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Increasing the resilience of transmission power lines to extreme events

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Abstract

Electricity transmission power lines are critical infrastructures in a country's electrical system, and wildfires represent extreme events that jeopardize their function. In addition, in the absence of proper vegetation management, these infrastructures can be the cause of ignition. The management of vegetation, or fuel, near these structures has specific rules, at least in Portugal, with the objective of protecting the infrastructure itself and minimizing the risk of ignition due to an electrical discharge or the physical contact of the vegetation with the conductors. The extent of the transmission power line network may hinder the application of extensive fuel management actions, and in many cases the trees that falls outside the fuel management that goes with it may also pose a danger.

This work explores the possibility of combining LiDAR with ancillary data and specific algorithms to identify those trees that may put the power line in danger in case they fall due to any external or internal circumstances. As a result of the application of the proposed methodology, it was possible to classify individual trees according to a risk class, as well as critical areas of intervention. With this information the Portuguese company REN, responsible for the transmission power line network, was able to plan and calendarize critical fuel management interventions in trees that fell outside the fuel breaks that they manage, but that posed imminent risk to the infrastructure.

1. Introduction

Urban infrastructures, such as power lines, are sometimes the cause of ignition (Miller et al., 2017; Viegas et al., 2017, 2019), and in case of a wildfire, their extension and diffusion in the landscape exposes them to a high probability of damage (Viegas et al., 2011). Some infrastructures have characteristics that, when hit by a fire, can lead to episodes of great danger. Besides being critical, many of these infrastructures are also strategic, since their affectation can compromise the response to the fire. The power (electric) network, water supply and natural gas infrastructures are good examples of this reality (Ribeiro et al., 2021).

In Portugal, as in many other countries, fuel breaks are maintained in the areas where the power lines are installed. This fuel (vegetation) management strategy aims fundamentally at 1) minimizing the probability of electrical cables producing ignitions, either by contact with vegetation or by discharges to the ground and 2) minimizing the probability of the fire affecting the structure itself, causing interruptions in the power supply. Although the importance of these strips may be higher in medium and low tension lines, because they are usually placed closer to the ground, the high and very high tension (VHT) lines have the same problems (Viegas et al., 2020). The width of these linear strips of fuel management depends on the voltage of the lines, and for the VHT that value is of 10 m for each side, counting from the most external line (Figure 1).

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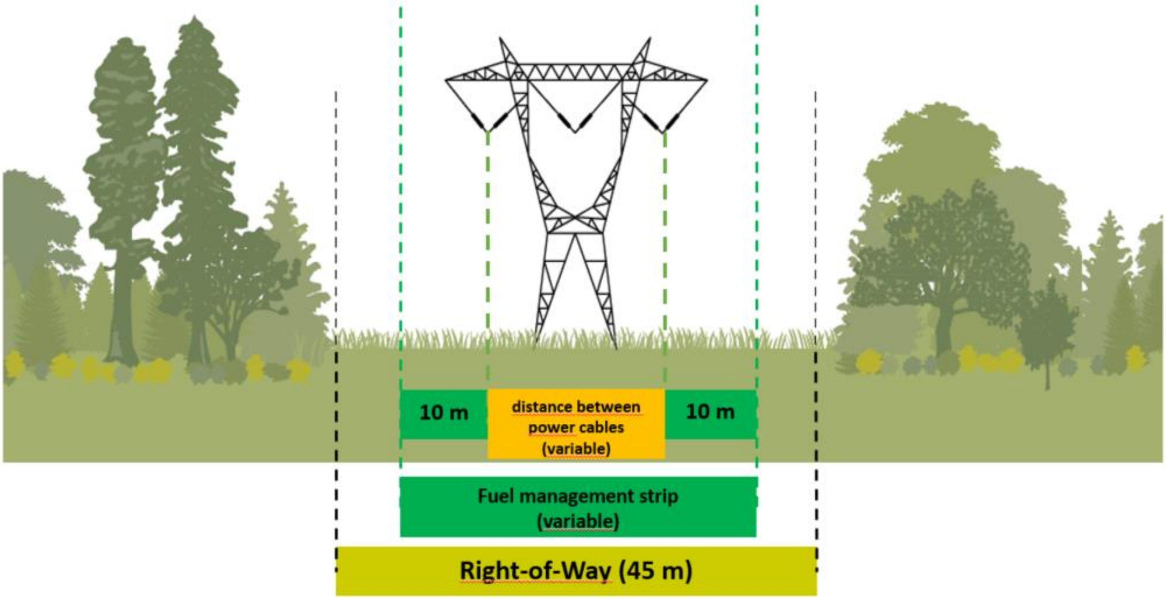

Figure 1. Power lines Fuel management strip vs. power lines right-of-way (RoW).

REN (*Rede Elétrica Nacional, SA*) is the Portuguese Transport System Operator (TSO) and is responsible for the operation and maintenance of the electric transport infrastructures. In their planning they have extended the fuel break width to at least 45 m, more than the legally mandatory distances, in what is called a “right-of-way” (RoW) strip, in a demonstration that their concern with all externalities that may pose danger to the infrastructure is very real. Nevertheless, often they identified several cases with the presence of trees that fall outside these linear fuel breaks that in case of falling, could potentially impact the cables. Trying to identify where and when this could happen was the genesis of this work, proposed to us by REN.

2. Objectives and methodology

The main goal of the work was to identify both individual trees that could impact on the electric power cables and critical areas of intervention where one or more trees could also pose danger to the infrastructure. The reason for having both outputs was to have a redundant mechanism, as the identification of individual trees may be subject to errors. Having in mind that the current fuel management is implemented in the RoW strip of at least 22.5m for each side of the line axis, it was a requisite that the analysis should be performed in an extension of that strip until 40 meters were reached (also counting from the axis of the line). The methodology consists in a series of algorithms implemented a sequence of models in ArcGIS Pro, allowing for a semi-automatization of the process of identification. It is based on the analysis of LiDAR and other ancillary data, mostly the possibility of identification of each pixel’s height to the ground. Generically, for each point on the terrain of the analysis area, a critical tree height was calculated, from which, in case of a fall, trees may eventually contact the power line. The critical tree height is nothing more than the height relative to the ground of each pixel of the vegetation height layer created during the processing phase ($H_{critical\_pixel}$ in Figure 2). For this purpose, the height of the vegetation in the analysis area, the height of the lower power line and its maximum deflection (corresponding to the maximum arrow), i.e. the maximum deviation that the line can assume in relation to an imaginary line horizontally joining the two supports where it is inserted (Figure 3), were taken into account.

Figure 2 schematically presents the reasoning behind the process described and Figure 3 illustrates the concept of “maximum arrow”.

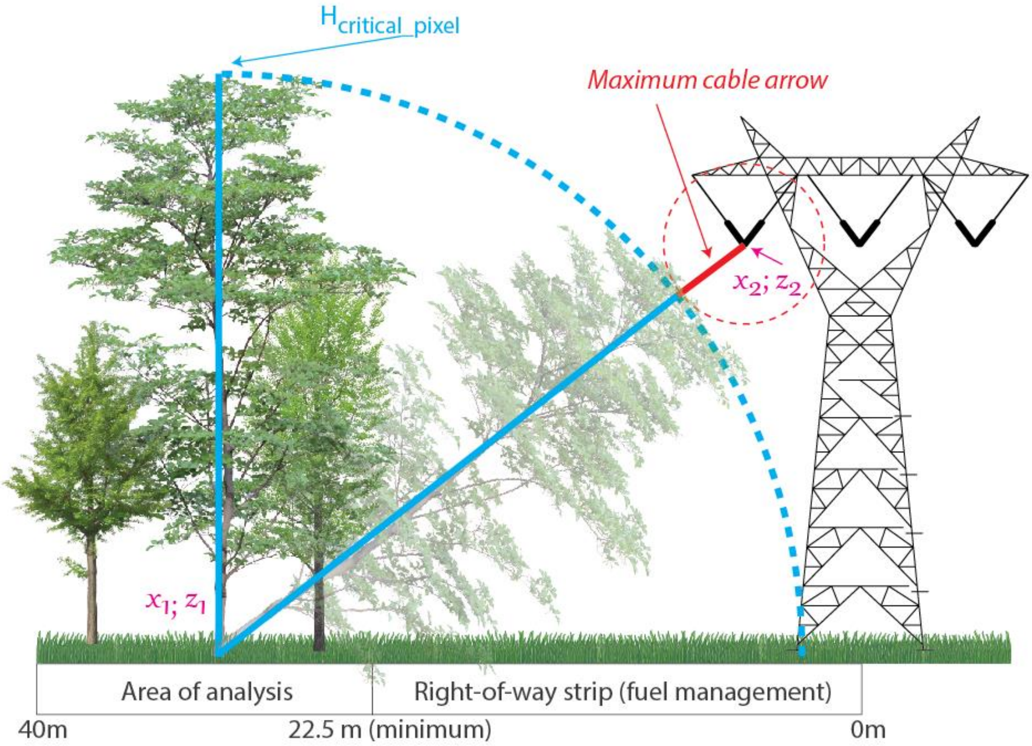

Figure 2. Simplified scheme of the relationship between critical vegetation height and maximum arrow (deflection).

The critical height was considered to be the height at which, if the tree falls, the curve it describes will cause it to touch the line, considering its arrow in the position closest to that curve. We also assumed the worst case scenario, i.e., that the tree falls with its axis of rotation at the point of contact with the ground, towards the line, while the cable wobbles with maximum deflection in its relative position on the line, towards the tree. Note that no whiplash effect was considered, although it can happen. Also, to simplify the algorithms, all power lines were considered to be of the same type (*Zambeze*) and the power line deflection to be in straight lines, forming 2 triangles between the imaginary straight line connecting the poles (black line connecting them in Figure 3) and the point of maximum deflection where the cable arrow is maximum (dashed blue line in Figure 3). The possible errors incurred by these assumptions are not significant in the overall analysis and having straight lines allows for the establishment of trigonometric relationships in the process.

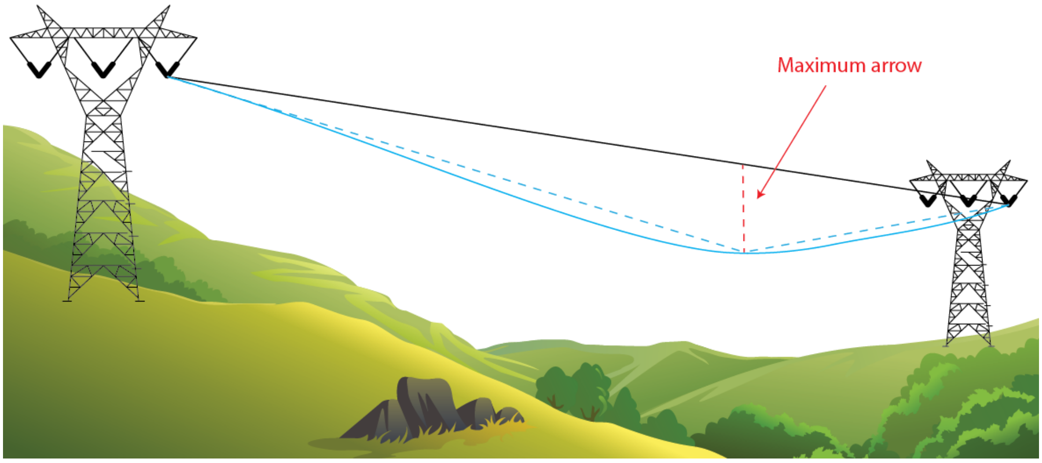

Figure 3. Concept of maximum arrow of deflection.

The calculation of this critical tree height, or pixel height, was performed using Equation 1.

$$\boldsymbol{H_{critic\_pixel}} = \sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2} - maximum\ arrow \qquad \textbf{\textit{Equation 1}}$$

Where

x_1 – Horizontal coordinate of each pixel to be analyzed, perpendicular to the line at point x_2.
x_2 – Horizontal coordinate of the line at each point, at the intersection location of a perpendicular of the line with the pixel being analyzed (x_1).
z_1 – Altitude of each pixel (= real height above ground).
z_2 – The actual altitude that the line assumes at the intersection location of a perpendicular of the line with the pixel under analysis.
$maximum\ arrow$ – Maximum distance of the horizontal line joining the two fixation points at the tangent to the maximum arc it actually makes.

Data preparation involved several consecutive operations, modelled in ArcGIS, and a brief resume is shown here.

2.1. Preparing and homogenizing data

The collected data from all lines was analysed for inconsistencies and stored with a common reference system in specific Geodatabases. The main datasets used were vectorial data from electric towers and power lines, alphanumeric data for tower characteristics (total height, height of cable insertion, dimension of cable connectors and width of cables insertion in relation to the axis) and LiDAR data.

2.2. LiDAR analysis and processing

The LiDAR data processing was divided in three steps. First the production of the raster layers for elevation (DEM), surface (DSM) and object height (or canopy height in the literature, CHM), based on the methodology described in ESRI (2020). This step included the metadata analysis, the quality assessment and the masking of the analysis area. The second step related to the individual trees identification, and was based on processes described in the existing literature, e.g. Popescu & Wynne 2004, Khosravipour et al., 2014 and Millikan et al., 2019. Finally, a visual inspection on LiDAR analysis, eliminating false positives, such as roofs, communication or electric towers, or other artificial or natural structures that were not trees. Figure 4 shows, from left to right, a) the insertion of one tower (yellow and black dot), the power line (orange line), the analysis area (red lines), b) the object height layer (CHM) and c) the individual trees identification prior to the visual inspection, showing the misidentification on roofs.

Figure 4. Example of the CHM and individual tree identification.

2.3. Powerlines and towers data processing

The maximum arrow for each line segment between poles was calculated following Sequeira (2009) and REN (2016). To achieve the best resolution possible in the final analysis, the power lines were then split into 1 m segments (to match the resolution of the DEM) and each segment was parametrized with all the needed variables for the models' calculation. Also, the towers were characterized with the needed parameters. Using trigonometric relations, the following variables were calculated: altitude of each 1-meter segment (z_2), distance of each 1 meter segment to the axis of the line (x_2) and the maximum arrow in each 1 meter segment (taking into account the real altitude of insertion of each tower).

2.4. Buffering variables to the analysis area

For the analysis of the possible intersection of the cables with the trees a raster processing methodology was adopted. The analysis area was populated with the variables needed at 1 meter resolution, with a process of buffering all the 1-meter segments of the power lines. The process was repeated for all the needed variables, creating as many raster files.

3. Results

The critical height of each pixel was calculated according to Equation 1 for each 1-meter cell of the analysis area. This height refers to the height a pixel should have (in this case the tree that stands on it) to impact on the power line in case it falls and in the worst possible conditions. The resulting raster layer with the critical height was then compared to the actual height of each pixel to assess if the trees were in fact posing a threat to the line, i.e., if the pixel was critical or not. The value of this critical pixel is the difference, in meters, between the height a tree should have to impact the line (if falling) and its real height. A risk scale was created assigning to each class a priority of intervention, as depicted in Table 1, allowing for the classification into critical areas of intervention.

The results of the analysis were obtained in the form of a raster layer for the critical areas of intervention and a vector layer for the individual critical trees. The critical height for each vector point was obtained from the respective raster layer.

Table 1. Risk levels, critical pixel value and priority of intervention.

Risk class	Risk	Critical pixel value (Pc)	Interpretation (in case a tree falls, for the worst scenario)	Priority of intervention
N/A	None	$Pc < -7$	No risk/no trees at risk of collision with the line	Ignored
I	Low	$-7 \leq Pc < -5$	Tree has to grow at least 5-7 meters to reach the line	4
II	Medium	$-5 \leq Pc < -3$	Tree has to grow at least 3-5 meters to reach the line	3
III	High	$-3 \leq Pc < 0$	The tree is at the limit of being able to reach the line or not	2
IV	Very high	$Pc \geq 0$	The tree has a height equal to or greater than the critical value from which it can hit the line	1

Figure 5 shows the result of the identification process, in the same area as the earlier example. From left to right we can see *a)* the raw critical pixel evaluation (the colours are merely indicative), *b)* the critical areas of intervention, as reclassified based on Table 1 (with the colours of the classes), and *c)* the respective critical trees.

Figure 5. Example of the processing results.

In total, 11 power lines were analysed, in a cumulative extension of more than 600 km and with an area subject to analysis of more than 2000 ha. Table 2 resumes the results for the priority of intervention 1 and 2.

Table 2. Resume of the results for priority levels 1 and 2.

Line	Entension (Km)	Analysis area (ha)	Area of intervention in priority 1 (ha)	Area of intervention in priority 2 (ha)	Number of trees in priority 1	Number of trees in priority 2
1	98.9	296.75	3.61 (1.22%)	3.81 (1.28%)	2137	2075
2	83.56	290.7	2.82 (0.97%)	2.48 (0.85%)	1729	1405
3	85.26	256.7	4.92 (1.92%)	3.81 (1.48%)	2994	2314
4	99.39	300.4	1.59 (0.53%)	1.39 (0.46%)	794	813
5	59.57	194.9	2.42 (1.24%)	1.44 (0.74%)	1155	580
6	21.18	63.9	1.18 (1.85%)	0.62 (0.97%)	553	568
7	75.54	226.6	1.51 (0.67%)	1.29 (0.57%)	709	753
8	23.25	70.2	0.41 (0.58%)	0.34 (0.48%)	216	176
9	34.49	130.4	3.40 (2.61%)	1.12 (0.86%)	1302	433
10	29.4	88.2	0.23 (0.26%)	0.31 (0.35%)	143	155
11	32.87	98.6	0.79 (0.80%)	0.67 (0.68%)	325	289

About 1.13 % of the total area was deemed as posing level 1 danger to the power line infrastructure, i.e., immediate risk of contact in case of falling. A total of 39205 trees were identified, being 12057 in class 1 and 9561 in class 2.

4. Validation and application

The validation of the methodology was performed by a series of field visits to the identified critical areas. In those areas, the critical trees were visually identified, and its height measured with a digital laser hypsometer. A total of 103 trees were visited and the relation between the observed and predicted height resulted in a R^2 of 0.98, which is representative of the good accuracy of the methodology. In terms of identification of trees, in some cases we identified points that were very close and referred to the same tree. This highlights the value of also producing the results as a raster of critical areas.

Since this work was developed, REN used the results to implement extraordinary fuel management actions in the areas identified, consisting of individual trees extraction (Figure 6), hence increasing the resilience of its infrastructure. Until now around 35500 trees were removed, but the work is still ongoing.

Figure 6. Example of an individual tree extraction, after being identified as critical.

5. References

ESRI. (2020). Data area delineation from lidar points—Help | Documentation. https://desktop.arcgis.com/en/arcmap/latest/MANAGE-DATA/LAS-DATASET/LIDAR-SOLUTIONS-DATA-AREA-DELINEATION-FROM-LIDAR-POINTS.htm

Khosravipour, A., Skidmore, A. K., Isenburg, M., Wang, T., & Hussin, Y. A. (2014). Generating pit-free canopy height models from airborne lidar. Photogrammetric Engineering and Remote Sensing, 80(9), 863–872. https://doi.org/10.14358/PERS.80.9.863

Miller, C., Plucinski, M., Sullivan, A., Stephenson, A., Huston, C., Charman, K., Prakash, M., & Dunstall, S. (2017). Electrically caused wildfires in Victoria, Australia are over-represented when fire danger is elevated. Landscape and Urban Planning, 167(July 2016), 267–274. https://doi.org/10.1016/j.landurbplan.2017.06.016

Millikan, P. H. K., Silva, C. A., Rodriguez, L. C. E., Oliveira, T. M. de, Carvalho, M. P. de L. C. e, & Carvalho, S. de P. C. e. (2019). Automated individual tree detection in amazon tropical forest from airborne laser scanning data. CERNE, 25(3), 273–282. https://doi.org/10.1590/01047760201925032630

Popescu, S. C., & Wynne, R. H. (2004). Seeing the trees in the forest: Using lidar and multispectral data fusion with local filtering and variable window size for estimating tree height. Photogrammetric Engineering and Remote Sensing, 70(5), 589–604. https://doi.org/10.14358/PERS.70.5.589

REN. (2016). Planeamento e Engenharia Projeto. Abertura da Linha Palmela – Fanhões, a 400 Kv para a Subestação de Alcochete. Memória Descritiva (Rev. 1).

Ribeiro, L. M., Viegas, D. X., Almeida, M., Alves, D., Barbosa, T., & Modarres, M. (2021). Planeamento da gestão de combustíveis : Efeito da distância e da frequência das limpezas na proteção das estruturas e rede viária. Relatório do Projeto financiado pela AGIF ao ForestWISE e subcontratado ao Centro de Estudos sobre incêndios Florestais da ADAI (Universidade de Coimbra).

Sequeira, N. (2009). Projecto de Linha Aérea de Alta Tensão conforme a norma EN50341-1. Relatório de Projecto Realizado No Âmbito Do Mestrado Integrado Em Engenharia Electrotécnica e de Computadores Major Energia. FEUP.

Viegas, D.X., Ribeiro, L. M., & Rossa, C. (2011). Incêndios Florestais (D.X. Viegas (ed.)). Verlag Dashöfer.

Viegas, Domingos Xavier, Almeida, M. A., & Ribeiro, L. M. (2020). Faixas de gestão de combustíveis. In M. J. Antunes, D. Lopes, & C. Oliveira (Eds.), Florestas e legislação: Planos Municipais Da Defesa Da Floresta Contra Incêndios. Instituto Jurídico Faculdade de Direito da Universidade de Coimbra. https://www.uc.pt/fduc/ij/publicacoes/pdfs/EbookFlorestas2019pdf

Viegas, Domingos Xavier, Almeida, M. A., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Rodrigues, A., Ribeiro, C., Lopes, S., Jorge, H., & Viegas, C. X. (2019). Análise dos Incêndios Florestais Ocorridos a 15 de outubro de 2017. https://www.portugal.gov.pt/pt/gc21/comunicacao/documento?i=analise-dos-incendios-florestais-ocorridos-a-15-de-outubro-de-2017

Viegas, Domingos Xavier, Almeida, M. F., Ribeiro, L. M., Raposo, J., Viegas, M. T., Oliveira, R., Alves, D., Pinto, C., Jorge, H., Rodrigues, A., Lucas, D., Lopes, S., & Silva, L. F. (2017). O complexo de incêndios de Pedrógão Grande e concelhos limítrofes, iniciado a 17 de junho de 2017. Centro de Estudos sobre Incêndios Florestais (CEIF/ADAI/LAETA). https://www.portugal.gov.pt/pt/gc21/comunicacao/documento?i=o-complexo-de-incendios-de-pedrogao-grande-e-concelhos-limitrofes-iniciado-a-17-de-junho-de-2017