The economic conditions for urban infrastructure mining: Using GIS to prospect hibernating copper stocks

Björn Wallsten, Dick Magnusson, Simon Andersson and Joakim Krook

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Abstract

In this article, we suggest a methodology that combines Geographic Information Systems (GIS) and material flow analysis (MFA) into a secondary reserve-prospecting tool. The approach is two-phased and couples spatially informed size estimates of urban metal stocks (phase 1) to the equally spatially contingent efforts required to extract them (phase 2). Too often, even the most advanced MFA assessments stop at the first of these two phases, meaning that essential information needed to facilitate resource recovery, i.e. urban mining, is missing from their results. To take MFA one step further, our approach is characterized by a high resolution that connects the analysis of the stock to the social practices that arrange material flows in the city, thereby enabling an assessment of the economic conditions for secondary resource recovery. To exemplify, we provide a case study of the hibernation stock of copper found in disconnected power cables in Linköping, Sweden. Since 1970, 123 tonnes of copper or ≈1 kg per person have accumulated underneath the city, predominantly in old, central parts of the city and industrial areas. While shorter cables are more numerous than long ones, the longer ones contribute to a larger share of the stock weight. Resource recovery in specific projects reliant on digging comes at great costs, but integrating it as an added value to ordinary maintenance operations render eight locations and 2.2 tonnes of copper (2% of the stock) profitable to extract. Compared to the budget sizes of regular maintenance projects, a significant share of the stock comes with relatively small economic losses. Therefore, we suggest integrated resource recovery and regular maintenance as an interesting environmental measure for any infrastructure provider to engage with.
1. Introduction

Based on the environmentally driven assumption that metal recycling is preferable to primary production, an academic treasure hunt for societal metal sinks has recently formed under the flag of “urban mining” (cf. Halada et al., 2009; Krook et al., 2011; Brunner, 2011; Cossu, 2013; Lederer et al., 2014; Nakamura & Halada, 2015). The core of this concept is that secondary metal stocks in urban locations constitute a potential alternative resource base in comparison to mountainous ores, and might plausibly be recovered for the benefit of the environment (UNEP 2010). Lederer et al. (in review) suggest that the assessment of such stocks should follow a two-phased logic similar to that of the traditional prospecting process of primary mineral resources. This process relies on the estimation of concentration and size of a certain reserve (phase 1), coupled with the required extraction effort to determine its economic potential (phase 2) (see also USGS, 1980; CRIRSCO, 2013; UNECE, 2013).

The most frequently used quantitative method to assess anthropogenic metals stocks and flows is material flow analysis (MFA). So far, even the most advanced MFA assessments stop at the first of the two prospecting steps above. Furthermore, many of these studies are characterized by an overly high level of abstraction (e.g. aggregated values for a city, country or even larger regions), meaning that essential information for resource extraction is missing such as the exact location and accessibility of the secondary metal reserves. A handful of previous studies have linked MFA with Geographic Information Systems (GIS) in order to add a spatial dimension and levels of detail to the analysis (Tanikawa et al., 2002; van Beers & Graedel, 2003; Tanikawa et al., 2004; van Beers & Graedel, 2007; Tanikawa & Hashimoto, 2009a; Tanikawa et al., 2009b; Wallsten et al., 2013a; Andersson, 2014; Rignell, 2014). However, these studies are more or less visualizations of estimated urban metal reserves and they stop at the still too aggregated level of city districts. While we ascertain the merits of using GIS to scrutinize metal stocks (cf. Zhu, 2014), we believe that an even higher resolution and spatial sensitivity is needed to fully assess the economic and technological conditions for urban mining, and to determine a secondary reserve’s economic potential. Such knowledge is much needed to facilitate the required extraction effort and the implementation of urban mining schemes, and has been suggested by previous research on resource recovery from for example landfills (Frändegård et al. 2015) and waste incineration residues (Fellner et al. 2015).

In this article, we suggest a methodology that combines GIS and MFA into a secondary reserve-prospecting tool. The methodology couples spatial size estimates of urban metal stocks to the also spatially contingent economic
and technological effort required to extract them. To exemplify the suggested approach and be able to discuss its strengths and weaknesses, we provide a case study of a local urban metal stock: the subsurface AC power grid in Linköping, Sweden. Our focus is here the cupriferous “frozen spots” of this grid, i.e., parts and zones of infrastructure systems where copper-content cables have been disconnected due to nonexistent system demand but remain in their subsurface location (Wallsten et al., 2013b). These frozen spots constitute a “hibernating stock” of copper that is not in-use but has not yet reached the waste sector (Bergbäck and Lohm, 1997).

2. Aim and Research Questions

The aim of the article is to assess how a GIS-based MFA with a local focus can function as a prospecting method of secondary reserves to advance urban mining in research and practice. Our suggested method combines MFA and GIS to achieve a coupled scrutiny of the size and spatial characteristics of secondary stocks (phase #1) as well as the technical and economic conditions for their recovery (phase #2). These two phases correspond to the two-part outline of the article, which are related to one research question each:

**RQ#1:** What kinds of knowledge about the spatiality and characteristics of hibernating metal stocks in urban infrastructure can be obtained by using GIS analysis?

**RQ#2:** How can hibernating metal stocks in urban infrastructure be spatially assessed in terms of variations in the technical and economic feasibility of metal extraction?

In the first section, we present a spatial screening for hibernating copper in Linköping’s AC power grid and a series of further analysis on the characterization of this stock. In the second section, we examine how the economic conditions for cable recovery depend on a set of spatial variables and whether recovery is done as separate projects or in the form of integrated maintenance and recovery (and thus as an added value to regular system upgrading). In the concluding section, we scrutinize the pros and cons of using GIS as a tool to enhance the capabilities of MFA, and problematize our suggested approach.
The empirical case of this article has an intentionally more narrow focus in comparison to traditional MFA studies. This is done to generate knowledge needed for implementing subsurface urban infrastructure mining. The case is limited in four ways: horizontally, vertically, and in terms of inventory and material.

Horizontally, our case concerns the city of Linköping, Sweden. Linköping is Sweden’s fifth largest municipality with 150,000 inhabitants of which 105,000 populate the city of Linköping (Statistics Sweden, 2015). Tekniska Verken, the municipally owned utility provider, is responsible for the majority of the city's urban infrastructure systems. Among these are the power grids for households and street lightning, the pipes for district heating, water and sewage, as well as broadband/ICT, and produces electricity, district heating, district cooling and biogas. Linköping has been served with electrical power since 1902 (Hjulström, 1940), and our study goes back to 1970, since the earliest of Tekniska Verken's archive maps that we have digitalized are from that year.

Tekniska Verken operates in a similar way to how most utilities are run in Swedish municipalities in general. The urban infrastructure in Linköping is like in all other Swedish cities predominantly located underneath the streetscape. This is the reason for our vertical focus of Linköping’s subsurface underworld.

Our inventory of the subsurface urban world of Linköping consists of one material entity: the city’s power grid. In particular, we are especially interested in those parts of this infrastructure system that can be referred to as “frozen spots,” i.e., where the system flow is nonexistent (Wallsten et al., 2013b). Frozen spots can be single cables, which freeze into “dormant cells” of infrastructure when disconnected in relation to maintenance and repair operations. Or they can be slightly larger zones of infrastructure that cause “paralysis” when they are disconnected in clusters in relation to larger infrastructure projects (ibid.). Just like the precursory studies done within our research group, the particular interest in hibernating cables is motivated by how they are theoretically directly available for recovery (Krook et al., 2011; Wallsten et al., 2013a; Andersson, 2014). Insofar as our studies do not aim for estimates of the total copper stocks of the chosen geographical areas, they are different from previous spatially informed MFA studies that make use of GIS (cf. van Beers & Graedel, 2003; Tanikawa & Hashimoto, 2009a) as well as those that do not (cf. Zhang et al., 2011; 2014).
Finally and from a material point of view, we assess only the cupriferous frozen spots in Linköping's subsurface power grid. Copper transmits most of Sweden's power, and so the significant amounts of copper residing in the hibernating stock together with copper's high scrap value indicated this metal's potential as a driver for taking urban power grid mining initiatives off the ground (cf. Wallsten et al., 2013a). Our fine-grained assessment of the hibernating stock characterizes each of the 2175 disconnected cables in Linköping individually and in terms of their specific type, length, location and copper content. This level of detail is enabled by the delimited inventory consisting only of Linköping's power grid, and is in sharp contrast to previous GIS-based MFA studies which are based on generalized assumptions of average material content in typical products and estimates of their frequency in a given area (cf. van Beers & Graedel, 2003).

3.1 Research Approach

Our suggested approach is two-phased and follows the logic of traditional prospecting. The first assessment concerns stock characterization in terms of size and spatiality (corresponding to research question #1), and the second the prerequisites for stock extraction (corresponding to research question #2). Just like in the traditional mining sector, the place-specific economic conditions for urban mining tentatively provide the key knowledge component to be able to move from the characterization and prospecting of a material stock to initiate extraction activities. To perform this kind of spatially dependent and multi-layered analysis, we constructed a method that combines MFA and geographic information system (GIS) as our assessment tool (see Figure 1).

At the core of the study is a spatially informed version of a bottom-up MFA. The bottom-up approach of MFA is characterized by making an inventory of all anthropogenic entities that occur within a decided area containing a chosen material of inquiry (cf. Drakonakis et al., 2007). The average material content for each of these entities is multiplied by an estimated frequency of that entity within the area and then added together to come up with approximations on the total material stock (Chen and Graedel, 2015). One of the further benefits of using a delimited study object and a detailed focus in an MFA, is that it enables interviews with particular actors with detailed knowledge (especially in comparison to the zoomed-out traditional MFAs on a regional/global level) (Wallsten, forthcoming).

With the exception of Analysis 2, all of the analyses performed in this article were done using ArcGIS 10.1, a computer software program for storage, analysis and visualization of geographical data. In all GIS software,
spatial data on streets, lakes, land use and so on is saved in layers that can be visualized in two forms: raster and vector data. This project predominantly relies on the latter, which are saved as polygons, points or lines, although we have also made use of raster analyses in some cases as well (Analysis 5-7). In raster analyses, the geographical data is stored in cells (or pixels), which is preferred for continuous data.

In principle, the GIS operations we have performed are quite basic, as we have mainly made use of the tools for overlaying and geographical selection in order to perform our calculations. Nevertheless, these analyses add an analytical dimension in comparison to previous MFA studies that have used GIS. In all, eight analyses are made in the article, four for each phase. For detailed information on the data content of the GIS layers and how they were obtained, see Appendix 1. Given the Swedish context of the case study, all costs and revenues are calculated in Swedish crowns (SEK), which at the time of writing sells at 1 SEK = 0,106 Euro.

Figure 1. Graphic display of our prospecting approach. Four analyses were performed in each of its two phases, resulting in a total of eight stock analyses to answer the two research questions.
3.2 Analytical Approach 1: Knowing Your Grid - Size and Spatial Characterization of the Hibernating Stock

The first section of our analytical approach corresponds to the first phase in the prospecting process and answers research question #1. It consists of four analyses that scrutinize the hibernating copper stock of Linköping’s power grid in terms of size and spatial characteristics. The characterization was carried out in order to understand the spatial variations in density of the hibernating copper stock. For detailed information on the layers continuously referred to in italics below, see Appendix 1, and for a schematic depiction of how they were engaged with in the analysis, see Figure 1.

3.2.1 Spatial Characterization (Figure 1, Analysis 1)

The GIS analysis performed to delineate the size of the hibernating stock was based on calculating copper content in kilograms in each cable by multiplying the object lengths and copper concentrations of all the hibernating cables (layer 3.2.1). The spatial characterization of this stock was calculated on the basis of Linköping's city districts (layer 3.2.2), a spatial category that has previously been shown as appropriate for spatial overview screenings of urban material stocks (cf. Tanikawa et al., 2002, 2004, 2009a, 2009b; van Beers & Graedel, 2003). We assigned each cable to a specific city district (objects crossing city district borders were split at the point of intersection) making it possible to calculate sum weights for all 27 districts in Linköping. Both the copper sum of disconnected cables as well as the district’ share of the total stock was estimated (see Map 1).

3.2.2 Histograms of Lengths and Weights (Figure 1, Analysis 2)

To further understand the characteristics of the hibernating stock in terms of how the copper amounts are distributed amongst the disconnected cables of Linköping, we made a histogram to assess the relationship between the length of hibernating cables and their copper content (see Figure 2).

3.2.3 Ore Veins of Cables and Streets (Figure 1, Analysis 3 and 4)

These GIS-based analyses were carried out in order to find “ore veins” of hibernating stock, i.e., those cables and streets with the highest copper content. The underlying idea was to further increase the level of detail and resolution regarding the spatiality of the hibernating stock and to find out where in the city urban mining projects should be engaged with if the aim is to recover as much copper in as few places as possible. We wanted to look further into streets (and not only cables) for three reasons. First, since the majority of urban infrastructure excavation works are performed in the streetscape, knowledge of which streets have the highest copper content could direct urban mining initiatives. Second, we wanted to know if co-
located cables are a common phenomenon and if so, to what extent these contribute to the stock weight in relation to singular cables. Third, the municipality of Linköping has GIS layers with metadata on streets regarding their flows of traffic, pedestrians and so on, implying that our knowledge about which streets have the highest copper content could be complemented with further analysis on where extensive excavation works for copper recovery would be most suitable.

Analysis 3 consisted of a simple GIS procedure: determining the 25 cables with the highest total copper content through a selection from the layer with hibernating cables (layer 3.2.1) and visualizing them together with the city districts (layer 3.2.2) (see Map 2). Analysis 4 consisted of a somewhat more advanced GIS analysis: using the city streets in Linköping (layer 3.2.3), to create a buffer from these, making an intersection between the buffer and the layer with hibernating cables (layer 3.2.1) and finally dissolving the intersecting layer based on names of city streets. Finally, a calculation of those 25 streets with the highest copper content could be performed and visualized (see Map 3).

3.3 Analytical Approach 2: Economizing the Urban Reserves - Prospecting of Hibernating Stock

In this section, we perform three economic analyses that compare technical extraction projects and one analysis of the recovery potential. These analyses are the most advanced in the article, as we wanted to find out the economic outcome of excavating the hibernating cables by comparing cost and revenues. While characterizing the stock, as described above, we learned about the spatial locations and distributions, and could thus find out the economic value of the cables based on their copper content. The revenue data was obtained from the Swedish metal recycling company Stena Recycling AB, but the analysis told us nothing about the extraction costs. For that purpose, cost calculations were made for two cable recovery approaches. In the first of these, the recovery was thought to be engaged with as separate projects, i.e., all the costs related to the excavation as well as the extraction and transportation of cables to a recycling facility were accounted for. In the second, cable recovery was thought to be an integrated part of regular maintenance projects, i.e., only the additional costs caused by cable recovery in comparison to the ordinary projects were included. Again: for detailed information on the layers referred to in italics below, see Appendix 1; for a schematic depiction of how they were engaged with in the analysis, see Figure 1.
3.3.1 Recovery Based on Digging Alone (Figure 1, Analysis 5)

Previous research (Krook et al., 2015) tells us that two spatially sensitive parameters largely influence the costs of recovery projects solely based on digging. The first is urban location (layer 3.2.6, in which city areas are all densely built areas in Linköping, and where digging is more expensive than in urban areas which are low-density ones), since excavation in city areas is more expensive than in urban areas. The second is surface materials (hard surfaces such as asphalt and cobblestone are far more costly to restore than soft surfaces such as grass). An interim analysis identifying parallel occurrences among the hibernating cables (layer 3.2.1), using the raster tool “line density,” was performed, generating layers for co-located parallel cables (layer 3.2.4) and singular cables (3.2.5). This way of analyzing made it possible to both calculate the total copper content as well as the digging costs for recovery of singular as well as parallel cables in one digging project. By overlaying the layers of urban location (layer 3.2.6) and surface material (layer 3.2.7) with the layers for singular (3.2.5) and parallel cables (3.2.4), each cable object was by intersection assigned to one out of four possible combinations of these parameters: urban/hard surface, urban/soft surface, city/hard surface and city/soft surface. This generated a total of eight interim layers consisting of single and parallel cables for each of the four possible combinations mentioned above.

Table 1. Cost per meter (in SEK) for projects in which recovery done solely by digging. These are divided on the four different interim layer combinations (based on urban location and surface materials) and project lengths (calculations based on Krook et al., 2015). Highest and lowest costs in red.

<table>
<thead>
<tr>
<th>Surface material</th>
<th>City Soft</th>
<th>City Hard</th>
<th>Urban Soft</th>
<th>Urban Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 - 100 m</td>
<td>715</td>
<td>890</td>
<td>520</td>
<td>700</td>
</tr>
<tr>
<td>&gt; 100 m</td>
<td>630</td>
<td>810</td>
<td>400</td>
<td>580</td>
</tr>
</tbody>
</table>

For these interim layers, cable extraction costs per meter were calculated based on previous research (Krook et al., 2015) and by taking cost impacts of the project length into account (see Table 1). The revenues per meter cable were also calculated for each object, as it differs between cables with plastic or paper cover, and as the metal recycler pays more for the former than the latter due to the kind of recycling processes installed. The actual numbers are not presented here due to confidentiality reasons. The
The economics of recovery projects based solely on digging were calculated for each of the eight combinations.

The results are not presented in a map but as a scatterplot (Figure 3) for two reasons. First, the sheer quantity of cables makes them difficult to visualize in a way that conveys the message clearly enough. Second, presenting the results in a scatterplot allowed for comparison between the two different suggested methods for extraction; digging alone and integrated maintenance and recovery (compare Figures 3 and 4).

3.3.2 Recovery Based on Integrated Maintenance and Recovery (Figure 1, Analysis 6-7)

The analyses made for this recovery strategy were justified on the basis that we wanted to scrutinize the economic conditions for recovery as an added value to the daily operations of the system provider Tekniska Verken. This proceeded in a similar way as the analyses done in Analysis 5, but with two exceptions. First, we did not have to include the effects of different surface materials as their removal and restoration would not add any additional costs to the regular maintenance work (Krook et al., 2011; 2015). Second, we did not take project length into consideration for exactly the same reason. The cost impacts of the urban location (layer 3.2.6), was taken into account however, since cable recovery as part of maintenance comes with some extra work for cable uncovering and extracting, resulting in time delays and higher costs in city areas than urban areas, e.g. due to higher fees per time unit for surface flow disruptions. The applied cost per meter for integrated recovery in the city was estimated to cost 95 SEK/m and 70 SEK/m in urban areas (based on Krook et al., 2015). The fact that maintenance will only be done in proximity to the operating grid was taken into consideration by identifying and disqualifying all cables positioned in other locations by overlaying the layers of singular (3.2.4) and parallel cables (3.2.5) with the layer containing the in-use grid (layer 3.2.8), allowing the hibernating cables to be located at maximum five meters from the in-use grid layer. In this way, we could scrutinize the total potential of integrated maintenance and recovery, i.e., the proportion of the stock that could be extracted by using this strategy, as cables outside of these five meters would not practically be accessible in the maintenance work. To be able to compare the results with analysis done on digging alone (Analysis 5) and because the quantity of cables makes visualization of each cable practically impossible (as with Analysis 5), the results are presented as a scatterplot (see Figure 4) and not a map. Furthermore, a scatterplot does not disclose the positioning of the in-use grid, which was not allowed for confidentiality reasons.
3.3.3 The Recovery Potential of Integrated Maintenance and Recovery (Figure 1, Analysis 8)

To further examine the potential of integrated maintenance and recovery, we overlaid the street excavation works (layer 3.2.9) and the share of hibernating cables known to be situated in proximity to the currently operating grid. This allowed us to calculate the stock percentage that had been uncovered during excavations on a yearly basis between 2003 and 2011. These numbers were then extrapolated to estimate how long it would take to dig up the entire hibernating stock in close proximity to the operating grid, using the integrated maintenance and recovery strategy. The results are presented in a table format (see Table 2).

6. Results from the Stock Characterization

6.1 Size and Spatial Characterization of the Hibernating Stock (Analysis 1)

Map 1. The spatial distribution of hibernating copper in Linköping’s power grid. Zoomed-in detail of Ryd, a student-housing area. Graded colors represent the city district shares of the total hibernating copper stock in the city while the copper stock in each city district is represented by the circular colored symbols. The age of buildings and their type is depicted in the above right. © Lantmäteriet, Dnr: i2012/898.

In total, 123 tonnes of copper were found in 2175 hibernating cables in Linköping’s power grid, Map 1 shows how they are spatially dispersed in Linköping’s 27 city districts. In terms of overarching patterns, Map 1 provides a first screening of where to look more in detail for hibernating copper and can give advice on where to target secondary recovery initiatives on a general urban level. It confirms previous findings insofar as the
amounts of copper increase as you move closer to the central city areas (cf. Andersson, 2014 and Wallsten et al., 2013a). The results also confirm previous findings of how industrial areas are likelier to contain more hibernating cables than residential areas, as the brown and red areas in the north are highly industrial districts. Furthermore, hibernating cables are in Linköping also more often found in older city districts than newer ones (cf. Wallsten et al., 2013a). However, and as the zoomed-in detail maps intend to show, there is reason to be cautious about such overviews and generalizations. These maps of Ryd (a district built in the 1970s with multi-unit student housing in the south and one- and two-dwelling buildings in the north), show how the large hibernating stock is partly a result of two particularly long cables that together weigh slightly over 4000 kg and contribute 26% of the copper stock in this district. If these two cables were not present, Ryd would shift from brown to red in the overview classification. The two long and thick feeder cables in Ryd were disconnected as part of a larger infrastructure project when Malmstätt (an exurb located 2 km outside Ryd to the west of Linköping), altered its power distribution to make way for a large housing expansion in the 1990s. As the power demand then increased significantly, the two thick feeder cables in Ryd were disconnected and the power grid relocated along another feeder route (Jönsson, 2015). Closer examination of the data layer underlying Map 1 indicates how detailed local knowledge about historical events related to the grid, city or in this case even exurb, is needed to accurately interpret the spatially summarized hibernating stock map. While the overview can give some guidance as to where in cities hibernating stocks primarily tend to accumulate based on city district characteristics such as age, function and degree of centrality, it cannot point with any significance to where one should start engaging with urban mining projects in a specific city.

6.2 How Common Are Particularly Long Cables? (Analysis 2)

An important message of Figure 2 is that long cables contribute substantially to the weight of the hibernating infrastructure stock of Linköping. Short cables are in the majority in terms of numbers, but they do not contribute to the total stock as much as long cables do. The median cable is 35 meters and weighs 22 kilos (the standard deviation for both of those numbers being very high), while the longest cable is also the heaviest, measuring 3.8 tonnes distributed over 1600 meters, i.e. a copper content of 2.3 kg per meter (one of the two feeder cables in Ryd). The underlying numbers of these histograms indicate that the recovery of the 400 heaviest cables would translate to 70% of the entire hibernating copper stock, and that the average copper content for these cables is 1.4 kg per meter.
Figure 2. Distribution of cable quantity vs. length and weight. Within intervals of 20 meters, the blue bars represent the share of total amount of cables (2175) while the red bars represent the share of total weight (123 tonnes). Cables between 0-20 meters make up approx. 30% of the total amount but only 4% of the total weight of hibernating cables.

From a methodological point of view, the numeric operations underlying the histogram are rudimentary in and of themselves. Nevertheless, they provide interesting results from a resource perspective, if for example legislative changes were introduced to enforce more ambitious recycling from societal stocks such as urban infrastructure. If the aim is to increase the recycling percentage regardless of the cost of such efforts, then the 400 heaviest cables would be the ones to go for first. Furthermore, the results can be added to those from the integrated maintenance and recovery assessment (see section 7.2), to be of further guidance concerning for example where to locate pre-emptive maintenance operations.

6.3 Where Are the Cable Ore Veins? (Analysis 3)

Map 2 shows the 25 heaviest cables in subsurface Linköping, equaling 23.5% of the hibernating stock. Thus, nearly one-fourth of the hibernating stock is found in the heaviest 1% of the cables. While these results exemplify the usefulness of the applied methodology for spatially locating specifically interesting cables from a metal resource and increased recycling percentage point of view, we can also denote a correspondence between city districts with a high copper content (see Map 1) and the districts where the heaviest cables are located. The presence of a single heavy cable thus seems to be an obvious contributor to a large hibernating stock share for a city district (again, think of Ryd, the example in section 6.1), while a larger number of lighter cables do not.
The Tallboda district in the far northeast is a case of this (city district 4 in Map 1), since it has a lot of short cables but not a large share of the total hibernating stock. However, the correspondence between thick cables and a city district's share of the total stock also entails that heavy cables demonstrate a pattern of centrality; their presence is scarcer the further outwards in the city you are (and in this specific case, the further into the relatively younger (residential) neighborhoods you go).
6.4 Where Are the Urban Street Ore Veins? (Analysis 4)


Given that infrastructure system upgrading and most city excavations are engaged with in the streetscape, knowledge about the most cupriferous streets is more useful for facilitating (integrated) cable recovery than knowledge about the heaviest copper cables. Map 3 therefore shows the 25 most cable-laden streets in Linköping, equaling 19% of the hibernating stock. The reason for why this percentage is somewhat lower compared to the percentage found in Linköping’s 25 thickest cables (Map 2), relates to the fact that the 25 heaviest cables are not always exactly located in streets (e.g. the two main cables in Ryd) and that certain heavy cables do not exclusively stick to one specific street but sometimes follow several streets as they intersect crossings and make turns. In general terms, street length is of great importance as most of the top 25 occurrences are comparatively long, which makes sense since a longer street has a higher possibility of containing more cables. The outlier example of this can be seen in one of the few but noteworthy differences between the ore vein cable map (Map 2) and the ore vein street map (Map 3): Vårdsbergavägen in Hjulsbro (city district 26 in Map 1), which is represented in the map of streets but not in the map of cables. This is an occurrence where a series of shorter cables in sequence make a great ore, a seemingly rare phenomenon, which in this particular case was caused by a major street-widening project in the 1990s (Jönsson, 2015). Eleven of the 15 heaviest cables from Map 2 follow one of the ore vein streets in Map 3 more than 75%. This indicates that locating
heavy cables is of particular importance when engaging in spatial stock characterization, as they will not only constitute a substantial part of the total stock, but also help in determining ore vein streets. However, singular heavy cables will not alone create heavy streets (as seen in Map 3): smaller ones are also of importance. Here, a scalar observation can be made concerning how short cables do not significantly contribute to the hibernating stock at large but might be of importance in certain cases of ore veins found in streets. This insight further reinforces the importance of a highly detailed analysis when assessing these kinds of stocks. Admittedly, a street with a high total cable weight is not necessarily a hot spot for urban mining, most notably if that street is very long. Therefore, it makes sense to also check for its concentration of copper per area unit. When doing this (the lower left depiction in Map 3), several of the 25 streets alter their color classifications. The street with the highest cable concentration is a short one, Vifolkagatan, with 1.6 tonnes of copper spread out over 877 meters (1.82 kg/m), while the street with highest copper content is the very long Västanågatan with 2.1 tonnes of copper spread out over 1657 meters (a lower concentration rate at 1.25 kg/m). Vifolkagatan is interestingly enough located in a housing area from the 1950s and thus not an area you would go for based on the copper stock overview (Map 1). However, two feeder cables that were a part of the 20kV grid pass through the area and thus again our assessment stresses the importance of detailed knowledge, of specific sites but also of the historical maintenance operations, to actually be able to pinpoint urban mining hotspots. On a more general level, Maps 2 and 3 show distinct similarities as to where the majority of occurrences are found, and these observations in turn correspond to the overview screening of Linköping as a whole. The majority of the top 25 streets as well as cables are located in areas with large shares of the total stock (those represented in brown and red in Map 1). What can be said, however and based on the Vifolkagatan-example just mentioned, is that caution is advised for generalizations based on the function or use of an area. It seems safer to suggest that the local history of street excavations (which in turn is related to urban transformation and historical grid events to a large extent) is the key component to find the hibernating ore veins of a city’s power grid, together with a certain importance of age of a district and degree of centrality. Now that we know the size and specific locations of the most significant frozen spots and thereby the important factors to determine the possible revenues of their recovery, we are able to continue with further GIS analysis concerning the recovery costs, based as these are on spatially relevant variables. The revenues also depend on the kind of extraction method chosen and so in the following, we will provide the results for the second phase of the prospecting approach and a discussion of the economic conditions for urban mining projects.
7. Results from the Prospecting of the Stock

7.1 Assessment of Recovery by Digging Alone (Analysis 5)

As the scatterplot shows, there is not a single cable section in Linköping that is profitable to recover by simply going out there and digging it up (see Figure 3). This is not surprising in itself as the unfavorable economics of extraction are one of the reasons why hibernating cables accumulate in the first place. Or in other words, if the economic conditions had been favorable, then the accumulation would arguably not be a recurring phenomenon (see Wallsten et al., 2013b). The thickest hibernating cable in Linköping results in recovery revenues of approximately 84 SEK/meter, while the most favorable extraction conditions (the disconnected cable is over 100 meters long, it is located in an urban area and under a soft surface) result in costs of about 400 SEK/meter (see Table 1). Let alone that such a calculation returns results that are nowhere near break-even, the chances of finding a situation where all of the above premises are satisfied are furthermore next to zero in Linköping (and tentatively anywhere else in any significant scale). However, hibernating cables are often co-located in shafts, so might parallel cables perhaps provide us with better chances of making the ends of cable recovery meet? An existing case in Linköping contains four parallel cables of 77 meters which could be sold to a metal recycler for approx. 13,400 SEK. However, even if these cables were located at the most favorable place they would generate losses of
17,400 SEK, since the excavation costs then would be 30,800 SEK. Another way of exemplifying the unfavorable economics of cable recovery based on digging alone, is that one of the most common cable types in Linköping yields 44 SEK/meter in recovery. This means that as many as nine parallel cables in perfect spatial conditions would result in reaching break-even (and again we would be back at an extremely rare occurrence). As a final example, the 25 heaviest cables from Analysis 3 would return losses of 6.5 million SEK if extracted by digging alone, which is a lot considering that these cables weigh 29 tonnes, i.e., a cost of 220 SEK per kg recovered copper. In other words: cable extraction by digging alone is not even close to being economically feasible under the current conditions.

7.2 Recovery Assessment of Cable Mining by Integrated Maintenance and Recovery (Analysis 6)

![Figure 4. The economic outcomes of integrated maintenance and recovery. Copper content (y-axis) is again plotted against the economic outcome (x-axis). Each dot represents a location in which one or more cables are (co-)located.](image)

From an economic perspective, it makes slightly more sense to engage with cable recovery as an added value to ordinary maintenance operations when the ground is dug up anyhow (see Figure 4). As an example, and under the assumption that the heaviest 25 singular cables would be available for integrated maintenance and recovery, the total cost to dig them up would be -0.6 million SEK, compared with -6.4 million SEK for digging alone. The maximum potential is smaller for this approach, however, as only 61.7% of the hibernating stock is located in proximity to the existing grid and could thus be recovered in relation to upcoming maintenance operations. The significant majority of occurrences would however still yield losses if recovered using this approach, but as can be seen by the scale of the y-axis, these are of a smaller magnitude than was the case for recovery by digging alone (see Figure 3). Here, it is also worth mentioning that a significant amount of the occurrences of hibernating cables are
almost profitable. For instance, close to 200 cases yield losses of less than 100 SEK, which is within a reasonable margin of error.

In total, there are 2.2 tonnes of copper in eight cases that at present would be profitable using integrated maintenance and recovery, all of them found in urban areas (in blue in Figure 3). Two of the profitable cases consist of singular cables with comparatively high copper concentrations spanning from 5.79 to 7.62 kg/m, one of them being plastic-insulated and the other paper-coated. In order for singular cables to be profitable in urban areas, paper-insulated cables need to be at least as high as 6.5 kg/m and plastic-insulated ones 4.2 kg/m, which is seldom the case (the median hibernating cable in Linköping contains 0.63 kg copper/m). The remaining six profitable cases consist of two to five parallel objects. The frozen spot yielding the highest outcome consist of four parallel paper-coated cables each containing 4 kg copper per meter. For two parallel cables in urban locations to be profitable, they need to contain at least 2.1 kg copper/m if plastic-insulated and 3.2 kg copper/m for paper ones, which again is rarely seen.

Applying our approach in this way makes it possible to categorize the entire hibernating copper stock in terms of its economic accessibility. Such detailed knowledge is essential to identify those few occasions when urban mining would pay off already under the current conditions, but could also be used for analyzing measures and changes for increased accessibility. If copper prices were to increase by 30% for example, the number of cases with positive outcome would increase from eight to 48, and the amount of copper from 2.1 tonnes to 10.4 tonnes. It is evident that there is a lot of potential in this stock if the price of copper or cost for excavation would change. In this respect, it is furthermore interesting to see that a significant share of hibernating cables would generate less than 10,000 SEK in additional costs for the infrastructure provider if recovery was integrated with upcoming maintenance. Additional costs in this order of magnitude do not appear overwhelming, given that many infrastructure upgrade and maintenance projects involve total costs of several hundred thousand or even million SEK (EBR, 2013).
7.3. Where Are the Integrated Maintenance and Recovery Hot Spots? (Analysis 7)

Map 4. The hot spots for integrated maintenance and recovery. Map showing profitable places for the recovery of hibernating cables in relation to maintenance, as well as zoomed-in detail and aerial photograph of one of them (the red square). © Lantmäteriet, Dnr: i2012/898.

The last map shows the spatial location for those eight places where hibernating cables can be profitably recycled through integrated maintenance and recovery (see Map 4). As seen, the spatial distribution to a large extent follows the previous maps and six of the hotspots are located in the center-northwest part. Four of them, for example the zoomed-in area, are in industrial areas while the others are predominantly in denser areas, although still in areas characterized as urban.

While the same city districts of Linköping are the most interesting in this case as in all the others, it should be noted that the top 25 cables are not at all correlated to where at present it makes the most sense to engage in integrated maintenance and recovery. Instead, these cases occur as the result of thick parallel cables in low-density and industrial areas. Their urban location as represented in GIS (i.e., urban or city area, layer 3.2.6) is crucial since several of the occurrences would not have been (as) profitable if situated in denser locations characterized as city, involving higher extraction costs.
The zoomed-in detail in Map 4 conveys exactly this message. This hot spot is located in Attorpsgatan in the industrial area of Tornby (city district 2 in Map 1), and is characterized by a plenitude of cables that used to connect the transformation station to the left with the one to the right. The most interesting spot is the six parallel paper cables just next to the western transformation station, spanning copper contents from 0.8 kg/m to 5.1 kg/m.

7.4. The Potential of Integrated Maintenance and Recovery (Analysis 8)

<table>
<thead>
<tr>
<th>Year</th>
<th>Sum Cu (kg)</th>
<th>% of Sum Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>137</td>
<td>0,2</td>
</tr>
<tr>
<td>2004</td>
<td>337</td>
<td>0,4</td>
</tr>
<tr>
<td>2005</td>
<td>437</td>
<td>0,6</td>
</tr>
<tr>
<td>2006</td>
<td>327</td>
<td>0,4</td>
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<tr>
<td>2007</td>
<td>391</td>
<td>0,5</td>
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<tr>
<td>2008</td>
<td>483</td>
<td>0,6</td>
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<tr>
<td>2009</td>
<td>1720</td>
<td>2,3</td>
</tr>
<tr>
<td>2010</td>
<td>2494</td>
<td>3,3</td>
</tr>
<tr>
<td>2011</td>
<td>853</td>
<td>1,1</td>
</tr>
<tr>
<td>Sum</td>
<td>7179</td>
<td>9,4</td>
</tr>
</tbody>
</table>

Table 2. The total amount of copper that could have been picked up during the period 2003–2011 using integrated maintenance and recovery in Linköping. A source of error in the underlying data is that we do not know if all excavation works actually are represented or not. When checking larger city redevelopment projects specifically, i.e. occasions when cables are removed to a relatively high degree, they were for example not present.

A weakness of the integrated maintenance and recovery approach is that the realization of its potential depends on the yearly maintenance activity of the system owner (which in turn is a consequence of where and when the grid fails and/or is in need of upgrading). Therefore, for our final analysis,
we examined how large a proportion of the disconnected infrastructure was uncovered on a yearly basis during street excavations in Linköping. This was done with the purpose of also analyzing how long it would take to recover the hibernating copper stock in Linköping by using integrated maintenance and recovery (see Table 2). During the years 2003-2011 a total of 7.2 tonnes of copper could have been picked up, equaling 9.4% of the 76 tonnes accessible through integrated maintenance and recovery. These numbers reveal that if maintenance were to continue with similar frequency as for the years for which we have data, and given that maintenance never occurs in the same location twice, then it would take approximately 100 years to recover the 61.7% of the current hibernating stock accessible through integrated maintenance and recovery. Depending on how such a finding is framed, we can either conclude that integrated maintenance and recovery is not enough since society might need these copper amounts faster than integrated maintenance and recovery can provide, or, on the other hand, and from the viewpoint of Tekniska Verken, these are far more reachable achievements than solely digging.
8. Discussion on Methodological Deficiencies and Uncertainties – Using GIS for Characterizing and Prospecting Hibernating Cables

Using a GIS-based MFA with a local focus to investigate the potential and economic conditions of urban infrastructure mining has been shown in this article to be a fruitful endeavor: it has enabled an investigation at several scales and levels, from specific cables up to the general city level. However, a method like this is not without significant uncertainties, some of them being specific for this paper and the studied case while others are more general, relating to GIS work at large.

First, there are data uncertainties originating from the digitalization of the disconnected cables from the original paper maps (i.e., covering disconnected cables from the period 1970s to 2000) into GIS. The quality of the documentation on these maps is essential and over time such documentation practices have varied, leaving room for errors. During the digitalization process, we found that a high amount of these old cables (approximately 60%) was marked as “unknown” rather than with the specific cable type (e.g. FKKJ 3x120) as is common nowadays. Without such specifics regarding cable insulation material, type of metal conductor and its dimension, the copper content and corresponding revenues are obviously difficult to estimate. In our case, such “unknown” objects were determined as paper-coated with a mix between copper and aluminum conductors and given an average copper/m-concentration (0.8 kg/m) based on consultation with an experienced maintenance project manager at Tekniska Verken (Jönsson, 2015). Although such an approach is necessary and useful for specifying the total hibernating copper stock and its overall spatial patterns (i.e., Map 1), its contribution to the ore veins and prospecting analyses is largely limited. Such “average cables” will never score high or low enough to make any significant difference in these analyses, but will rather end up in the middle of everything, both in terms of copper content and economic prospects for their recovery. Another implication of this lack of information is that some of these “unknown” cables might in fact constitute thick copper cables of high relevance for urban mining initiatives.

Another important data uncertainty regards the applied cable recovery costs in the economic prospecting analyses. This data has been taken from a previous study (Krook et al. 2015), in which typical extraction costs were assessed given certain differences in site-specific factors (e.g. surface materials and urban locations) and project settings (e.g. solely digging or integrated recovery and maintenance). The important message here is that in a specific urban mining project such costs could vary considerably (i.e.,
both up and down), dependent as they are on which depth the specific cable in question is located, if there are archeological interests in the area and so on. Given our intention to demonstrate the usability of the developed method and prospect the entirety of all hibernation cables in Linköping, we believe that such a simplification using typical extraction costs that take selected spatially dependent parameters into account is reasonable.

Third, there are internal GIS inconsistencies to be aware of. For example, when using overlay tools, e.g. while determining the surface material (soft or hard), GIS clips vector objects based on the reference layer used, which means that there will be more objects in the program than actually exist in the real world. The total copper content will be recalculated based on length and copper content per meter however, meaning that the total copper content will be the same. Then, and when analyzing parallel cables in particular, these needed to be dissolved from many cable objects into one “shaft object” representing all the relevant parallel cables at that location, which resulted in the attributes for each cable being merged. Attributes, such as minimum, maximum and mean copper per meter were recalculated for these new shaft objects, but the level of detail was altered. Comparing the total sum of copper in the new shaft objects with the initial copper content in each specific cable, we could detect a small total overestimation of the stock at 1%, which is well within the margin of error.

The calculations for hot spots generated a margin of error and this was handled through a manual control of the potential hot spots. One final GIS-related source of error is that different layers might have different projections and the transformation might lead to mistakes when combining layers from different sources. All of these GIS matters were handled through manual work and the results were continuously controlled against existing, original layers.

By applying our method, we have been able to scrutinize both the hibernating copper stock characteristics and its economic accessibility to a greater level of detail than previous studies within the MFA field. However, there are still further steps to take in order to approach the level of detail and specifics dealt with in traditional prospecting, i.e., drilling and sampling of the specific ore in question, detailed on-site investigations, and so on. Until such a detailed analysis is engaged with, it can never be known if all of the cables represented on the maps are still present under the streetscape of Linköping or if some of them might have been recovered e.g. during larger city redevelopment projects (cf. Wallsten et al., 2013b). On the other hand, there are 70 years’ worth of electric power operating services that is not covered in the data set (prior to the year 1970 when our study starts), rather suggesting an underestimation of the total hibernating
stock. To sum up, and given that the included data sets are socially constructed and historically contingent, some method of triangulation would be greatly beneficial to make sure that the estimates represent reality correctly enough. A geo-scanning survey like the one engaged with in the Mapping of the Underworld project in the UK (Wang et al., 2011), could tentatively verify our estimates. Given time and cost constraints, however, no such method could be tested in our study.
9. Conclusions

The empirical results of this article confirm some previous research findings. For example, the hibernating copper amounts in Linköping’s copper grid show a similar spatial dispersion in the city compared to the neighboring city of Norrköping (Wallsten et al., 2013a). In our studies on Norrköping, we outlined that hibernating clusters of system parts, or instances of “infrastructure paralysis” as we termed them, were hot spots for cable recovery in urban mining initiatives (Wallsten et al., 2013b). Those observations are confirmed by the results in this article, as shown by three examples of where larger historical events in the power grid resulted in possible urban mining hotspots due to a resulting high number of hibernating cables: the two heavy feeder cables in Ryd (Analysis 1), the street widening project in Vårdsbergavägen in Hjulsbro (Analysis 4) and the substation taken out of service in Attorpsgatan in Tornby (Analysis 7). All of these occasions, but from slightly different perspectives that depend on the underlying motives, provide good opportunities to engage in urban infrastructure mining activities, some from a recovered stock size perspective and some from the economy perspective.

Even though the cases that make economic sense are few under current conditions, the suggested approach makes it possible to characterize the hibernating stock in its entirety to determine locations where urban infrastructure mining can be economically justified. It gives detailed insights into how these locations are dependent on spatially contingent factors and how far from break-even the recovery of hibernating cables actually is. Given this, the approach can be used to evaluate how different changes in maintenance practice, decision-making and infrastructure provision would affect the economic recoverability of the stock. In reverse, it can provide estimates about how high copper scrap prices need to be to make larger shares of the hibernating stock economically available and point with some confidence to where profitable urban infrastructure mining projects could then be engaged with in the city.

Additions to the method are of course highly conceivable. For example, it would be interesting to add the environmental conditions for urban infrastructure mining to the analysis, to be able to estimate costs for avoided CO₂ emissions. This would allow us to compare urban infrastructure mining to other measures that an infrastructure provider can take to lower the environmental impact of their activities.

Furthermore, it would also be interesting to overlay our power grid-related results with the other infrastructure systems found in subsurface Linköping such as street lighting and telecommunications. This could give further advice to the discussions of increasing the co-ordination of maintenance
between local infrastructure providers. For example, synchronized integrated maintenance and recovery measures between system owners could be suggested so that whenever an actor digs in a city street, it is required for every provider that has a system located at this location to collect its remainders. Such a coordination of excavation works is currently in place in Bergen, Norway (Graveklubben, 2015). Furthermore, we might suggest investigations in technological development of so-called non-digging technologies such as Cable-X and different techniques for horizontal directional drilling (HDD). Using such technologies for cable recovery would in principle obliterate all the spatially dependent cost parameters (cf. Krook et al. 2015), since those are related to surface conditions that these technologies never interfere with.

Another suggestion starts from the fact that our approach is only concerned with the already existing hibernating copper stock and does not say anything about how the future accumulation of disconnected cables could be dealt with. Doing the same kind of analysis but on the operating grid would provide infrastructure owners with a relevant tool to manage maintenance operations. For example, these could include also the recovery of those sections that are to be replaced, instead of only focusing on the recovery of already disconnected cables found while engaging in maintenance operations, as we have suggested here.

Finally, the performed analysis starts from Tekniska Verken’s action space, that is, it assesses the recovery potential of the hibernating copper stock as if the main responsibility for resource efficiency was the private actor’s, acting as it is on market-based conditions. As such, the suggested approach is an example of what Langdon Winner terms “reverse adaptation” (1977), where the goal is adjusted to match the available means to reach it (and not vice versa which is tentatively preferred but not always politically possible). The limits of starting in such a position are seen empirically in our results insofar as it would take 100 years at the current rate to recover the hibernating stock in Linköping if this was to be achieved simply by altering maintenance practice. With a reversed perspective, the analysis could equally as well have started from the perspective that society needs these stocks for other purposes at an earlier moment in time. Let’s say that the estimated extra 290 Mt of copper needed to build a global energy system based on renewable resources (García-Olivares et al., 2012) are needed by 2020 to reach the two-degree target agreed to by the Copenhagen Accord, and that a certain share of this amount has to come from stocks already used in society (which is not inconceivable, given some estimates that there are only something like 500 Mt remaining in mineral reserves globally (Zittel, 2012)). Then, and since the Swedish infrastructure companies own a copper stock of a size comparable to the remaining reserves in Swedish
mountains (Krook and Baas, 2013), copper recovery targets from infrastructure could be set on a yearly basis, to have these actors alter for example their maintenance practices to make them pitch in their share of the responsibility.

While further analysis is needed to arrive at such share estimates with a high enough degree of confidence, it is an example of what can be achieved by using a method such as the one suggested in this article but from a different perspective. It creates the possibility to connect not only local numbers (which is customary for traditional bottom-up MFA approaches) but also the social practices that dictate material flows locally to the global context. Thereby, the possibility would open up to assess how far concrete measures could reach in trying to meet the resource challenges of our century. Insofar as MFA scholars continue in our vein of locally focused studies that also acknowledge the local practices of material flows, that would also assure this academic field a high degree of policy relevance for the future.

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7. References


Appendix #1: The GIS layers

3.2.1. Hibernating Cables
Data on hibernating cables was collected from Tekniska Verken’s currently operating GIS system, which was commissioned in the year 2000. Since this data predominantly contained cables disconnected between then and 2012, further collection of historical data was needed. In all, 419 maps were digitalized, i.e., scanned and vectorized, to detect all disconnected cables during the almost thirty years of operation between 1970 and the late 1990s. These paper maps were provided to us by getting access to Tekniska Verken’s archive, in which digitalization occurred on a full-time basis over the course of two months. The resulting vector layer used in the analysis contains hibernating cables as polyline objects with attribute data of their type, length and metal concentration.

3.2.2. City Districts
The city of Linköping is divided into 27 districts, which we obtained in map form from the Linköping municipality. The city districts are represented as polygon objects in this vector layer, which is primarily used in order to understand the spatial distribution of the stock.

3.2.3. Streets
This layer contains all the streets in Linköping, and we used it in our analysis to determine those whole and parts of cables that were located underneath the immediate streetscape. To do this, we created a buffer zone from each street object and then used the clip function.

3.2.4-3.2.5 Parallel and Singular Cables
These layers were created based on the hibernating cables (3.2.1), since we needed to detect all the locations in which two or more cables objects are co-located in parallel. The GIS operation was first carried out as a raster-analysis using “line density,” which generated a raster showing places with two or more parallel cables. This layer was transformed into vector format and could then be intersected with the hibernating cables, in order to find parallel and singular cable objects. This operation resulted in two layers that were used for further analyses. In Analysis 6 and 7 however, we compared them with the in-use grid (3.2.8), since we then assumed that disconnected cables positioned outside of the operating grid would never be uncovered during ordinary maintenance activities. The GIS operation was

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1 For detailed information about the digitalization process, please consult Andersson (2013).
based on proximity, and we selected every hibernating cable within five meters of the operating grid as a candidate for recovery.

3.2.6 Urban Location

On average, it is typically 30% more expensive to perform street excavations in Swedish city centers than in more peripheral urban locations (EBR, 2013). There are two reasons for this. First, storage space for unearthed material is in shorter supply in central locations compared to the urban area, implying that transport costs for its removal is higher. Second, the re-routing and shutting-off of street traffic is more expensive in city centers than urban areas (cf. Krook et al., 2015). To account for these cost differences, a GIS map in vector form was created that delineates between the city center and the remaining urban area, in order to make further analyses for excavation costs.

3.2.7 Surface Material

Performing any kind of work on subsurface infrastructure relies on the removal and restoration of surface material. Highly present examples of such materials in Swedish cities are asphalt, cobblestones and grass, each resulting in different costs for excavation and restoration work. Maps of surface material were developed based on GIS maps from the municipality showing streets and other “hard” surfaces which were be merged into the same layer, as well as data from Lantmäteriet containing surface material data for areas not covered by the municipal layer. This generated two layers, one for “hard surface” and one for “soft surface.”

3.2.8 In-use Grid

Containing classified content, we were very thankful to obtain spatial information on the operating power grid from the local infrastructure provider Tekniska Verken. This vector layer represents the power grid cables as polyline objects and was used with utmost confidentiality.

3.2.9 Excavations

The final data layer used for the GIS analysis in this article contains spatial data of historical excavations in relation to maintenance work in Linköping. The data covers the years from 2003 to 2011 and shows the kind of maintenance work done and its spatial location as polygon objects. Since maintenance work today is not synchronized between the different system providers in Linköping, we singled out and kept only those excavations done for power grid maintenance while disregarding the rest (such as water and sewage, district heating and so on). This vector layer was provided to us

2 Public Swedish authority responsible for mapping, the Swedish national geodic grid and property division.
by Tekniska Verken and we used it for the analysis already outlined under 3.2.4–3.2.5 above, as well as to determine the number of hibernating cables uncovered during excavation works for each of the included years.

3.2.10 Background Data Layers
Complete maps of buildings, roads and so on were acquired from Linköping municipality and from Lantmäteriet.