RIGA TECHNICAL UNIVERSITY

Diāna Gauče

THE USE OF SMART ROBOTIC SOLUTIONS IN DATA COLLECTION AND PROCESSING FOR OPTIMIZING THE MAINTENANCE OF TECHNICAL DATA IN ENGINEERING INFRASTRUCTURE SYSTEMS

Summary of the Doctoral Thesis

RTU Press
Riga 2025

RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science, Information Technology and Energy
Institute of Photonics, Electronics and Telecommunications

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The Doctoral Thesis was partially performed with the support of JSC "Sadales tīkls", using the testing infrastructure provided by the company, available experimental data, and software for their processing. Collaboration with an industrial partner allowed for application-oriented research in real conditions, thus increasing the practical significance and scientific validity of the work.

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph.D), the present Doctoral Thesis has been submitted for defence at the open meeting of the RTU Promotion Council on 27 June 2025 at the Faculty of Computer Science, Information Technology and Energy of Riga Technical University, 12 Āzenes Street, Room 201.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph.D) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Diāna Gauče ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, five chapters, Conclusions, 90 figures, 33 tables, and six appendices; the total number of pages is 157, excluding appendices. The Bibliography contains 109 titles.

ABSTRACT

The Thesis is dedicated to data-driven automation solutions aimed at improving the maintenance processes of overhead engineering infrastructure. A solution for implementing infrastructure inspection processes is developed and investigated, utilizing RGB and LIDAR datasets collected via unmanned aerial vehicles (UAVs) and leveraging machine learning for assessing the technical condition of infrastructure elements through large-scale data processing.

The research is structured into five chapters, each addressing a critical aspect of modernization and analysis of power systems: a theoretical analysis of the structure of the power system and changes in its development trends, an overview of digital transformation in the energy sector, an investigation into the inspection processes of Latvia's electricity distribution system infrastructure, a theoretical evaluation of alternative methods for identifying visual and geospatial defects, and an experimental study on RGB and LIDAR data-based inspection solutions. Together, these components provide a comprehensive perspective on integrating new, more efficient methods into energy system management and fostering innovation within Latvia's power grid.

The outcomes of the Thesis were developed in collaboration with JSC "Sadales tīkls", ensuring an industrial context for the research. The findings have been published in five scientific papers.

CONTENTS

LIST OF ABBREVIATIONS

Abbreviation	Explanation
3D	Three-dimensional
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
ASPRS	American Society for Photogrammetry and Remote Sensing
AWS	Amazon Web Services
BI	Business Intelligence
CPU	Central Processing Unit
DMS	Distribution Management System
FOV	Field of View
FTP	File Transfer Protocol
GIS	Geospatial Information System
GPS	Global Positioning System
HDTI	High-Detail Topographic Information
HPP	Hydroelectric Power Plant
HV	High Voltage
ID	Identifier
IR	Infrared
IS	Information System
JSC	Joint-Stock Company
LAS	LIDAR Aerial Survey (file format)
LCS	Latvian Coordinate System
LDAP	The Lightweight Directory Access Protocol
LEC	Latvian Electrotechnical Commission
LIDAR	Light Detection and Ranging
LV	Low Voltage
ML	Machine Learning
MMS	Maintenance Management System
MV	Medium Voltage
NDVI	Normalized Difference Vegetation Index
NeRF	Neural Radiance Field
NIS	Network Information System
OHL	Overhead Line
PLC	Power-Line Communication
R-CNN	Region-based Convolutional Neural Network
RGB	Red-Green-Blue (color model)
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SAR	Synthetic Aperture Radar
ST	JSC "Sadales tīkls"
TO	Technical Object
UAV	Unmanned Aerial Vehicle
UI	User Interface
UTG	Utility to Go
UV	Ultra Violet
UX	User Experience
WGS	World Geodetic System
YOLO	You Only Look Once (real-time object detection system)

INTRODUCTION

Relevance

Engineering infrastructure serves as the foundation for societal functionality and economic development, ensuring continuous access to essential resources and services. The power supply system is a critical infrastructure that impacts national security, the economy, and sustainable development by integrating renewable energy resources. The energy sector is undergoing significant changes driven by environmental shifts, including the restructuring of cross-border energy flows, market liberalization, and electricity generation from renewable resources. In response to this rapidly evolving environment, energy companies are adapting their business and technological processes, increasingly focusing on digital transformation solutions that facilitate energy distribution optimization [1]. To ensure the safe and efficient operation of the power supply system, regular monitoring and maintenance of the infrastructure are essential.

Digital technologies are increasingly impacting various industries, providing significant economic benefits. Technologies such as artificial intelligence, smart meters, big data analytics, the Internet of Things, robotics, blockchain, and cloud computing drive process automation and efficiency [2]. However, in the energy sector, there is still a lack of sufficient research on which of these new technologies can be practically applied to the development of distribution system infrastructure, specifically in the processes of monitoring the technical condition of assets. Furthermore, in Latvia, the inspection of the distribution system network infrastructure is still carried out manually, utilizing human resources, which highlights the need for additional technological solutions to enhance automation and efficiency. As digital technologies evolve, various data formats, such as synthetic aperture radar (SAR), satellite data, thermal and ultraviolet data, and point cloud analysis, can be used to optimize the inspection process.

Several experiments have been conducted, and studies have been published on data processing methods, specific calculations, and their potential applications in technical infrastructure inspections. The studies examined the following approaches: satellite image processing and classification methods for vegetation monitoring and risk assessment [3], machine learning and deep learning methods for object detection [4], remote sensing and geographic information processing methods using image classification, time series analysis, and index calculations (for example, normalized difference vegetation index (NDVI)) for vegetation health assessment [5], as well as 3D LiDAR point cloud processing methods for anomaly detection in infrastructure objects [6]. However, these studies do not sufficiently address all the requirements for assessing the technical condition of distribution system infrastructure, as they do not fully take into account the specific characteristics of infrastructure topology, the materials used for network infrastructure elements, and the climatic factors of the surrounding environment, based on the example of Latvia's distribution system infrastructure.

Practical experiments and studies were performed within the scope of this research on data acquisition and processing methods, enabling data-driven decision-making processes that promote the technological sustainability of the distribution operator's infrastructure.

The goals and tasks of the Thesis

The main goal of this Thesis is to theoretically explore and practically validate the development of data-driven alternative methods for the technical inspection of the medium-voltage overhead infrastructure in the distribution system (visual assessment of technical condition and conducting geospatial measurements).

To achieve the defined goal, the following tasks are set:

1. Perform an in-depth analysis of the literature and existing research on digital transformation and data-driven solutions in the energy infrastructure sector.
2. Investigate the technical maintenance needs of Latvia's distribution system infrastructure and identify the specific challenges related to the monitoring and control of infrastructure elements.
3. Evaluate the suitability of different data formats (SAR images, optical satellite and aerial photography data, thermal data, infrared data, and point cloud datasets) for assessing the technical condition of infrastructure.
4. Develop functional and non-functional requirements for data capturing and processing processes, taking into account the specific needs of the infrastructure inspection business process of JSC "Sadales tīkls".
5. Perform an experimental study of the visual assessment method for the technical condition of infrastructure in real-object test areas to validate the effectiveness and adaptability of the developed solution.
6. Perform an experimental study of the geospatial measurement assessment method for the technical condition of infrastructure in real-world test areas to validate the effectiveness and adaptability of the developed solution.
7. Develop recommendations for integrating the developed inspection method into the distribution system operator's medium-voltage overhead infrastructure technical maintenance processes, based on its validation using the example of Latvia's distribution system operator JSC "Sadales tīkls".

Scientific novelty and the main results

The following results have been obtained during the research:

- A new alternative method for technical inspections has been developed and validated, based on the collection of RGB and LIDAR data of overhead infrastructure elements and subsequent data analysis.
- Functional and non-functional requirements for data capturing and processing have been developed and defined, tailored to the specific needs of the distribution system operator's infrastructure inspection process.
- A plan for obtaining practical experimental results to validate the proposed new inspection method has been developed, based on the defined technical requirements.
- An experimental test has been performed on the overhead infrastructure polygons of Latvia's distribution system operator JSC "Sadales tīkls":
    - o visual assessment of the infrastructure's technical condition based on the collection and processing of RGB data;

- geospatial measurement assessment of the infrastructure's technical condition based on the collection and processing of LIDAR data.

- Detailed recommendations have been developed and formulated for the integration of the developed method into the distribution system operator's technical processes.

Theses for defence

The following Theses are formulated and put forward for defense in this Doctoral Thesis:

1. The RGB datasets collected using unmanned aerial vehicles (UAVs), in conjunction with the network element geographic information system (GIS) data and defect annotation functionality, can ensure the identification of visual defects in the technical condition of the distribution system operator's medium-voltage overhead infrastructure. This is achieved with consistent data quantity (at least four images per point object) and quality (images with a 2 cm visibility for defect identification), while reducing the data collection time in the field by at least two times compared to manual inspection speed, enabling data acquisition at a rate of at least 12 km per day.
2. LIDAR datasets with a point density of at least 50 points/m^2, collected using unmanned aerial vehicles (UAVs), can ensure the identification of specified geospatial defects in the distribution system operator's medium-voltage overhead infrastructure. This is achieved by vectorizing the network model using analytical tools with defined measurement requirements for infrastructure elements. Additionally, it can reduce the data collection time in the field by at least three times compared to the speed of manual inspection, achieving a data collection rate of at least 18 km per day.
3. Point cloud datasets, with a density of at least 50 points/m^2 and data quality precision of up to 10 cm in relation to line heights, can enable the management of vegetation in the overhead line corridors and protection zones of the distribution system operator's medium-voltage overhead infrastructure.

The research methodology

To achieve the set goals, the research methodology includes the development of several stages.

An in-depth literature review is conducted, covering studies on digital transformation and its application in the energy sector. The construction of Latvia's energy supply system is analyzed, with a particular focus on the specifics of the distribution system infrastructure. A detailed analysis of JSC "Sadales tīkls" medium-voltage fault detection process was performed, examining the types of infrastructure defects and their levels of severity. The scientific literature was reviewed regarding various data sources (SAR images, optical satellite and aerial photography data, thermal data, ultraviolet data, point cloud datasets) that could potentially be used for assessing the technical condition of the distribution system infrastructure, and the advantages and limitations of these data were compared.

Based on the conducted theoretical research, technical parameters and data quality criteria for the acquisition of RGB and LIDAR data were developed, taking into account the specific requirements of JSC "Sadales tīkls" for the identification and assessment of network faults.

A detailed experimental plan and scope were developed to perform data-driven fault detection for overhead power transmission lines with a total length of 650 km, using digital inspection technologies and methods. The experimental plan includes several testing stages in real field conditions, utilizing RGB and LIDAR data capturing and processing technologies:

- Experimental RGB data collection using the UAV DJI Mavic 2 Pro and its built-in 20MP optical camera for acquiring RGB data of all infrastructure elements included in the experimental plan.
- Experimental LIDAR data collection using the UAV DJI Matrice 300RTK and the YellowScan Mapper LIDAR sensor for acquiring point cloud data of all infrastructure elements included in the experimental plan.
- Processing and analysis of the acquired RGB and LIDAR datasets using specialized software that allows for the processing of large-scale image and spatial data. During the data processing, custom algorithms are developed, and criteria are established to ensure data classification and interpretation: defining threshold values based on multidimensional analysis tools to accurately define various technical condition indicators and identify visual and geospatial defects.

Based on the obtained results, conclusions are provided regarding the practical applicability of the developed methodology and its adaptation for future infrastructure inspections, based on data analysis.

The research object

The research object of the Doctoral Thesis is the medium-voltage overhead infrastructure of the distribution system operator and its technical condition assessment process – inspections.

Practical application of the research results

The practical application of this research lies in developing data-driven technical maintenance and inspection processes for the electricity distribution system, utilizing advanced data collection and processing technologies. The results provide solutions directly applicable to infrastructure inspections, enabling more efficient and accurate assessment of the technical condition of infrastructure elements, which is critical for ensuring continuous and reliable electricity supply.

- Data availability is ensured through using UAV and LIDAR technologies, enabling a twofold reduction in infrastructure inspection time, even in hard-to-reach areas.
- The processing of RGB and LIDAR datasets using specialized software ensures a unified decision-making process, eliminating inconsistencies present in previous methods (differences in expertise, access to assets, and human error).

The research results can provide a valuable contribution to the modernization of Latvia's energy sector, strengthening the adoption of innovative technologies and their practical application in the management of critical infrastructure.

Approbation

The results of the Doctoral Thesis have been published in five scientific articles included in the proceedings of the following international conferences and scientific journals.

1. D. Gauce and A. Litvinenko, "Impact of data synchronization methods on the quality of engineering NIS data from several integrated applications in GIS architecture," *2021*

IEEE 9th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), Riga, Latvia, 2021, pp. 1–5, doi: 10.1109/AIEEE54188.2021.9670142.
2. D. Gauce, A. Lektauers, I. Solovjova, R. Grants, D. Kolosovs, A. Litvinenko, Application of Digital Twin in Medium-Voltage Overhead Distribution Network Inspection. *Remote Sens.* 2023, *15*, 489. doi: 10.3390/rs15020489.
3. D. Gauce, D. Kolosovs, and A. Litvinenko, "Analysis on RGB Dataset Requirements for Remote Inspection of Power Grid Infrastructure," *2023 IEEE 10th Jubilee Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, Vilnius, Lithuania, 2023, pp. 1–5, doi: 10.1109/AIEEE58915.2023.10134938.
4. D. Gauce and A. Litvinenko, "Experimental Validation of RGB Dataset Analysis for Distribution System Operator Infrastructure Inspections," *2024 IEEE 11th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, Valmiera, Latvia, 2024, pp. 1–6, doi: 10.1109/AIEEE62837.2024.10586699.
5. D. Gauce and A. Litvinenko, "LIDAR Dataset Validation for Enhancing Vegetation Management in Distribution System Operator Powerline Infrastructure," *2024 IEEE 65th International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS)*, Riga, Latvia, 2024, pp. 1–5, doi: 10.1109/ITMS64072.2024.10741947.

The author of the study has presented the obtained results at several scientific conferences, providing an overview of the most significant findings and their practical applications, as well as participating in discussions on the relevance of the topic and future development perspectives:

1. International Conference "MTTW'22: Workshop on Microwave Theory and Techniques in Wireless Communications", Riga, Latvia, October 5–7, 2022.
2. Riga Technical University`s 63rd International Scientific Conference, Riga, Latvia, October 7, 2022.
3. International Scientific Conference "2023 IEEE 10th Jubilee Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)", Vilnius, Lithuania, April 27–29, 2023.
4. Riga Technical University`s 64th International Scientific Conference, Riga, Latvia, October 6, 2023.
5. IEEE International Information and Communication Technology Festival "IEEE ICTfest" (Industrial Discussion), Riga, Latvia, October 4–6, 2023.
6. International Scientific Conference "The 11th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering AIEEE'2024", Valmiera, Latvia, May 31 – June 1, 2024.
7. Riga Technical University`s 65th International Scientific Conference "2024 IEEE 65th International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS'2024)", Riga, Latvia, October 3, 2024.
8. Riga Technical University`s 65th International Scientific Conference (Section "Photonics, Electronics, and Electronic Communications"), Riga, Latvia, October 11, 2024.

The Master’s Thesis supervised by the author:

- M. Pavlovskis, Master's thesis with a project part "Implementation of Digital Visual Assessment of Overhead Power Grid Infrastructure in the Technical Condition Evaluation Process" in the Master's professional study program "Information Technology Project Management", 18.01.2024.

Structure of the Thesis

The Thesis is structured to systematically present the topics and their significance in the field of electricity. The Thesis consists of an Introduction, five main chapters, and Conclusions.

- Introduction. The introduction provides a general overview of the research topic, the objectives and tasks set out, and highlights the significance of the study and its potential contribution to the field of energetics.
- Chapter 1 discusses the organization and operation of the electric power system, focusing on its three main components: electricity generation, transmission, and distribution.
- Chapter 2 explores the aspects of digital transformation in the energy sector. It examines the implementation of digital solutions and their impact on process efficiency and business operations.
- Chapter 3 discusses the current inspection practices related to the infrastructure of Latvia’s electricity distribution system.
- section, Chapter 4, presents a proposal for a new method for inspecting the overhead infrastructure of the distribution operator, aimed at defect identification.
- Chapter 5 presents the results of the study obtained by testing the digital inspection solution on the overhead infrastructure polygon of JSC "Sadales tīkls".
- Conclusions summarize the main results of the research, providing evidence to support the validity of the proposed theses.

1. STRUCTURE OF ELECTRICAL POWER SYSTEM

The electricity system is a network of electrical components used to generate, transmit, distribute, and utilize electric power. It plays a critical role in delivering electricity from power plants to homes, businesses, and industries. The components of the electricity system include energy generation, transmission, and distribution infrastructure.

1.1. Electricity Generation

Energy generation refers to the process of converting various forms of energy into electricity. There are several methods of electricity generation, each with its own advantages, disadvantages, and environmental impacts. Some common methods include:

– fossil fuels (dominant in the energy production sector but with depleting reserves over time [7]) – coal, natural gas, and oil;
– renewable energy – solar energy, wind energy, hydroelectric power, geothermal energy, and biomass;
– nuclear energy.

In Latvia, 70 % of the total electricity produced annually comes from renewable energy sources, primarily generated by the Daugava hydroelectric power plants (data for 2022 indicates 2.7 TWh, summarized in Table 1.1) [8]. The remaining electricity is generated in thermal power plants using natural gas.

Table 1.1

The Largest Energy Producers in Latvia (Data for 2022)

Energy source		Generated electricity, GWh	Power, MW
Pļaviņas HPP	water	1487	908
Riga HPP	water	661	402
Ķegums HPP	water	522	248
TPP-1	natural gas	111	electrical – 158 thermal – 493
TPP-2	natural gas	1012	electrical – 832 (in cogeneration mode), 881 (in condensing mode thermal – 1124)

1.2. Electricity Transmission

Electricity transmission is the process of delivering electrical energy from the generation source to the locations where it is needed for consumption. It involves transmitting electricity over long distances using various components and technologies. The primary goal is to transfer power with minimal losses and maintain the required voltage levels. The main components of the transmission network are:

- Transmission substations – step-up transformers in these substations increase the voltage of the electricity generated in power plants for efficient long-distance transmission.
- Transmission lines – high-voltage transmission lines carry electricity over long distances from power plants to distribution substations. These lines are supported by towers and can use various technologies, such as overhead lines or underground cables.

The transmission system operator in Latvia is JSC "Augstsprieguma tīkls", which ensures the operation, maintenance, and repair of high-voltage lines, substations, and distribution points, as well as the further development of the transmission network. The 330 kV network of Latvia's energy system serves as the central part of the Baltic states' energy system, connecting the northern and southern parts. Of the 17 substations, 16 have dual-feed power supply, as shown in the summarized transmission network parameter data in Table 1.2 (Latvia [8], Estonia [9], Lithuania [10]).

Table 1.2

The Transmission Network Indicators of the Baltic States (Data for 2022)

Performance indicators	**Maintainer**	**Latvia**	**Estonia**	**Lithuania**
		"Augstsprieguma tīkls"	"Elering"	"LitGrid"
Line length, km	330 kV lines	1764.50	1634.00	1961.00
	110 kV lines	3895.84	3473.00	5069.70
	6–35 kV	–	28	–
Number of substations	330 kV (highest voltage)	17	13	16 +1* * 400 kV
	110 kV (highest voltage)	123	156–13	219
Number of autotransformers and transformers	330 kV (highest voltage)	26	No data	24+3* * 400 kV
	110 kV (highest voltage)	245	No data	4
Installed capacity, MVA	330 kV (highest voltage)	3800	No data	4400 + 768* * 400 kV
	110 kV (highest voltage)	5156.5	No data	92.6

1.3. Electricity Distribution

The electricity distribution network is a system that delivers electricity from the transmission grid to end users (homes, businesses, and industrial facilities). This network plays a critical role in ensuring a reliable and efficient electricity supply to meet various consumer needs. The key components of the electricity distribution network:

- Distribution substations, which receive electricity from the transmission grid and use step-down transformers to lower the voltage to levels suitable for local distribution.
- Distribution lines, which deliver electricity from substations to various areas and end users. These lines operate at lower voltages than transmission lines and can be either overhead or underground cables.
- Transformers that are used throughout the distribution network to further adjust voltage levels as needed. They reduce voltage for residential and commercial use.
- Distribution equipment and circuit breakers, which are similar to the transmission grid, the distribution network uses distribution equipment and automated breakers to control power flow, protect against overloads, and isolate faults.
- Metering and billing infrastructure – meters installed at consumer locations measure the amount of electricity consumed. Data from these meters is used for tracking consumption and billing purposes.

The leading distribution operator in Latvia among the 11 registered operators is JSC "Sadales tīkls", which supplies electricity to 99 % of consumers in the country. For comparison, Table 1.3 provides the technical parameters of the distribution networks in the Baltic states (Latvia [11], Estonia [12], Lithuania [13]).

Table 1.3

Technical Parameters of Distribution Networks in the Baltic States (Data for 2022)

Performance indicators	**State**	**Latvia**	**Estonia**	**Lithuania**
	Maintainer	"Sadales tīkls"	"Enefit"	"Eso"
Line length, km		92,407 *39.5 % cable lines 60.5 % overhead lines*	63,000 *33 % cable lines 66 % overhead lines*	127,504 *34.4 % cable lines 65.6 % overhead lines*
Distributed electricity, GWh		6241	6708	10,010
Electricity losses, %		3.73	3.8	5.05
Average power outage duration index (SAIDI) minutes (unplanned)		130	238	178.73
Average electricity interruption frequency index (SAIFI)		1.9	1.77	1.52
Number of connection points		1,114,462	683,660	1,891,190

1.4. Summary

The electricity system comprises three main components – generation, transmission, and distribution – that form an interconnected network to deliver electricity from producers to consumers.

- The electricity generation stage involves various energy sources, such as fossil fuels, nuclear energy, and renewable resources (wind, solar, hydro), which are converted into electrical energy.
- The transmission system is a high-voltage power network that transports electricity from generation facilities to distribution networks or directly to large consumers.
- The distribution component ensures electricity delivery from the transmission system to end consumers – households, businesses, and public facilities. The distribution network operates at lower voltage levels and requires continuous monitoring and maintenance, as distribution infrastructure is often exposed to local environmental conditions and higher wear and tear.

These three stages of the electricity system are essential for ensuring efficient and reliable power supply while integrating new technologies and addressing technical challenges at all levels and within core technical processes.

2. DIGITAL TRANSFORMATION IN THE ENERGY SECTOR

This chapter is dedicated to the exploration of digital transformation in the energy sector, focusing on processes that involve the application of various information technologies and data analytics to optimize energy supply, enhance energy efficiency, and reduce environmental impact.

2.1. Review of Smart Metering Technologies

Electricity metering is one of the fundamental processes regulated by legislation, and smart metering represents a significant step in digital transformation. The smart grid (advanced metering infrastructure (AMI)) can be considered a key component of network modernization and development. As a result, a large volume of data is collected (smart meters provide real-time data not only on electricity consumption but can also record various installed events, for example, voltage fluctuations), which opens up opportunities for data analysis to potentially improve operational efficiency. The data from smart meters can be used to improve and assess the benefits of voltage and variability optimization [14], evaluate distribution line losses, identify and quantify energy theft [15], and provide enhanced load forecasting, outage management, and distribution system analysis [16].

2.2. Application of GIS Systems for Maintaining Infrastructure Technical Data

A Geospatial Information System (GIS) is an integral part of any modern infrastructure operator, and currently, central databases are being developed at the national level [17], where high-detail topographic information (HDTI) is maintained. These databases define specifications with the required amount of information and classification. Additionally, GIS includes mechanisms for storing, acquiring, visualizing, modifying, and processing geographic data, as well as decision-making, analysis, and knowledge acquisition capabilities. Its functionality can be divided into four core GIS operation principles: maps, data, analysis, and applications [18].

2.2.1. Geospatial Data Visualization

In the context of the electricity distribution operator's infrastructure maintenance, geospatial data visualization can be divided into the following components:

- Background maps: raster maps (scanned plans, scanned geographic maps, orthophoto maps) – an image as an object, and vector maps (1 : 500 scale topographic map) – map objects.
- Electrical network maps: network infrastructure view, schematic topology view.
- Maps of other utility providers (in case of data exchange agreements).
- Maps of specific objects/layers (e.g., archaeological sites, nature parks).

2.2.2. Maintenance of Technical Data in GIS

In Geospatial Information Systems (GIS), infrastructure operators (such as electricity transmission and distribution system operators, telecommunications operators, etc.) maintain data related to the physical infrastructure assets (infrastructure components) and all associated attribute information (technical parameters). The elements of the electrical network infrastructure are divided into three types of visualizations:

– points (e.g., transformers, poles);
– lines (e.g., cable line, overhead line);
– polygons (e.g., buffer zone of a protection zone).

2.2.3. GIS Data Interpretation and Analysis

The advantage of geospatial analysis is the ability to combine information from multiple independent sources and generate, as well as visualize, new datasets using data analysis functionalities such as interpolation, geostatistical simulation, utilities for merging and validating datasets, and creating new information layers. Data quality significantly affects the accuracy of the analysis results, and this must be taken into account.

2.2.4. GIS Functional Applications

For the maintenance of the distribution operator's infrastructure, the GIS structure consists of several applications, with the core applications shown in Fig. 2.1.

- NIS (network information system) – for maintaining the geographic and technical parameters of assets, network elements.
- MMS (maintenance management system) – for managing network maintenance and repair work.
- DMS (distribution management system) – for network monitoring and remote control.
- Mobile GIS version – a mobile application for real-time data management (from the objects).

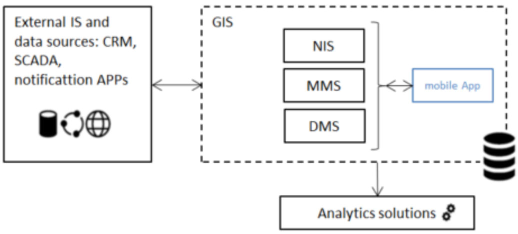


Fig. 2.1. Example of the GIS structure [19].

2.3. Application of the Digital Twin Concept in the Energy Sector

The concept of the digital twin is particularly relevant for research because, among the intelligent solutions applied in the energy sector [20], it is the least developed compared to the applications of forecasting and automation solutions.

2.3.1. Conceptual Overview of the Digital Twin

A digital twin is formally organized as a digital representation of the physical environment in real life. According to [21], the digital twin concept is based on the interaction between physical and virtual entities in both physical and virtual environments, using physical-to-virtual and virtual-to-physical connections. This includes "cooperation", meaning data exchange between the virtual and physical partners. A digital twin can consist of one physical and virtual entity pair or multiple physical entities with corresponding virtual representations. As noted in [22], a real twin system and a digital twin system are collections of physical and virtual entities.

The key components of virtual entities that ensure the functionality and accuracy of the digital twin are data collection and processing, simulation, and visualization.

2.3.2. Digital Twin for Energy-Efficient Building Management

Digital twins can represent digital models of buildings and their systems, providing information on energy efficiency, heating and cooling systems, and other systems [23]. This allows for improved building management and optimized energy resource usage. Building energy efficiency is a key issue in the context of smart cities, and it should involve a greater use of renewable energy sources.

2.3.3. Digital Twin for Renewable Energy Sources

The concept of digital twins is also applied to enhance the efficiency of renewable energy sources. Mathematical models for parameter control have been proposed for the normal operating conditions of power systems with high integration of renewable energy resources. The placement of panels has an impact on production, and simulation tools allow for the selection of the optimal configuration based on multiple criteria: the use of northern regions increases production by approximately 10 %, while the overall usage and internal return rate are slightly lower. Simulations help reveal that some surfaces experience up to 50 % losses due to shading, making them unsuitable or less efficient for real-world use [24].

2.3.4. Digital Twin of the Distribution Operator's Overhead Infrastructure

The creation of a digital twin for the overhead network infrastructure can radically transform the network management processes [25]. The development of the digital twin involves data collection and analysis, resulting in automated data-driven inspection of the medium-voltage overhead infrastructure. Figure 2.2 illustrates the transition from the traditional method of assessing the technical condition of the infrastructure in the field, where defects are identified by humans (with the possibility of subjectivity), to fully remote data analysis. The updated approach improves the accuracy and reliability of defect detection and identification while reducing the duration of the network inspection process.

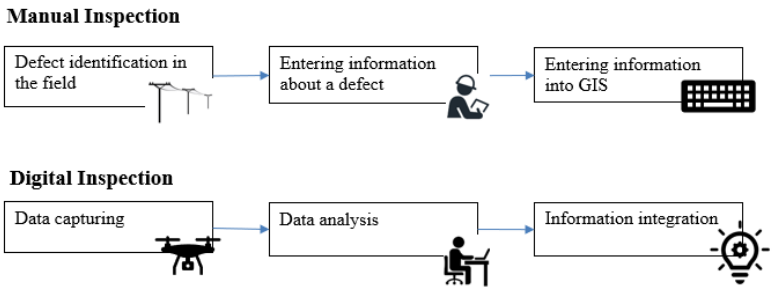


Fig. 2.2. Manual and digital inspection process flows.

2.4. Summary

This chapter analyzes significant digital transformation solutions in the energy sector (smart meter technologies providing consumption data sets for detailed analysis, GIS applications for complex data analysis, and digital twin applications), emphasizing their important role in improving infrastructure management and maintenance efficiency. The Thesis presents a new approach using the digital twin concept, evaluating the technical condition of physical infrastructure, based on data processing from infrastructure assets.

3. INSPECTION PROCESS OF LATVIA'S ELECTRICITY DISTRIBUTION SYSTEM INFRASTRUCTURE

One of the primary tasks of an infrastructure operator responsible for engineering communication networks is to maintain the infrastructure under their management. The inspection process is a core technical network management activity that ensures continuous monitoring of the infrastructure's technical condition.

3.1. Management and Organization of the JSC "Sadales tīkls" Inspection Process

Latvia's largest electricity distribution system operator, JSC "Sadales Tīkls", maintains a total of 92,407 km [11] of power lines. Infrastructure or electrical equipment inspection is a preventive maintenance activity involving the visual assessment of infrastructure elements to identify and document deviations from technical regulatory requirements. The inspection process is divided into two categories: planned inspections (performed periodically as per a predefined schedule) and unplanned inspections (performed independently of the set schedule to identify the causes of recurring technological disruptions or detect defects upon request).

Currently, the planned inspection process for JSC "Sadales tīkls" infrastructure is conducted according to the scheme presented in Fig. 3.1. The physical inspection of the entire infrastructure is carried out on a four-year cycle by 115 inspectors across Latvia. The process consists of the following steps:

- Definition of inspection criteria – a defect catalog is developed and maintained in accordance with the network's specifications and environmental conditions.
- Long-term inspection plan for a 4-year cycle – the plan is maintained in the GIS MMS module, managing network maintenance activities and specifying inspection periodicity in the attributes of technical objects.
- Short-term inspection plan – the current year's plan is divided into quarters, with real-time GIS MMS data analysis providing execution reports for the plan.
- Inspection – assessment of the technical condition of network elements in the field. Inspectors (holding at least Group A electrical safety certification [26]) use the GIS mobile application to log identified defects at the locations.
- Assessment of inspection results – this involves analyzing the performance indicators of the inspection and conducting quality checks using business intelligence solutions, as well as performing random checks at the objects in the field.

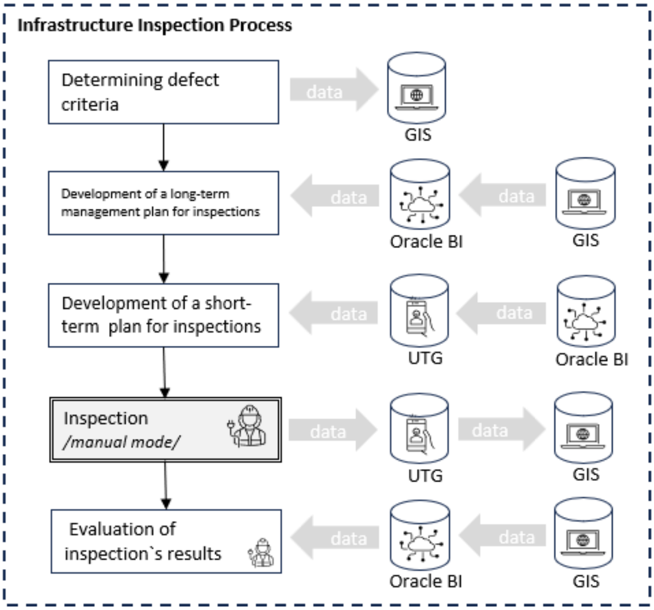


Fig. 3.1. Planned inspection process flow.

3.2. Classification of Medium Voltage Infrastructure Defects

A medium voltage infrastructure defect is any damage to a component of the infrastructure that may affect its operation or safety. According to the defect catalog defined by JSC "Sadales tīkls", defects can be divided into two groups:

1. Visual defects – a visual assessment of the technical condition of infrastructure components, as well as the determination of the conditions of the associated protection zones.
2. Geospatial measurements – detection of geospatial deviations, which include: minimum distance from wires to the ground in spans, wire misalignment measurements (sag), wire placement on poles, determination of poles leaning, and identification of vegetation presence in the corridor areas.

In addition to the defect group gradation, defects are classified according to the urgency of their elimination.

- Operationally hazardous defect – a defect in electrical installations that poses a threat to public electrical safety from an electrical hazard perspective, as well as significantly reduces the safety of the user's power supply system, which could directly cause outages and damage to the electrical grid. Such defects must be eliminated as quickly as possible, with the dispatcher evaluating the operational situation, but the maximum repair time is up to 48 hours. The list of operationally hazardous defects for the medium-voltage overhead infrastructure is as follows:
    - 6–20 kV OHL (overhead line) dislodged hook threatening to come into contact with other line elements;

  - o overhead line pole is damaged, broken, or hanging on the wires;
  - o a bird's nest or a pile of branches is located on the current-carrying parts of the 6–20 kV overhead line;
  - o the line clearance to the ground or to an engineering structure is less than the permissible limit;
  - o a visible damage (break) in the grounding wire connection point to the grounding electrode on a 6–20 kV overhead line.
- High urgency (hazardous defect) – a detected defect that poses a potential threat to the environment and human safety and must be rectified as soon as possible, but no later than 30 calendar days from the time of detection.
- Low urgency defect – a detected defect that is neither hazardous nor operationally dangerous.

3.3. Summary

In this chapter, the importance of infrastructure inspection by the distribution system operator for effective network management is outlined. JSC "Sadales tīkls" inspections cover both regular infrastructure checks and unscheduled inspections. The Thesis focuses on the distribution system's medium voltage overhead infrastructure – network element defects, including mechanical damage and geospatial measurements. Improving inspections promotes proactive risk identification, reducing the likelihood of accidents and disruptions to the power supply.

4. ALTERNATIVE METHODS FOR DEFECT IDENTIFICATION

JSC "Sadales tīkls" manages a medium-voltage overhead network spanning 26,798 km and a low-voltage overhead network extending 28,646 km (according to the 2022 data [11]). The current inspection process is entirely manual, requiring network inspectors to visit objects and visually inspect all network components. Observations of identified defects are recorded in the UTG system. According to JSC "Sadales tīkls" estimates, the standardized inspection rate for the medium-voltage network is 1.4 person-hours per kilometer, while the low-voltage network requires 3 person-hours per kilometer. Additionally, a network inspector requires at least the following equipment: a vehicle, a boat (for flood-prone areas), a quad bike (for forested areas and plots where vehicle access is restricted), a field tablet with the UTG application, a laser rangefinder (0.01–100 m), a conductor height meter, a pole rotting level detection device.

Considering the complexity of the manual inspection process and the extensive equipment required for employees, the study proposes a data-driven inspection solution, which would simplify and automate the inspection process.

4.1. Methods for Detecting Visual Defects

The visual assessment of the technical condition of network components is one of the key elements of defect detection, during which any unwanted changes or damages to the infrastructure components are identified. To promote the digitalization of this process, the study explores the use of image data, allowing network inspectors to perform inspections by analyzing data (without visiting the objects), as well as adapting data analysis technologies to simplify the execution of the process as much as possible.

4.1.1. Data Types for Defect Identification

The work explores potential applications of data types for the inspection process, such as synthetic aperture radar (SAR) images, optical satellite images, optical aerial photographs, thermal images, and ultraviolet images.

4.1.1.1. SAR Images

Synthetic aperture radar (SAR) images are obtained using synthetic reflection technology. The working principle of this technology is as follows: the radar sends radio waves to the Earth's surface, and these waves are reflected back to the radar antenna. The reflected wave properties, including their phase and amplitude, are recorded, and the corresponding signal is processed to create an image. It has been studied that SAR is effective for vegetation mapping and monitoring. It allows the identification of dense shrubs and trees that could pose a threat to power line infrastructure. SAR can also be used for defect detection, such as identifying broken poles or fallen trees along power lines [27], [28].

4.1.1.2. Optical Satellite Images

Optical satellite images are images obtained using optical sensors installed on space satellites that capture various types of electromagnetic wave bands, including visible light, infrared, and ultraviolet radiation. The resolution of optical satellite images is typically up to 10 meters, while higher-resolution commercial offerings can achieve up to 30 cm [29]. Satellite images can be less effective in cloudy weather or during nighttime, but they offer several advantages in power grid fault detection. They cover large areas and allow for the identification of various objects and materials. Primarily, satellite images are used for vegetation monitoring in the power grid's protection zones. An example of their application can be seen in the UK, where the electricity and natural gas company "National Grid" uses optical satellite images for vegetation management [30].

4.1.1.3. Optical Aerial Images

Optical aerial photographs (RGB color model) are images captured from the air using cameras or photographic equipment. These images are taken from airplanes or unmanned aerial vehicles (UAVs) and provide high-resolution images of the Earth's surface. They offer detailed and accurate information, with the most common resolution for aerial photographs ranging from 0.1 m/px to 0.001 m/px, which can provide visibility for identifying infrastructure defects.

4.1.1.4. Thermal Images

Thermal images are images obtained by measuring the temperature of objects or the surrounding environment and displaying them as a color map, with different temperature types being distinguishable. These images use thermal cameras or infrared (IR) camera technology to capture infrared radiation (heat) emitted by objects and visually represent it. These images can be used to identify damage in electrical network components that conduct electricity, thereby determining their temperature and analyzing deviations from the norm. Thermal images provide valuable data that can be used in power grid defect detection in objects such as substations and transformers, where changes in heat indicate potential faults [27], [28], however, for line infrastructure (sections without active equipment), temperature changes are difficult to identify because they do not indicate any mechanical damages.

4.1.1.5. Ultraviolet Images

Ultraviolet (UV) images are captured using specialized cameras that can detect ultraviolet radiation, which is typically invisible to the human eye. UV image data can be used to identify corona discharges, which are undesirable for electrical flow, as they can lead to defects in power lines and energy losses [31].

4.1.1.6. Data Type Comparison

According to the summarized comparison in Table 4.1 regarding the use of data for visual assessment of the overhead power transmission infrastructure, the most suitable data source is optical aerial images – RGB data (RGB color model).

Table 4.1

Data Sources for Visual Defect Detection Methods

Data type	Advantages	Restrictions	Potential application in infrastructure inspections
SAR data	Uses radio waves. Not affected by weather conditions. Day and night operation. High resolution is possible (depending on budget).	Limited color resolution. Complicated to interpret (requires specific knowledge of radar and image generation process). Relatively large data volume.	Vegetation monitoring. Post-storm monitoring (unplanned inspections).
Optical satellite data	Uses visible light and other spectral bands. Color images. High resolution is possible (depending on budget).	Lighting and weather constraints: clouds, fog, precipitation, winter period. Data availability in a specific area and period.	Vegetation monitoring.
Optical aerial photo data	Flexibility in data acquisition, especially from helicopters or drones. High resolution and detail are possible (depending on budget).	Lighting and weather limitations: clouds, fog, precipitation. The method of data acquisition can affect the quality of the images.	Vegetation monitoring. **Assessment of the visual condition of infrastructure elements.**

Table 4.1 (continued)

IR data	Uses infrared radiation. Thermal information. Day and night operation.	Complexity of data processing (requires specific knowledge). Lighting and weather constraints: clouds, air pollution.	Thermal monitoring of power grid elements.
UV data	Uses ultraviolet radiation. Day and night operation. Distinct information – the ability to obtain additional information not visible with other spectral band data, thus allowing the identification and analysis of objects and defects that would otherwise be invisible.	Complexity of data processing (requires specific knowledge). Lighting and weather constraints: clouds, dust, air pollution.	Assessment of power grid elements (corrosion, corona discharges).

4.1.2. Devices for Capturing Optical Aerial Images

Research indicates that optical aerial images are the most suitable for the visual technical assessment of network infrastructure. RGB image capture is achieved using optical cameras that detect red, green, and blue spectra, providing the color accuracy and quality required for inspections. Such cameras are found in various devices, including mobile phones and digital cameras.

Considering the requirement to capture image datasets in motion (e.g., from the air or ground while surveying infrastructure using unmanned aerial vehicles (UAVs), commonly known as drones), a gimbal is an essential component of the camera system. A gimbal is a mechanism that stabilizes the camera, maintaining its orientation even as environmental conditions change or the operator moves. It consists of multiple rotating axes that allow the camera to move freely across all three rotational dimensions. Within the scope of the study, the gimbal and camera specifications of the UAV models DJI Mavic 2 Pro [32], DJI Mavic 3 Pro [33], and DJI Mini 4 Pro [34] were compared.

4.1.3. Types of Vehicles for Capturing Optical Aerial Photo Data

Specially equipped devices with appropriate sensors and camera systems are used for collecting optical aerial photo data. These devices perform precise flights over areas of interest, capturing high-resolution RGB images. Table 4.2 summarizes various types of vehicles used for data collection, highlighting their advantages and limitations.

Table 4.2

Comparison of RGB Data Collection Vehicles for Inspection Process Needs

Data capturing vehicle	Advantages	Limitations
Manual method (Human resources)	Distance from infrastructure. Flexibility in data collection (adapt to the situation in the field, change the angle of data collection, volumes).	Difficult access to forest and swamp areas. Limited speed (up to 6 km/day). Load capacity (no possibility to collect RGB, IR, LIDAR data in parallel). Safety risk for personnel.

		Table 4.2 (continued)
Robot	Distance from infrastructure. There is an opportunity to automate the mission route.	Limited speed (up to 6 km/day). Difficult passage in forest and swamp areas (overcoming obstacles). Sensitivity of electronics and sensors (impact from the magnetic field of the power grid).
Unmanned aerial vehicle (drone)	Distance from infrastructure. Speed (up to 30 km/day). Possibility to automate the mission route. Load capacity (possibility to collect RGB, IR, LIDAR data in parallel). No restrictions on access to forest and swamp areas.	Regulatory restrictions for flights within visibility only.
Piloted aircraft (helicopter)	Speed (up to 200 km/day). Load capacity (possibility of parallel collection of RGB, IR, LIDAR data). No restrictions on access to forest and swamp areas.	Distance from infrastructure (± 150 m).
Satellite	Speed (instantaneous). No restrictions on access to forest and swamp areas.	Distance from infrastructure. No flexibility in data collection (only optical and radar data).

In addition to the technical advantages and limitations of the mode of transport, the choice of data collection vehicle depends on parameters such as efficiency, detail of the inspections, budget size, and future prospects.

4.1.4. Data Analysis for Visual Defect Detection

Optical aerial photo data processing involves the analysis of images obtained with optical sensors in order to identify visually visible defects in the power grid infrastructure in the most automated way. Figure 4.1 presents a data processing scheme in which images and their metadata are integrated with GIS asset data, regularly updating and supplementing information with the highest quality data.

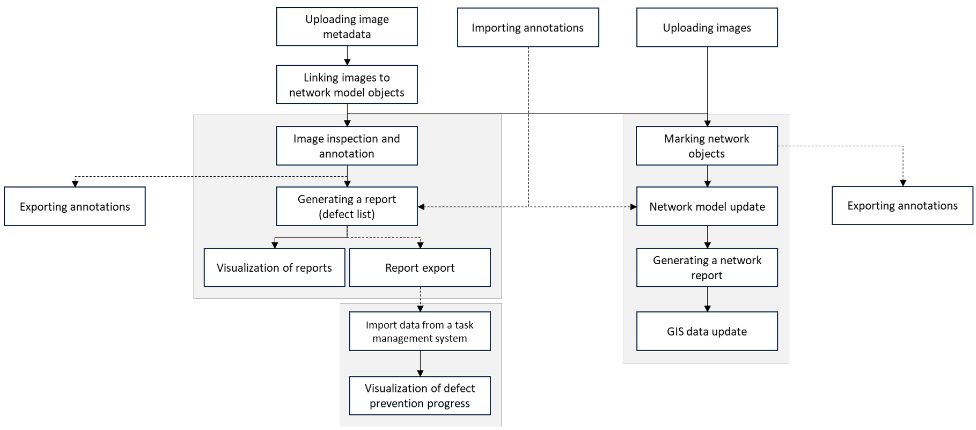


Fig. 4.1. Potential image data analysis workflow.

Automated processes with machine learning algorithms, such as YOLOv4 [35], Faster R-CNN [36], and Mask R-CNN [37], should be used to identify infrastructure defects.

4.2. Geospatial Defect Detection Methods

The second essential component of inspection involves geospatial measurements of infrastructure, which ensure public safety by verifying distances between wires and the ground or assessing pole stability by identifying leaning instances. Measurement accuracy is a critical factor in achieving reliable results. Currently, JSC "Sadales tīkls" performs all measurements manually, using human resources and calibrated measuring devices. This process is time-consuming as measurements need to be taken every 60–70 meters, equivalent to the average span length. 3D modeling, or a digital twin, provides the capability to monitor, predict, and control the condition of assets in real time [38].

4.2.1. Data Types for Implementing Geospatial Measurements

A point cloud is a set of data points in space that represent the three-dimensional (3D) shape of objects, defined by a coordinate system. These points are obtained using 3D scanners – LIDAR, which measure surfaces by reflecting laser pulses from various objects. LIDAR pulses can be reflected multiple times, reflecting different objects (treetops, ground surface, infrastructure elements). In addition to positional values (x, y, z), the system also stores other attributes – intensity and number of reflections. Point clouds are used to develop 3D models and digital twins.

4.2.2. LIDAR sensor

LIDAR systems emit light pulses and measure their return time to determine the distance to an object using the speed of light. The principle of operation involves a laser beam reflecting off an object and returning to the sensor. With a 360° view, a point cloud of the surrounding area can be generated. LIDAR offers high accuracy (within a few centimeters over distances up to 100 m), but its performance can be affected by adverse weather conditions. LIDAR sensors are used for distance measurement, geospatial infrastructure assessments, and atmospheric monitoring.

This study compares the technical parameters of three different sensors (DJI Zenmuse L2, Yellow Scan Mapper, and CHCNAV ALPHAAIR), considering factors such as absolute accuracy, weight, laser class, point density, number of returns, precision, repeatability, field of view, and scanning speed. For overhead infrastructure inspection, special attention must be paid to point density and accuracy. Medium-voltage cables, such as the AXLJ-F 3 × 50/16 mm^2 with a 55 mm diameter, are small-scale elements requiring high point density to ensure precise identification along their entire length during LIDAR data processing.

4.2.3. Vehicles for Capturing Point Cloud Data

LIDAR data acquisition can be performed using various types of transportation, and a comparison of their advantages and disadvantages is summarized in Table 4.3, taking into account the requirements of the inspection process.

Table 4.3

Comparison of LIDAR Data Capturing Vehicles for Inspection Process Needs

Data capturing vehicle	Advantages	Restrictions
Manual method (manually carried LIDAR scanners)	Able to access hard-to-reach areas (where air traffic is not allowed). High level of detail.	Limited speed (up to 6 km/day). Payload (no possibility to collect RGB, IR, LIDAR data in parallel). Safety risk for personnel.
Cars (mobile LIDAR sensors)	Mobility. Speed (up to 40 km/h).	Limited access to off-road areas. Limited distance from infrastructure.
Unmanned aerial vehicle (drone)	Speed (up to 30 km/day). Possibility to automate the mission route. Payload (possibility to collect RGB, IR, LIDAR data in parallel). High accuracy. No restrictions on access to forest and swamp areas.	Regulatory restrictions for flights only in the visual range. Additional flight licenses, coordination according to regulations. Limited flight time.
Piloted aircraft (helicopter)	Speed (up to 200 km/day). Load capacity (possibility of parallel collection of RGB, IR, LIDAR data). High accuracy. No restrictions on access to forest and swamp areas.	Costs. Additional flight licenses, coordination according to regulations. Competent personnel.
Piloted aircraft (airplane)	Speed (up to > 500 km/day). Load capacity (possibility to collect RGB, IR, LIDAR data in parallel). High accuracy. No restrictions on access to forest and swamp areas.	Cost. Access to airports is required. Additional flight licenses and regulatory approvals. Competent personnel.

When choosing a LIDAR data collection vehicle, the size of the survey area, geographical features, data detail requirements, and available budget should be considered.

4.2.4. Data Analysis for Geospatial Defect Detection

LIDAR data analysis will assist in identifying geospatial deviations of infrastructure. The data processing for inspections should be divided into five steps, as shown in Fig. 4.2:

- Data cleaning and classification, which results in the removal of incorrect data caused by dust, rain, or other external factors. Then, the data must be classified – divided into components: ground, vegetation, infrastructure (poles, power lines), buildings, according to the LAS 1.4 classification code [39].
- Data vectorization and network model creation – the geometric representation of objects.
- Data analysis – this step consists of geospatial measurements: distances from objects (between power lines and the ground, distances from power lines to the nearest tree branches, shrubs, or other objects), as well as structural tilt measurements for identifying potential deformations.

- Report generation process, which involves preparing detailed data reviews to identify anomalies and deviations from established thresholds, as well as determining potential risks and hazard zones.
- Result visualization – the geospatial overview will provide the opportunity for data-driven decision-making.

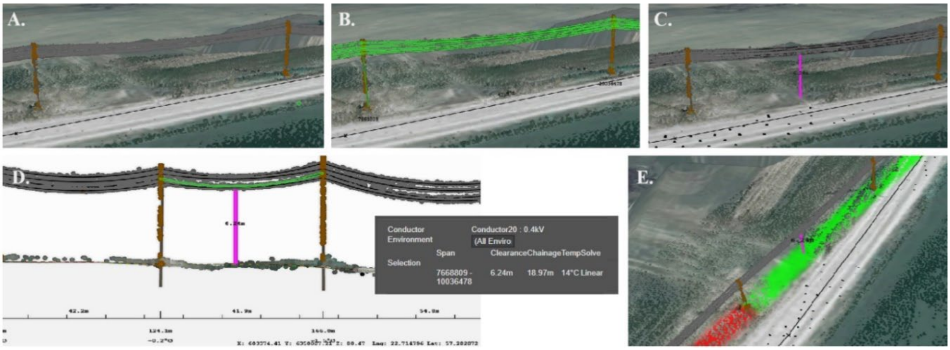


Fig. 4.2. The process of LIDAR data processing: A. classification; B. vectorization; C. analysis; D. Reporting; E. visualization.

4.3. Summary

This chapter discusses alternative methods for identifying visual and geospatial defects and proposes a digital inspection solution (Fig. 4.3), the components of which are:

- data capturing vehicle;
- sensors for data acquisition;
- optical aerial images or RGB data for visual defect detection, point cloud or LiDAR data for geospatial defect detection;
- data processing tools;
- information integration (if necessary for the implementation of the process).

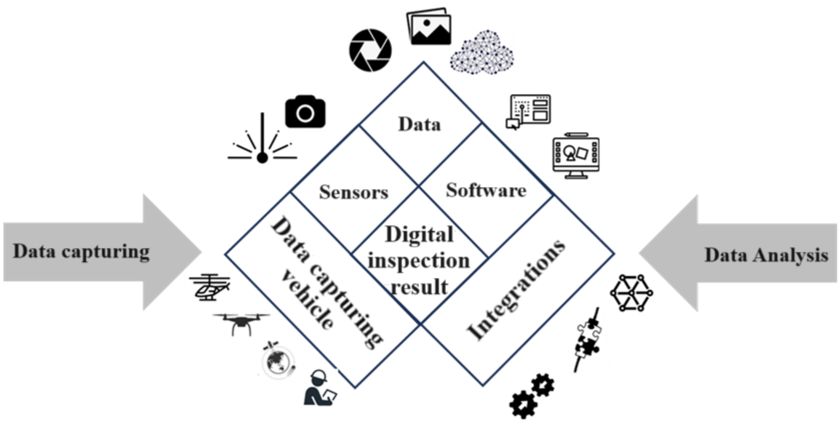


Fig. 4.3. Proposal for a digital inspection solution.

The next step of the research is the practical validation of the solution.

5. EXPERIMENTAL STUDY OF THE DIGITAL INSPECTION SOLUTION

This chapter discusses the empirical testing of the digital inspection and the evaluation of its practical applicability in real-world process implementation. The practical part of the study was carried out in collaboration with JSC "Sadales tīkls", which provided technical and methodological support.

The goal of the study: empirical verification of the theory – to practically confirm the digital alternative to the existing methodology for assessing the technical condition of the network with experimental and practical evidence, and to identify the most cost-effective and promising method.

Scope of the study: The study is designed to carry out defect detection on 650 km of overhead power transmission lines of JSC "Sadales tīkls", including 550 km of medium voltage lines and 100 km of low voltage lines, using digital defect detection technologies and methods.

Tasks of the study:

1. Define the requirements for the RGB and LIDAR data acquisition process and the functionality of data processing tools, considering the specific needs of the JSC "Sadales tīkls" infrastructure inspection process.
2. Perform an experimental study on the capturing and processing of RGB datasets and evaluate the suitability of the visual inspection method for assessing the technical condition of infrastructure in real-field conditions.
3. Perform an experimental study on the capturing and processing of LIDAR datasets and evaluate the suitability of the method for performing geospatial measurements of infrastructure in real-field conditions.

5.1. Data Acquisition Process

Data capturing is a critical part of the research process, providing the necessary information to achieve the stated objectives.

5.1.1. Technical Parameters for Dataset Acquisition

For the implementation of the research experiment, the technical requirements for the RGB and LIDAR dataset parameters have been developed and summarized in Table 5.1, in accordance with the needs of the inspection process, which must be ensured during the data capturing implementation.

Table 5.1

Technical Requirements for RGB/LIDAR Data Capturing Parameters

Parameter	**Description of the technical requirement**	
	RGB data	***LIDAR data***
Data acquisition implementation period	April–June, September (in the territory of Latvia).	
Delivery of the final version of the dataset	Data delivery to the FTP server of JSC "Sadales tīkls". Data classification into folders by asset groups and identifiers must be ensured.	
Data capturing implementation	Observe the national regulations of Latvia and ensure the fulfillment of all necessary conditions [40], including, if necessary, informing the residents about the planned works shortly before the data collection process is carried out (in cases where data collection will take place within populated areas).	

		Table 5.1 (continued)
Data format	JPEG, JPG	LAS, LAZ
Coordinate system	WGS84 or other generally accepted (LKS-92 TM used in Latvia [41])	
Dataset scope	For point objects, at least 4 images (2 of them with zoom), obliquely in two vertical directions, and from above. For linear objects, visibility must be ensured along the entire span, the number of images depending on the length of the span.	100 % data coverage. 100 % data completeness – the corridor width is defined up to 30 m on each side of the line's central axis at treetop height.
Data quality criteria	The quality metric is to ensure visibility of a 2 cm visual defect. Brightness/contrast: Images should be uniform in quality, where objects are clearly visible – consistency of image quality across the dataset is important for model training and computer vision tasks. Target resolution (image size): Optimal resolution should be provided to detect a 2 cm defect.	Accuracy/precision – the LIDAR system must provide accuracy and repeatability with the manufacturer's specification error value of less than 5 cm. Point cloud density – at least 50 pt/m^2 Pulse returns: The LIDAR device must be able to capture at least two return pulse responses. The quality metric is to ensure that there is no corrupted data, and there should be no gaps or holes in the point clouds that could affect the completeness and accuracy of the data.
Metadata and georeferencing	Geotags (with a certain accuracy), camera angle, field of view (FOV), date and time stamps, and source information.	The dataset should be supplemented with appropriate metadata and accurately georeferenced to ensure integration into GIS and mapping software, including temperature data, date and time stamps. Point attributes – data points should include attributes: intensity values or classification categories.
Designations	The components of the dataset must be named according to their content, and the labels provided must be correctly aligned with the content of the images.	Labels should be included that are consistent with the planned data collection mission.
Documentation	Documentation must be provided that includes information on the origin of the dataset (data collection devices), collection methods, technical parameters of the dataset, and any special specifications.	Detailed documentation should be provided on data sources, collection methodology, technical parameters, LIDAR sensor calibration, and specific factors or limitations that may affect data quality or usability.

5.1.2. Dataset Acquisition Scenario

The scope of the infrastructure elements within the experiment is defined in Table 5.2. The geographical scope of the study covers the network in the regions of Talsi and Tukums municipalities, where the analysis of the inspection volume for one period is carried out. In this region, the technical condition of the electrical grid infrastructure is studied, assessed, and analyzed using the proposed solution (Fig. 4.3).

Table 5.2

Planned Volumes of RGB and LIDAR Datasets

Medium voltage power lines			Low-voltage power lines		
km	Number of poles	Number of spans	km	Number of poles	Number of spans
550	7990	8426	100	2352	2508

Specific technical devices were selected for data collection, which meet the requirements defined in Table 5.1, in order to collect and process the necessary information in accordance with the study's objectives and the needs of the inspection process:

- For the capturing of RGB datasets, the DJI Mavic 2 Pro drone was used, equipped with a built-in 20-megapixel camera.
- For the capturing of LIDAR datasets, the DJI Matrice 300RTK drone was used, equipped with the YellowScan Mapper LIDAR system.

The output data for route planning and determining the data volume were collected from JSC "Sadales tīkls" GIS in the format shown in Fig. 5.1.

a.

Iecirkn	TO_I	Iezīme	ID	Tabula	Tabula	Klases I	Klase	Grupa	Efektīvais g	X1	Y1	X2	Y2	Guldīšanas vide
Talsi-1	cbfg8	33071#E0189	2.05E+08	201	VS līnijas elements	1006	AS-3x35 20 kV darba spr.	Kailvadu līnijas	76.10570563	347847.8398	414968.3164	347807.9727	415033.1445	Lauksaimniecībā izmantojama zeme (10)
Talsi-1	cbfg8	33071#E0189	2.05E+08	201	VS līnijas elements	1006	AS-3x35 20 kV darba spr.	Kailvadu līnijas	77.93623338	347616.1211	415358.8203	347576.7188	415426.0625	Lauksaimniecībā izmantojama zeme (10)

b.

Iecirknis	TO_II	Iezīme	ID	Klases	Klase	Grupas	Gru	X	Y	X (WGS)	Y (WGS)	Iezīn	Izg	Pasta	Pastaba esamīb
Talsi-1	cbfg8	33071#E0189	2.05E+08	600	VS koka I	1092	Koka	347807.973	415033.145	57.2653962	22.5912176	6	2018	-	BEZ pastabiem
Talsi-1	cbfg8	33071#E0189	2.05E+08	600	VS koka I	1092	Koka	347769.32	415098.762	57.2650613	22.5923185	5	2018	-	BEZ pastabiem

Fig. 5.1. The output data (a. linear elements, b. point elements) from the GIS database for flight planning.

5.1.3. Dataset Acquisition Implementation Parameters

To ensure stable RGB and LIDAR data acquisition for inspections, a workflow is required that includes coordination, route planning, data collection, and processing for quality validation. The necessary actions and competencies are summarized in Table 5.3.

Table 5.3

Activities of Organizing Data Acquisition Implementation

Implementation components	Activities/tasks	Competencies
Operational management of data acquisition	Coordination of communication between all stakeholders. Coordination of data collection processes. Achieving the planned results in the process.	Project management skills. Resource management experience. Extensive knowledge of UAV operations and flight planning. Experience and knowledge in distribution system infrastructure inspection.
Flight planning	Providing flight permit applications (Civil Aviation Agency) and flight route planning. Coordination of communication between operational management and pilots.	Extensive knowledge of UAV operations and flight planning. Experience and knowledge in distribution system infrastructure inspection. A1/A3 category pilot training, A2 category training. LVS-EN 50110-1:2013 electrical safety training.

Table 5.3 (continued)

LIDAR dataset capturing	Flight execution. Ensuring LIDAR data acquisition. Ensuring the operation of the UAV and LIDAR sensor.	Extensive knowledge of UAV operations and flight planning. Experience in overhead power line inspections and UAV flights (at least 200 flight hours recorded). A1/A3 category pilot training, A2 category training, and specific category training. LVS-EN 50110-1:2013 – electrical safety training
RGB dataset capturing	Flight execution. Ensuring the acquisition of RGB images. Ensuring the operation of the UAV.	Extensive knowledge of UAV operations and flight planning. Experience in overhead power line inspections. A1/A3 category pilot training, A2 category training. LVS-EN 50110-1:2013 – electrical safety training.
Data analysis	RGB and LIDAR data management. Dataset quality control and validation. Coordination of communication between the data processing and capturing parties.	Experience in overhead power line inspections. Data analytics skills. Experience with GIS applications and geospatial data analysis. Extensive knowledge of UAV operations and flight planning. LVS-EN 50110-1:2013 – electrical safety training.

5.1.4. Summary of the Experiment Results

In this section, a practical validation of the RGB and LIDAR data collection method with unmanned aerial vehicles to identify power line defects for maintenance and inspection is performed, based on the results of data processing. As a result, RGB (0.79 TB, 159235 files) and LIDAR (4.02 TB, 828 files) datasets were collected, covering 550 km of medium voltage overhead lines and 100 km of low voltage overhead lines.

The results obtained in the study regarding data collection and the existing experience of JSC "Sadales tīkls" regarding inspections of Latvian medium-voltage overhead infrastructure are summarized in a comparison (Table 5.4).

Table 5.4

Comparison of Data Capturing Efficiency: Analysis of UAV and Manual Methods

Criteria	Data capturing using UAVs	Manual inspections
Speed	20 km/day (RGB dataset) 30 km/day (LIDAR dataset)	6 km/day
Data volume	Large, diverse (*.jpg, *.las)	Limited (based on expert decision at the facility, depends on access, information only about the fixed defect)
Safety	High, remote control	Low, increased risk
Accessibility	Good, independent of ground conditions	Limited, dependent on access to objects (forests, swamps)
Flexibility	High, fast adaptation	Low, slow adaptation (additional special equipment)

Digital inspection with UAVs significantly improves the efficiency (data capturing up to 20 km/day), safety (reducing risks in challenging environmental conditions), and accuracy compared to manual methods. This chapter serves as the foundation for data analysis and conclusions to achieve the research objectives.

5.2. Data Analysis Process

According to the chapter "Alternative Methods for Defect Identification" of the Thesis, the second step of the digital inspection is data analysis and defect identification, aimed at accurately assessing the technical condition of the infrastructure. This step involves reviewing, preprocessing, and analyzing the collected data, applying artificial intelligence-based object recognition models to identify visual defects. Visual defects refer to mechanical damages to the network elements, while geospatial defects are related to vegetation, distance measurements, and the sagging of supports and wires. The precise selection of analysis tools and methods is crucial for ensuring effective data processing.

5.2.1. Technical Specifications for Functionality Requirements for Dataset Processing Tools

Technical requirements for data processing software have been developed (Table 5.5), which include functional and non-functional (performance, interface, and security) requirements for the general system module, as well as specific functionalities for geospatial analysis of LIDAR data and visual defect analysis of RGB images.

Table 5.5

Technical Requirements for Data Processing Software for Inspection Process Needs

Requirement type	**Description of requirements**
General system module	
Functional	IS ensures the data analysis process for LIDAR datasets, RGB image datasets, and GIS data (including the network element GIS dataset and attribute dataset, such as maintenance data), in accordance with the business requirements for technical inspections, specifically, the defect catalog.
Functional	IS provides automated geospatial measurements using LIDAR data to create a network model or digital twin.
Functional	Geospatial data processing and interpretation.
Non-functional performance	Performance and scalability - Efficiency – algorithms to efficiently process huge data sets - Scalability – ability to scale to the size and complexity of RGB and LIDAR data Asset volumes for high-performance data operations Experiment scope: MV/LV overhead infrastructure – 650 km (10,342 point elements) JSC "Sadales tīkls" total overhead infrastructure volumes: MV/LV overhead infrastructure – ~ 60,000 km
Non-functional performance	Number of users: 20 (concurrent users).
Non-functional performance	Data storage with high-speed capability (at least 1 Gbit/s) for uploading and processing large datasets.
Functional	IS provides raw data preprocessing (including processing, cleaning, and analysis).
Functional	Supported file formats: *.las (Point Cloud), *.laz, *.csv, *.jpeg, *.json, *.jpg (environment navigation and timestamps).

Requirement type	Description of requirements
	Table 5.5 (continued)
Functional	Integrations – APIs or plugins for integration with JSC "Sadales tīkls" GIS software or other relevant platforms.
Functional	The IS provides simulation capabilities (digital twin model functionality with AI/ML features aimed at implementing predictive maintenance).
Functional	Libraries: Network components and network component parameters.
Non-functional security	Cloud solution within the EU zone (with a local alternative).
Non-functional security	Security and data management: Without third-party access to ST data – the IS ensures data integrity and security during processing and storage. Tools for efficient organization, storage, and management of huge datasets.
Non-functional security	Users with two-factor authentication and verification. LDAP (Lightweight Directory Access Protocol) (recommended, not mandatory).
Functional	Coordinate system with the ability to convert to LKS-92 or another suitable alternative (according to GIS data management and data collection requirements).
Functional	The developer must ensure the workflow of the IS architecture, including: data import, preprocessing, analysis, report templates, and data output to the internal IS of ST (GIS, JIRA, etc.).
Non-functional interface	IS supports configurable multiple view layouts (3D model screen from the point cloud, 2D asset data from GIS, image collection view based on selected elements) on a single screen.
Non-functional interface	User interface (UI) and user experience (UX): - Intuitive interface – a user-friendly interface designed for easy navigation and smooth operation - Customization – the ability to adjust views, tools, and workflows according to the user's preferences - Documentation and support – comprehensive documentation and support resources for users - Operational technical support and assistance – providing operational technical support and help when ST users report IS issues, in accordance with business objectives.
LIDAR data analysis module	
Functional	IS ensures data input and compatibility: - Support for multiple file formats: the ability to read various LIDAR data formats, such as LAS, LAZ, etc. - Integration with LIDAR sensors – compatibility with various LIDAR sensors and their data outputs.

Functional	IS ensures point cloud data processing:
	- Point cloud processing – algorithms to efficiently manage and process point cloud data
	- Filtering and noise reduction – tools for removing noise, outliers, and irrelevant points
	- Data segmentation and classification – the capability to segment various objects or terrain types and classify points:
	  o network elements: spans (wires), poles, transformers, cross-arms
	  o environment: vegetation (bushes, tree trunks, tree canopies), water bodies, roads, railways, buildings (e.g., transformer substations)
	  o line crossing points: intersections with other utility infrastructure (e.g., other wires, pipelines)
	  o terrain features: ground surface and elevation details
	  o etc. (additional layers): other supplementary layers as needed
	- Feature extraction – algorithms for identifying and extracting specific features (edges, corners, etc.) from the point cloud
	-

Requirement type	Description of requirements
	Table 5.5 (continued)
	- Registration and alignment – capability to register multiple scans and accurately align them to create a comprehensive view Interpolation and reconstruction – techniques to fill gaps and reconstruct missing parts in the point cloud
Functional	IS provides automated creation of a 3D model for ST overhead infrastructure: - Functionality to model the infrastructure according to configurable pole placement (preferred, not mandatory) - Functionality to model the infrastructure according to the configurable line type
Non-functional interface	LIDAR data synchronization in navigation with active data (GIS data) in 2 layers.
Functional	IS provides the configuration of analysis criteria: - Vegetation and corridor zone parameters according to regulatory requirements and business needs - Geospatial measurement parameters (distance measurements, pole lean analysis) - Functionality to model infrastructure according to configurable weather parameters (with the goal of creating a model for geometric changes of lines – distances, overstretched wires)
Functional	IS ensures the maintenance of LIDAR attributes and additional data parameters: - Dataset creation data and timestamp - Dataset capturing temperature - Dataset import from internal IS according to the process requirements
Non-functional interface	IS provides visualization and analysis: - Color 3D visualization – interface for visualizing point cloud data in 3D layers - Measuring tools – tools for measuring distances, angles, volumes, and other parameters from the point cloud (distance measurement, pole lean measurements, distances between wires and tree branches, and canopy measurements) o reports in table format excel, csv o distance, angle, and volume measurement for configurable weather conditions - Cross-section analysis – the ability to create cross-sections and perform analysis in specific areas of interest. - Change detection – tools for comparing multiple scans and detecting changes over time. The model is reusable for future flights, and the system should be able to identify differences between the existing state and the newly acquired data
Non-functional interface	Navigation (zoom in/zoom out, pan, and rotate)
Functional	Data export and integration: - Export formats – the ability to export processed data in various formats for use in other software or systems - Integration API – there should be the capability for API or plugin integration with ST GIS or other relevant platforms
Non-functional interface	Filtering, searching, and visualization in the map view of configurable violations
Functional	IS provides an accuracy assessment. Validation tools to evaluate the accuracy of processed data compared to reference data
Functional	IS provides report generation (both tabular and visual) and export functionality: - LIDAR data coverage report - GIS data accuracy – asset location accuracy - Vegetation clearance of the track - Conductor distances in spans - Conductor sagging in spans - Pole lean - Distance of conductors, hooks on poles

Requirement type	Description of requirements
	- Conductor position (vertical, horizontal, vertical-triangle, horizontal-triangle, rectangle) - Extreme changes (simulation results)
	Table 5.5 (continued)
	RGB image dataset analysis module
Functional	Automatic and manual defect identification, according to the defect catalog and labeling with additional attribute data (for example: defect ID or name, hazard level, priority)
Functional	IS provides image input and compatibility: - Multi-format support – ability to view various image formats (JPEG, JPG) - Camera integration – compatibility with various camera types, resolutions, and color spaces
Functional	IS provides preprocessing and enhancement: - Noise reduction – filters and algorithms to reduce noise and artifacts in images - Image enhancement – tools for adjusting brightness, contrast, sharpness, etc. - Color correction – methods to correct color balance and ensure consistent color representation
Functional	IS provides segmentation and object identification: - Segmentation algorithms – the ability to segment images into regions or objects of interest - Object detection and recognition – algorithms for representing identified and recognized objects
Functional	IS provides export of defect annotation with coordinates, defect ID, hazard level, and image ID
Functional	IS provides feature extraction and analysis – tools for detecting edges, corners, textures, etc., feature extraction, and algorithms for analyzing texture patterns in images
Functional	IS provides statistical analysis – tools for performing statistical analysis of image data
Functional	IS provides classification and categorization: - Machine learning models – integration of machine learning models for image classification and categorization - Semantic segmentation – techniques for assigning semantic labels to different parts of an image
Non-functional interface	IS provides visualization and presentation: - Image display – user-friendly interface for displaying images, image location on the map with viewing angle and a polygon with visible area, and their analysis results - Associating an image with assets according to the visible area of the image - Annotation tools – tools for annotating and marking objects or elements in images for better visualization and understanding - Comparative analysis – tools to compare and analyze multiple images or polygons side by side
Functional	IS provides data export – the ability to export processed images or analysis results in various formats (*.xls, *.csv, etc.)
Functional	IS provides scalability – the ability to process images of different sizes and resolutions
Functional	IS provides annotation of defects captured in images and storage of results in accordance with computer vision and machine learning standards

The following data have been prepared for data analysis: GIS data with object placement and attribute information, LIDAR dataset, RGB dataset, vegetation limits, pole construction, and line types, as well as defect threshold values for defect risk assessment.

5.2.2. Visual Assessment of the Technical Condition of the Infrastructure

The image processing process involves multi-step procedures for extracting useful information. The Hepta Insights software platform was used in the study, which meets the technical requirements (as outlined in Table 5.5) and provides functionality for visual defect identification in inspections. The software utilizes the YOLO (CNN – Convolutional Neural Network) object recognition model, trained with the yolov8 version on AWS (Amazon Web Services) GPU (Graphics Processing Unit) machines.

Data processing involves several steps. First, the data must be downloaded into the software. After downloading, the images are classified based on metadata coordinates and viewpoints, linking them to the nearest point-based elements from the GIS (such as poles, distribution points). Once the data is classified, it needs to be processed to identify network elements, and for process automation, defect recognition functionalities should be utilized. The sequence for developing the defect detection model is shown in Fig. 5.2.

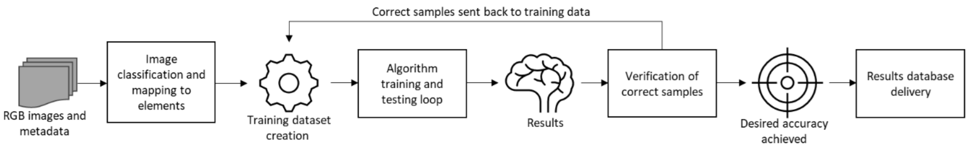


Fig. 5.2. High-level schematic overview of the machine learning development process for detecting an object of interest.

Image classification and element assignment are essential in data analysis. The process requires object libraries that describe the identifiable elements, serving as reference databases for training and testing machine learning models. The process of creating object libraries includes:

- identifying and describing elements;
- defining and structuring element attributes (element type and material; defect groups, defect values, defect severity levels);
- training data preparation in object libraries should include example images depicting each element in different conditions and perspectives to ensure the model's robustness;
- data annotation and labeling;
- library maintenance and expansion.

Once the object libraries are created and each element is thoroughly defined, the machine learning image processing process is initiated on the Hepta Insights software platform to identify elements in the images. For each identified element instance, the model assigns a detection probability percentage, indicating the confidence with which the element is recognized. In the case of pole type identification, the results obtained in the study range from 71 % to 97 %. This result was achieved using the pole identification ML model in Hepta Insights software, where 3196 images of the infrastructure of JSC "Sadales tīkls" were used in the training phase and 565 images in the testing phase.

After identifying the network elements, the Hepta Insights software model analyzes the image to detect defects using two main stages:

- defect recognition – defect identification based on visual cues: cracks, corrosion, or mechanical deformations (e.g., changes in shape);
- defect classification – classification of identified defects based on the urgency of their resolution, using pre-trained model libraries, which facilitate the planning of network maintenance tasks.

This experiment was performed in the following stages:
- Data processing – initially, the RGB dataset was processed using a model that identified 654 defects with an average confidence level of 65 % at medium voltage and 39 defects with an average confidence level of 61 % at low voltage (see Table 5.6).
- Manual annotation – after processing the dataset, each identified defect was manually annotated in the Hepta Insights software to verify the model's accuracy (Fig. 5.3 provides an example of image annotation).
- Expert validation – the manual and model-generated annotations were validated and aligned with the inspectors of JSC "Sadales tīkls," who provided their expert assessment for each identified defect.

Table 5.6

The Result of Network Element Defect Identification

Defect identification method, criteria	**Medium voltage level (1–20 kV)/** degree of urgency for defect remediation						**Low voltage level (0.4–1 kV) /** degree of urgency for defect remediation					
	1	*2*	*3*	*4*	*5*	*total*	*1*	*2*	*3*	*4*	*5*	*total*
Number of defects (identification model)	255	202	175	21	1	654	13	1	25	0	0	39
% of defect identification reliability	62 %	73 %	66 %	81 %	41 %	65 %	49 %	54 %	71 %	–	–	61 %
Number of defects (manual inspection)	1563	579	3479	494	6	6121	175	150	239	102	8	674
Total length of lines in km	550 km						100 km					
Number of images	134,752						24,487					

The results indicate that the amount and quality of data are crucial factors influencing the performance of automatic defect detection. To optimize the defect detection process, consideration should be given to expanding and diversifying the data collection, as well as developing additional methods (for example, approaches such as "cut-paste-learn" combined with convolutional neural networks [42], or image generation using neural radiance field -based synthetic image creation and post-processing methods [43]) that could improve the accuracy of models, even when the available data volume is limited.

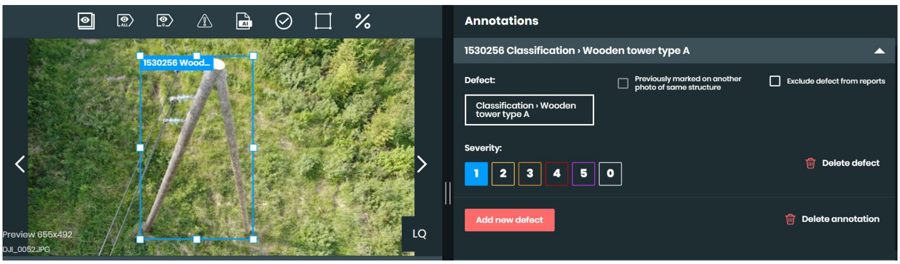


Fig. 5.3. Example of annotating an element in Hepta Insights software.

5.2.3. Geospatial Infrastructure Measurements

The second key component of infrastructure technical assessment (after visual evaluation) is geospatial measurements, which provide a detailed inspection by analyzing parameters such as height, distance, and object contours, as well as their placement in the environment. The alignment of geospatial measurements with technical standards (Latvian Energy Standard [44]) is essential in the maintenance of powerline infrastructure, as it systematically identifies and quantifies deviations from regulatory parameters that signal potential defects and damages. Geospatial measurements for support structures and conductor placements, based on LIDAR data analysis, include determining the accuracy of network element placement, clearance measurements, conductor sag detection, distance measurements between wires in spans, determining wire placement on supports, distance measurements between conductors in spans, determining pole lean values, and vegetation management in corridor and protection zone areas.

For the realization of the study, Neara software was used – a web-based CAD (computer-aided design) tool with built-in industry-specific LIDAR data processing functionalities: engineering network design and analysis tools, including automated point cloud classification functionality, network model reporting, and data visualization features, which meet the defined technical requirements for the LIDAR data analysis module (Table 5.5).

As described in Section 4.2.4, "Data Analysis for Geospatial Defect Detection", the initial and critically important phase of LIDAR data analysis involves careful data classification, which determines the accuracy and efficiency of all subsequent analytical actions. The classification must include the following layers (Table 5.5): network elements – line (conductor) spans, poles; environment – vegetation (bushes, tree trunks, tree crowns), water bodies, roads, buildings; and terrain.

The classification process applies advanced algorithmic methods to ensure high accuracy and alignment with the real-world situation. The automated classification model uses the supervised learning algorithm method [45] – previously trained network samples spanning ten thousand kilometers of corridors are used to automatically classify each point in the point cloud. After data classification, each point is assigned to a specific class, allowing for more precise interpretation and analysis of the obtained data (Fig. 5.4). The dataset used in the study was loaded into the Neara software, and the automated classification process was executed. In cases of error identification, point category corrections were made using the manual classification functionality.

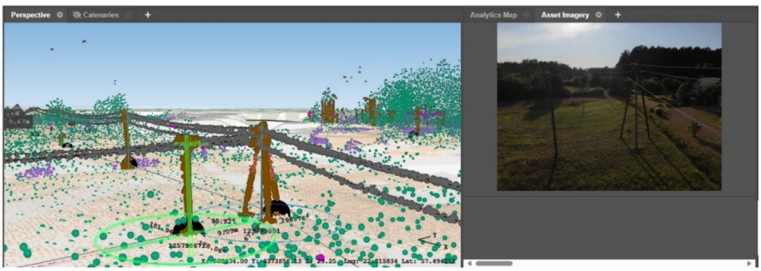


Fig. 5.4. The classification and vectorization results for the JSC "Sadales tīkls" infrastructure.

The next step after object classification is the vectorization or creation of the engineering model – the conversion of classified points into mathematical shapes. Points that align with linear structures, such as power transmission lines, are connected to form lines or polylines. Polylines consist of multiple connected segments that accurately represent the contour of the object, reflecting the real infrastructure. This process creates a geospatial virtual replica of the infrastructure, also known as the digital twin of the physical infrastructure (see Fig. 5.4). Vectorization provides a mathematically precise description of objects, enabling detailed engineering calculations, accurate evaluation, infrastructure planning, and the ability to export data to CAD or GIS systems.

5.2.3.1. Determination of Spatial Location of Power Line Poles

The accuracy of the distribution operator's infrastructure element placement is one of the critical requirements. The network model provides the coordinates (x, y) and height of the poles, allowing for the comparison of the accuracy of different sources (Table 5.7) and visualization of the differences between GIS and LIDAR data.

Table 5.7

Comparison of the Spatial Arrangement of the Poles of the Technical Object cc4bc

GIS data											*LiDAR data*			
Zone	TO_ID	Feature	Network element ID	Class ID	Class	Group ID	Group	GIS data, X (WGS)	GIS data, Y (WGS)	Year of construction	Actual location (LIDAR): X	Actual location (LIDAR): Y	Actual location (LIDAR): Z (from ground level)	Perpendicular height of the pole above the ground, m (from ground level to the top of the pole)
Tukums-5	cc4bc	33085#E5807	10224234	600	VS koka I	1092	Koka	56.71049	22.85377	2006	56.710492	22.853772	127.1513	10.985
Tukums-5	cc4bc	33085#E5807	10224235	601	VS koka A	1092	Koka	56.70642	22.84841	2006	56.706446	22.848479	127.3235	10.281
Tukums-5	cc4bc	33085#E5807	10224236	600	VS koka I	1092	Koka	56.70851	22.85115	2006	56.708124	22.850685	128.7603	9.769
Tukums-5	cc4bc	33085#E5807	10224238	600	VS koka I	1092	Koka	56.70714	22.84935	2006	56.706945	22.849148	128.4907	9.91
Tukums-5	cc4bc	33085#E5807	10224239	600	VS koka I	1092	Koka	56.70606	22.84736	2006	56.706052	22.847323	127.7503	11.253
Tukums-5	cc4bc	33085#E5807	10242565	600	VS koka I	1092	Koka	56.71362	22.85783	2004	56.713609	22.857831	126.3888	12.426
Tukums-5	cc4bc	33085#E5807	11093504	600	VS koka I	1092	Koka	56.71401	22.85835	2004	56.714124	22.858512	125.4007	10.305
Tukums-5	cc4bc	33085#E5807	**186747087**	600	VS koka I	1092	Koka	56.70779	22.85021	2017	56.707518	22.849894	128.789	9.931
Tukums-5	cc4bc	33085#E5807	254426807	600	VS koka I	1092	Koka	56.71459	22.85912	2021	56.714589	22.859128	123.9493	10.354

When analyzing the differences, it is clear that GIS data often does not match the real-world location of objects. For example, a pole with the identifier 186747087 is registered in the GIS database with a significant offset (approximately 35 m) from its actual location. This situation highlights the importance of high-precision data provided by LIDAR technology, which offers detail down to 10 cm, far exceeding traditional GIS data. The integration of LIDAR with GIS systems significantly improves data accuracy and enhances infrastructure analysis, planning, and maintenance, reducing risks and costs associated with inaccurate data.

5.2.3.2. Clearance Measurements

Clearance measurements – determining the minimum distance of each span from the ground, which is a critical measurement for ensuring public safety. These measurements help prevent potential safety risks that may arise from low-hanging power lines. The network model created from LIDAR data, which includes detailed attribute data, was configured with specific parameters and thresholds (threshold values according to the Latvian Energy Standard [44] and the Protection Zone Law [46]), defining the technical requirements and standards that the measurement values must meet.

The LIDAR data model was enhanced with detailed attribute data, including various technical parameters: line installation environment, voltage level, cable type and manufacturer, and the types of end points for line segments (e.g., pole, transformer, connection to a building). For each combination of these values, distance thresholds were defined to identify whether a specific measurement complies with technical standards [47]. After configuring the parameters, LIDAR data analysis was performed to determine the minimum distances between power lines and the ground, identifying spans that do not meet the established standards. This process automatically compares the data against the set thresholds, detecting any discrepancies.

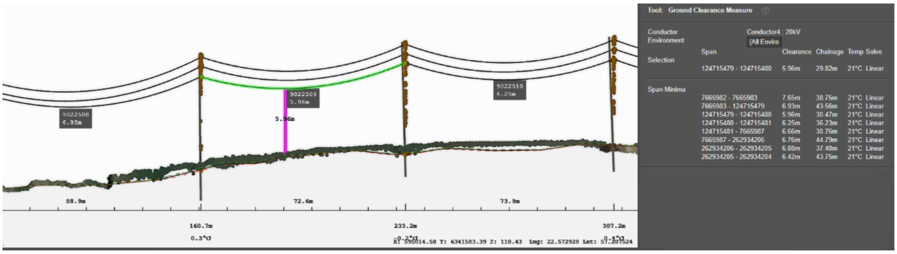


Fig. 5.5. Automatic measurement detection in Neara software.

The reports obtained from the study show that a detailed analysis is provided – the analysis of the line segment (ID 9022509) (Fig. 5.5) reveals that the minimum distance to the ground surface in this segment is 5.96 meters (the minimum allowable distance value in this case for the AS-3x70 20 kV overhead cable is 6 m [44]), and this minimum distance is recorded 29.82 m from the starting point of the segment, whose coordinates are indicated at the location of the pole with the identifier 124715479.

To ensure that the results achieved in the study are correct, validation was organized at three levels in the facilities:

- Comparison with measurements taken during the manual inspection process.
- Expert verification to ensure the accuracy of the analysis, experts manually check critical areas and confirm the results of automatic processing.
- Additional measurements – where necessary, additional measurements were taken to clarify inaccuracies or check borderline cases.

In the comparison between LIDAR data analysis and manual defect detection, the average deviation is 0.09 meters, with variations ranging from a few centimeters to 97 centimeters. A detailed analysis of the results is provided in Table 5.8.

Table 5.8

Comparison of LIDAR Data Analysis Results with Manual Inspection Results

Deviation size	% of deviations	Action
Up to 10 cm	41 %	A deviation of up to 20 cm is considered an acceptable limit, as it includes measurement inaccuracies arising from physical access difficulties and changes in environmental conditions.
Up to 20 cm	27 %	

Table 5.8 (continued)		
Up to 50 cm	17 %	An expert review was performed on 10 randomly selected cases to verify the accuracy of the LIDAR data analysis results. The findings indicate that, in all cases, the results of the LIDAR data analysis were deemed correct, with the variation in values primarily caused by factors such as the measurement operators' lack of experience and environmental conditions (difficult physical access).
Above 50 cm	15 %	Additional measurements were taken for 10 randomly selected cases to verify the accuracy of the LIDAR data analysis results. The results of the verification indicate that, in all cases, the LIDAR data analysis results were deemed correct.

5.2.3.3. Conductor Misalignment

Conductor misalignment – determining the actual sag values of the conductors in each span, taking into account the air temperature at the time of data capturing, as temperature fluctuations significantly affect the sag. This information is crucial for assessing the strength and safety of the conductors under various climatic conditions. During the study, several quantitative values were defined to achieve the set goals for these calculations:

- Environmental temperature (°C) (temperature at the time of LIDAR data collection).
- Actual span length (m) determined as a result of LIDAR data processing.
- Actual number of conductors – total number of wires in the span.
- Conductor placement in the span – each conductor is precisely positioned in relation to other conductors and the surroundings (horizontal, vertical, triangular vertical, triangular horizontal, rectangular).
- Conductor sag in the span in meters (bottom wire L1, 2nd wire from the bottom L2, 3rd wire from the bottom L3, 4th wire from the bottom L4).
- Minimum mutual distance of conductors in the span (between L1 and L2, between L2 and L3, between L3 and L4).
- Conductor sag: uneven, conductors can get tangled: Factor 1 (ratio of wire distance between L1 and L2 to wire distance between L2 and L3) and Factor 2 (ratio of wire distance between L1 and L2 to wire distance between L3 and L4).

The obtained data is compared with the permissible values according to the requirements of the Latvian Energy Standard [47].

Neara software provides options for parameter configurations and 3D visualization tools for conductor sag analysis, displaying power line profiles and terrain. The analysis determines sag values and minimum distances to the ground or other objects, identifying conductors with excessive sag that pose a risk to safety standards. Figure 5.6 illustrates a case where a 2-meter discrepancy creates a safety hazard.

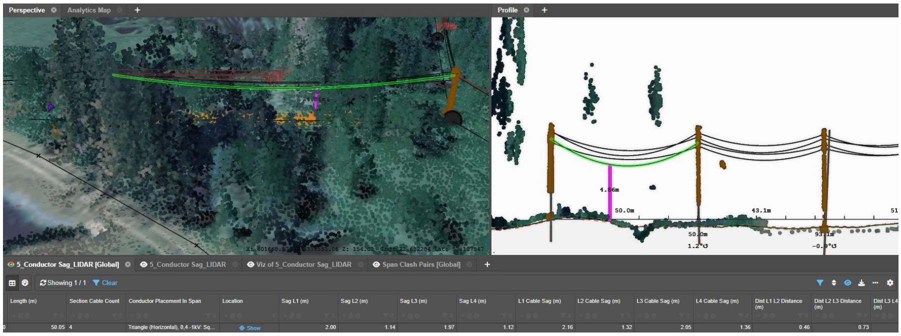


Fig. 5.6. Example of determining conductor alignment from data from a study in Neara software.

The experiment results show that with a 2-meter sag, the minimum safety distance to the ground is not maintained in more than 50 % of cases, while with a 3-meter sag, non-compliance exceeds 80 %. This highlights the need for careful monitoring of conductor sag to reduce safety risks and maintain the integrity of the power line network.

The definition of these parameters and the large-scale automated analysis of LIDAR data enable precise modeling and monitoring of power transmission line conditions, ensuring a reliable and safe power line network.

5.2.3.4. The Placement of Conductors on Poles and the Distances between Conductor Fittings

The placement of conductors on poles and the distances between conductor fittings, distance measurements between conductor fittings on poles, are crucial to ensure the structural integrity and stability. To identify critical values and detect defects that could threaten the integrity and operation of the power lines, it is essential to perform calculations for these parameters:

- vertical distance between conductors in the pole (from the first wire (bottom) to the second wire);
- vertical distance between conductors in the pole (from the second wire to the third wire);
- vertical distance between conductors in the pole (from the third wire to the fourth wire).

Vertical distance calculations, based on the mathematical description of the infrastructure vectorization model (see Section 5.2.3), were performed for all poles. As shown in Fig. 5.7, for poles with vertical conductor geometry, the calculated values are close to zero, indicating that these parameters are not critical for defect detection. In power transmission network maintenance, conductor placements and vertical distances on poles are crucial, especially in constructions with vertical placements, which in this study represent 78 % of all pole structures.

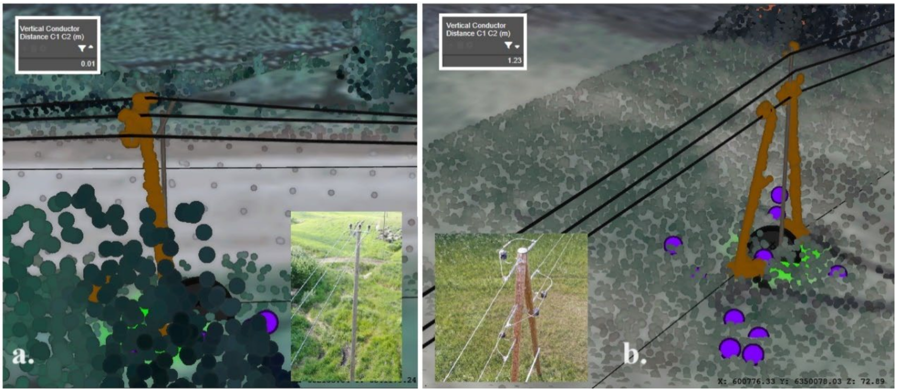


Fig. 5.7.Vertical distance measurement of conductor fittings in Neara software: a. the pole with a horizontal conductor placement type; b. the pole with a vertical conductor placement type.

The study found that the average distance between vertically arranged conductors is 0.93 m, while in triangular configuration structures, it is 0.84 m. Deviations greater than 20 cm were classified as defects, accounting for 0.54 %, which need to be addressed to ensure the safety of the network.

5.2.3.5. Pole Lean Values

Pole lean is a critical parameter that affects the stability and safety of power line infrastructure. During the study, a detailed analysis of pole lean was conducted, covering the following aspects:

- the pole is located outside the alignment axis;
- the pole is leaning in the direction of the line, or tilted in the direction of the line.

The geometric deviations of the poles were determined using the vectorized model to measure the distances between the center of the pole at the ground and the vertical axis at the top, classifying them according to the leaning criteria – either in the direction of the line or off the line axis. The data visualized in Neara software allow for a detailed analysis of the pole tilt deviations by performing the appropriate configuration settings, so that the calculation results are visualized (see Fig. 5.8).

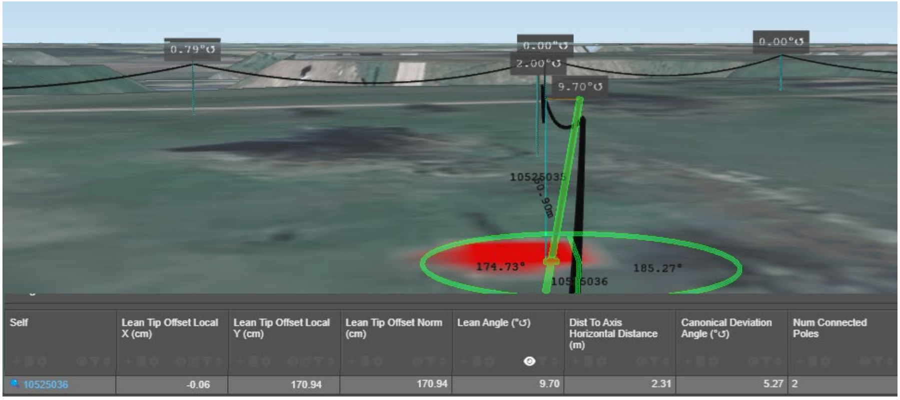


Fig. 5.8. Example of pole lean detection in Neara software.

The study included an analysis of all the poles within the scope, where 68.4 % of the poles had a lean angle of up to 2 degrees and 0. According to JSC "Sadales tīkls" requirements, a lean angle exceeding 7 degrees (as shown in Fig. 5.8.) indicates potential structural instability, which could endanger the safety of the line. The study found that 1.5 % of the poles reached the permissible lean limit, but manual results revealed discrepancies. A detailed analysis concluded that small tilts, which are difficult to detect by eye, were significantly more accurate using LIDAR data compared to manual methods.

5.2.3.6. Vegetation Management in Track Corridors and Protection Zones

The most important factor affecting the operation of power lines is the presence of vegetation in the power line corridor, its growth, and the associated risks. One of the operational tasks of the Latvian distribution network is the clearing of overgrown vegetation along power line corridors, which threatens the safety of the lines. Traditional methods, such as manual measurements and visual inspections every four years, are time-consuming and resource-intensive.

The width and height values for track corridors and protection zones are defined in regulatory documents [45], [46], depending on the voltage level and installation environment of the power line. These criteria establish vegetation management requirements that align with the risk profiles and technical specifications of different voltage levels. They ensure effective vegetation control, maintaining infrastructure safety and optimizing resources. The study determined specific calculation values that will enable data-driven organization of vegetation management:

- S, (%) – percentage of vegetation cover area, indicating the level of vegetation in a given area (span).
- Yes/No – vegetation inclusion in the route indicates the presence or absence of vegetation in the power line track.
- $h_{\text{vert min}}$, (m) – minimum permissible vertical distance between tree branches and wires, measured between two horizontal planes.

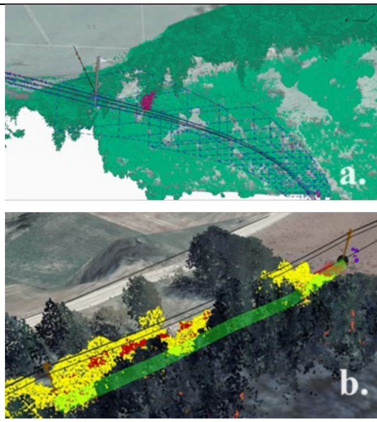
- $w_{\text{horizon min}}$, (m) – minimum permissible horizontal distance between tree branches and the vertical axis of the power line, measured between two vertical planes.
- d_{min1}, (m):
  - 6–20 kV – the closest permissible distance between a tree branch and a power line wire, measured to the branches that are included in the power line track. The outer edge of the track is defined as the conditional vertical surfaces on both sides of the line, starting from the ground and continuing to an unlimited height.
  - 0.4–1 kV – the closest permissible distance between a tree branch and a power line wire in the air, measured from the ground to the horizontal plane of the lower wire. The outer edge of the track is defined as the conditional vertical surfaces on either side of the line, starting from the ground and continuing to the horizontal plane of the lower wire.
- d_{min2}, (m) – for low voltage 0.4–1 kV power lines – the closest permissible distance between a tree branch and a power line wire in the air space, measured from the ground to the horizontal plane of the lower wire. The outer edge of the track is defined as the conditional vertical surfaces on both sides of the line, starting from the ground and continuing to the horizontal plane of the lower wire.

Geometric structures were generated in the Neara software using the vectorized model of power lines, configured according to the requirements of JSC "Sadales tīkls" (Table 5.9). These configurations accurately reflect the layout of the power grid conductors and their relationship with the surrounding vegetation. The data processing results are presented in Table 5.9, where the extent of vegetation within the corridors can also be visually observed for Corridor ID 125462403-7673718. In addition to the calculations, a risk assessment was configured to allow for grading by levels. Risk levels are determined based on the distance from the power lines: the zone within a 1-meter radius of the conductors is classified as a high-risk level (marked in red), while areas beyond 1 meter are considered medium-risk zones (marked in yellow) (Table 5.9).

Table 5.9

Example of a Result of LIDAR Data Analysis of Vegetation Detection

Parameter	Value
Element ID	125462403-7673718
Cable type	A-3 × 70 20 kV, bare wire line
Span length	78.37 m
Investment environment	Land used for agriculture
Track corridor width	13 m
S, (%)	84.73 %
Joining the track	Vertical + horizontal
$h_{\text{vert min}}$	1.22 m
$w_{\text{horizon min}}$	0.15 m
d_{min1}	0.36 m
d_{min2}	0.87m



The accuracy of LIDAR data was compared with manually obtained vegetation assessments conducted by JSC "Sadales tīkls" specialists. The results, presented in Table 5.10, showed the largest discrepancies in the medium-risk (10.30 %) and high-risk (9.09 %) vegetation classifications.

Table 5.10

Comparison of Vegetation Analysis Results

Risk level	**Presence of vegetation in the span**	**Number of spans**		**Coefficient of discrepancy between the results of the two methods**
		LIDAR dataset analysis	**manual inspection**	
No risk	**0–0.2**	6786	6834	0.70 %
Low risk	**0.2–0.4**	779	746	4.42 %
Medium risk	**0.4–0.6**	411	421	2.38 %
Medium-high risk	**0.6–0.8**	182	165	10.30 %
High risk	**0.8–1**	96	88	9.09 %

The inspections confirmed that LIDAR calculations were accurate across all tested spans, with discrepancies primarily arising from human errors (approximately 10 %). This underscores the reliability of LIDAR technology in vegetation risk assessment.

5.2.4. Parameters of Data Processing Implementation

To ensure systematic RGB and LIDAR data processing for the inspection process, an organized workflow is required. This includes data processing coordination, LIDAR and RGB data processing, and technical support. Table 5.11 summarizes the implementation components.

Table 5.11

Organizational Activities for Data Analysis Implementation

Implementation components	**Responsibilities**	**Competencies**
Coordination of data processing	Ensuring RGB and LIDAR data management. Maintaining communication between the data processing and collection parties.	Process management skills. Experience in distribution system infrastructure inspection. Extensive knowledge of BGK operations and flight planning. LVS-EN 50110-1:2013 – electrical safety training.
LIDAR data processing	Quality control and validation of LIDAR data and analysis. LIDAR data processing using specialized software tools. Geospatial measurement. Geospatial feature and defect identification.	Electrical engineering competence – technical understanding of the structure and operation of power lines Experience in distribution system infrastructure inspection. Understanding of LIDAR technologies, their operating principles, and applications. Ability to work with LIDAR data processing software and tools.
RGB data processing	RGB data quality control and validation.	Electrical engineer competence – technical understanding of the structure and operation of power lines.

Table 5.11 (continued)		
	RGB dataset analysis and annotation. Visual defect identification.	Experience in distribution system infrastructure inspection. LVS-EN 50110-1:2013 – electrical safety training.
Interpretation of results	Reporting. Requirements definition and maintenance.	Electrical engineering competence – technical understanding of the structure and operation of power lines. Experience in distribution system infrastructure inspection. LVS-EN 50110-1:2013 – electrical safety training. Ability to analyze and interpret complex data, developing conclusions and solutions. Understanding of statistical methods and analysis principles.
Technical support	Configuration provision Training and evaluating AI models for automatic defect detection. Providing data exchange with other IS.	IS engineer competencies. Practical and theoretical knowledge in data processing, programming languages (Python), machine learning libraries, and tools. Data analytics.

5.2.5. Summary of the Experiment Results

The study validated a method for processing RGB data to detect mechanical damage and visual defects in network elements, as well as processing LIDAR data for performing geospatial measurements to identify spatial defects. As a result, the following datasets were processed within the included polygon:

- RGB dataset of 0.79 TB for identifying mechanical and visual damage to infrastructure elements.
- LIDAR dataset of 4.02 TB for performing geospatial measurements of infrastructure elements.

Table 5.12 provides a summary of the identified number of defects and measurements in the medium-voltage polygon study conducted by JSC "Sadales tīkls", comparing RGB analysis with AI, manual analysis, and LIDAR data analysis in terms of defect count and evaluation.

Table 5.12

Summary of Comparison Results of RGB and LIDAR Data Analysis and Manual Inspection Methods

Type of defects	**RGB dataset analysis** (AI)	**RGB dataset analysis** (manual)	**LIDAR dataset analysis** (massive calculations)	**Manual inspection method, comment**
Visual defect in the technical condition of a network element	654 (number of defects)/	6,126 (number of defects)/	–	6780 (number of defects)
Determination of poles, spatial arrangement	–	–	7803 pole coordinates	Visual assessment, based on the placement's attachment to existing objects in the environment (buildings, trees). The current process has not been fully implemented for the entire volume.

Table 5.12 (continued)

Clearance measurements	–	–	8254 spans	Out of 8254 measurements performed, discrepancies exceeding 50 cm were identified in 15 % of cases. The additional validation process confirmed the accuracy of LIDAR data calculations.
Conductor misalignment	–	–	8254 spans	Manual adjustment of wires, based on visual assessment, was performed only in cases of non-compliant clearance measurements. The detected defects, as identified by LIDAR measurements, were confirmed as accurate but without quantitative values.
The placement of conductors on poles and the distances between conductor fittings	–	–	8254 spans, number of defects – 45	It has not been measured so far, as the manual process is time-consuming.
Pole lean values	–	–	117 poles (over 7°)	In the case of 124 poles with deviations exceeding 7°, discrepancies were checked both on-site and through data analysis, and it was confirmed that the LIDAR data calculations were more accurate.
Vegetation management in track corridors and protection zones	–	–	1468 spans with risk	In the case of 1420 spans with risk, discrepancies were checked both on-site and through data analysis, and it was confirmed that the LIDAR data calculations were more accurate.

5.3. Recommendations for the Implementation of Digital Inspections

To successfully implement digital inspection of the medium-voltage infrastructure (according to the proposed digital inspection solution in Fig. 4.3), based on the conducted experiments, the following recommendations for risk reduction for distribution operators have been developed.

- To improve the inspection of medium-voltage infrastructure, it is recommended to evaluate the existing processes, review the defect catalog, and analyze the inspection tools. Since the digital solution does not ensure the identification of defects at ground level, it is advisable to implement a hybrid model, where digital inspection covers overhead lines and poles, while manual inspection covers elements at ground level and in enclosed spaces. By reviewing the frequency and scope of inspections, resources can be used more efficiently, and defect detection can be improved.
- It is recommended to develop standardized procedures for the digital inspection process, including data collection planning, processing, and analysis. This will ensure more effective coordination, maintain process continuity, reduce errors and repetition, improve the adaptation of AI models to specific tasks, and facilitate an accurate assessment of the infrastructure's condition.
- It is recommended to choose software tools for RGB and LIDAR data processing that automate the detection of damage and anomalies in infrastructure elements. The tools should provide visual defect analysis, geospatial measurements, 3D modeling, and integration with existing systems. The accuracy of processing algorithms, the level of automation, configuration flexibility, and the ability to handle large data volumes (e.g.,

4.81 TB of data for a 650 km line) should be considered, ensuring fast analysis to meet the needs of distribution operators.

- Before implementing the digital inspection, a thorough verification of network elements and defect recognition is required to assess the solution's effectiveness and address any shortcomings. The software configuration and libraries should be improved to ensure accurate data interpretation. Issues identified in the study, such as incorrect pole typology (Fig. 5.9), were resolved after updating the library. Verification helps reduce the number of errors and enhances the reliability of the solution.

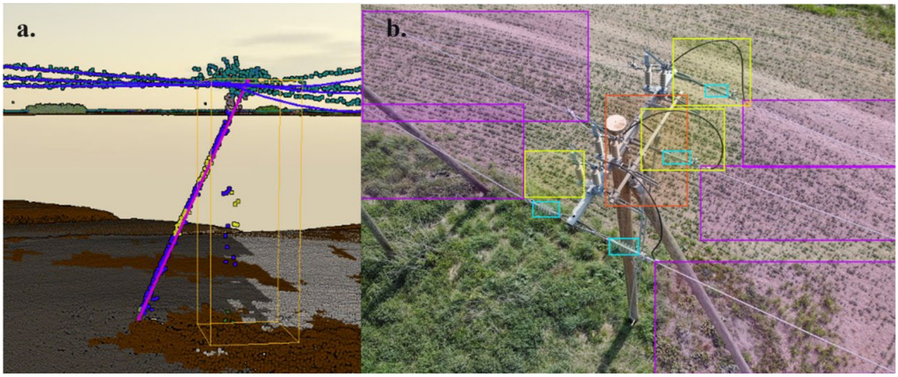


Fig. 5.9. The network element type is incorrectly described: a. result of pole vectorization; b. pole photofixation.

- For the sustainable implementation of digital inspection, investments in data collection infrastructure (UAVs, sensors, equipment), specialized software, and data storage should be assessed, taking into account IT policy requirements. Additionally, maintenance costs should be planned to ensure long-term functionality and continuity, while developing a strategy for the continuous improvement of the inspection process.
- The implementation of digital inspection requires the expansion of employee competencies in data processing, analytics, and information systems, as well as training for UAV operators. Targeted training programs should be developed to ensure employees' ability to effectively use new technologies and make data-driven decisions, thereby improving infrastructure management.

These recommendations foster digital transformation by enabling the implementation of digital inspection and reducing technical risks. Full or hybrid implementation promotes resource planning, optimization, and decision-making based on data analysis, which is crucial for the modernization of the energy sector.

5.4. Summary

This chapter describes the digital inspection solution experiment conducted at JSC "Sadales tīkls" polygon with 650 km of overhead lines, using DJI Mavic 2 Pro RGB data and DJI Matrice 300RTK with YellowScan Mapper LIDAR data acquisition, as well as data processing for assessing infrastructure condition. The technical parameters and methods of data collection are outlined, tailored to meet the needs of the Latvian distribution system operator. Consideration is given to the infrastructure layout, climatic conditions, physical characteristics, and the defect catalog, all of which influence the data capturing requirements.

The study developed data processing methods for infrastructure condition assessment, including visual defect identification and geospatial analysis. During the image processing phase, elements are linked to network components, and annotation is introduced for training artificial intelligence models. Methods for clearance measurements, analysis of conductor and pole placement, as well as vegetation assessment in corridor areas, are proposed. The results are compared with manual inspection data, confirming the effectiveness of the solution in infrastructure management.

The chapter concludes with a summary of the study's results and provides recommendations for risk reduction in implementing digital inspection. The suggestions cover ensuring data capturing and processing, investments in technology and specialist training, as well as strategies for the sustainable development of the solution.

CONCLUSIONS

This Thesis is dedicated to the experimental study of a data-driven method for inspecting the overhead infrastructure of a distribution system operator.

To achieve the set goal – to theoretically explore and practically validate the development of data-driven alternative methods for the technical inspection of the distribution system's medium-voltage overhead infrastructure – the following tasks have been completed:

- A thorough analysis of the literature and existing research on digital transformation and data-driven solutions in the energy infrastructure sector has been conducted.
- The technical maintenance needs of the overhead infrastructure of the Latvian distribution system have been explored, and specific challenges related to the monitoring and control of infrastructure elements have been identified.
- The applicability of various data formats (SAR images, optical satellite and aerial photos, thermal data, infrared data, and point cloud datasets) for assessing the technical condition of the infrastructure has been evaluated.
- Functional and non-functional requirements for data acquisition and processing processes have been developed, taking into account the specific business process needs of JSC "Sadales tīkls" infrastructure inspection.
- An experimental study has been performed on the visual assessment method for the infrastructure's technical condition in the real polygons of the Latvian distribution system operator JSC "Sadales tīkls" to validate the effectiveness and adaptability of the developed solution.
- An experimental study has been performed on the geospatial measurement assessment method for the infrastructure's technical condition in the real polygons of the Latvian distribution system operator JSC "Sadales tīkls" to validate the effectiveness and adaptability of the developed solution.

- Recommendations have been compiled for integrating the developed method into the technical processes of the distribution system operator's medium-voltage overhead infrastructure inspection, based on the case study performed on the infrastructure of the Latvian distribution system operator JSC "Sadales tīkls".

During the study, the possibilities of transforming the manual overhead infrastructure inspection process into a data-driven digital approach were analyzed and practically validated, using current infrastructure object RGB and LIDAR data sets. The results confirm that the application of data technologies significantly improves the infrastructure inspection process, enhancing both accuracy (decision-making in defect identification based on data) and efficiency (data capturing speed, accelerated by the use of UAVs). This ensures a more automated and reliable assessment of the infrastructure's technical condition:

- Visual technical condition assessment – the analysis of RGB datasets allows for the identification of visually detectable defects with a visibility range of up to 2 cm (mechanical damage, structural changes in infrastructure elements). This level of detail for pole structures at the upper level cannot be achieved during manual inspections, thereby improving accuracy through data analysis. The experiment demonstrated that using UAVs significantly accelerates the data acquisition process for identifying visual defects in infrastructure. In the study, RGB datasets were obtained using the UAV DJI Mavic 2 Pro, achieving an average speed of 20 km per day, which is three times faster than traditional manual inspections (up to 6 km per day).
- Geospatial assessment – LIDAR data analysis provides up to 10 cm accuracy in determining the geospatial position of infrastructure elements, including their positioning relative to the surrounding environment and other engineering elements. LIDAR enables precise modeling of infrastructure topology and geometry, identifying potential deviations from allowable parameters (clearance measurements, conductor misalignment, pole lean), where manual measurements would be both time-consuming and less accurate, especially in areas with difficult access. The experiment proved that using UAVs significantly accelerates the data acquisition process for identifying geospatial deviations in infrastructure. In the study, LIDAR data sets were obtained using the UAV DJI Matrice 300RTK, achieving an average speed of 30 km per day, which is five times faster than traditional manual inspections (up to 6 km per day).
- Vegetation assessment – LIDAR data analysis provides a quantitative evaluation of vegetation presence and volume in designated corridor and buffer zones with an accuracy of up to 10 cm, allowing for precise identification of its potential impact on infrastructure. This technology offers significantly higher precision, up to 10 cm, compared to manual inspections, particularly in hard-to-access areas or large protection zones (up to 60 m in forested areas). LIDAR data processing enables detailed measurement of vegetation height, density, and distribution, which is crucial for risk management and network operations. In manual mode, this is technically challenging and time-consuming to achieve.

The obtained results and knowledge promote the development of innovative and efficient technical inspections based on data analysis and modern technologies, enabling the digital transformation of infrastructure inspection processes in Latvia. The proposed hybrid model for JSC "Sadales tīkls", which combines manual inspections with RGB and LIDAR methods, offers advantages in improving sustainable development, environmental management, and resource efficiency, and can serve as a benchmark for other operators.

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