A time and space framework for overhead grid maintenance optimisation

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This paper introduces a framework for the optimisation of high voltage grid maintenance combining data from project, asset management, inspection, remedial actions and audits. This framework is based on geo-referenced and time-changing databases and probabilistic models for asset condition and risk management.

1. Motivation

Electrical grid operators have been struggling in recent years to deploy new lines to meet demands for more energy and higher quality of service. Regardless of their success in that endeavour, every grid operator is now asked to push the use of existing lines until the limits of safety.

Defining grid maintenance as a cycle of processes that keeps the electrical grid running includes inspection, quality and condition audits and remedial actions. The proposed framework to optimise this cycle features an architecture and a tool set to aggregate data and methods from different sources into a consistent model for grid maintenance. Figure 1 shows one model of the cycle with twelve main tasks, organised as a clock dial, where green background represents field tasks and sand background represents office tasks.

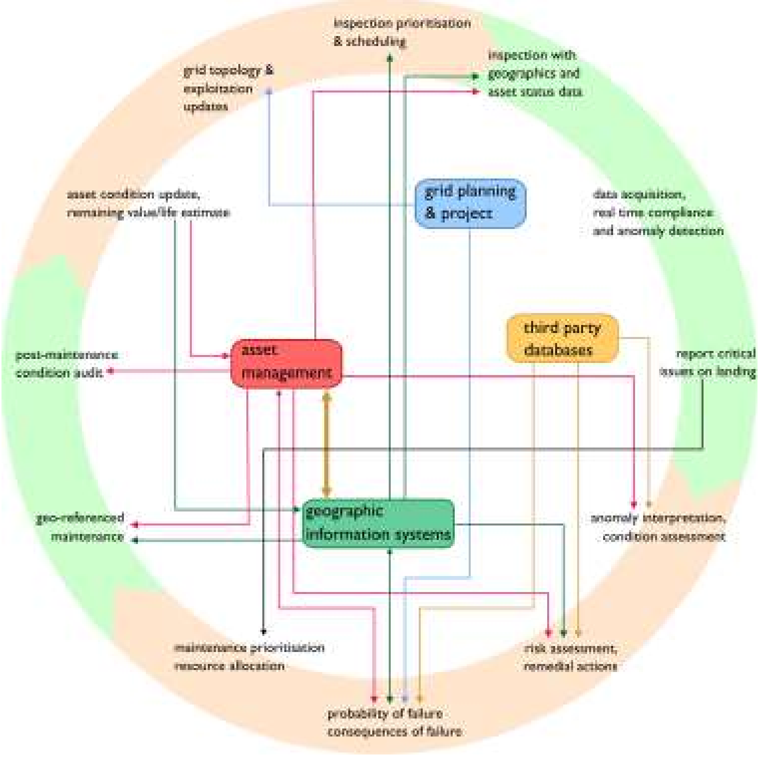

Figure 1 - maintenance cycle

Entering the cycle at one o’clock, there is the over-head line (OHL) inspection. Asset management data is used to highlight previous known issues and features of each element that are relevant for inspection while geographic information systems (GIS) help inspectors find the right lines to inspect and plan optimal routes.

At two o’clock, there is data recording with space and time stamps and real time issue detection, as an option. The latter is used to help inspectors optimise the procedures according to the perceived condition of the line, triggering a thorough review of any candidate issue [1]. Moreover, real time allows for critical issues to be reported just after the inspection (3 o’clock), which is decisive for contingency operations.

Back to the office, experts perform a detailed analysis (4 o’clock), comparing faulty elements with similar ones from asset data and third party sources to estimate its current condition. The next step (5 o’clock) is quite innovative and not yet implemented in many utilities. It involves assessing the risk associated with each issue as a function of the degree of non-compliance. Since risk encompasses many aspects (performance, reputation, safety, sales, ...), for each type of issue there is a function of risk. A human expert based approach, termed Condition Based Risk Management [1] was introduced for mechanical and wear issues by EA Technology, while the authors favoured an automatic approach to risk vegetation management [3].

Converting risk into probability of failure and estimating the consequences of failure is the most novel task (6 o’clock). It aggregates data from all information systems to compute the most complex models. The first step is to estimate the effects of single and combined issues in a single OHL; the second step is to compute the aggregated risk across the grid, taking all potential risks into account. All solutions found for this task involve past empirical statistics or educated heuristics.

The prioritisation of maintenance (7 o’clock) is based on criticality reports, costs of maintenance and distances between neighbouring issues computed from GIS. Some practical approaches are commonly found but a rich framework allows optimal solutions to the multi-variable “travelling salesman problem”. The field maintenance is the next, universal step (8 o’clock); however, enhancing it with geo-referenced data increases the process efficiency and reporting. The audit to the maintenance action (9 o’clock) is sometimes simultaneous with maintenance, depending on local practices and the nature of issues repaired. Returning to the office, asset managers conclude their role updating the grid condition after maintenance on their information systems as well as on GIS (10 o’clock) and their net asset value and remaining lifetime. This task is homologue to the condition assessment at 4 o’clock. Half the cycle (from 5 to 10 o’clock) was dedicated to optimisation remedy (=maintenance) while the other half is dedicated to the optimisation of diagnostics (=inspection).

Finally, It is necessary to update the grid topology as new lines enter service and others are uprated (11 o’clock). Defining an optimal route and scheduling for the next round of inspections is the last task (12 o’clock). The information infrastructure supporting this cycle involves other departments (not shown) and it is summarised by the thick gold arrow uniting GIS and asset management.

2. Architecture

Our architecture consists of a server with connections to geographical information systems (GIS) and asset management systems, running modular applications, with access to relational databases implemented over PostgreSQL, and with http-based communication.

Inspection reports, as well as tower coordinates, or characteristics of the electrical lines, may thus be provided to external authorized users, such as service providers. It is also possible to validate reports and upload new ones.

There should be two databases with information supporting the desired applications and possible future ones: 1) a database containing the electrical grid topology, with all its relevant components and features; 2) a 'lower-level' database containing the raw data produced by line inspections, such as vegetation management, equipment faults, navigation systems data, and so on.

The 'topology' database contains information concerning four categories. Without intending to delve into the details, the current schema is shown in Figure 2, where each of the categories corresponds to a different rectangle region. Some regions overlap and, of course, are related to others:

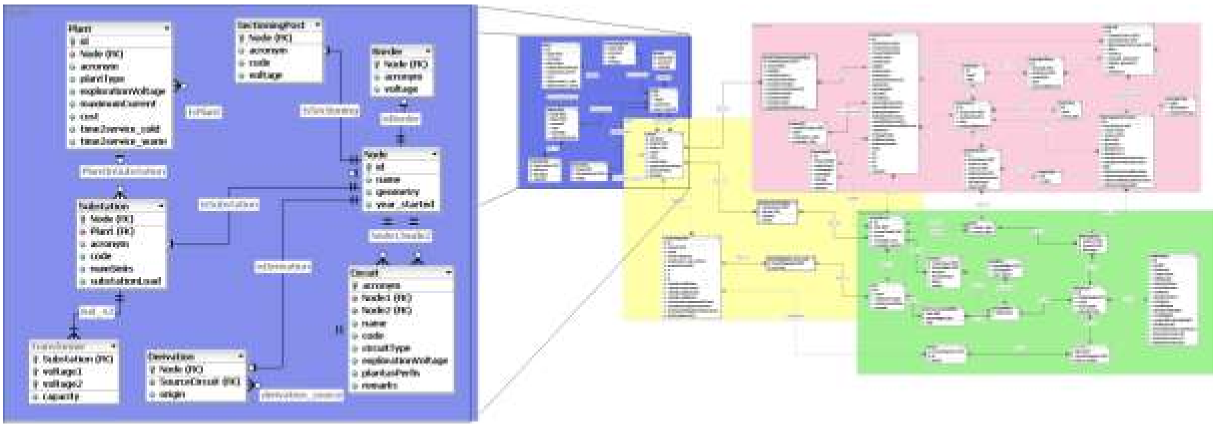

Figure 2 – Database schema

1. Graph (blue & zoom): the grid topology itself, which defines a graph with nodes such as substations, plants, or sectioning posts, and where arcs are the electrical circuits connecting two nodes.

2. Lines (yellow): aerial lines carrying the electrical circuits, with their towers and respective numbers. Includes also underground circuit segments, and electrical characteristics.

3. Assets (green): towers and wires as grid assets, with their characteristics, their use, and their relations.

4. Inspections (pink): general part of inspections already performed, containing identification, and processed data, such as identified towers, wires, environment, and anomalies. Historical data lies mainly in this category.

On the left of Figure 2, the 'Graph' region is magnified, as an illustrative example. Electrical circuits are the graph arcs, connecting two nodes, with some exploitation voltage. Each node has geographical data and can be either a substation, or a plant (if not part of a substation), or a sectioning post. It can also be a simple derivation from some circuit. Border nodes are also considered when lines reach a different country to allow for cross border energy trade. Notice that substations are also modelled with transformation capacities between different voltages, via the *Transformer* table. This part of the database allows performing global analyses of the grid, calculating critical paths, for instance.

3. Toolset

Once the architecture has been deployed, tools that address every issue are required. Given the wide span of issues found on OHL it is important to formalize a common set of features all tools should share to keep them consistent:

Modularity

The tools should follow the modular structure of the database so that every function or set of functions can be changed without modifying related data.

Quantitative, probabilistic outputs

Although many of the available inputs and desired outputs are tacit or qualitative, an effort should be made to express all of these in numerical forms, using stochastic variables where appropriate, so that different modules can be compared and merged or grafted on different sections of the grid model.

Independence

The functions or procedures associated to each tool should be kept autonomous of the underlying data, to the maximum possible extent. This allows competitive tool development and benchmarking and incremental innovation on the tools. Independence also promotes better and more thorough tool specifications.

Traceability and benchmarking

It should be possible to “trace-back” every result and every operation to each method used to a) benchmark results; b) correct errors, c) analyse the sensitivity of the tools to parameters or data variations, and, ultimately, d) refine methods.

The most innovative tools being developed focus on tasks depicted at 4 to 7 and 12 o’clock in Figure 1. We briefly outline some of them to show the practical aspects of the framework:

Pattern matching (condition, 4 o’clock)

Once the time and space database contains every issue found with links to asset management and maintenance audits, it is possible to search for patterns in the whole set of issues recorded. Matches in different fields (examples: manufacturer, time of day, pollution, line load) can then be detected by data crunching, highlighting common factors hitherto unnoticed.

Timeline (condition, 4 o’clock; risk, 5 o’clock; remaining value/life, 10 o’clock)

Some issues progress over time and are noticed long before remedial action is taken. For instance, vegetation growth and mechanical faults detected by thermography are monitored so that one can project evolution timelines and determine the optimal time and scope of remedial actions. Post-maintenance audits and fault reports benchmark the timelines against reality and remaining value/life estimates are refined as a consequence.

Difference detection (inspection, 1 o’clock; condition, 4 o’clock; risk, 5 o’clock)

Let us assume a given issue has been detected and no remedy action occurred. If the next inspection fails to detect the issue, this difference opens two lines of reasoning: a) inspectors failed to use the best methods, thus inspection should be audited and enhanced; b) some missing element concealed or destroyed the issue: the pattern matching analysis should detect such candidates, and risk assessment will consider their influence. In either reasoning, it is useful for inspectors in the field to have access to asset status to ensure known issues are not missed[1]. If maintenance has occurred, inspection acts as an *ad-hoc* audit: missing issues validate maintenance, while resilient issues denote underlying causes that were not tackled by remedy actions.

Condition based risk estimation (advance from 4 o'clock to 5 o'clock)

Most companies are seasoned in condition estimation of all their assets. However, estimating the risk associated to each condition issue is a rarer task, sometimes performed on after-fault diagnosis or laboratory trials performed in samples of the equipments. Depending on the issues, it may involve the quantification of tacit knowledge of linemen, environment modelling, weather statistics, *etc.*. Extending this knowledge to a whole grid involves wrapping each asset subject to each sort of fault with a model of the environment as rich and detailed as possible.

Sometimes, risk is only reviewed after a fault caused by a seemingly constant condition that previously caused no faults. For instance, line sag is moderately affected by plastic elongation and this contribution is stronger on lines subject to sudden load variations. If the dispatch strategy of a given line changes for some reason, a previously faultless line could trip unexpectedly due to excessive sag.

Probability of failure based on risk estimation (advance from 5 o'clock to 6 o'clock)

While risk estimation is good enough for many line managers to drive maintenance decisions, the ultimate resource allocation criteria for grid management are probabilities and costs of failure since their toolset reaches beyond maintenance (in addition to multiple maintenance strategies one can opt for new lines to reinforce reliability instead).

The method to translate issue risk estimation into local probability of failure may be based on statistics of past events, heuristics or models on how issues change with operational scenarios[2]. The next step, integrating local probability of failure into the whole grid analysis, is easier to express formally using probability laws but eludes analytic expressions for any but the most basic grid, calling upon numerical simulations and algorithms. Results are trustworthy only if they cope with the many factors affecting the line and if they predict the behaviours observed in the grid.

Maintenance resource allocation (7 o'clock)

Maintenance targets are often set as "how to maximise quality of service (or minimise the probability of failure) with a given budget or, symmetrically, minimise the budget that meets a specified quality of service (or risk factor, or probability of failure). The nature of issues determines the maintenance methods; whenever these are independent, the optimisation strategy may be restricted to a single

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[1] Some inspectors dispute this approach; they say there is the risk that one keeps looking for known issues instead of inspecting the line with a "fresh view".

[2] This field has so many unknowns that a simple scale factor $p(failure|A) = k * r(A)$, where $p(failure|A)$ is the probability of failure given "A", k is a constant based on the frequency of faults due to "A" and r(A) is the risk estimator associated to "a", may be used to develop the first models.

issue analysis with moderate losses. One typical example is vegetation management, which is independent of repairs on line equipment.

Vegetation management is a major resource-consuming activity and one that has evolved significantly over the last decade following higher public awareness to environmental issues. Traditional optimisation strategies were based on incremental improvements over established practices which were made impractical due to external changes (in some cases regulations moved from clear ground right-of-ways rules to tree trimming to minimise erosion and support ecosystems). Instead, computational methods are used to determine the optimal maintenance schedule, involving clearance measurements, tree density and species growth estimation, distances from roads to right-of-ways, among others. The result may be a sequence of small sections requiring maintenance separated by large swathes with minor risks. If geographic rules are extensively used, even remedies for low risk spans become worth doing, if they are performed while maintenance is done on a line nearby[3].

Inspection scheduling (12 o'clock)

This task is homologue to the previous one, substituting maintenance for inspection. The purpose is to replace full line inspection at fixed intervals with sections of different lines inspected at optimal intervals and connected to minimise travelling between inspections. However, this task is more complex since each type of inspection requires its own frequency, and decoupling is rarely efficient.

4. Examples

The authors and their colleagues introduced time and space analysis in [4], where several practical examples of different faults are presented. The examples herein focus on time and space analysis aspects of the framework.

Let us consider a section in a transmission grid with one voltage level, a total line distance of 350km with a main power source at A (S≤800MVA) and reserve power source at D (S ≤ 160MVA) and distribution injectors at C (S≤240MVA) and E (S≤240MVA) (see Figure 3 (left)). The maximum recommended load over each line is shown in red next to each line and a possible operation scenario is shown in black.

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[3] As a side benefit, bidding and auctioning becomes fairer and more transparent as the amount of work to be done and its exact location is better stated.

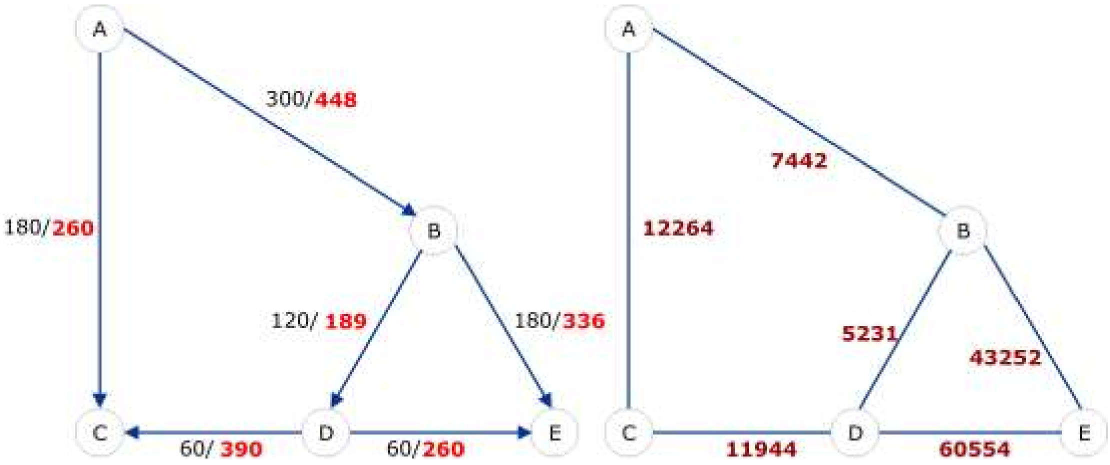

Figure 3 - grid with line loads (left) and risk factor (right)

Using condition based risk estimator methods, the aggregated risk factor for each line is shown in Figure 3 (right). If management sets a ceiling on the individual probability of failure, the total extension to maintain (depending on the risk assessment for each span) is the dashed curve in Figure 4. Setting the ceiling at 0.005 requires 86.3 km to oversee, which is only 25% of the overall length. However, if the redundancy in BDE triangle and the spare capacity at BE are considered, the maintenance effort in the highest risk line, DE, can be reduced, thus lowering the overall cost. The determination of the optimal point involves the value of customers on each injection point, the cost of energy at each source, the cost of emergency remedy against programmed maintenance, among other lesser factors.

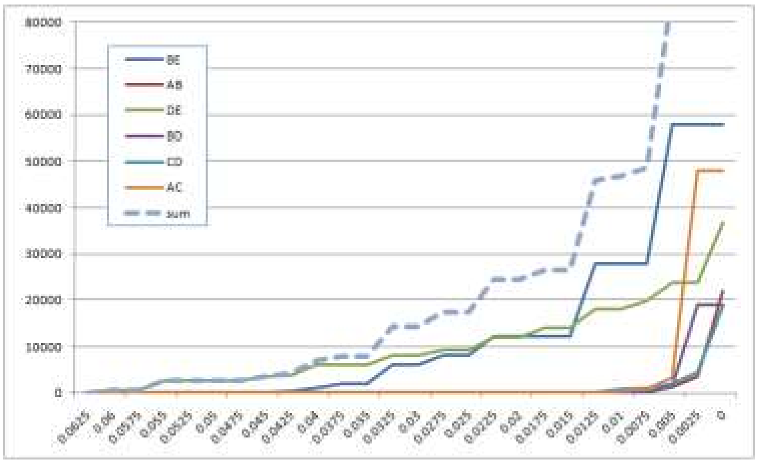

Figure 4 - Length [m] to maintain on each line as a function of maximum probability of failure

Figure 5 shows part of the condition assessment related to vegetation management for a 79-span OHL. The top row defines the span as rural (green), mixed (cyan) or urban (blue). The middle row shows the growth rate of the dominant species: growth speed increases from green to red. The bottom row shows the density of vegetation increasing from green to red.

The first choice criterion is span classification since maintenance in urban and mixed area calls for different methods than rural ones. The second choice focuses on fast growth trees first (in some cases, clearances are inferior to the growth expected during the maintenance cycle period) ; in this example, fast growth trees depicted in red coincide with high density (it is a region with eucalyptus), while medium growth trees depicted in orange (pines) occur both in sparse and dense woods. The optimal schedule should balance the work load between short period and long period cycles and seasonal variations.

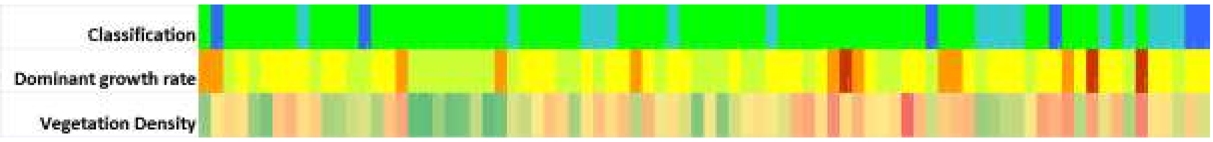

Figure 5 – Right of way classification along a 79-span line

5. Conclusions

The proposed framework offers a consistent environment to support a better insight into the variables relevant for maintenance optimisation. Its ability to combine disparate data, to tag observations with time and date references, the expandable database architecture and traceability of operations make it an ideal candidate for research and development of the best tools for tomorrow's grid managers.

6. References

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