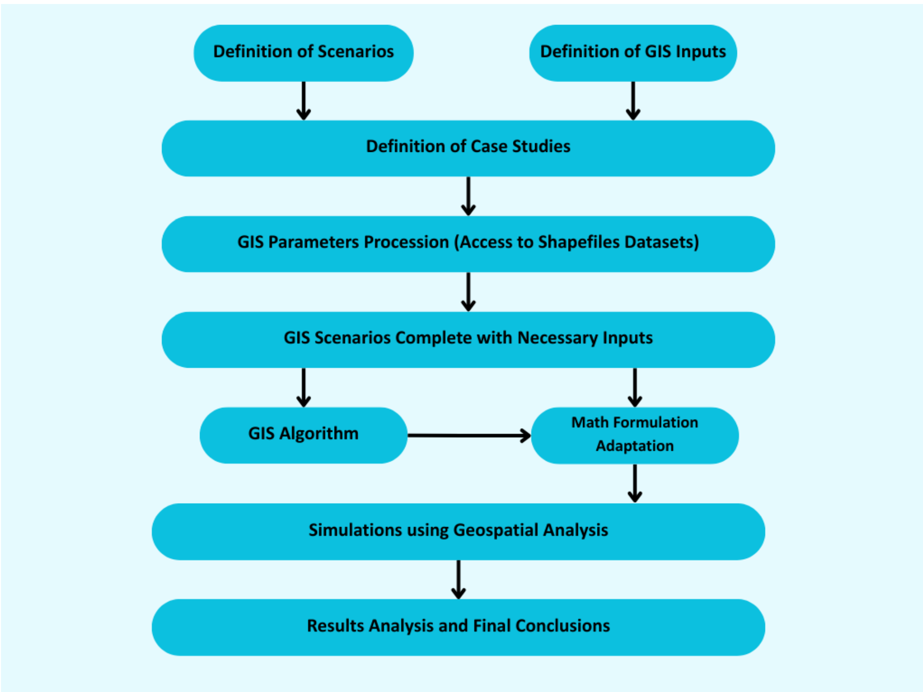


Figure 10 - Methodology Workflow with Respective Steps

As it was said before, the creation of the case studies presented in Table 5, occurs through the definition of GIS inputs and the scenarios, followed by the process of GIS parameters. This step is important since it focuses on obtaining and preparing spatial data, such as shapefiles, for analysis. Once the GIS scenarios are completed with all necessary inputs, the methodology branches into two parallel tasks, which are the GIS algorithm implementation and mathematical formulation adaptation, ensuring both spatial and computational constraints are accounted for. These components feed into the simulations using geospatial analysis, where different scenarios are tested to optimize grid expansion. Finally, the results analysis and consequently the study conclusions evaluate the effectiveness of the proposed solutions, guiding decision-making for MV network expansion while considering geospatial restrictions.

3.2 Definition of Geospatial Analysis Parameters

The planning of MV grid expansion must consider multiple geospatial parameters that influence the feasibility and cost of installation. Railways, roads, and water bodies introduce both physical and regulatory constraints that affect power line routing. Railway corridors and major roads require special safety clearances and construction coordination to prevent interference with transportation infrastructure. Similarly, water bodies such as rivers, lakes, and reservoirs pose challenges in network connectivity, often requiring additional engineering solutions like bridges or underground cabling. Arderne et al. [25] highlight the role of open geospatial data in optimizing power grid expansion by pre-identifying these constraints. Table 6 demonstrates a quick summary about the necessary inputs considering their importance for the analysis and their source of databases.

Table 6 - Summary of the QGIS's inputs considered important for the geospatial analysis

Parameter	File Type	Description	Impact	Source
Railways	Line (Shapefile)	Railway infrastructures that may affect the placement of power lines	Medium	[40]
Water Bodies	Line (Shapefile)	Rivers, lakes, and other water bodies that pose installation constraints	High	[41]
Roads	Line (Shapefile)	Road network relevant for accessibility and maintenance of infrastructures	Medium	[42]
Terrain Slope	Raster	Elevation variations influencing installation costs and feasibility	High	[43]
Sports and Leisure Facilities	Polygon (Shapefile)	Theme Parks or Sports Stadiums must be avoided	Medium	[44]
Buildings	Polygon (Shapefile)	Urban and industrial buildings can obstruct power line routes	Medium	Made in QGIS

Protected Areas	Polygon (Shapefile)	Environmental conservation zones restricting infrastructure placement	High	[44]
Airports	Polygon (Shapefile)	Airport zones where height restrictions may limit power line installation	High	[44]
Military Facilities	Polygon (Shapefile)	Restricted areas due to security concerns and national regulations	High	[44]
Land Use	Polygon (Shapefile)	Classification of land for urban, agricultural, forest, or industrial purposes	Medium	[44]

The slope of the terrain and the type of soil are equally important as they impact the feasibility of an installation. Increased steepness escalates the engineering difficulties, requiring additional structural supports for poles and transmission lines. Other soils, like clayey and sandy soils, may pose risks of foundation instability, which makes soil classification alongside geotechnical studies imperative in geoengineering. Custodio and Trindade [28] , in their studies, highlight the need for a GIS-based terrain model to evaluate these variables to improve a network's resilience.

Environmental and urban planning constraints must also be considered in grid expansion. Protected areas and urban zones impose legal and social restrictions that limit infrastructure placement. Conservation areas are subject to strict environmental regulations, requiring mitigation measures to prevent ecosystem disruption. Densely populated urban regions introduce additional complexities due to land use planning and regulatory constraints, which impact routing flexibility and construction permits. As noted by Resch et al. [25], a GIS-based assessment of reliability and environmental impact is essential in ensuring compliance with these restrictions. Further, airports and military zones present critical security and operational constraints for power line expansion. Airports enforce strict height restrictions to ensure airspace safety, while military bases impose exclusion zones where infrastructure development is heavily regulated. These constraints require careful route planning using advanced GIS-based methods, as explored by Bosisio et al. [30] in their research on geospatial modelling for power grid planning.

The automated generation of large-scale distribution grid models, as proposed by Hebbeln et al. [24], highlights the potential of QGIS in integrating open-source data and optimization algorithms. This approach enhances decision-making by evaluating expansion scenarios under technical, economic, and regulatory constraints. Similarly, Tendolkar [8] underscores the importance of geospatial factors in medium voltage network modelling, advocating for the combination of GIS analysis and power system simulations to optimize grid topology. Moreover, Castro et al. [26], [27] propose a multi-investment framework that incorporates geospatial analysis, uncertainty modelling, and DER remuneration. This aligns with the study's objective to balance cost-efficiency, reliability, and environmental sustainability in MV network expansion.

The expansion of MV distribution networks must comply with national and international regulations governing environmental protection, infrastructure safety, and energy efficiency. In Portugal, grid expansion must adhere to Decree-Law No. 15/2022, which establishes planning criteria for integrating renewable energy sources while minimizing environmental impact. European directives, such as the EU Renewable Energy Directive (2018/2001), further mandate the consideration of sustainable land use in network planning. Best practices, as outlined in IEEE 1547-2018, emphasize distributed energy integration, reliability standards, and geospatial data accuracy to optimize network expansion. By incorporating QGIS-based geospatial analysis in compliance with these regulations, the study ensures that MV grid expansion aligns with legal, environmental, and technical best practices.

By utilizing QGIS and integrating the geospatial parameters identified in table, this study adopts a data-driven approach to MV grid expansion planning. The integration of terrain, land use, and infrastructure data enables cost-effective and regulatory-compliant network development. Leveraging insights from Castro et al. [26], [27] and Bosisio et al. [30], the study further aims to enhance grid resilience through GIS-based modelling and optimization techniques. As the energy transition accelerates, incorporating spatial intelligence into MV distribution network expansion will be crucial for achieving sustainable, scalable, and adaptive grid solutions.

3.3 Processing and Analysis of GIS Inputs

For this study, Shuttle Radar Topography Mission (SRTM) and Advanced Land Observing Satellite (ALOS) AW3D30 were considered as two key DEM datasets [43]. Both datasets provide global elevation data at a resolution of approximately 30 meters (m), but there were notable differences in their quality. While ALOS AW3D30 offers higher vertical accuracy, it was observed that it contains more void pixels, particularly in certain orbital strips. These missing data points required additional interpolation, which could introduce uncertainties in the final elevation model. In contrast, SRTM-DEM was found to be more complete with fewer void pixels, especially after applying interpolation techniques. The NASA-processed version of SRTM-DEM already includes some gap-filling algorithms, making it a more reliable choice for large-scale terrain analysis. Therefore, SRTM-DEM was selected as the preferred DEM model for this study due to its higher completeness, better overall consistency, and lower need for manual corrections.

To conduct this analysis, localized elevation data was collected and processed to ensure an accurate representation of the terrain. The Digital Elevation Models (DEM) were obtained from open-source datasets, primarily from NASA's Earth Data portal [45]. These datasets provide high-resolution elevation information from sources such as the SRTM and other satellite-based elevation models. However, as is common with DEM datasets, certain areas contained void pixels, which are regions where elevation data was missing due to factors such as cloud cover, steep terrain, or water bodies. To address this issue, void pixels were filled using interpolation techniques available in the Geospatial Data Abstraction Library (GDAL) toolkit. Specifically, the "Gdal_fillnodata" command was applied, which performs interpolation based on surrounding elevation values, effectively estimating missing data and improving the continuity of the terrain model.

Once the data gaps were filled, the DEM was then reprojected to the Portuguese national coordinate reference system, PT-TM06 / ETRS89 (EPSG:3763). This transformation was executed using the "Gdalwarp" command, ensuring that the dataset was accurately mapped to its correct geographical location. The reprojected dataset was sourced from Derek Watkins's SRTM Downloader [43], which provides access to SRTM 1 Arc-Second Global data in an approximately 30 m resolution. Given that mainland Portugal spans multiple DEM tiles, several files corresponding to different regions of the Portuguese continental territory were downloaded and merged to create a continuous elevation dataset. After preprocessing, the DEM was imported into QGIS to proceed to the geospatial analysis. Within QGIS, terrain analysis was conducted to extract key topographical features such as slope gradients, elevation variations, and terrain classifications. These analyses provided valuable insights into the morphology of the study area, enabling effective visualization and interpretation of the landscape.

To extract water bodies specific to Portugal, the "Europe and Middle East" shapefile from the HydroRIVERS dataset [41] was downloaded, as it provides extensive river network data suitable for this purpose. To focus on the Portuguese territory, the QGIS geoprocessing tool 'Intersection' was utilized, intersecting the HydroRIVERS vector data with a shapefile representing the Portuguese territory as a raster. This process resulted in a refined dataset containing only the water bodies within Portugal, optimizing the data for targeted analyses. The data concerning the railways, imported from the Natural Earth Portal [40], was filtered the same way the data related to the water bodies, due to the international areas who were not needed for the study.

Road network data was obtained from the Humanitarian Data Exchange platform, which provides an OSM-based export of Portuguese roads in Environmental Systems Research Institute (ESRI) shapefile format. This dataset includes all types of roads, from highways and primary roads to secondary, local, and unpaved roads, ensuring a comprehensive representation of the transportation network across Portugal. By integrating this dataset into the study, potential corridors for new infrastructure were evaluated, key transport routes facilitating grid expansion were identified, and the overall efficiency of the spatial analysis process was enhanced. In addition to the road network, railway shapefiles were also incorporated to enrich the geospatial context of the analysis further. These railway data were downloaded from the Natural Earth platform [40]. The use of both shapefiles is crucial to make sure the pole position does not stand on any transportation road.

Land use data were also integrated into the study through shapefiles obtained from the *Atlas do Ambiente* platform, which provides official geographic information for Portuguese continental territory. These datasets included classifications for military facilities, airports, agricultural zones, urban areas, sports venues, and leisure parks. The incorporation of this information was crucial, as certain land use types, such as military zones and airports, are strictly prohibited for infrastructure development and therefore had to be excluded from any potential routing of the MV grid. Moreover, understanding the land use context allowed for the identification of more cost-effective pathways by avoiding areas likely to incur higher compensation costs, such as densely urbanized or privately owned agricultural land. This approach contributed to a more realistic and efficient planning process that respects both regulatory constraints and economic considerations.

3.4 Mathematical Formulation

The objective function in the mathematical formulation is crucial as it encapsulates the goal of the optimization model, which is to minimize the total costs associated with the expansion of the MV distribution network. This study utilizes a deterministic model, with the objective function in Eq. (1) closely resemble ng the one proposed by Castro et al. [27], who, however, formulated their approach within a stochastic framework. In essence, the objective function serves as a critical decision-making tool within the context of the optimization problem. By explicitly outlining and quantifying the various cost components associated with the expansion of the distribution network, like transmission lines cost (C_{line}), poles cost (C_{pole}), equipment cost ($C_{equipment}$) and installation cost (C_{inst}). The model, with these parameters added, can efficiently identify the most cost-effective expansion path, balancing economic feasibility with practical constraints and requirements. Thus, it seeks to enable optimal planning in the context of necessary investments for future energy distribution infrastructure, thereby improving the sustainability and reliability of energy supply. The objective function was adjusted to include terrain costs (C_T), which account for expenses related to utilizing private land, including compensation for landowners.

$$Min\ Z = \sum_{p \in P} x_p \left(C_{line} + C_{pole} + C_{equipment} + C_T + C_{inst}\right) \qquad (1)$$

The restrictions affecting the expansion of the medium voltage distribution network, consider environmental, social, and technical factors. Terrain constraints, such as steep slopes, impact infrastructure installation, while environmental considerations require avoiding ecologically sensitive areas. Proximity to existing power lines influences routing decisions, and social factors, including land ownership and community acceptance, can introduce additional costs and complexities. Technical constraints involve proper equipment placement, accounting for line sag and tension. Regulatory and safety standards also play a crucial role in network design. In the case study, these factors were analysed using geospatial tools to identify the most feasible expansion path, balancing cost-efficiency with compliance and practical limitations.

Several constraints influence the expansion of the MV distribution network, ensuring feasibility and efficiency. It is mandatory to use a single expansion path for each pathway of each case study. The Eq. (2) ensures that only one route (x_p) is chosen from the possible options. This decision is critical for maintaining a structured and optimized expansion process. Directional changes and pole placement are also essential considerations. The placement of poles at direction changes is governed by Eq. (3), ensuring that poles are positioned whenever a shift in direction occurs (z_{ps}). This requirement is reinforced by Eq. (4), which accounts for terrain constraints and ensures that poles are placed where necessary to maintain network stability. Additionally, Eq. (5) links path selection to pole placement, making sure that once a path is chosen, poles can be installed along it as required. By integrating these constraints into the planning process, the network expansion model achieves a balance between technical, environmental, and regulatory requirements. These equations help structure the expansion in a way that optimizes resources while ensuring compliance with practical limitations.

$$\sum_p x_p = 1 \tag{2}$$

$$y_{ps} \geq z_{ps} \;\; \forall_p \in P, \forall_s \in S \tag{3}$$

$$z_{ps} \geq T_{ps} \;\; \forall_p \in P, \forall_s \in S \tag{4}$$

$$y_{ps} \leq M \cdot x_p \tag{5}$$

Eq. (6) defines how poles are placed along the route, using a normalized spacing of 150m (D). If the remaining distance is less than 150m, a final pole is placed at the end. If it is between 150 and 300m, one pole is placed halfway and another at the end (for example, with 200m left, poles are placed at 100m and at the end). For distances greater than 300m, poles are placed every 150m until the remaining segment is 300m or less, after which the same rule is applied. This ensures consistent pole spacing while adapting to different route lengths. Eq. (7) ensures that after each pole is placed, the model recalculates the remaining distance by subtracting the distance already covered by previously placed poles. This keeps the spacing consistent as the algorithm progresses along the route.

$$y_{ps} \geq \left[\frac{d_{ps}}{D}\right] + \left[\frac{d_{ps} - \left[\frac{d_{ps}}{D}\right] \cdot D}{D}\right] + 1 \;\; \forall_p \in P, \forall_s \in S \tag{6}$$

$$Pd_{ps} \geq d_{ps} - \sum_{s<'s} y_{ps'} \cdot D \;\; \forall_p \in P, \forall_s \in S \tag{7}$$

3.5 GIS Algorithm and Parameters Constraints

The GIS software used in this study was QGIS, an open-source platform for spatial data analysis. The workflow began by uploading the necessary shapefiles and raster datasets previously downloaded and compiled for the project. The Coordinate Reference System was set to EPSG:3763 - ETRS89 / Portugal TM06, which is appropriate for spatial accuracy within mainland Portugal. Two key points were representing the starting and ending locations for the proposed expansion. These points served as spatial anchors to delineate the area of interest, allowing the filtering and analysis of relevant geospatial data specifically within the surroundings of the path between them. Additionally, a shapefile containing information on land use and area types (e.g., military zones, airports, agricultural fields, forests, etc.) was created by merging multiple sources. This unified shapefile was then categorized by area type, enabling a clearer distinction between different land uses and supporting more accurate spatial classification in subsequent analysis.

For the analysis of each network expansion scenario, a total of four key locations were identified for each Case Study previously mentioned. One destination point represents the final target location and three origin points, consist of one primary origin and two secondary alternatives. To represent these locations spatially within the GIS environment, it was necessary to manually create new vector point features corresponding to each of these coordinates. These points served as the basis for simulating potential connection paths and evaluating routing alternatives based on predefined criteria.

Following this step, two different tools were employed to filter the data specifically to the defined study area in which the four key points were defined. Figure 12, illustrates the configuration of the “Clip Raster by Mask Layer” tool in QGIS, which was employed to extract elevation data corresponding specifically to the defined study area. In this operation, the input raster layer (dem_srtm_pt_25m), containing altitude data at a 25m resolution, was clipped using the polygon vector layer (e.g. AreaCut), which delineates the geographical extent of the study area. The tool was configured to match the extent of the clipped raster to the boundaries of the mask layer and to retain the original resolution of the input raster. These settings ensured that the output raster maintained spatial accuracy and data quality. The coordinate reference system (CRS) used throughout the process was EPSG:3763 – ETRS89 / Portugal TM06, ensuring spatial consistency across all layers involved in the analysis. This step was essential to isolate only the relevant elevation information required for the analysis, thereby optimizing processing efficiency and avoiding the inclusion of unnecessary data from areas outside the study region.

To spatially constrain the national land use dataset to the area of interest, the Intersection tool from the Geoprocessing Tools suite in QGIS was utilized. This tool performs an overlay analysis between two vector layers and generates a new output layer containing only the geometries and attribute information that spatially overlaps between both inputs. In this operation, the national land use layer was selected as the input layer, while the predefined boundary of the study area served as the intersecting layer. The resulting layer includes only the land use features that fall within the limits of the study area, effectively excluding all data outside the designated region. As seen in Figure 11, this procedure not only ensures that the analysis is geographically focused on the relevant extent but also optimizes the workflow by reducing data volume and enhancing processing efficiency in subsequent steps. Each colour represents a different area or land use type. For example, in the case represented in Figure 11 (Case Study 2), the most extensive class in the study area corresponds to temporary crops (orange), while other visible classes include olive groves (light green), agroforestry systems (dark blue), water bodies (pink), farms (blue grey), and areas of mineral extraction (red). This perspective provides an immediate visual understanding of how different land use types are spatially distributed within the study boundaries, highlighting the landscape's heterogeneity. After this, the altitude raster was used to input the slope raster for the "Slope" tool within the Raster Analysis toolbox in QGIS to generate the slope raster. This operation produced a new raster layer that represents the slope in percentage for each pixel, allowing for detailed visualization of terrain steepness across the study area. Figure 12 demonstrates the slope raster obtained. Figure 14 displays the values associated to each colour in the raster represented in Figure 12, where the brightness parts correspond to the highest areas, while the darkest tones represent the lowest.

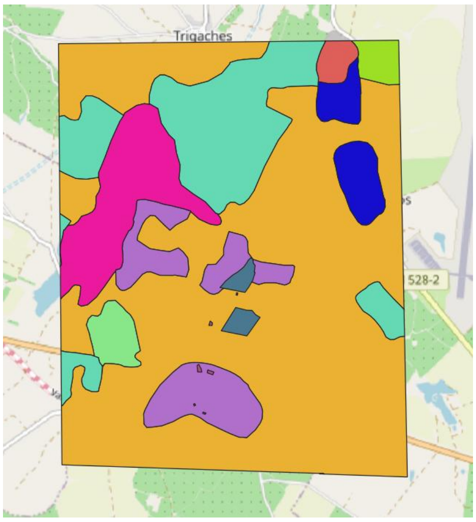


Figure 11 - Land Use Vector Cut for a specific area (Case Study 2)

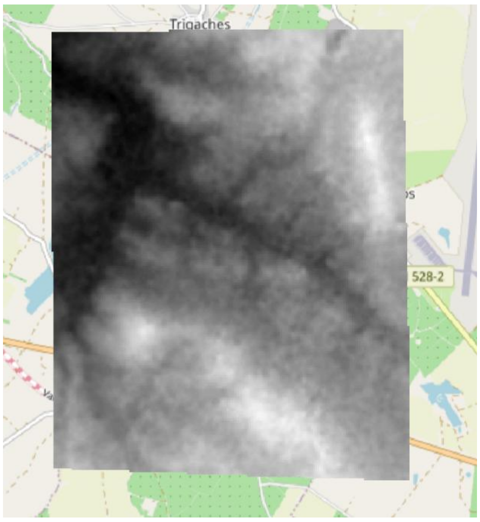


Figure 12 - DEM Raster Cut for a specific area (Case Study 2)

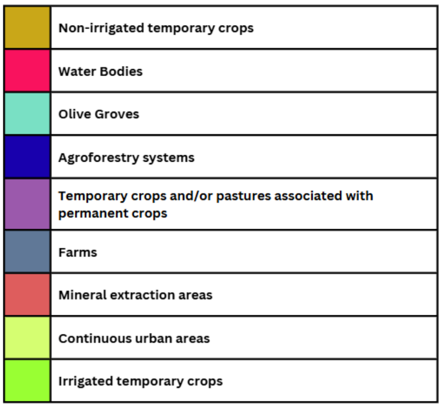


Figure 13 - Colour legend for each type of Land Use, represented in Figure 11

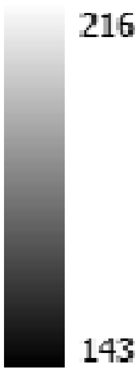


Figure 14 - Height values towards the sea level for Figure 12

In Sawyer [39], a threshold of 15% slope was used as a standard to distinguish between low and high resistance areas. For the purposes of this thesis, and following the advice of the coordinators, a maximum slope of 20% was defined as the limit for the MV grid pathway analysis. To respect this condition the Raster Calculator was used to create a binary raster, where cells with a slope less than or equal to 20% were assigned a value of 0, and those exceeding 20% were assigned a value of 1 However, in some parts of the study area particularly in the northern and central regions applying the 20% limit, proved to be highly restrictive due to the naturally steeper terrain. To address this issue, the constraint was adjusted to less than 25%, which represents the technical and safety limit for MV line deployment in rugged terrain. This solution ensured that the model remained realistic and applicable across the entire study region while still considering terrain constraints. To address this issue, the constraint was adjusted to less than 25% to proceed with the analysis. The expression used to create this raster is shown in Figure 20.

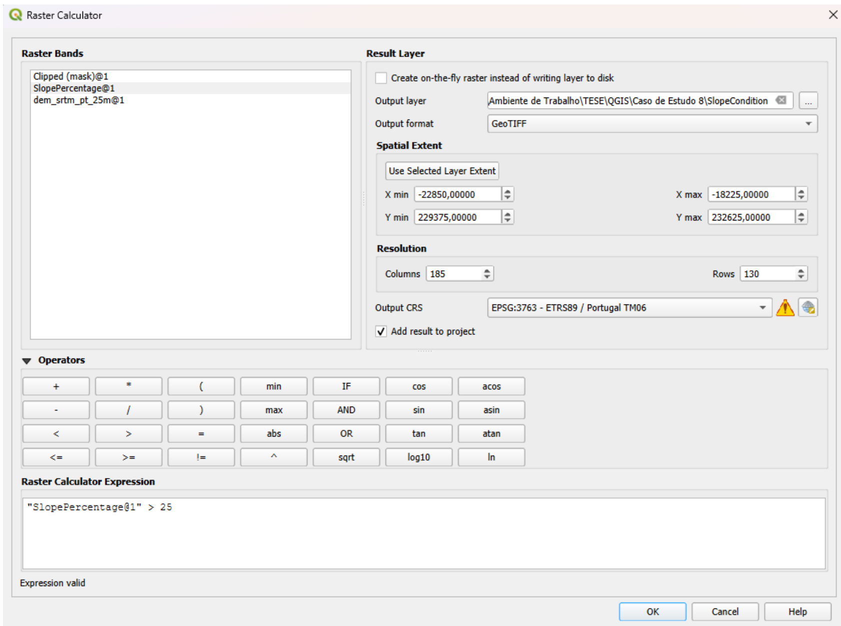
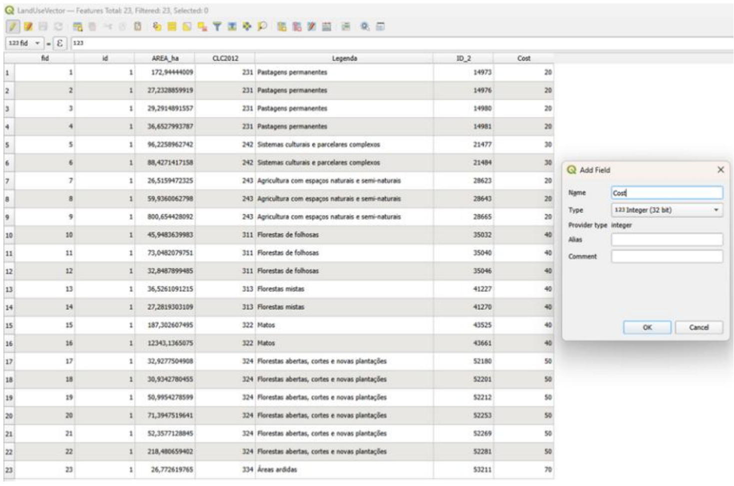


Figure 15 - Definition of the areas where the slope is less than 25%

To incorporate land use constraints into the cost analysis, the vector layer representing land use within the study area was first edited. A new field named "Cost" was added to the attribute table, as Figure 16 shows, where each land-use class was assigned, a numeric value reflecting its relative difficulty or restriction level for infrastructure development. These cost values ranged from 10 to 999, with lower values attributed to areas of easier access or lower environmental impact, such as permanent pastures, and higher values assigned to more restrictive zones like dense forests, urban areas, or regions affected by wildfires.



LandUseVector — Features Total: 23, Filtered: 23, Selected: 0

	fid	id	AREA_ha	CLC2012	Legenda	ID_2	Cost
1	1	1	172,94444009	231	Pastagens permanentes	14973	20
2	2	1	27,2328859919	231	Pastagens permanentes	14976	20
3	3	1	29,2914891557	231	Pastagens permanentes	14980	20
4	4	1	36,6527993787	231	Pastagens permanentes	14981	20
5	5	1	96,2258962742	242	Sistemas culturais e parcelares complexos	21477	30
6	6	1	88,4271417158	242	Sistemas culturais e parcelares complexos	21484	30
7	7	1	26,5159472325	243	Agricultura com espaços naturais e semi-naturais	28623	20
8	8	1	59,9360062798	243	Agricultura com espaços naturais e semi-naturais	28643	20
9	9	1	800,654428092	243	Agricultura com espaços naturais e semi-naturais	28665	20
10	10	1	45,9483639983	311	Florestas de folhosas	35032	40
11	11	1	73,0482079751	311	Florestas de folhosas	35040	40
12	12	1	32,8487899485	311	Florestas de folhosas	35046	40
13	13	1	36,5261091215	313	Florestas mistas	41227	40
14	14	1	27,2819303109	313	Florestas mistas	41270	40
15	15	1	187,302607495	322	Matos	43525	40
16	16	1	12343,1365075	322	Matos	43661	40
17	17	1	32,9277504908	324	Florestas abertas, cortes e novas plantações	52180	50
18	18	1	30,9342780455	324	Florestas abertas, cortes e novas plantações	52201	50
19	19	1	50,9954278599	324	Florestas abertas, cortes e novas plantações	52212	50
20	20	1	71,3947519641	324	Florestas abertas, cortes e novas plantações	52253	50
21	21	1	52,3577128845	324	Florestas abertas, cortes e novas plantações	52269	50
22	22	1	218,480659402	324	Florestas abertas, cortes e novas plantações	52281	50
23	23	1	26,772619765	334	Áreas ardidas	53211	70

Figure 16 - Attribute Table of the Land Use Vector

Once the cost values were defined, the vector layer was converted into a raster format to spatially represent each polygon’s cost as individual pixel values. This transformation was performed using the "Rasterize" tool (Vector to Raster) in QGIS. As shown in Figure 17, the input vector layer used was the land-use layer, clipped to the study area. The “Cost” field was selected as the burn-in value, allowing each polygon’s cost to be transferred to the corresponding pixels. The raster resolution was set to 1x1 georeferenced units to maintain spatial accuracy. The output data type was set to Float32 to ensure that all cost values were preserved with the necessary precision.

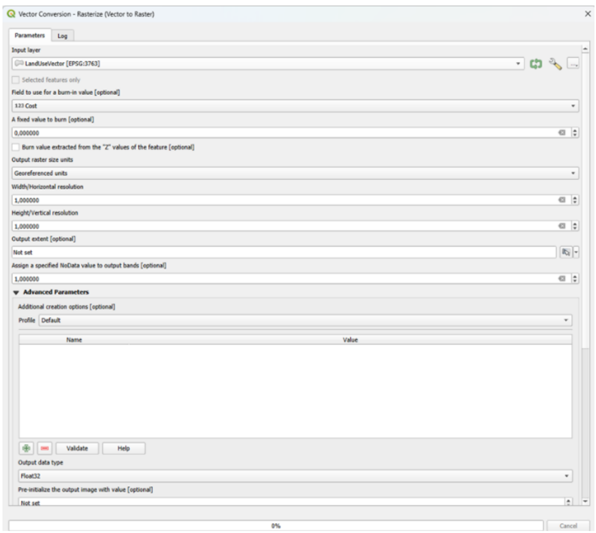


Figure 17 – Conversion of the Land Use Vector to Raster using Cost field as indicator

The result in Figure 18 was a cost raster where each cell reflects the relative effort or restriction associated with crossing that area, according to land use. This raster was then integrated into the larger cost surface used for modelling optimal routes in network expansion.

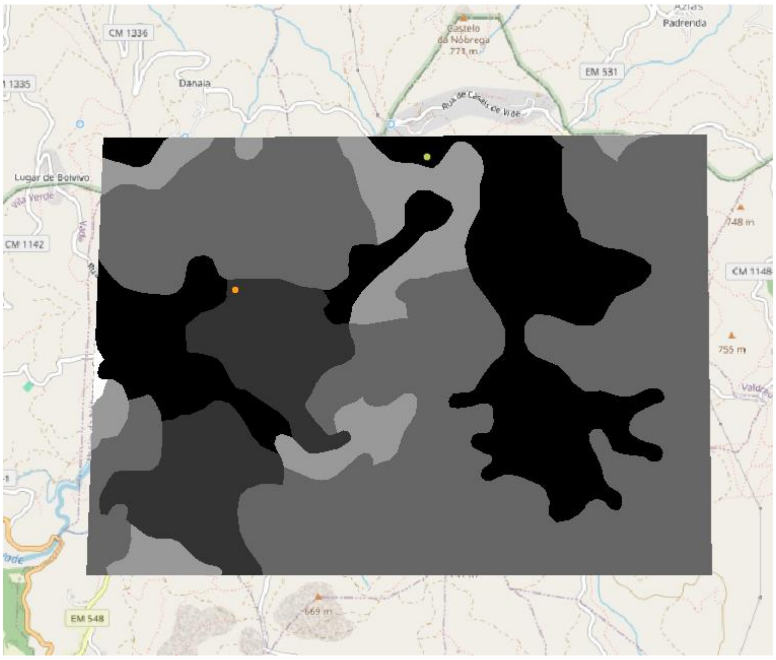


Figure 18 - Result of the Land Use Raster (Case Study 8)

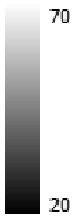


Figure 19 - Combination of cost and slope values scale obtained by raster calculator for Figure 18

To combine both land use cost and slope constraints into a single cost surface, a conditional expression was applied using the Raster Calculator in QGIS. This expression aimed to generate a raster in which each pixel reflects the difficulty or cost of traversing that area, considering not only the inherent resistance associated with land use types but also the limitations imposed by steep terrain. This technique was made based on the methodologies used in Lima et al. [34] and La Riccia [35] frameworks.

This method uses the raster that pixels where the slope exceeds the limits. These areas are considered significantly limiting for expansion or movement. In such cases, the expression increases the cost value dramatically by adding 999 to the original land use cost. This effectively marks those areas as nearly impassable or highly undesirable for the intended analysis. For the remaining areas where the slope does not exceed the defined threshold, the base land use cost is preserved and slightly adjusted about the slope, ensuring a continuous and realistic variation in values. The resulting raster captures both dimensions of physical constraint, land use, and terrain into a single, integrated surface for use in subsequent spatial analyses. In Figure 18, an example of one of the formulas used to obtain a raster capable of merging the land use and terrain constraints.

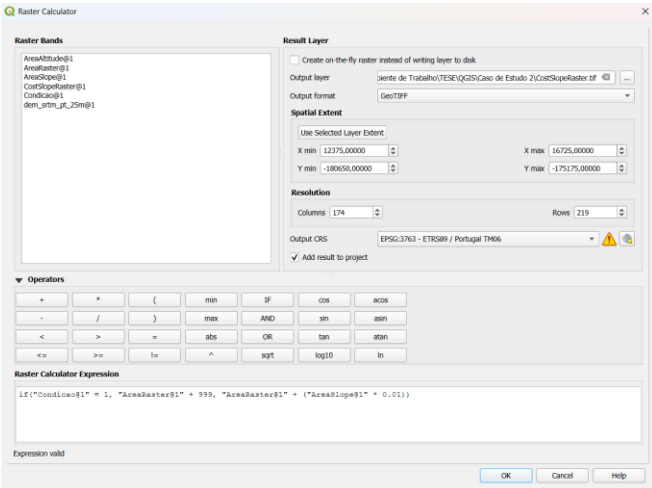


Figure 20 - Raster Calculator Expression for the Cost-Slope mixed Raster

As it was said earlier this method was repeated two more times for two different expressions, to obtain different pathways for the later economic analysis for a set of possible paths. Once the final cost raster was generated integrating both the land use resistance values and the slope restrictions it became possible to carry out an LCP analysis. This analysis aims to determine the most efficient route between a starting point, and a destination point by minimizing the cumulative cost of traversing each pixel in the raster. In this case, the LCP tool in QGIS was used. The previously calculated cost raster was set as the cost surface, representing the difficulty of moving across each spatial unit. The origin and destination points were defined through two separate vector layers, each containing the respective coordinates of the initial and final locations. By processing this information, the algorithm computed the optimal route, selecting the path of the lowest accumulated cost based on the values in the raster. This resulted in a polyline that represents the most favourable trajectory across the landscape, accounting for both terrain slope and land use characteristics. Figure 21 represents the function’s configuration.

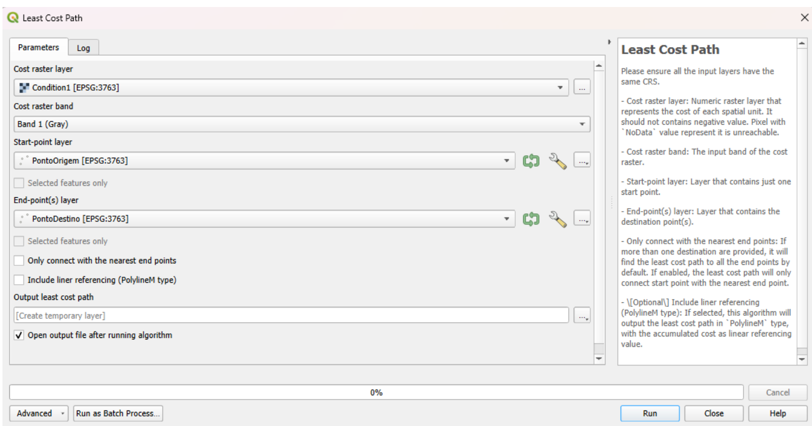


Figure 21 - LCP Function Set

The output vector generated by the LCP analysis represented the most efficient route between the origin and destination points according to the cost values derived from land use and slope. However, the resulting path was characterized by an excessive number of directional changes, resulting in a highly irregular and impractical line. To address this, the "Simplify" tool from the Vector Geometry menu in QGIS, shown in Figure 22, was applied to reduce the number of vertices in the path without compromising its spatial accuracy. The simplification was executed using the Distance (Douglas-Peucker) method, which simplifies the geometry based on a set tolerance distance. After testing multiple configurations, the tolerance was set to 50m, as this value provided a balanced simplification retaining fidelity to the original constraints of the terrain and land use while significantly improving the visual and practical clarity of the path. This final step ensured that the route remained realistic and usable while respecting the conditions established in the cost analysis.

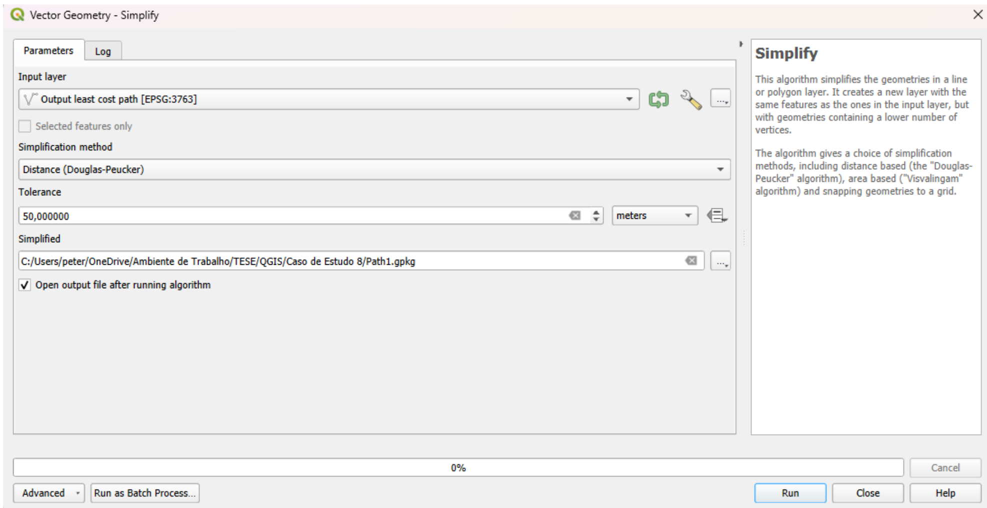


Figure 22 - Simplify Function Set

To define the final placement of poles along the selected route, it was essential to ensure that poles were located not only at every significant directional change but also spaced consistently between those points. In accordance with Castro et al. [27] work the spacing between consecutive poles had to respect the constraint of maintaining a distance of 150m.

To achieve this, a combination of geoprocessing tools in QGIS was employed. First, the "Points Along Geometry" tool was applied to the simplified path vector, generating evenly spaced points with a minimum distance of 100m, starting from both the origin and destination points. This ensured that the linear sections of the route were properly covered by poles at regular intervals. In parallel, the "Extract Vertices" tool was used to obtain points from the original geometry of the path line, capturing every turn where a pole would be required due to a change in direction. Once both point sets were created, they were combined using the "Union" tool under Vector Geometry, resulting in a unified layer containing all proposed pole positions both those placed due to spacing and those required by curvature. Although the objective was to maintain a normalized spatial distance of 150m between poles, as adopted by Castro et al. [27], the merging of poles obtained through the

Points Along Geometry and Extract Vertices tools did not allow for a perfectly regular spacing. As a result, the distances between poles ranged from 100 to 200m, aiming to keep values close to 150m. These limits were defined by the author to avoid poles being placed too close together (less than 100m) or too far apart (more than 200m), while also allowing for the irregularities created by the QGIS tools. This approach kept the spacing practical and consistent with the 150m reference used in the literature. This limitation was subsequently addressed in a later stage through the optimization model implemented in Python code. This irregularity did not affect the outcomes of the present work, since the generation of poles in QGIS was intended to provide a representative approximation of potential pole locations rather than to yield the final pole distribution. In addition, visualizing the preliminary pole arrangement in QGIS made it possible to identify any pathways that required disproportionately more poles compared to others within the same case study.

Finally, a spatial inspection was performed to identify and remove any poles that were spaced too closely together, particularly those found to be less than 100m apart, ensuring full compliance with the technical constraints of pole distribution. This process yielded a coherent and optimized set of pole locations that respected both the geometric structure of the path and the imposed engineering criteria. The result can be seen in Figure 23.

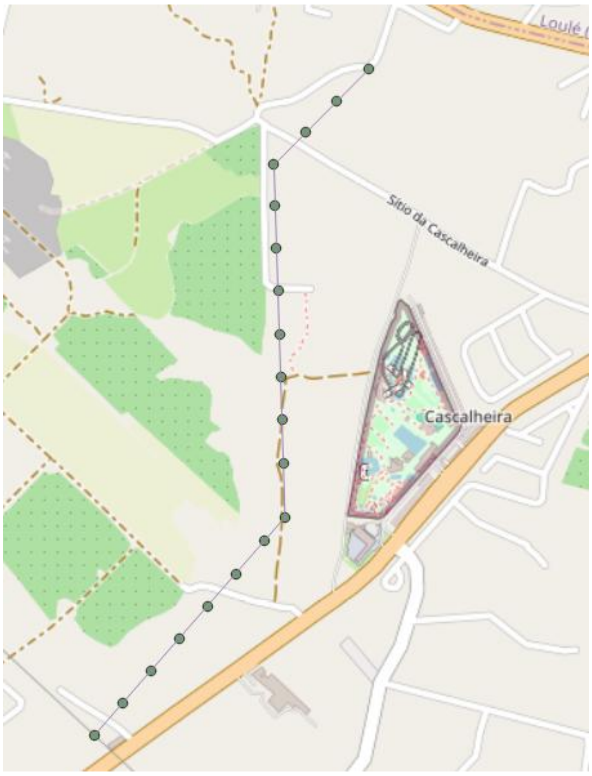


Figure 23 - Result of one of the Pathways Generated (Case Study 1)

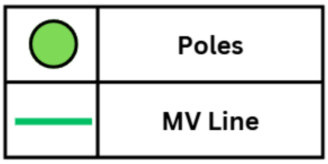


Figure 24 - Elements from Figure 23

The procedure from the LCP analysis to the placement of utility poles was systematically repeated five times for each Case Study to generate distinct route alternatives and enable comparative assessment based on technical feasibility and estimated implementation costs. This repetition aimed to evaluate how different conditions and configurations influence the resulting paths and to later compare them in terms of estimated costs. Five different route alternatives were generated for each case (except in the seventh case study, that was only generated three paths), since QGIS's “LCP” function returns only a single optimal path per run. Thus, five distinct conditions were manually created for each Case Study to simulate a broader range of planning possibilities.

The first three routes were produced using the same origin and destination points but differed in the way terrain slope was integrated into the cost surface. In each case, a conditional raster expression was used to combine land use and slope information, where a previously calculated “SlopeCondition” raster flagged areas with slopes above the acceptable threshold (over 20 or 25 %, depending on the geographic area) with the value 1, and all other areas with 0. This decision was influenced by Sawyer et al. [39] methods on the terrain slope evaluation. These high-slope areas were considered unsuitable and therefore assigned a very high-cost value of 999 to discourage the path from crossing them, similar to the methods used by Lima et al. [34] and La Riccia et al. [35] .

The cost surface equations used in these conditions were implemented as code expressions in the QGIS Raster Calculator, which are not conventional mathematical formulas but rather coded expressions specific to the tool. These three variations allowed for testing different sensitivities of the cost surface to terrain steepness, helping to evaluate how small or large changes in slope interpretation might impact the final route. To complement these, two additional conditions were created (Conditions 4 and 5), using the same cost expression as Condition 1, but with different origin points. While the destination point remained unchanged, the start location was shifted to two alternative positions close to the original substation. This method simulates practical cases where more than one grid connection point might be available, or where spatial constraints require adjusting the route entry location.

The first path was generated by Eq.8 that added a small weight to the base cost from the land use raster, proportional to the slope percentage. The multiplication by 0.01 serves to reduce the impact of the slope percentage values (which range from 0 to 100), so that they do not disproportionately outweigh the land use cost.

$$if(SlopeCondition = 1, AreaRaster = 999, AreaRaster + (SlopePercentageRaster * 0.01)) \quad (8)$$

For Eq.9, applied for the second condition, the slope values are directly added without adjustment. This makes slope a dominant factor in the path calculation, strongly penalizing steeper areas.

$$if(SlopeCondition = 1, AreaRaster = 999, AreaRaster + SlopePercentageRaster) \quad (9)$$

For the third path, the slope was measured in degrees instead of percentage. Multiplying by 0.1 ensures that the range of slope values (usually 0–45 degrees) contributes proportionally to the cost, keeping a balanced relationship with land use costs, as shown in Eq. 10.

$$if(SlopeCondition = 1,\ AreaRaster = 999,\ AreaRaster + SlopeDegreesRaster * 0.1) \quad (10)$$

Together, these five manually generated routes per scenario enabled a comparative assessment not only of how slope and land use weightings affect pathfinding, but also of how route viability changes with different spatial configurations. This provided a more robust basis for evaluating and estimating the cheapest and most technically feasible MV grid expansion path, adapting to diverse terrain and planning conditions across the Portuguese territory.

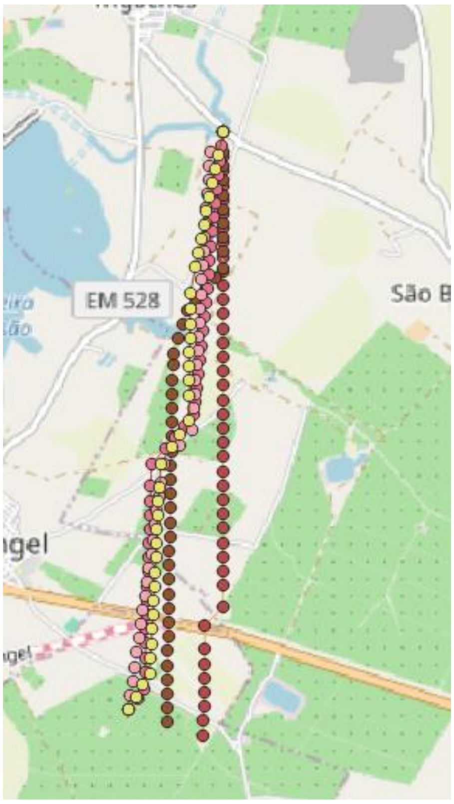


Figure 25 - Set of all Pathways Generated (Case Study 2)

This comprehensive and repeatable workflow ensured that each proposed path was generated according to consistent technical and spatial parameters. By producing five distinct route options per Case Study, as seen in Figure 25, the methodology allowed for a comparative analysis not only in terms of terrain and alignment suitability but also in terms of cost estimation. These alternatives were then used to calculate and identify the most cost-effective solution, supporting an informed decision-making process for infrastructure planning.

3.6 Python Code for Economic Analysis

The Python code used for the final analysis, originally provided by Professor Fábio Castro used in his study [27], was adapted with modifications to better align with the objectives of the present study. Its primary purpose is to integrate spatial outputs obtained from QGIS LCP analyses with economic optimization techniques to determine the most cost-efficient route for MV grid expansion and determined an optimal number of poles using a normalized space distance of 150m, which was not possible to determine in QGIS. Each candidate route is represented as a set of segments defined by their length and presence of direction changes, while the script calculates the required number of poles, line lengths, and associated costs. These computations are grounded in realistic engineering and financial parameters, such as pole installation, materials, licensing, and line costs, ensuring the results reflect actual implementation conditions.

The optimization framework was implemented using Pyomo, in combination with the Gurobi solver. Binary decision variables were assigned to each path, with the objective function minimizing the total cost of expansion. To ensure engineering feasibility, poles were set at fixed intervals (150m) with additional considerations for long spans or bends, thus respecting installation and safety standards. A constraint requiring the selection of exactly one path guarantees that the outcome is a single, optimal solution suitable for planning purposes. Through these adjustments, the adapted code directly connects the geospatial analysis to practical decision-making in MV network planning.

Table 7 – Cost Values Inputs used in the Python Code for the Economic Analysis

Variable	Cost	Source
Pole cost	$ 3,400.00	[46]
Equipment/Materials	$ 1,050.00	[46], [47]
Licenses	$ 350.00	[46]
Excavation	$ 1,200.00	[47]
Transmission Lines (per m)	$ 38.00	[47]

In terms of inputs for the Python code calculating the costs of MV grid expansions, the following cost values presented in Table 7, such as pole cost, equipment/materials, licenses, excavation, and transmission lines (per m), were crucial for this part of the analysis. These values were used as the base parameters for estimating total investment requirements in the grid expansion model for each path generated by QGIS.

The execution of the script was performed in the Spyder IDE on an OMEN HP laptop with an Intel(R) Core (TM) i5-8300H CPU @ 2.30 GHz, 16 GB of RAM, running Windows 11. This configuration proved adequate for handling both the geospatial datasets and the optimization problem. By adapting the code to the context of this thesis, the process successfully translates GIS-derived path alternatives into a rigorous cost-minimization framework, yielding a final recommendation that balances technical feasibility with economic efficiency.

3.7 Results Possible Limitations

This study aims to present a robust and comprehensive geospatial analysis for the expansion of the MV, although certain limitations must be acknowledged. These limitations come mostly from challenges in accessing complete and freely available data, which in turn affected the precision and scope of some of the GIS-based simulations. As with many studies dependent on open data sources and GIS tools, the availability and granularity of spatial information can greatly influence the final quality and reliability of the results.

As previously mentioned, the land use data acquired for this study specifically covered the continental territory of Portugal. Due to the absence of equivalent and detailed geographic datasets for the autonomous regions, the Azores and Madeira Islands were not included in the scope of this analysis. Consequently, all case studies and geospatial evaluations were limited to mainland Portugal. This decision ensured consistency and reliability in the input data used, particularly for land classification, which was essential for identifying restricted areas and optimizing the placement of MV infrastructure within the constraints of the territory.

One of the primary limitations involved difficulties in obtaining complete and reliable geographic datasets suitable for use in QGIS. In several instances, no publicly available or freely accessible shapefiles could be found that covered specific elements of interest, such as the delimitation of private properties and agricultural land, in detail, throughout the Portuguese territory. This lack of data constrained the ability to fully incorporate land-use restrictions and associated compensation costs into the model. Nonetheless, some gaps were addressed through alternative methods. For example, in the absence of a shapefile for existing buildings, features were manually delineated in QGIS using OSM as a reference. A similar approach was adopted for mapping military bases, ensuring that the analysis respected prohibited areas. While these solutions mitigated some limitations, the overall experience underscores the importance of improving access to detailed and accurate geospatial data for future infrastructure planning efforts. Finally, the LCP approach in QGIS did not account for the additional cost associated with excessive changes in direction. As a result, some generated paths may include too many turns, which in practical terms could increase construction complexity and overall project costs.

4 Case Studies and Results Analysis

4.1 Case Study 1 – Algarve Water Park

This one carried out in the district of *Faro*, the goal was to find the best path to connect the MV line to a service area. The study area included different types of land uses that influenced the choice of the route, such as exploration sites, industrial zones, and a water park. These features made the analysis more complex, as some areas increase construction costs or present restrictions for passing the line. By using the LCP method in GIS and assigning costs to each type of land use, it was possible to compare different alternatives and select the most suitable route that ensures a balance between cost, feasibility, and avoiding major conflicts with existing infrastructures. Figure 26 demonstrates the GIS map with pathways generated through the obstacles.

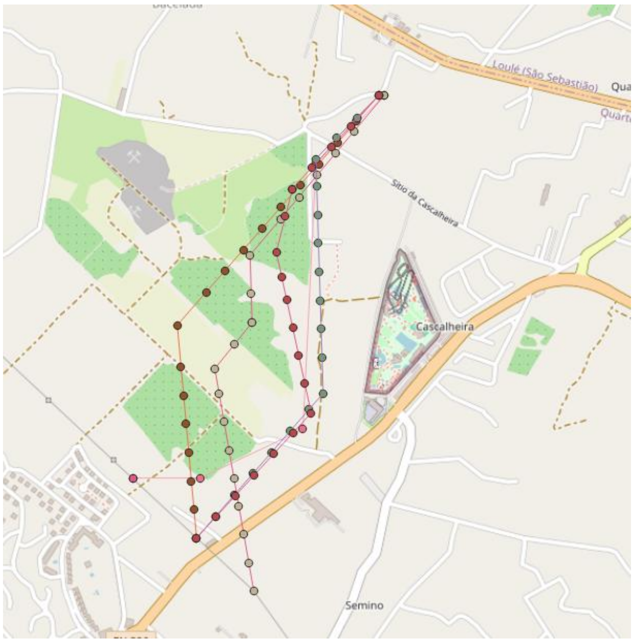


Figure 26 – Pathways generated in QGIS for Case Study 1

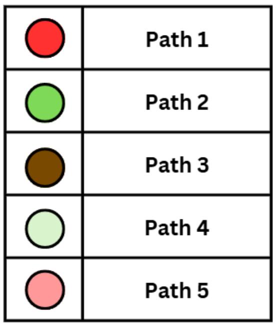


Figure 27 – Pathways Generated in Studt Case represented in Figure 26

As shown in Figure 28, the graph for Case Study 1 demonstrates total costs ranging from about 108,014$ in Condition 1 to 139,624$ in Condition 3. Condition 1 presents the most cost-efficient path, while Conditions 2 and 3 represent higher values, likely due to additional constraints or detours caused by slope or land use restrictions. Conditions 4 and 5 fall in between, reflecting intermediate levels of restrictions where the algorithm had to slightly adjust the route to avoid unsuitable areas.

This cost distribution indicates that, although more restrictive conditions help ensure technical feasibility and compliance with land use constraints, they also push the path toward less direct and more expensive alternatives.

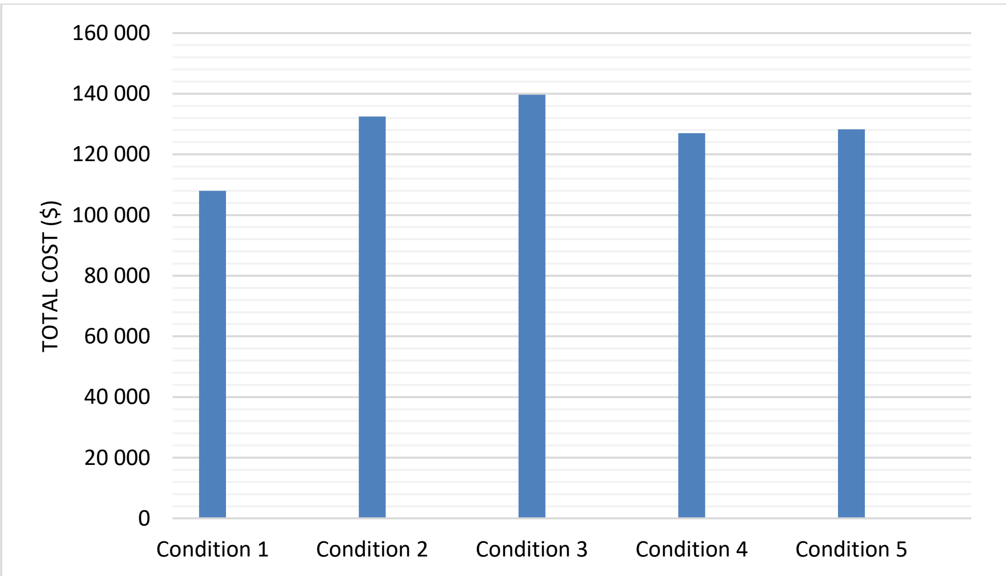


Figure 28 - Total Cost of each Condition obtained by Python Code for Case Study 1

4.2 Case Study 2 – *Pisão* Reservoir

In Case Study 2, conducted in the district of *Beja*, the objective was to connect the MV line near the village of *Beringel* to the entrance of another location called *Trigaches*. The study area presented several obstacles that influenced the path selection, such as agricultural farms, vineyards, and water reservoirs. These land uses required careful consideration, as they can increase construction costs or create restrictions for line installation. By applying the LCP approach in GIS, different route alternatives were generated and evaluated, allowing the identification of the most cost-effective and technically feasible solution to ensure a reliable connection while minimizing impacts on existing land uses. The resulting pathways can be observed in Figure 29, which shows the GIS outputs alongside the study area, clearly illustrating the possible alternatives for the MV grid expansion.

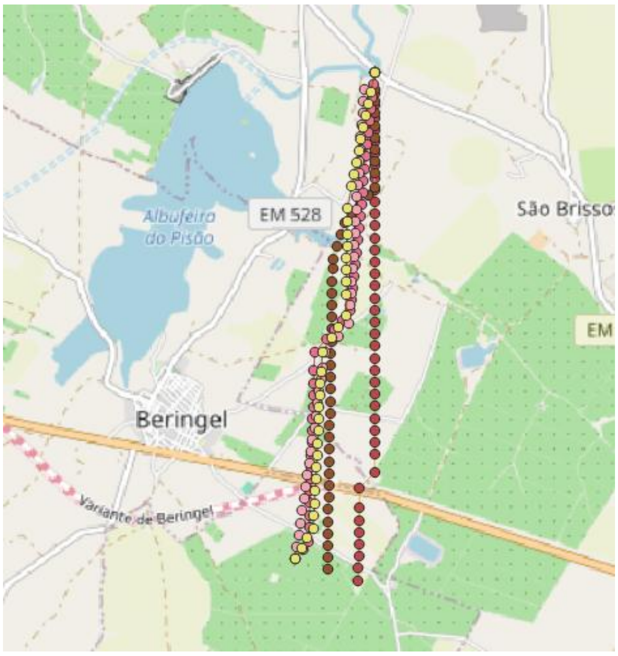


Figure 29 – Pathways generated in QGIS for Case Study 2

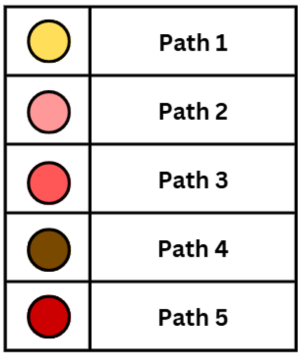


Figure 30 – Pathways Generated in Study Case 2 represented in Figure 29

In Case Study 2, the total costs vary from 292,540$ under Condition 1 to 344,648$ under Condition 5. The steady rise across the conditions demonstrates how additional restrictions, particularly those related to avoiding farmland, vineyards, and water reservoirs, significantly affect routing decisions. This suggests that more stringent land use and slope constraints force the model to adopt longer and more complex paths.

Figure 31, shows the increase of more than 50,000$ between the cheapest and most expensive conditions shows that the chosen path is highly sensitive to the constraints applied. For network planners, this emphasizes the importance of balancing land use preservation with economic feasibility, as stricter conditions inevitably lead to higher investment costs for the MV expansion.

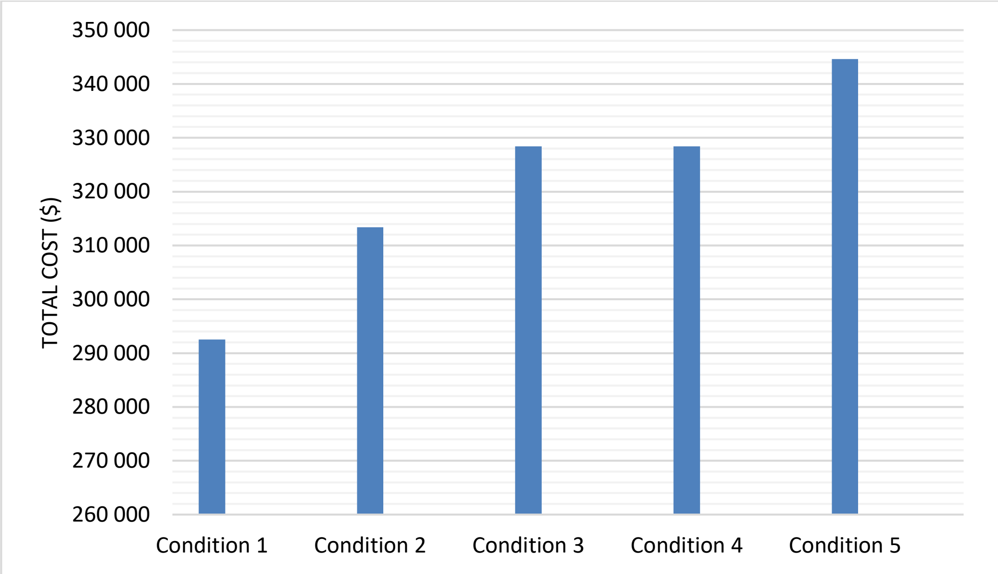


Figure 31 - Total Cost of each Condition obtained by Python Code for Case Study 2

4.3 Case Study 3 – *Santarém* Amphitheatre

In Case Study 3, conducted in the city of *Santarém*, the objective was to connect the MV grid to three important destinations: the leisure zone with an amphitheatre, the industrial zone, and the *Santarém* aerodrome. The main challenge in this case study was the slope conditions, which significantly influenced the technical and economic feasibility of the network expansion. Steep terrain not only complicates construction but also leads to higher installation costs and additional infrastructure requirements. By applying GIS LCP analysis, different alternatives were generated to evaluate the most efficient routes while minimizing these constraints. The resulting pathways are shown in Figure 32, which illustrates the GIS outputs for the study area, highlighting the possible solutions for connecting the MV grid to the identified zones while accounting for the slope limitations.

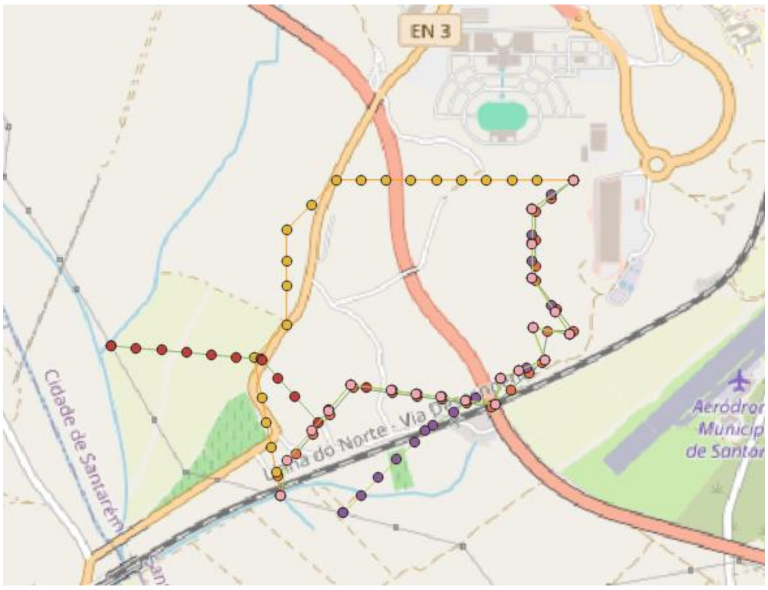


Figure 32 – Pathways generated in QGIS for Case Study 3

Figure 33 – Pathways Generated in Study Case 3 represented in Figure 32

Case Study 3 presents the widest variation among all case studies, with total costs ranging from only 32,210$ till 32,590$ in Conditions 1, 4, and 5, to a peak of 165,852$ in Condition 2. With Figure 34, it is possible to check the dramatic increase proving that the slope condition has a critical impact in this area. The steep terrain forces the optimization model to select significantly longer or more difficult routes, sharply rising costs.

This behaviour highlights how physical obstacles, such as slope, can outweigh other land use restrictions in determining final costs. While land uses (industrial areas, aerodrome, and leisure areas) play an important role in avoiding conflicts, the topography of Santarém appears to be the decisive factor, showing the strong dependency of MV expansion costs on terrain conditions.

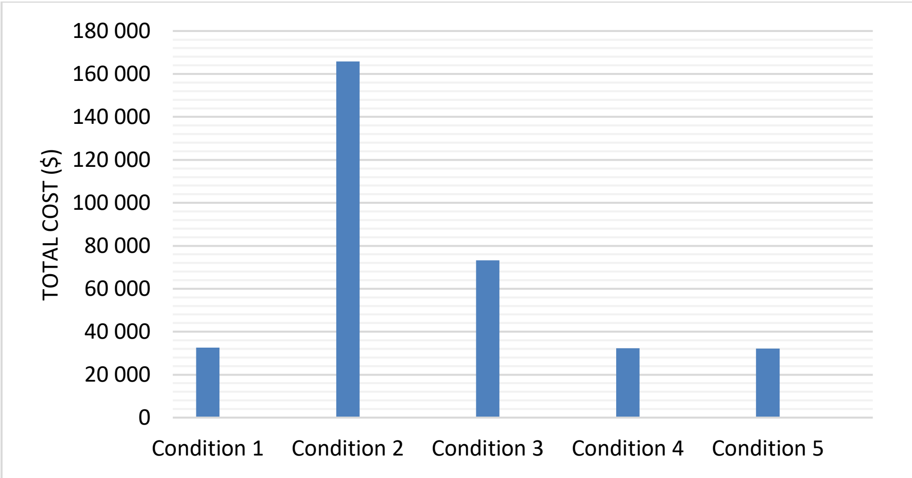


Figure 34 - Total Cost of each Condition obtained by Python Code for Case Study 3

4.4 Case Study 4 – *Monte Real* Air Force Base

In Case Study 4, developed in the district of *Leiria*, the objective was to connect the MV grid to the *Monte Real* Air Force Base. The main obstacles identified in this study area were the dense building structures located in the towns of *Ortigosa* and *Monte Real*, which limited the available corridors for grid expansion. These urban constraints required careful path selection to avoid highly built-up areas while still ensuring technical feasibility and cost-effectiveness. Using GIS analysis, alternative pathways were generated to identify the most suitable routes for overcoming these restrictions. The resulting pathways are presented in Figure 35, where the GIS outputs illustrate the possible solutions for connecting the MV grid to the *Monte Real* Air Force Base while minimizing conflicts with urban structures.

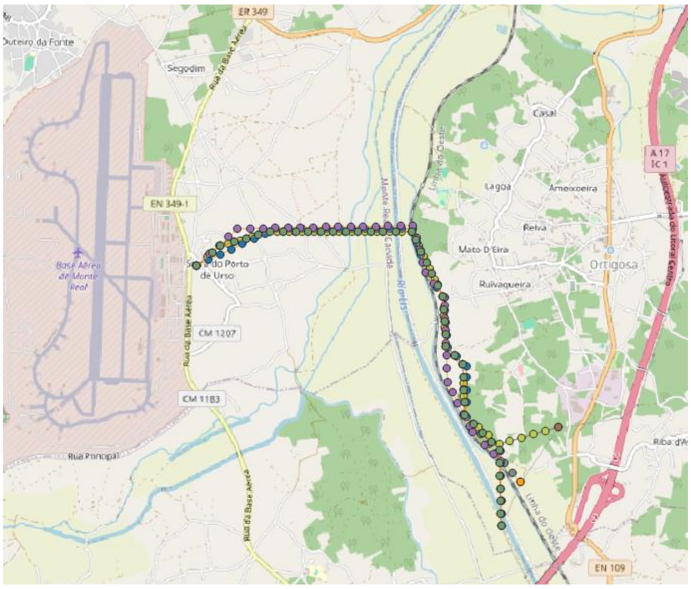


Figure 35 – Pathways generated in QGIS for Case Study 4

Figure 36 - Pathways Generated in Study Case 4 represented in Figure 35

Looking at the cost results for Case Study 4, shown in Figure 37, we can see how the different conditions impacted the overall project expense. Condition 1 presented the lowest cost at 258,012$, making it the most favourable solution from a financial perspective. Condition 4 followed closely with 261,584$, also appearing as a cost-efficient option. On the other hand, Condition 2 was the most expensive pathway, reaching 304,700$, while Condition 3 and Condition 5 stood in between with 291,232$ and 267,360$, respectively. These variations highlight how the choice of pathway, strongly influenced by the need to avoid the dense urban areas of *Ortigosa* and *Monte Real*, directly affects the total cost of the project.

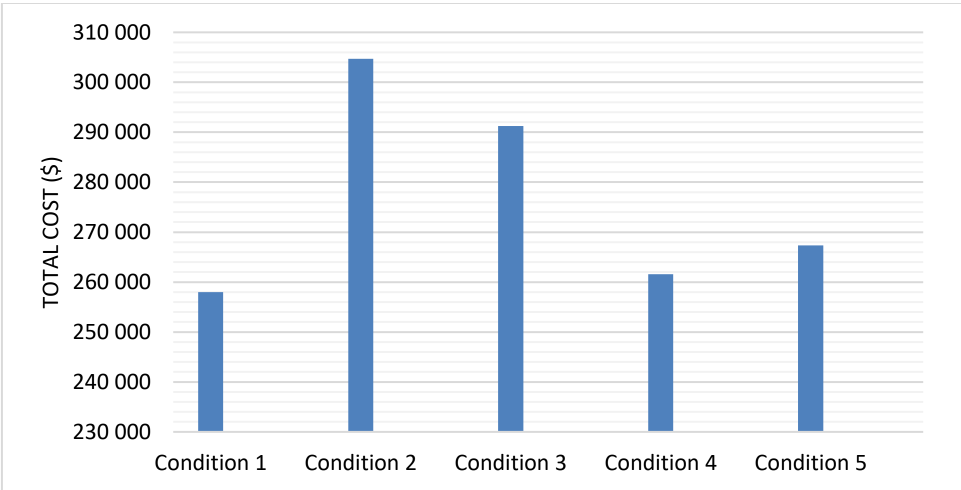


Figure 37 - Total Cost of each Condition obtained by Python Code for Case Study 4

4.5 Case Study 5 – *Cernache do Bonjardim* Industrial Area

In this case, the main challenge was the steepness of the terrain *around Cernache do Bonjardim* in the *Castelo Branco* district. The goal was to expand the MV grid from an existing pole to a nearby village, but the elevation differences in the area made routing more complex. Using GIS analysis, three potential alignments were generated, all of which are represented in Figure 38. Although each path followed slightly different directions to avoid steep gradients, the estimated lengths were very similar, ranging between 2,045 and 2,100m. This shows that GIS was able to optimize the alternatives while respecting the slope restrictions, ensuring that the selected path was both technically feasible and reasonably efficient.

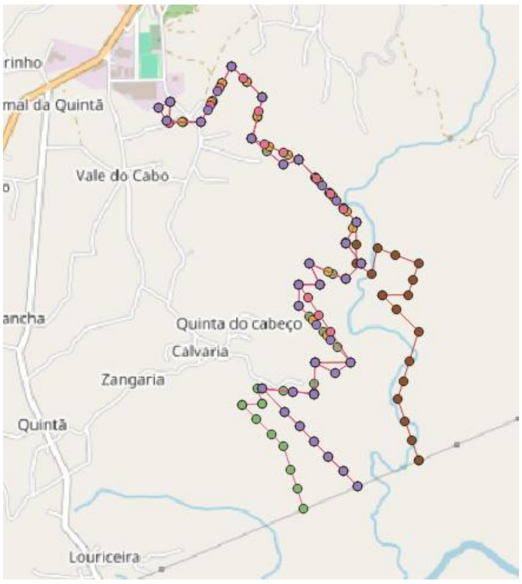


Figure 38 – Pathways generated in QGIS for Case Study 5

Figure 39 – Pathways Generated in Study Case 5 represented in Figure 38

Case Study 5 exhibits a clear descending cost trend, from 206,876$ in Condition 1 to 172,280$ in Condition 5. Unlike the previous cases, this scenario shows that applying additional restrictions reduces total costs. This outcome indicates that the base solution (Condition 1) likely included paths through costlier areas, and the imposed restrictions helped redirect the network into more efficient corridors.

This result highlights an important insight, which is the fact that not all restrictions necessarily increase costs. In some cases, constraints can guide the algorithm toward technically and economically superior alternatives. Therefore, applying slope and land use conditions can serve as a valuable mechanism to avoid misleading “cheaper but impractical” solutions, ensuring that the final expansion pathway is both cost-effective and feasible.

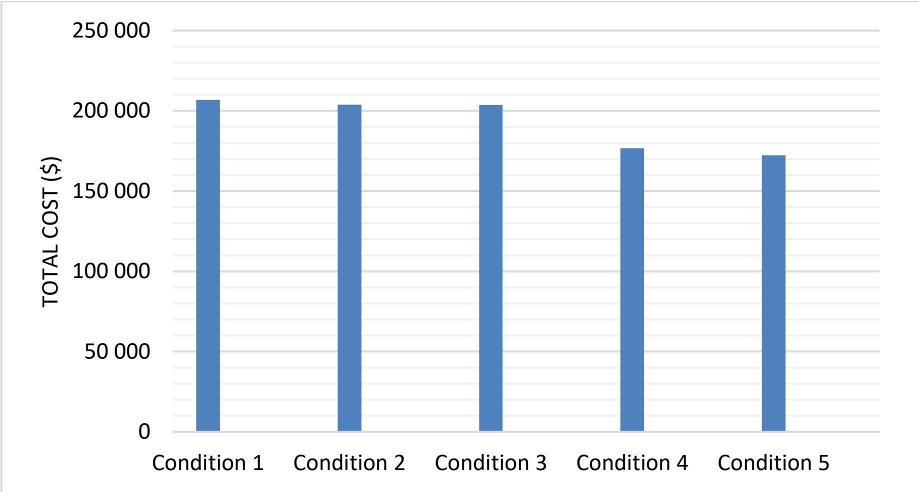


Figure 40 - Total Cost of each Condition obtained by Python Code for Case Study 5

4.6 Case Study 6 – *Penafiel* Theme Park

The situation in *Penafiel*, *Porto* district, also involved slope-related obstacles. Here, the objective was to connect an MV pole to “Magikland” leisure park. GIS modelling was applied to test different possibilities, producing three route alternatives, as illustrated in Figure 41. The differences between the other options were minimal, with total lengths varying between 2,640 and 2,650 m. The results reflect the way GIS streamlines the decision-making process, guiding the path along the most practical terrain while avoiding excessive climbs or descents. Despite the natural slope constraints, the tool showed that several efficient routes could be achieved with only marginal differences in cost and distance.

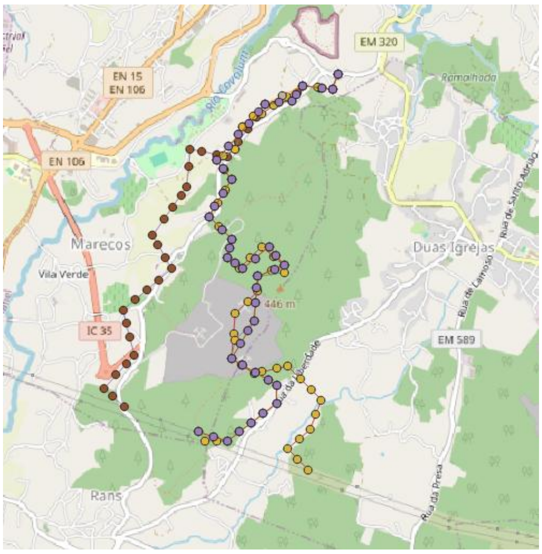


Figure 41 – Pathways generated in QGIS for Case Study 6

Figure 42 – Pathways Generated in Study Case 6 represented in Figure 41

In Case Study 6, the costs fluctuate between 144,874$ under Condition 5 and 202,314$ under Condition 3. Condition 3 emerges as the most expensive scenario, indicating that the combination of slope and land use constraints forced the optimization process into less favourable paths, increasing the total infrastructure requirements. On the other hand, Condition 5 yielded the lowest cost, showing that in this study area, the restrictions effectively guided the algorithm toward more efficient routing solutions.

The contrasting results highlight how the interaction of slope, land use, and regulatory restrictions can have different impacts depending on the geographic and spatial configuration of the study area. While stricter constraints often increase costs (as observed in other case studies), here they also revealed more efficient pathways that the unconstrained model had overlooked. This reinforces the importance of testing multiple scenarios, as the optimal solution is not always found in the "least restricted" conditions but rather in the balance between technical feasibility and cost minimization.

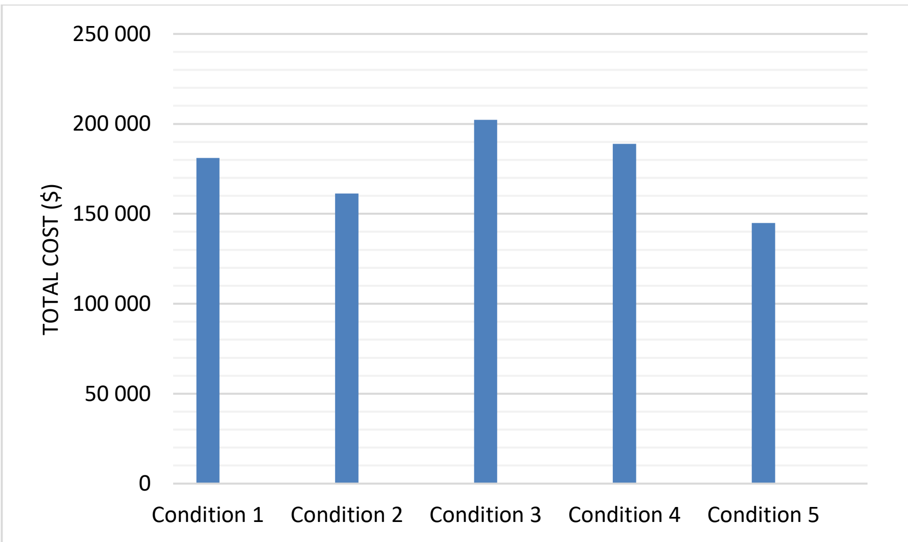


Figure 43 - Total Cost of each Condition obtained by Python Code for Case Study 6

4.7 Case Study 7 – *Vila Real* Airfield

The seventh scenario differed slightly from the others because the connection started from a substation rather than an MV pole, with the destination being an airport. The main limitation was again the surrounding terrain slope, but given the location of the substation, the number of viable alternatives was reduced to three. As shown in Figure 44, GIS analysis identified feasible alignments that avoided the steepest parts of the landscape, producing an estimated length of about 1,900m. This is notably shorter than the previous cases, showing how the strategic positioning of the substation contributed to a more direct solution. The results here highlight the advantage of GIS in adapting the methodology depending on the infrastructure starting point.

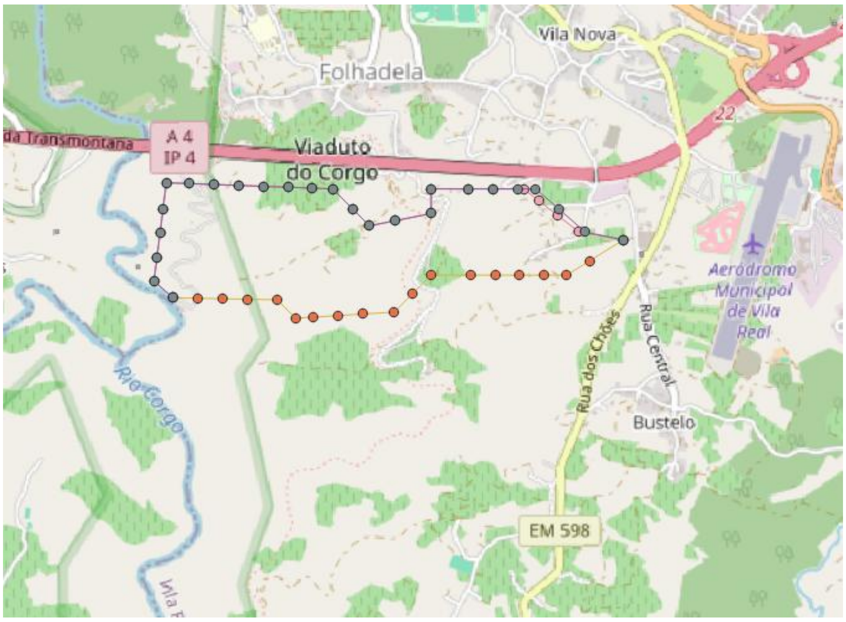


Figure 44 – Pathways generated in QGIS for Case Study 7

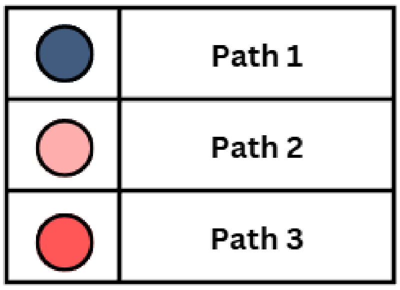


Figure 45 – Pathways Generated in Study Case 7 represented in Figure 44

The results obtained for Case Study 7 indicate a clear decreasing trend in costs across the three evaluated conditions. Condition 1 presented the highest investment, with an estimated value of 117,134$, followed by Condition 2 at 107,162$, and finally Condition 3 at 96,720$. This gradual reduction highlights the effect of adjusting the routing strategy and technical assumptions on the overall cost of MV grid expansion. The progressive decline demonstrates how certain constraints or land-use considerations can be optimized to achieve more cost-effective solutions.

From a planning perspective, Condition 3 emerges as the most advantageous pathway, striking a balance between feasibility and cost efficiency. The results reinforce the importance of exploring multiple alternatives, as the difference of more than 20,000$ between Conditions 1 and 3 shows how significant savings can be achieved through careful analysis. This case also illustrates the strong contribution of the optimization framework in narrowing down to the most efficient configuration, ensuring that the expansion strategy remains both technically reliable and financially sustainable.

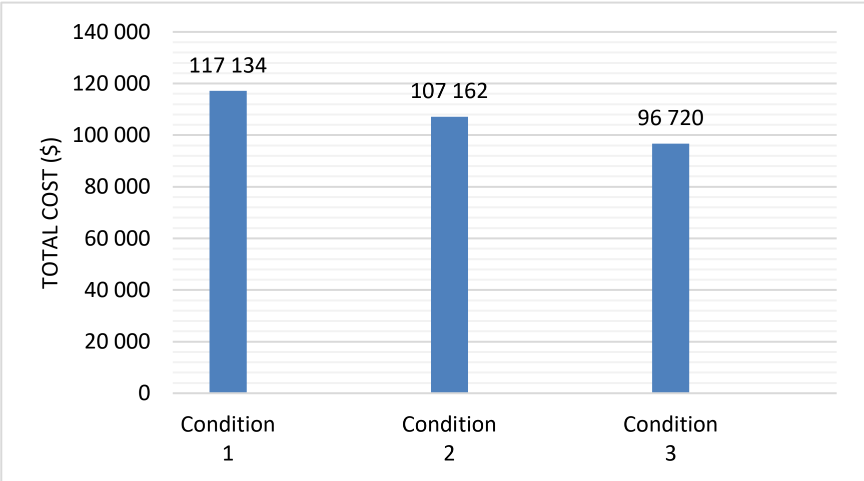


Figure 46 - Total Cost of each Condition obtained by Python Code for Case Study 7

4.8 Case Study 8 – *Aboim da Nóbrega* Village

For the final test, the major obstacle was not natural terrain but rather the presence of dense building areas that restricted the path options. The task was to extend the MV grid from a pole to a village while avoiding conflicts with urban structures. GIS proved particularly useful in tracing routes that minimized the impact of these obstacles. Three feasible alignments were identified, with distances ranging from 1,740 to 2,000m, and the results are illustrated in Figure 47. Compared to slope-constrained cases, the variation between routes here was more pronounced, reflecting the complexity of bypassing built-up areas. Still, GIS allowed a clear visualization of alternatives, balancing distance, feasibility, and minimal disruption to the existing environment.

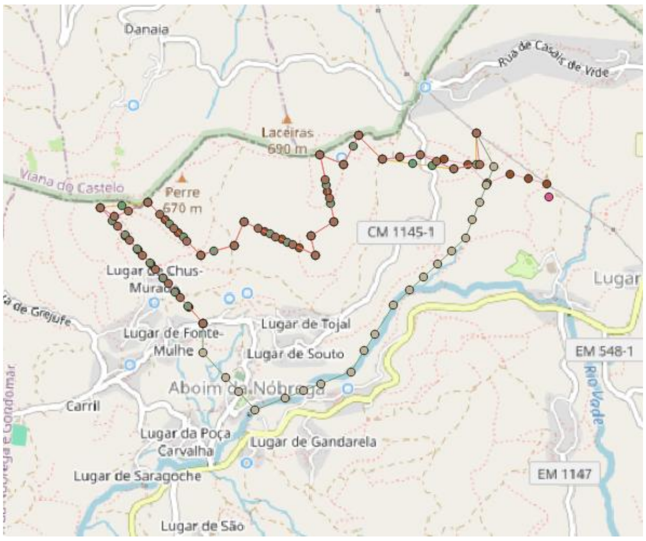


Figure 47 – Pathways generated in QGIS for Case Study 8

Figure 48 – Pathways Generated in Study Case 7 represented in Figure 47

In Case Study 8, the distribution of results revealed more variation across the conditions. Condition 4 registered the highest cost at 215,152$, closely followed by Condition 1 (206,222$) and Condition 2 (204,018$). In contrast, the lowest cost was observed in Condition 3, with a value of 147,360$, while Condition 5 presented an intermediate result of 178,770$. This significant spread, with differences exceeding 67,000$ between the most and least costly conditions, demonstrates the impact that environmental obstacles, land-use restrictions, and routing alternatives can have on the total investment required.

The analysis highlights that Condition 3 consistently outperformed the other scenarios, offering a much more efficient pathway from an economic perspective. Meanwhile, the high costs of Conditions 1, 2, and 4 suggest that their routing alternatives likely involved more complex terrain, land occupation conflicts, or additional construction requirements. As such, this case reinforces the need to integrate spatial and economic assessments, since overlooking these aspects could lead to unnecessarily high expenditures. Ultimately, Case Study 8 showcases the robustness of the applied methodology, proving its ability to identify optimal solutions even in highly variable planning contexts.

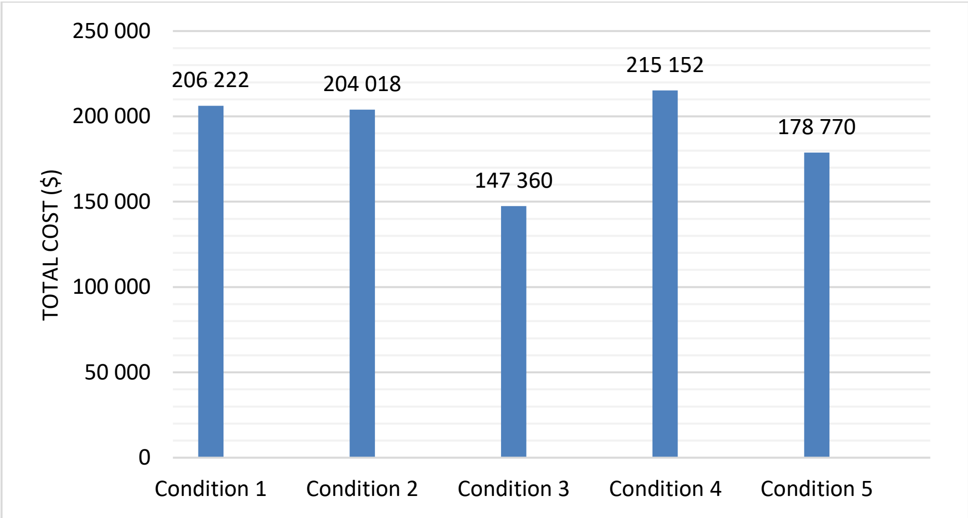


Figure 49 - Total Cost of each Condition obtained by Python Code for Case Study 8

4.9 Section Conclusions

The analysis conducted across the eight case studies demonstrated the effectiveness of combining GIS-based LCP analysis with an optimization framework in identifying cost-efficient routes for MV grid expansion. Each case study presented unique geographical and infrastructural challenges, such as industrial zones, agricultural land, aerodromes, or slope constraints, which directly influenced the costs of potential pathways. The results consistently showed significant variations in total investment requirements between conditions, with differences often exceeding tens of thousands of dollars. This highlights the importance of systematically evaluating multiple alternatives to ensure that network planning aligns with both technical feasibility and economic sustainability.

Overall, the optimization process proved capable of distinguishing the most suitable routes in each scenario by integrating engineering constraints, such as pole spacing and bends, with real cost parameters including materials, licensing, and installation. The outcomes reinforced the critical role of spatial and economic integration in planning, as overlooking one dimension would likely result in suboptimal solutions. Importantly, several case studies showed that minor adjustments in routing could yield substantial cost savings, validating the adaptability and robustness of the adopted methodology.

Figure 50 summarizes the proportion of optimal conditions selected across all case studies. Condition 5 emerged as the most frequent optimal solution, accounting for 50 % of the cases, followed by Condition 1 with 37%, and Condition 3 with 13%. This distribution reflects the methodological strength in testing multiple scenarios, while also revealing that some conditions consistently offered more competitive outcomes. The predominance of Condition 5 suggests that this configuration often balanced technical feasibility with economic efficiency, making it the most reliable option in varied geographical contexts.

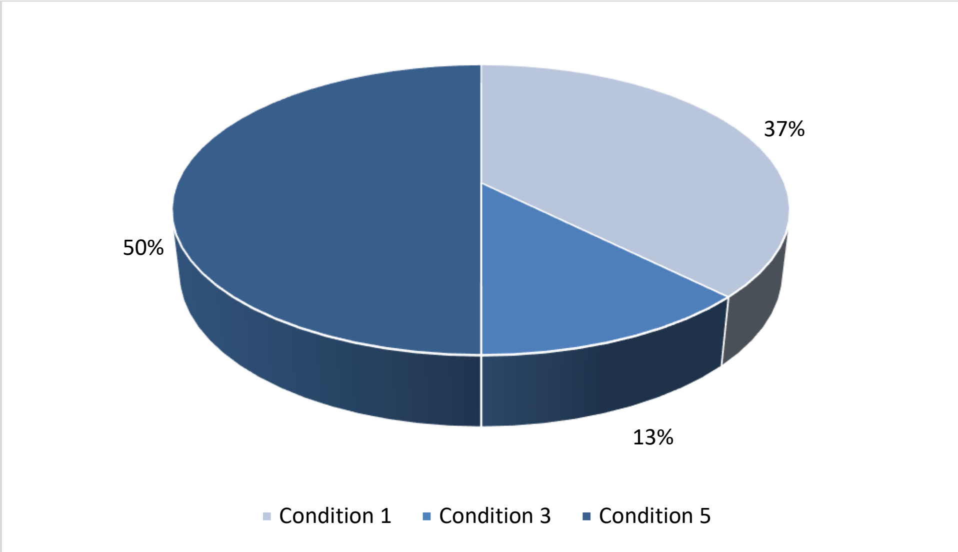


Figure 50 – Percentage of Conditions Selected as Optimal Pathway in Overall

Reflecting on these results, it becomes evident that no single condition can be universally applied, as the optimal outcome is highly dependent on the local terrain, land use, and infrastructural barriers. Nonetheless, the concentration of optimal results in a limited number of conditions demonstrates a certain robustness and replicability of the methodology. This reinforces the value of applying GIS-integrated optimization for strategic energy infrastructure planning, ensuring that future expansions of MV grids can be carried out in a cost-effective and technically sound manner.

While this was enough to provide a clear understanding of how GIS can be applied to different terrains and contexts, a greater number of case studies would have offered a broader range of possibilities and more varied scenarios to analyse. Even though the selected cases covered different regions across mainland Portugal, expanding the sample would have strengthened the conclusions and provided a deeper insight into the adaptability of the methodology.

5 Conclusions

5.1 Final Conclusions

This work set out to explore how geospatial analysis and optimization methods can support MV grid expansion in Portugal by addressing the complexity of planning reliable, cost-efficient, and technically feasible pathways. Building on the SotA, which emphasized the role of GIS and LCP approaches in integrating spatial, regulatory, and environmental constraints, the study sought to apply these concepts to real-world contexts. By transforming land use data into cost surfaces and incorporating slope penalties and other physical restrictions, the methodology ensured that the proposed routes reflected not only theoretical cost minimization but also practical feasibility for construction and long-term operation.

The methodology developed for this work combined GIS-based cost surface modelling with optimization principles to evaluate multiple routing alternatives in diverse Portuguese landscapes. Across the eight case studies, conducted in different regions of mainland Portugal, the process generated five alternative conditions per scenario, each representing a potential strategy for grid expansion. These case studies included challenges such as urban density, agricultural land, industrial zones, aerodromes, and varying slope conditions, reflecting the range of constraints faced in real network planning. The results revealed substantial variability in investment costs between conditions, often exceeding tens of thousands of dollars, proving the importance of testing multiple scenarios rather than relying on a single assumed pathway.

A key finding of the study was the identification of trends across the eight case studies. While local conditions largely determined the optimal solution in each area, certain configurations emerged as consistently favourable. As illustrated in Figure 42, Condition 5 was selected as the optimal pathway in 50% of the cases, followed by Condition 1 at 37% and Condition 3 at 13%. This distribution highlights the robustness of specific configurations, which often provided a better balance between economic efficiency and technical feasibility across diverse terrains. At the same time, the fact that no single condition was universally optimal reinforces the need for flexibility and context-sensitive analysis in MV grid planning.

Overall, the work demonstrated that combining GIS-based analysis with optimization techniques is a powerful decision-support tool for MV grid expansion. The methodology allowed for cost savings through small but strategic adjustments in routing, while simultaneously ensuring technical viability. It also confirmed that spatial and economic integration is critical by overlooking either dimension would result in suboptimal solutions. By successfully applying this framework to varied case studies, the research validated its adaptability and potential to guide future infrastructure planning in Portugal and beyond. In this way, the thesis contributes both to academic discourse by bridging theoretical approaches with applied case studies and to practical applications, by offering a replicable methodology for more resilient and efficient MV grid expansion.

5.2 Work Limitations

Despite the valuable insights generated, this work was not without limitations. The main restriction was the limited scope of the analysis, which was constrained to eight case studies and five conditions per study. While these scenarios were carefully chosen to represent different regions of mainland Portugal and to reflect diverse planning challenges, a larger set of cases would have provided a broader understanding of how the methodology performs across an even wider range of terrains and infrastructures. Similarly, generating only five alternative pathways limited the diversity of solutions, potentially excluding configurations that could have performed better in terms of cost, technical feasibility, or environmental impact.

At first, it was planned to use Plotly, since it is an open-source tool capable of creating an interface to visualize the results of the spatial analysis. Although this was one of the initial objectives, Plotly was ultimately not used because the combination of QGIS and the Python optimization model already provided sufficient analytical and visualization capabilities. Therefore, Plotly was not essential for obtaining valid results. However, its use could have enhanced the interactivity of the result presentation.

Another limitation was the focus on cost and technical feasibility as the main evaluation parameters. Although this approach ensured pragmatic and economically sound results, it did not fully incorporate other crucial dimensions such as environmental sustainability, social acceptance, or long-term maintenance costs. For example, pathways with slightly higher upfront costs could have offered advantages in terms of reduced ecological disruption or improved reliability over time. The absence of these additional criteria narrows the scope of the conclusions and highlights the need for a more comprehensive, multi-criteria analysis in future studies. Time constraints also shaped the scope of the work, restricting the possibility of deeper comparative validation against real-world implemented projects. While the methodology showed adaptability and robustness within the simulated case studies, benchmarking against actual grid expansion projects would have strengthened the practical validation of the results.

For future work, expanding the number of case studies and increasing the number of generated pathways per study would enhance the generalizability of the conclusions and provide a richer set of scenarios to analyse. Integrating multi-criteria evaluation encompassing environmental, social, and long-term operational factors would make the analysis more holistic and reflective of real-world decision-making processes. Furthermore, validating the GIS-based outputs with existing infrastructure projects or stakeholder input would provide an added layer of reliability and relevance.

In summary, while the limitations influenced the scope and depth of the results, they also point the way to improvements for future research. Expanding the scale, broadening the evaluation criteria, and strengthening validation processes would allow the methodology to evolve into a more comprehensive planning tool, capable of supporting energy infrastructure development in a sustainable and resilient way.

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