NOVEL APPROACH FOR AUTOMATED CROSS-SECTORAL RENEWAL PLANNING FOR POWER AND GAS GRIDS

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Abstract: This submission presents a novel approach for a cross-sectoral renewal strategy for cables and pipes of energy grids. The approach is simulated in an automated way with the software QGIS. As strategy an extended Period-based Maintenance Strategy for the energy grid lines is carried out. As basis for a joint exchange of cables and pipes from different sectors, a spatial reference of the lines is detected through various functions in QGIS. Thereupon, a cost calculation for a jointly exchange in a common trench, if necessary with a temporal shift of line exchange measures, and for a separate exchange is carried out and compared with each other. If a cost advantage is achieved, a cross-sectoral exchange takes place. This approach is applied to a real grid area with a low-voltage grid and a part of a gas grid. The simulation results show that in the selected grid area about two thirds of the cables and pipes can be exchanged cross-sectorally with cost savings. The achieved cost savings are around 9 %.

Keywords: renewal planning, asset management, cross-sectoral, time-based maintenance, automated planning

1 Introduction

The energy transition triggers a transformation in energy supply, mobility and heat provision which poses a challenge on energy grids, especially the electricity grid. These new challenges will not be met without an expansion of the electricity grids, which will lead to major infrastructure investments in these grids [1]. Thereby, optimal maintenance and ongoing renewal of the energy grids are crucial, due to the high age structure of the operating resources as well as the mentioned current and future challenges in the energy sectors [2]. For this, there are various strategies that can be used. The maintenance and renewal strategy used by the grid operators varies depending on the equipment and sector. This paper presents a concept for automated renewal planning that applies the strategy cross-sectoral. The aim is the reduction of the costs through a cross-sectoral renewal with a common trench for electricity cables and gas pipes. This reduces the number of measures, the customer acceptance of these and the total incurred costs by the grid operator.

2 Overview Renewal Planning Strategies

2.1 Definition

According to [3], maintenance may be subdivided into the subsections inspection, upkeep, repair and improvement. Inspection refers to the determination and assessment of the actual condition. Upkeep is a measure to maintain the nominal condition. Repair is understood to be the repair or the replacement of equipment. Improvement is a combination of technical and administrative points to increase the functional safety. In the following, maintenance is defined by the replacement of equipment.

2.2 Renewal plannings strategies

Based on [4-6], there are five renewal strategies in the electricity sector: The first strategy is the Corrective Maintenance Strategy. By using this strategy, equipment is replaced exclusively after a defect that leads to a supply interruption. Since the Corrective Maintenance Strategy only reacts to malfunctions, the actual condition of the equipment is not taken into account. Therefore, it is not possible to plan any measures with this strategy. Another strategy is the Period-based Maintenance Strategy. Here, the equipment is replaced after a predefined time-period. A correlation between probability of default and the age of the equipment is assumed. In addition to these two simpler strategies, there are more complex ones that need more data on the condition of assets as well as the continuous updating of this data. The Condition-Based Maintenance Strategy can be listed here. Different diagnostic procedures are used to determine the condition of the equipment and, if necessary, compare it with previous conditions. The replacement of the equipment is done according to the condition, whereas age, location and importance are not taken into account. A strategy with focus on the importance of the equipment is the Reliability-Centered Maintenance Strategy. The importance of the equipment is used as a basis for determining the replacement. The condition of the equipment is included through a failure rate. The last strategy is the Risk-Based Maintenance Strategy. To determine the replacement of the equipment, the individual risk is identified. The risk is defined by the failure probability of the equipment and the resulting defect consequence.

Comparing these five renewal strategies of the electricity sector to the common strategies in the gas sector, it is noticeable that, apart from the Reliability-Centered Maintenance, the strategies also exist in the same extent in the gas sector. Based on this, one renewal strategy can be selected for the cross-sectoral evaluation. [7- 9]

2.3 Current status at grid operator

The strategies presented before are all used from grid operators. The Corrective Maintenance Strategy is primarily used for low-voltage and medium-voltage cables. The application of the Condition-Based Maintenance Strategy depends strongly on the possibility of determining the condition. However, it can be seen that any strategy is exclusively used in its respective sector. The examination of an exchange in other sectors takes place after the determination of the measures. No cross-sectoral planning of the exchange measures takes place in advance. This will be implemented in the method in Chapter 3. [9]

3 Approach

In the following, a new concept for automated cross-sectoral renewal planning is shown. The automation is performed as a python script for the geoinformation software QGIS [10]. In this novel approach the focus rests on electricity cables and gas pipes due to the installation in a common trench and resulting cost reductions. For this purpose, an extended Period-based Maintenance Strategy [11] with the consideration of different lifetimes for material types is applied.

3.1 QGIS functions

The core functions for the automated process are the QGIS functions buffer zone, intersection and symmetrical difference (see Figure 1). In addition, there are other functions like selection of objects with constraints used. These functions are modeled in an external python script and run QGIS as processing software.

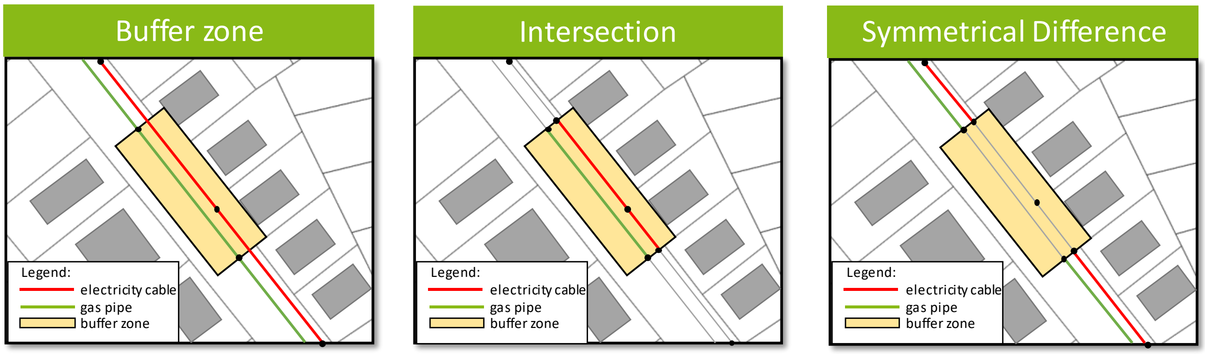

Figure 1: Illustration of the used QGIS core functions

3.1.1 Buffer zone

The buffer zone function is used to create a distance area around a vector object. This can be a point, line or polygon. The buffer zone has a predefined distance to the vector object and its length. The area within this distance is represented by the buffer zone as an area. By this function a spatial connection between different objects can be determined. In this approach, the function is used to create buffer zones around line segments. Other lines that are located in the buffer zone are considered for a possible joint exchange. [12]

3.1.2 Intersection

The intersection function uses an algorithm to extract overlapping parts of objects in an input layer and an overlay layer. The input layer can be a layer with points, lines or polygons. The overlay layer is a vector layer with polygon. During the intersection, all objects that are spatially located in the overlay layer are retained. If the objects of the input layer are larger than those of the overlay layer, they will be truncated at the boundaries of the overlaying object. In addition, the attributes of the overlay layer are added to the objects of the input layer. This function can be used to extract line objects in a buffer zone and additionally assign the buffer zone attributes to them. [12]

3.1.3 Symmetrical Difference

The symmetrical difference function operates in exactly the opposite way as the intersection function. The algorithm extracts partial objects of an input layer that are not located in the areas of the overlay layer. If objects or parts of them are inside the overlay layer, they will be truncated and removed. [12]

3.1.4 Select objects with constraints

The select objects function allows to select objects that fulfill certain attribute criteria within an input layer and save them in a separate vector layer. The attributes of the objects serve as filters of the selection of objects. These can be geometric attributes such as the length of the line objects or other attributes such as material types or installation years. Thus, for example, all lines can be selected according to a certain installation year. [12]

3.2 Procedure

The concept for the automated cross-sectoral renewal planning is shown in Figure 2. Three vector layers are used as input parameters, each of them contains the lines of the corresponding sector and the associated attributes. As attributes, the algorithm requires the material type and the installation year. As additional information for the algorithm, the technical lifetime of the installed and standard cables and pipes are required. Further information such as the length can be generated through geometric functions in QGIS.

In the first step, the future exchange years for each electricity cable and gas pipe are determined on the basis of the material type, installation year and technical lifetime. Then, the years of observation are examined iteratively within a specified time period (e.g. 2022 – 2050). In this approach, the electricity cables are always analyzed first, followed by the gas pipes as input lines. If there are lines that will be replaced in the current observation year, they are selected and buffer zones are created around them. The first buffer zone out of these will be selected for the further process. Thus, all lines will be examined iteratively.
With the buffer zone as overlay layer, additional electricity cables and gas pipes, which are located in the buffer zone, are extracted by the intersection function. Thus, a vector layer is created that contains all electricity cables and gas pipes which can potentially be exchanged in a common trench. Additionally, a symmetrical difference is formed to store all lines outside the buffer zone in a layer. For the selection of the lines for a common trench further filters are applied. A direction vector is set up for each line through the start- and end-coordinates. Afterwards, the angle between every line and the input line (associated line of the buffer zone) is calculated with formula (1). $\overrightarrow{L_1}$ and $\overrightarrow{L_2}$ are the directional vectors of the lines.

$$\overrightarrow{L_1} = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} \qquad \overrightarrow{L_2} = \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} \qquad \alpha = cos^{-1} \frac{(x_1 \cdot x_2) + (y_1 \cdot y_2)}{\sqrt{{x_1}^2 + {y_1}^2} \cdot \sqrt{{x_2}^2 + {y_2}^2}} \tag{1}$$

Lines with an angle greater than 10 degree and less than 170 degree are sorted out. This means that only lines pointing in the same or opposite direction are selected. This is necessary to sort out crossing or bending line objects. These out sorted lines are stored in a separate vector layer. The next step is the cost calculation described in chapter 3.3. In there the lines are checked whether they are located behind or next to each other. A detailed explanation follows in chapter 3.4. This allows to determine the correct trench width and depth. In the following, all combinations of joint and separate laying of the lines are examined depending on the exchange year for the common exchange. The most cost-effective combination is then selected, as shown in chapter 3.3.

After selecting the lines that are replaced together in the observation year, the installation and exchange years of these lines are updated based on the specified standard materials and their technical lifetime. Subsequently, the replaced and rejected lines are combined into one layer again. This layer is then divided into the several vector layers based on the sector of the respective lines. The process then starts again form the beginning by determining the number of lines with the year of observation as exchange year. Then the next lines (low-voltage cables or gas pipes) are checked, if no medium-voltage cables with the current observation year as exchange year left. After all cables and pipes in the observation year are checked and replaced, the next observation year is simulated.

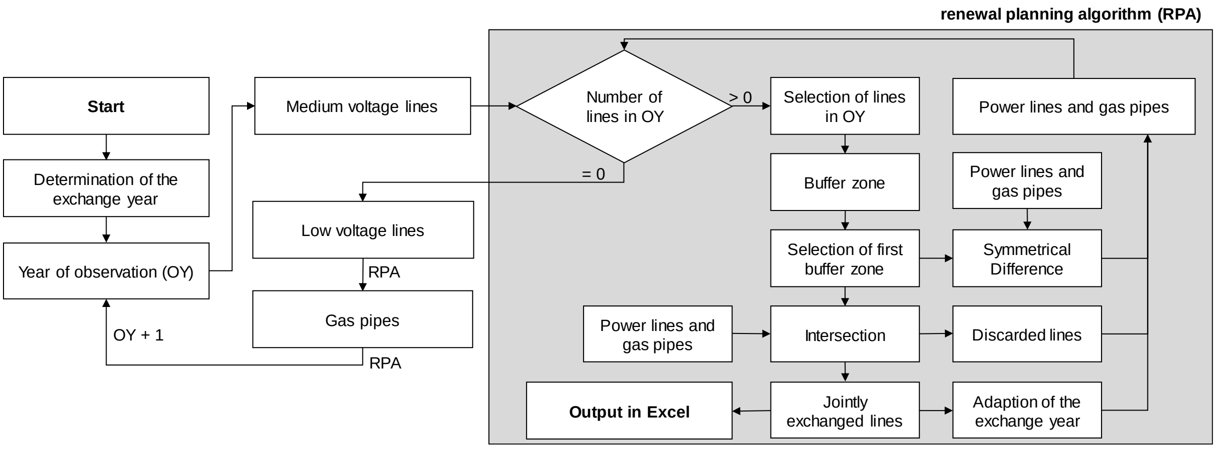

Figure 2: Flow chart of the automated cross-sectoral renewal planning

3.3 Cost calculation

For the cost calculation of the combinations for joint and separate laying of the electricity cables and gas pipes, the vector layer generated in the procedure is used. This layer contains all lines that are located in the buffer zone and whose angle proves the same or similar line course (see Figure 3). In the first step, a list of the exchange years (EY) of the cables and pipes is created, for determining which lines should be exchanged together. The exchange years are then checked iteratively in the following. All lines with the current exchange year or earlier are placed together in a trench at the time of the first exchange year. For this purpose, the procedure of determining parallel lines from chapter 3.4 is applied. Based on this result, the trench costs are calculated in the trench model in chapter 3.5. Thus, a trench price (C_{trench}) per meter is obtained from the trench model. This is multiplied by the length of the buffer zone (l_{trench}). In addition, the cable and pipe costs of the lines (C_{line}) which will be jointly exchanged are determined by multiplying the given prices per meter by the respective line length (l_{line}) see formula (2). The costs for the lines which are not selected for the joint replacement through e.g. a higher exchange year are determined as well through a single exchange in the related exchange year. To ensure the comparability formula (3) is used. These costs must be discounted to the exchange year of the common trench with the NPV with p = 0.06 [13].

$$C_{common} = C_{trench} \cdot l_{trench} + \sum C_{line} \cdot l_{line} \tag{2}$$

$$C_{single} = (C_{trench} \cdot l_{trench} + C_{line} \cdot l_{line}) \cdot (1+p)^{(EY_{single\ exchange} - EY_{common\ exchange})} \tag{3}$$

$$C_{total} = C_{common} + \sum C_{single} \tag{4}$$

Finally, the listed costs are summed up in formula (4) and written into a cost list. This analysis is performed for all exchange years in the exchange year list. Finally, the lowest cost value is selected from the cost list and the associated exchange year is determined. All lines with an exchange year equal to or less than the determined associated exchange year are exchanged in a common trench in the first exchange year. The lines with a later exchange year than the exchange year and consideration are replaced later individually. Thus, the replacement is carried out on the basis of the greatest cost benefit.

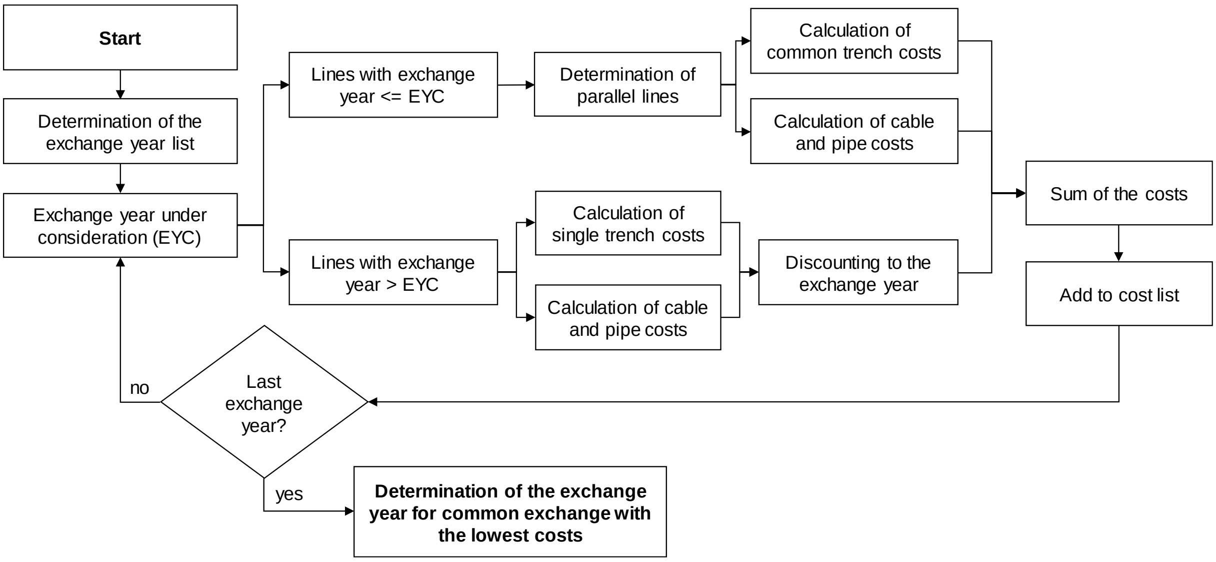

Figure 3: Flow chart of the cost calculation

3.4 Determination of parallel lines

For the determination of the number of parallel lines, the vector layer generated in each investigated case in the cost calculation is used with the lines for the common exchange. In the first step, the start and end coordinates for all lines are generated through geometric functions and saved as attributes. In the next step, the lines are extracted into different vector layers depending on sector and voltage level. The following procedure is performed for every generated layer.

First, the number of lines in the vector layer is evaluated. In case of multiple lines, they are iteratively checked and compared with the other lines. Then it is checked whether the start coordinate of line 1 corresponds to either the start or end coordinate of line 2. If this is the case, a variable is incremented. This variable counts how many lines lie behind each other. The variable then can be used to determine the number of parallel lines by subtracting the variable from the number of lines. The result is written in a list to generate the following code. This code is required as input parameter by the in the following presented trench model in chapter 3.5.

[number of parallel MV-lines, number of parallel LV-lines, number of parallel gas lines]

3.5 Trench model

The specifications of the German standards are used to determine the trench width and depth in the model. The basis for this is the “sparse trench width” in relation to the trench depth from DIN 4124 [14]. There, a minimum width of 30 cm is specified for a trench depth of up to 70 cm. The trench depth is obtained from the minimum cover zone of the cables and pipes according to DIN 1998 [15] in combination with a cable/pipe zone and a bedding zone. In addition, the recommended minimum spacing of the lines and pipes must be checked. If these result in a wider trench than in DIN 4124, the trench width must be increased consequently. For this purpose, the DVGW standard 462 [16] and DVGW standard 472 [17] is used for the spacing of electricity cables and gas pipes. For the spacing between electricity cables, values commonly used in practice are applied as in [18]. On the basis of this information, the trench width and depth can be calculated for all combinations of medium-voltage and low-voltage cables as well as gas pipes. From this, the corresponding trench costs can be calculated for the cost calculation.

As an example, the combination of one gas pipe and one low-voltage cable can be listed. The zone is determined using DIN 4124, so the minimum trench width is 40 cm. In this case, the minimum distance of 20 cm according to DVGW standard 472 can be maintained. This results in a 75 cm deep and 40 cm wide trench.

4 Results

For the application of the presented method, a real grid area with a low-voltage grid and a part of a gas grid in the time period 2022 to 2050 is considered. Figure 4 shows both, the low-voltage grid and the gas grid with the respective installation years in color.

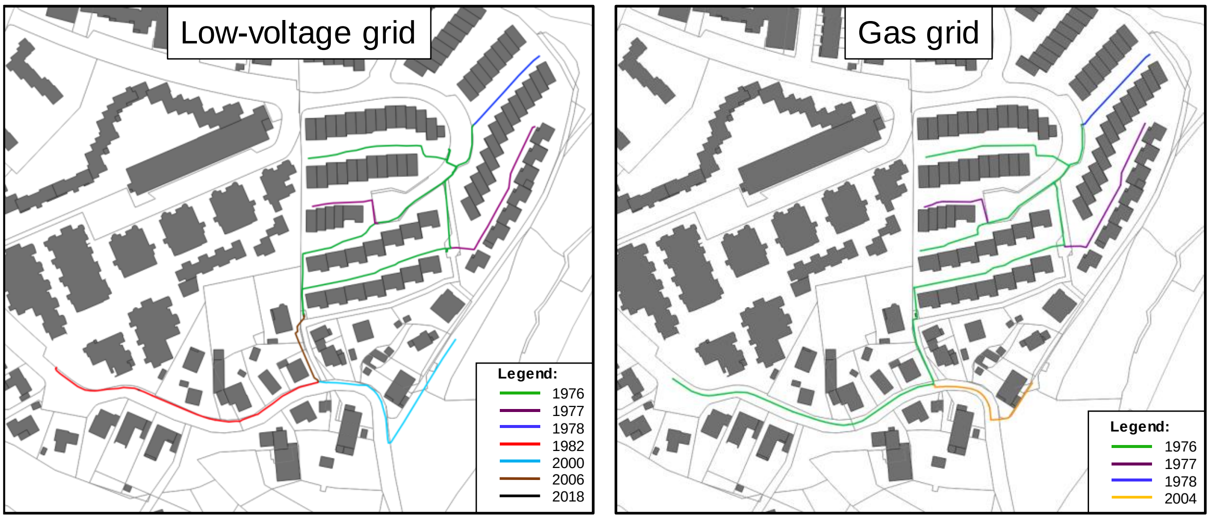

Figure 4: Low-voltage grid (left) and gas grid (right) with installation years

The first step in the shown method is the simulation of the exchange years, which are calculated in Figure 5 with the use of the installation years, material types and the technical lifetimes.

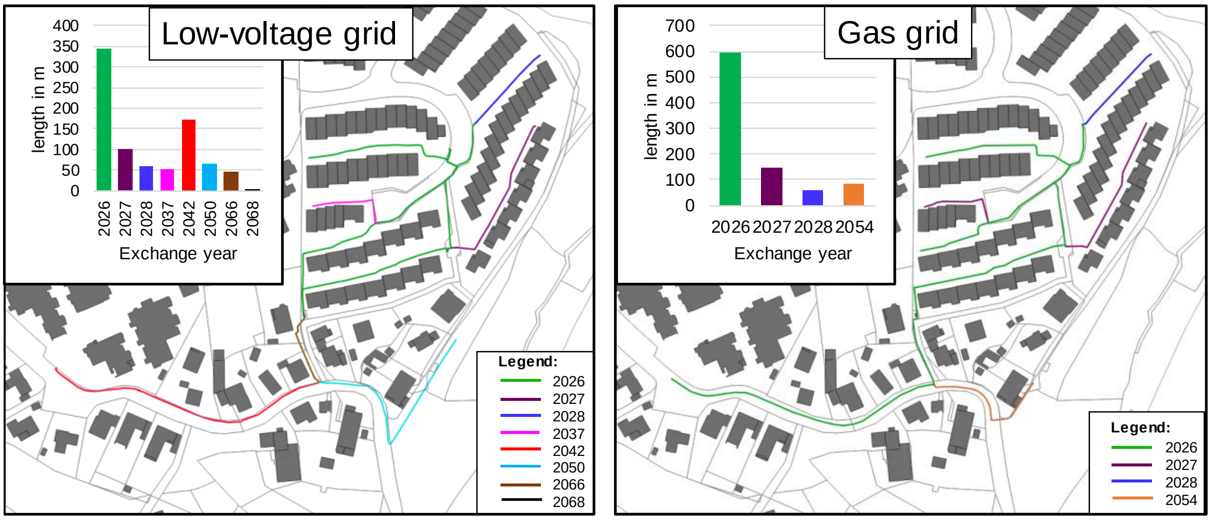

Figure 5: Low-voltage grid (left) and gas grid (right) with exchange years and lengths

The evaluation of the cross-sectoral renewal planning in Figure 6 of the low-voltage grid and the gas grid shows that about two thirds of the grid area can be exchanged cross-sectoral or with more electricity cables in one trench with a cost advantage. In the lower grid area, there are two areas in which no joint exchange takes place. In the right-hand area, this is due to the fact that the gas pipe end earlier and thus the low-voltage cable can only be replaced individually. In the area on the left, as can be seen in Figure 5, the difference between the exchange years of the cables is very high or outside the considered time period. The low-voltage cables were laid in 1982 and 2006, and thus the scheduled exchange should take place in 2042 and 2066. The gas pipes were laid in 1976 and are scheduled for exchange in 2026. Thus, the method examined whether there is a cost advantage in postponing the exchange of the low-voltage cable from 2042 or 2066 to 2026. Looking at the blue marked section in Figure 6, the costs for the individual exchange of the low-voltage cable and gas pipe in the respective replacement years amount to 80,000 €. Bringing forward the measure of replacing the low-voltage cable results in total costs of 99,500 €. This results in additional costs of 19,500 €, which results not in a postponement of the exchange of the low-voltage cable.

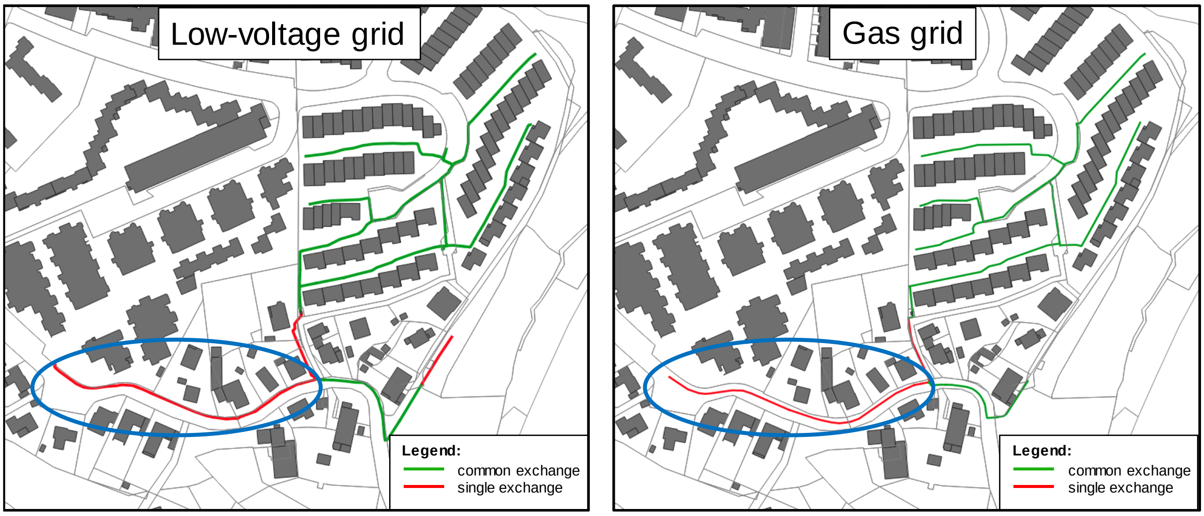

Figure 6: common and single exchange in the low-voltage grid (left) and gas grid (right)

Considering the costs for the entire grid area, a sector-separated exchange would result in renewal costs of 984,000 €. The implemented cross-sectoral renewal planning achieves costs of 894,000 € for the grid area. This results in a cost saving of 90,000 € (9.2 % cost reduction). This cost advantage results primarily from the reduction from 3,158 m to 2,396 m of the total required trench length of all measures.

5 Conclusion and Outlook

In conclusion, the shown method provides results with a cost saving through the cross-sectoral renewal planning for an exchange of cables and pipes from different sectors through the definition of spatial references in a geoinformation software. In a large part of the grid area, a temporal shift of measures takes place through a cost saving elicited by the exchange in a common trench. However, it is also shown that depending on the difference in the exchange years of the cables and pipes, a postponement is not always cost-saving and should therefore not be carried out across the board. Thus, a precise analysis and simulation of whether measures should be carried out cross-sectoral is necessary.

In the future, the model can be extended to include district heating pipes in order to simulate grid areas with all three sectors to see whether cost savings can also be achieved by electricity cables and or gas pipes in combination with district heating pipes. In addition, a simulation of a longer period of time in which cables and pipes are renewed several times could achieve even higher cost advantages through the parallelization of the exchange years of the different sectors. The simulation of other asset strategies is possible either by extending the code or by determining the exchange years in advance.

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