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Innovative techniques for the predictive maintenance of overhead power lines. Practical application in the improvement of efficiency in felling and pruning in Northern Spain

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SUMMARY

Within the OPEX budget, vegetation felling and pruning work is the most important activity for electricity distribution companies. As a general rule, the corridors are treated at fixed intervals along the line as a whole, which leads to low levels of efficiency, given the varied nature of both the vegetation, with its very different growth rates, and the distances from its conductors along the line.

In addition, the new Spanish regulatory framework obliges distributors to seek maintenance optimisation tools that focus on "asset management."

This article describes the methodology applied by a Spanish Distribution System Operator (DSO) to increase the efficiency and effectiveness of its felling and pruning maintenance plans and operations, involving a transition from a cyclical maintenance model to a predictive maintenance model, in which the time between interventions in each span of the power line is maximised in a controlled manner.

The strategy for implementing this approach is based on the use of innovative techniques and technologies, such as LiDAR data and related value-added processing, which considerably increase the efficiency of the actions carried out, and which has to date been impossible due to the lack of high precision and quality information.

The efficiency is improved by means of three key factors:

1. Improved knowledge of the network and the vegetation underneath it

Transportation and distribution companies spend millions of Euros every year on vegetation management, but do not have sufficient information about it to maximise the efficiency of this treatment. With the right information, it is possible to find out where the vegetation is within the network, the area it occupies and its growth rate, and based on these details it is possible to calculate the optimum frequency for the treatments. Furthermore, an enhanced knowledge of the network and the vegetation for the providers of the felling and pruning services will lead to a reduction in the cost of their operations.

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2. Prioritisation of work based on the asset's criticality.

In this article, we examine the "Total Criticality by Risk" method - a semi-quantitative analysis that considers weighted risk factors including industrial safety, the environment, the quality of service, availability and corrective maintenance costs. The result is a hierarchical classification of assets as "critical", "semi-critical" and "non-critical."

Inspection, maintenance and felling and pruning in power electric lines will therefore be prioritised based on a quantified risk due to the inability of the assets to perform their tasks.

3. Focusing the work based on business needs.

The results obtained in the points above will provide extremely valuable information that will ultimately maximise management efficiency in the network, channelling the work of the felling and pruning services provider in a way that is consistent with business needs.

The information will be managed on a centralised basis by means of a felling and pruning Management System based on GIS technology.

The implementation of the strategy presented herein will provide the DSO with an annual saving of 33% in forest works, while at the same time significantly improving their efficiency and digitalisation of the company.

KEYWORDS

Predictive maintenance - Asset management - Improvement of efficiency - Criticality - Vegetation growth - Vegetation management - Risk management - Overhead power lines - LiDAR.

1. INTRODUCTION

The DSO in this article manages a distribution network of around 12 600 km of high and medium voltage lines in northern Spain. This involves the maintenance of approximately 10 400 km of lines, 12 600 km of conductors and more than 76 000 pylons. Bearing this in mind, the maintenance is not only subject to adverse weather conditions, but also a difficult terrain that makes it difficult to access the work point, and once there, determine the type of machinery to be used and even means that the task must be undertaken manually.

Table 1.1 shows the gradients associated with the corridor to be maintained by the DSO distribution network on the left 30% of the high voltage network and 21% of the medium voltage network have a steep or very steep gradient. The accessibility of the assets in the distribution line is shown on the right of Table 1.1, and only 9% of the high voltage network and 28% of the medium voltage network are easily accessible.

Gradients in the corridor in the DSO Distribution network

Type of gradient	HV lines	MV lines
0% - 35%	70%	79%
35% - 60%	22%	15%
> 60%	8%	6%

Accessibility of the DSO distribution network

Type of access	HV lines	MV lines
Normal Vehicle	9%	28%
4-wheel drive vehicle	52%	44%
On foot	39%	28%

Table 1.1.- Gradients in the corridor and accessibility to assets in the DSO distribution network

These two issues make the management and coordination of the maintenance plans more complex, as well as increasing the costs compared to the same distribution network located in a more favourable terrain.

The new regulatory framework obliges the distributor to seek optimisation tools, modulating OPEX costs as much as possible and rationalising investments in CAPEX.

Within the budget of OPEX for the maintenance of the assets in the distribution network, the allocation for the maintenance of the service corridors by felling and pruning vegetation for the five-year period 2016-2020 accounts for between 48% and 63% of the total. As such, optimising the maintenance process for service roads or corridors is a priority for the distributor.

Management of forest works in the DSO has gone through various phases in recent years, ranging from a contract based on fixed treatment cycles to a Service Level Agreement contract, based on technical specifications for the finish and maintenance of the corridor in a variable timeframe. The main conclusions are:

- Annual fixed cycles generate high costs, with over-maintenance taking place in many cases.
- Service Level Agreements require the contractor to have a very in-depth knowledge of the vegetation in each of the lines to be maintained, in order to optimise costs and fulfil the conditions of the contract.

Given the low efficiency of the first option and the difficulty of compliance with the second, the DSO has decided to optimise the felling and pruning activities based on three main areas:

1. Increase knowledge of the network (assets, terrain, vegetation, etc.).
2. Prioritise work based on the asset's criticality.

3. Take control of the work, focusing it according to the needs of the business.

The combination of these three factors will enable an increase in efficiency, and reducing its cost. The anticipated annual savings is 33%.

Each of these three factors is considered in detail below.

2. INCREASE KNOWLEDGE OF THE NETWORK[1]

Vegetation in the vicinity of overhead power lines can represent a hazard for public safety and the environment, and is one of the primary causes of power cuts in the distribution network.

Unlike the other elements that may appear in the area affected by a power line and which may be hazardous depending on their distance from it (crossings, buildings, roads, terrain, etc.), vegetation is a dynamic element that changes over time, and is increasingly close to the conductors as it grows.

There is still a great deal of potential for improved efficiency in forest works as part of preventive maintenance, thanks to the appearance of new technologies and methods that enable data that simply did not exist a few years ago to be analysed, and which can predict the future behaviour of the vegetation and its influence in each location in the network.

Management of the vegetation of the network must be undertaken as a whole, on the understanding that as a dynamic element of the installation, it has higher rates of growth in some places than in others. Accordingly, monitoring and intervention on the vegetation should not be proportional or cyclical, but instead concentrated in the areas that are most hazardous.

This improvement in efficiency will be by means of a "Felling and pruning optimisation plan" to achieve the following objectives:

- Ensure compliance with Spanish national and regional regulations.
- Optimise maintenance costs, moving from an approach involving the cyclical treatment of a complete line to one focused on each span, according to type of vegetation and criticality of the asset.
- Predict as accurately as possible the frequency of the interventions in each span and even the quantification of those interventions, in order to carry out an accurate planning of investments.
- Optimise the selection of the type of machinery to carry out the works according to the type of gradient in the corridor.
- Improve the programming of the works by knowledge of the accessibility to each asset in the network.
- Improve the processing of the annual plan by identifying the organisations affected for each span.
- Minimise the impact environmental of felling and pruning works, and reduce the carbon footprint of the company's work.
- Reduce workplace accidents, as a result of fewer interventions.

The calculation and optimisation of the frequency of the interventions is the key parameter, and is examined in depth in this article.

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[1] The predictive maintenance solution for overhead power lines based on vegetation management referred to in this section has **© All Rights Reserved / U.S.C.O. Reg. TXu 2-049-863, TXu 2-049-923 and TXu 2-051-384.**

Felling and pruning optimisation process

Improved efficiency in the felling and pruning is the result of a series of complex, innovative analyses, in which it is useful to apply a significant technological base so that the starting information is of sufficient quality.

As explained above, one of the parameters that is considered crucial for optimising the forest works needed is the precise calculation (at span level) of the frequency of the interventions. The factors that influence this frequency are as follows:

- Type of vegetation in the vicinity of the power line and its exact location within each span.
- Annual growth rate in vegetation height in each place.
- Terrain relief of the corridor.
- Location of pylons and conductors and safety distances to be applied.

The different phases that are part of the applied methodology for calculating the frequency are presented below:

- **PHASE 1:** Production of a highly detailed vegetation map for all the HV and MV lines in the DSO.
- **PHASE 2:** Modelling of vegetation growth.
- **PHASE 3:** Laying out of the entire network in 3D (assets and terrain)
- **PHASE 4:** Calculation of intervention frequencies at span level.

In addition to this main core of activities, the following points have been developed to further enhance knowledge about the network:

- Mapping of accesses to the HV and MV pylons.
- Identification of the organisations affected by the work.
- High precision mapping of gradients in the entire corridor.

Each of the phases outlined is then is described.

PHASE 1. Production of a highly detailed vegetation map

To undertake an overall management of the vegetation around the electrical installations, it is first necessary to determine the type of vegetation at each point. It is impossible to manage what is not known.

Due to the factors outlined above, it is essential to develop a vegetation map for the entire network. A high level of detail is necessary, as in electrical installations a single tree can lead to an incident that affects the service. If the level of detail of the vegetation map is low, many tree clusters (or isolated trees) will be overlooked simply because they do not have the minimum area for representation on the scale at which the mapping takes place.

A vegetation map for the entire network also provides its manager with information about total wooded areas and scrub, by type, in the entire network. From the strategic point of view, this information is crucial in the design of current and future maintenance plans.

Finally, vegetation mapping provides the basis for modelling vegetation growth rates, thereby enabling an assessment of the danger in the time period studied.

In the mapping produced for the entire High and Medium Voltage network, the vegetation has been classified into several types according to their speed of growth and their subsequent treatment or level of protection, such as riverbank vegetation. It was not considered necessary to reach the level of type of species due to the cost-benefit balance.

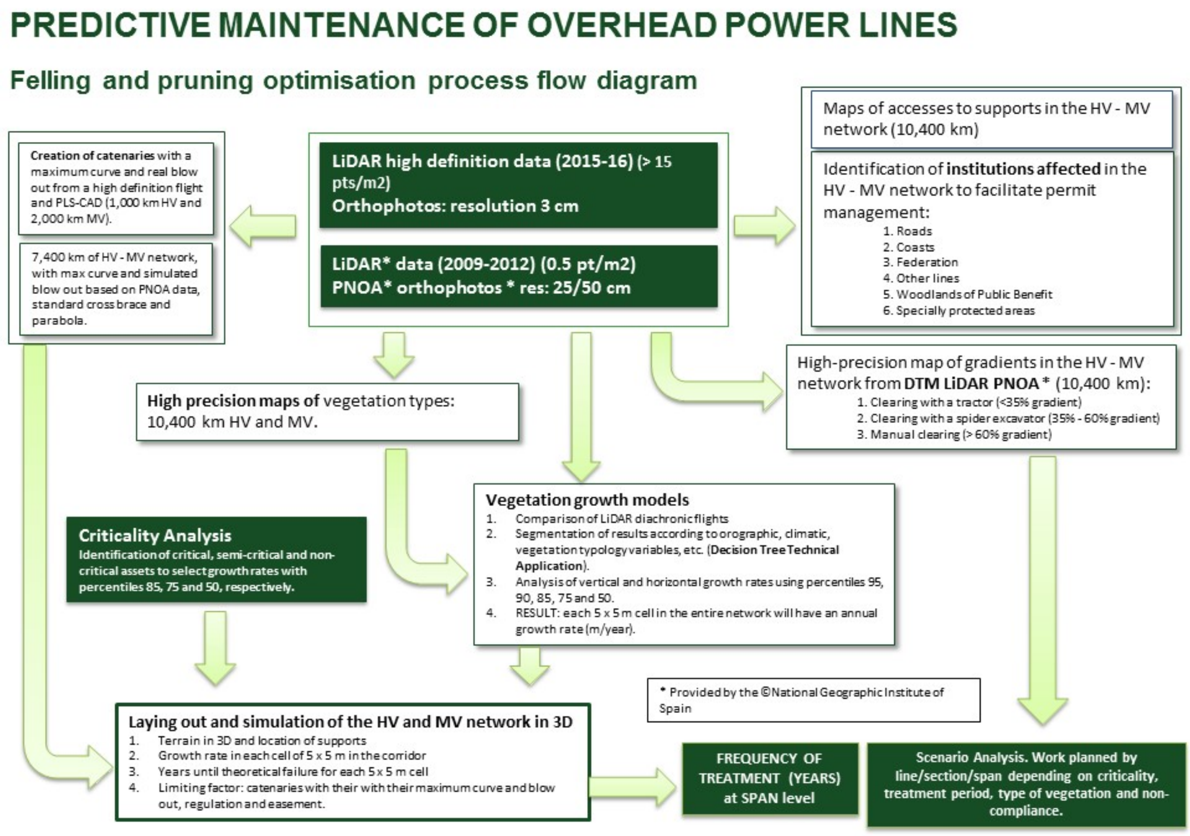

Figure 2.1. Felling and pruning optimisation process flowchart.

The types of vegetation categorised in this case were as follows:

- ✓ Eucalyptus plantations
- ✓ Coniferous formations (including ornamental)
- ✓ Broad-leaved formations (except for riverbank forests)
- ✓ Riverbank forests (considered to be gallery forests bordering riverbeds and streams).
- ✓ Fruit trees
- ✓ Scrub in the corridor
- ✓ Poplar plantations

Closely mixed formations (those consisting of two or more types which cannot be easily separated) were included in the most restrictive category for the purposes of speed of growth.

The results of the mapping show that 43% of the DSO network has vegetation, and is therefore subject to some type of maintenance. However, this vegetation can be divided between 17% scrub and 26% wooded areas. These wooded areas can in turn be classified by type of vegetation as follows:

Type of vegetation	% Wooded
Eucalyptus	18%
Conifers	16%
Broad-leaved	56%
Riverbank Forests	7%
Fruit trees	2%
Poplar plantation	1%
TOTAL	**100%**

Table 2.1.- Composition of the woodland in the corridors of the HV and MV power lines of the DSO

Figure 2.2. Result of the identification of the type of vegetation in a section of line.

PHASE 2. Modelling of the vegetation growth

The objective of this phase of the study is to model the growth of the vegetation so that it can be predicted.

Until now, it has only been possible to produce vegetation growth models based on the very limited information available, normally from a small sample of National Forest Inventory field plots.

However, the appearance of new technologies such as LiDAR (Light Detection And Ranging) makes it possible to measure of the height of trees directly, quickly and over large areas. Accordingly, if diachronic data are available, it is possible to directly measure the height of growth of the existing vegetation in each location on the electric line, and to make much more reliable growth models for the places where there is no diachronic observation.

The methodology applied was the following:

1) Capture of a representative sample of diachronic information of vegetation heights.
2) Identification of variables that may lead to different growth for the same type of vegetation (site index).
3) Generation of models.
4) Extrapolation of the results to the areas where there are no diachronic measurements.

The sample used to produce the models comes from the following initial information:

- LiDAR data from the IGN[2], within the Spanish National Aerial Orthophotography Plan. Density: 0.5 pts / m2. National coverage, except for some areas awaiting delivery. Captured in various years (2009-2012) and applied to 7,400 km of network (71%).
- LiDAR data obtained on flights by the DSO in 3 000 km of network (29%). Density: 15 pts / m2. Captured in 2015-2016.

Hundreds of thousands of diachronic observations were thereby obtained (geospatial big data), which were used to model growth and to predict how the vegetation in each place will behave.

This sample discriminated between groups, using the statistical technique called "decision trees". This method, which is extensively used in artificial intelligence and data mining, consists of segmenting the sample based on the predictive variables that discriminate the variable studied to the greatest extent - growth in this case.

Furthermore, the young states of development of the total sample were isolated to analyse the growth in these initial stages. The reason for this is on one hand, because the growth rate for the height of the trees is in general higher in the early stages than at the middle or the end of their life (meaning that we will be making a conservative estimate) and on the other, because the trees that have appeared since the most recent intervention will do so due to the regrowth of stumps or by regeneration and therefore belong to these young stages.

Figure 2.3 graphically represents the growth value for the observations in the case of 1. Eucalyptus Plantations and 2. Conifers. For each group of vegetation analysed, the graphs compare the height (m) for the trees in the sample in the first *set* of LiDAR data available (year t0) with the growth for each tree during the time period between the two *sets* of LiDAR data available (t1-t0).

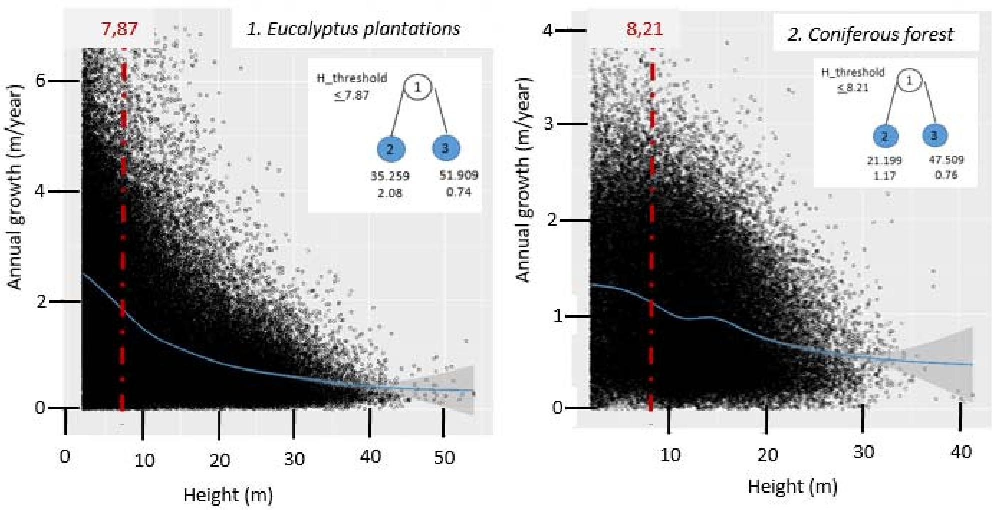

Figure 2.3. Graphic representation of the growth value for the observations in the case of 1. Eucalyptus plantations and 2. Conifers

From the resulting information, the growth was modelled for each vegetation typology, taking into account the variables in each place that affected the site quality and which were significant.

Finally, the growth rates were calculated according to different percentiles, so that in the simulations of growth and calculations of frequency can be conservative to a greater or lesser extent in each location, taking into account factors such as criticality of the lines, for example.

[2] Provided by the ©National Geographic Institute of Spain

The final result will be a georeferenced height growth map (m/year), divided into cells of 5 m^2 for the entire 10,400 km of lines in the HV and MV network of the DSO. This resolution is a result of optimization based on the data density used for this study.

The maintenance manager can apply the growth percentiles that they consider appropriate based on the criticality of each span (increasing or decreasing the level of demand), and can create different scenarios to optimise management.

PHASE 3. Laying out of the entire network in 3D

The aim in this phase is to have a three-dimensional model of the HV and MV network (terrain, pylons and conductors) to project the calculated growth rates of vegetation on it and to thereby obtain the frequency of interventions at span level.

Obtaining 3D installations takes place almost immediately for all the lines flown with high resolution LiDAR.

However, for the other installations, it is necessary to adopt a range of criteria that enable the network to be simulated in three dimensions, characterising the minimum clear height from the land under line design conditions.

PHASE 4. Calculation of the optimal frequency for the intervention

The objective behind calculating the frequency of the interventions for each span is to be able to produce reliable vegetation maintenance plans, and to focus monitoring and interventions on the places where it is really necessary.

The frequency of intervention for each type of vegetation has been established based on the following factors:

- National legal requirements and those of each autonomous community regarding minimum distances between trees and conductors.
- The growth rate of each type of vegetation, defined in the vertical and horizontal growth models described in the previous section.
- The vegetation growth rates were applied to the 3D model of the installations generated to obtain the optimum frequency in each place and for each type of formation.

Based on the work carried out, it is therefore possible to simulate several scenarios everywhere, which will lead to different felling plans with different financial provisions, providing greater control and an evident improvement in the efficiency of the management.

The whole study is the result of analysing 32 273 ha of power line corridors, divided in ca. 13 million cells. Total amount of big data analysed to obtain final results was ca. 800 million records.

3. PRIORITISATION OF WORK BASED ON THE ASSET'S CRITICALITY

In this article we propose the "Criticality by Risk" method for the criticality analysis, which includes the following requirements:

1. The process must be applicable to a large scale of systems in service.
2. As mentioned in the previous point, the scope of the analysis must be the same as the scope for which the actual preventive maintenance programme is developed and implemented;
3. The analysis must support changes in scale adopted to measure the consequences of asset failures (dynamic).

4. The process should allow for new maintenance needs for assets that become critical, as a result of changing operating conditions;
5. The general guidelines for the design of the maintenance strategy are based on the results of the analysis (of the resulting criticality of the assets and the sources thereof) and must be clearly defined;
6. There must be a connection with the business asset management system, which should enable the reproduction of the automatic form of the analysis, with some cadence in time;
7. The process must have been proven in the industry, and the distribution networks, demonstrating good practical results.

Process description

The process that has been applied is following:

1. Determine failure frequency levels;
2. Select the criteria to consider (usually related to the integrity of the assets and the sustainability of the business) and their levels to assess the severity of the functional loss of the asset;
3. Determine of cases of inadmissible consequences of a functional loss;
4. Determine the weights (contribution) of each criterion to the severity of the functional loss;
5. Define the categories of failure severity, or levels, for each criteria to be considered;
6. Obtain frequency data for asset failures;
7. Obtain data for possible effects caused by the functional loss of each element and for each selected criterion;
8. Determine the criticality of the asset for its current frequency;
9. Obtain results (criticality matrix) and guidelines to follow to establish the maintenance strategy by asset.

The first five steps are used to determine the elements that configure the algorithm of the mathematical model which is then used to rank assets, after the necessary data has been captured from the company's systems. Steps 6 and 7 are for obtaining / collecting data. Finally, steps 8 and 9 are for calculating the criticality and presenting the overall results for the set of assets.

Figure 3.1 specifies the five factors used to assess the consequence of the functional loss of the element or failure.

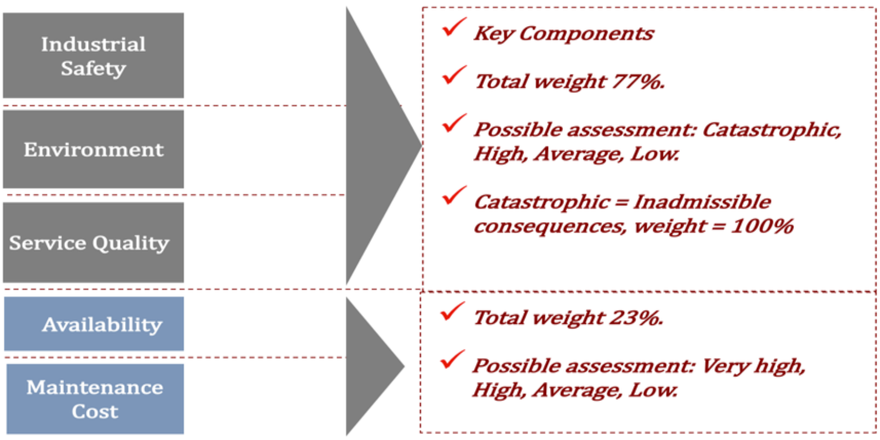

Figure 3.1 Factors to assess the consequence of the element or failure.

As an example of the application of the criticality analysis to DOS's High Voltage (HV) lines, the result was as follows:

- 27% of Critical assets
- 25% of assets are semi-critical
- 48% of assets are non-critical

After the criticality analysis has been applied to the set of assets, it will be possible to:

- Identify critical points.
- Optimise inspection plans.
- Increase the effectiveness and efficiency of corrective maintenance plans.
- Objectively address preventive maintenance.
- Prioritise investment plans.

Once the criticality analysis of all the assets of the HV and MV network has been obtained, it is possible to plan actions based on the risk associated with each line segment, i.e. a reduction in the treatment periods in "Critical" and "Semi-critical" sections based on the type of vegetation, and to increase the treatment periods of "Non-critical" sections according to the vegetation type.

4. FOCUSING THE WORK BASED ON BUSINESS NEEDS

From the operational point of view, it will be necessary to move from a "line" intervention level to a "span" level to optimise the maintenance plans.

The information associated with each span that will be used as the basis for establishing the annual maintenance plan will be as follows:

- Record of measures
- Period of treatment/span
- Criticality of the span
- Defects identified by regulatory inspection or LIDAR review, and complaints issued by an autonomous governmental body
- % of vegetation/span
- Organisations affected
- Gradients in the corridor
- Accessibility of each span

Figure 4.1 describes the management process, in which the main characteristics are as follows:

- Centralised management of work based on GIS technology.
- Planning of work with a five-year timeframe
- Annual work plan, listing actions at span level and including the result of the checks and reviews of the facilities.
- Production by the DSO of detailed proposals for annual action per line/section/span, to be validated in the field by the felling and pruning services provider. Precise measurements of the work units to be carried out, such as m2 of scrub clearing, pruning, pruning at height and felling will be obtained based on the high precision data captured (LiDAR).
- There will therefore be a transition from a complete lack of knowledge about the work to be carried out to an execution within a project, with the work units and measurements to be executed in each specific place.
- Authorisation of any activity not included in the work order.
- Incorporation of the real results of the action in the field into the management system. Planning and monitoring of isolated actions resulting from annual checks, ensuring compliance with legal requirements.

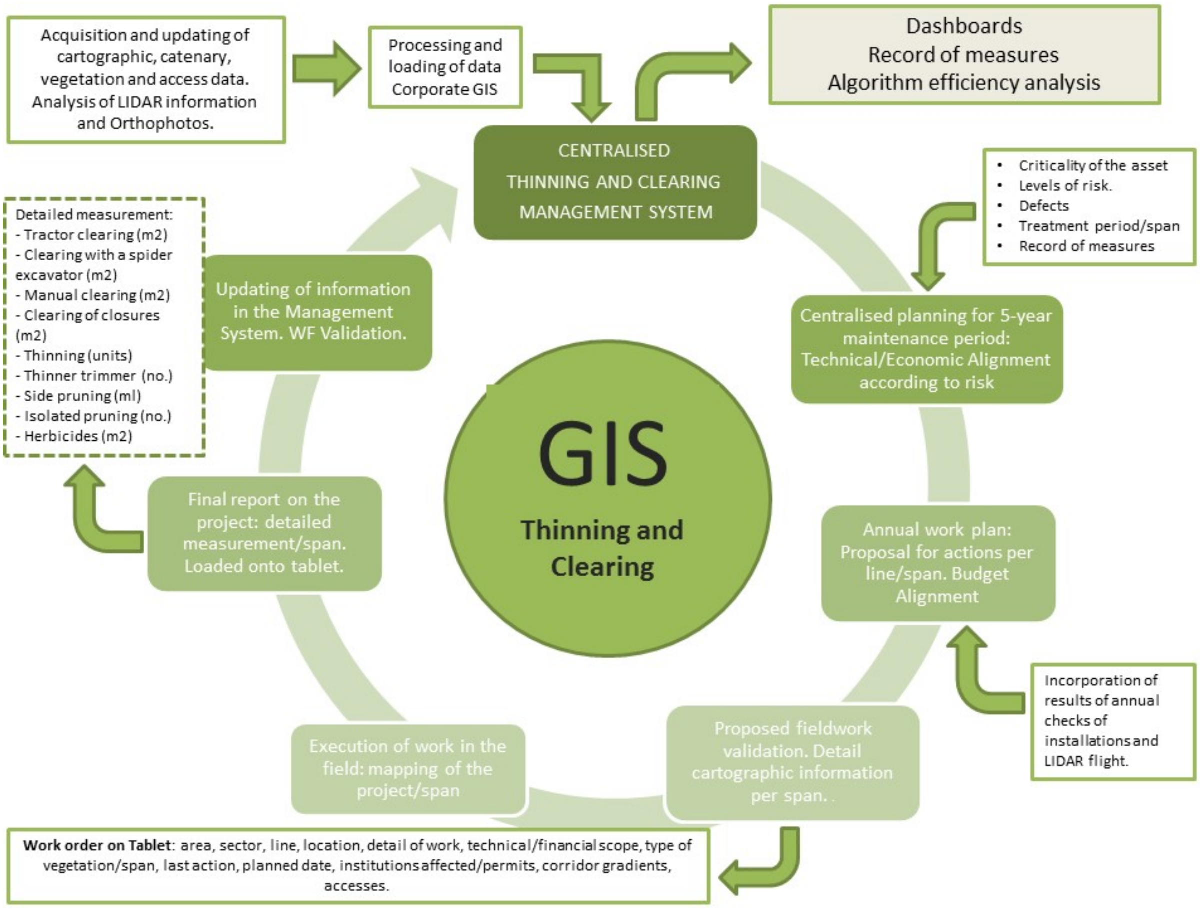

Figure 4.1. Felling and pruning management process

5. CONCLUSIONS / FUTURE CHALLENGES

Increasing the efficiency and effectiveness of felling and pruning is possible by acting in three key areas:

1. Improving knowledge of the network (vegetation, terrain, location of assets, etc.).
2. Applying advanced asset management techniques.
3. Focusing work based on business needs.

The combination of these three factors will optimise maintenance management and achieve **significant savings**, which in the case of the DSO in this study have been calculated at **33% per year**.

To achieve this, it is necessary to invest in the application of new data capture technologies (geospatial big data) and data mining methods to exploit them, as part of a firm commitment to the digitalisation of the distribution or transport company.

For the DSO in this study, it was decided to change the way the regulatory checks were undertaken, so that the assets were checked every 3 years. These checks will be performed with varying frequency, depending on the criticality of the assets and the situation of the vegetation obtained from the sensors that capture the high precision data continuously throughout the network. As this is a legally required verification, the change in the review periods has been agreed with the competent autonomous regional government body. This will increase efficiency considerably, as well as the effectiveness of the work done, by solving the problems identified, ensuring that the work is carried out properly and exactly where it is needed. In addition, the information captured will enable total traceability of the evolution of the problem in the future, giving the DSO a record of its status, and thereby optimising the algorithms for calculating the probability of the problem occurring.

Furthermore, the distribution company can modulate the risk based on its experience, business requirements and even changes to national and regional regulations, thereby improving the company's flexibility and adaptability.

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