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The Aesthetics of the Underworld

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Abstract

Although the development of computational aesthetics has largely concentrated on 3D geometry and illustrative rendering, aesthetics are equally an important principle underlying 2D graphics and information visualization. A canonical example is Beck's design of the London underground map, which not only produced an informative and practical artefact, but also established a design aesthetic that has been widely adopted in other applications. This paper contributes a novel hybrid view to the debate on aesthetics. It arises from a practical industrial problem, that of mapping the vast network of underground assets, and producing outputs that can be readily comprehended by a range of users, from back-office planning staff through to on-site excavation teams.

This work describes the link between asset drawing aesthetics and tasks, and discusses methods developed to support the presentation of integrated asset data. It distinguishes a holistic approach to visual complexity, taking clutter as one component of aesthetics, from the graph-theoretic reductionist model needed to measure and remove clutter. We argue that 'de-cluttering' *does not mean loss of information, but rather* repackaging *details to make them more accessible. In this respect, aesthetics have a fundamental role in implementing Schneiderman's mantra of 'overview, zoom & filter, details-on-demand' for information visualization.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Design, Human Factors

1. Introduction

In the UK and many other countries, underground networks are used to deliver a range of services to households and businesses, including cable TV, telecommunication cables, gas (service pipes and/or mains), electricity (ducts and cables), water mains, and sewers. These are rarely laid out within single, well planned conduits, more often the networks have evolved separately and haphazardly. Maintaining and upgrading these networks are major undertakings, and as many are buried beneath roads and pavements, these undertakings are a major source of disruption. It is estimated that the direct cost of trenching and reinstatement work on UK highway for utilities is in excess of £1 billion per annum [BFN*04]. Within the UK, these services are owned and managed by a range of private companies; in the sequel, we will follow commercial practice and refer to the services mentioned above as 'assets', and the service drawings that depict these assets as 'service plans'.

Although service plans can be characterized as node-link diagrams where nodes are structural features (delivery points, junctions, etc.), they usually involve elements of both geographic and network visualization. For site work, a plan will be interpreted in the context of an above-ground location, with surface features (e.g. 'street furniture' such as manhole covers) used to correlate between the routing information depicted in the plan, and the reality of the locale. This is further complicated by three factors:

- the quality of the original data is subject to wide variation, ranging from GPS-positioned assets through to pre-computer plans of the water and sewer networks (see an example in Figure 1).
- different tasks performed with service plans require different levels of accuracy, or indeed different notions of accuracy - geographic versus topological versus schematic.
- standards for depiction vary between asset companies; in some cases, abstractions are used to simplify the portrayal of assets within particularly congested regions.

In a bid to reduce the impact of street-works, recent legislation requires the exchange of asset data between companies. Beyond the question of how to integrate these heterogeneous data, there is another challenge, portraying the result as truthfully as the data allows, while avoiding a complex and confusing view. Figure 2, a service plan from a highway reconstruction project, shows the nature of the visualization

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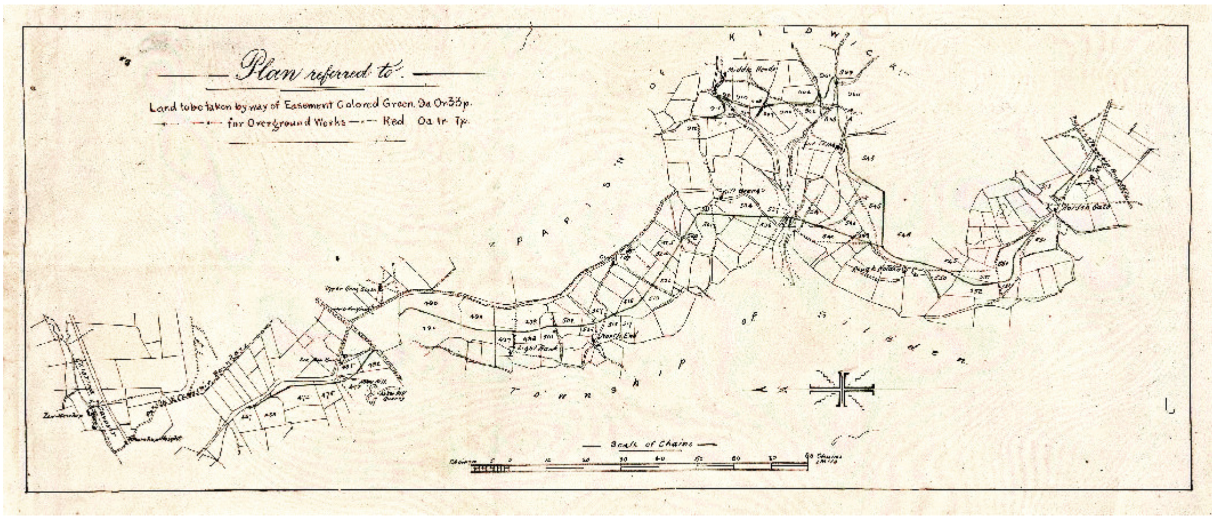

Figure 1: *A service plan dated 1895 showing a water aqueduct. Antique maps are often seen as having an aesthetic value*

problem. In attempting to represent all detail at a common level of abstraction, the plan serves neither as good overview nor as interface to fine detail. Our contention, explored in the remainder of this paper, is that data integration should not lead to view confusion; our challenge is to find appropriate abstraction and simplification methods, or, in analogy with Beck's underground map, to develop suitable aesthetics for the underworld.

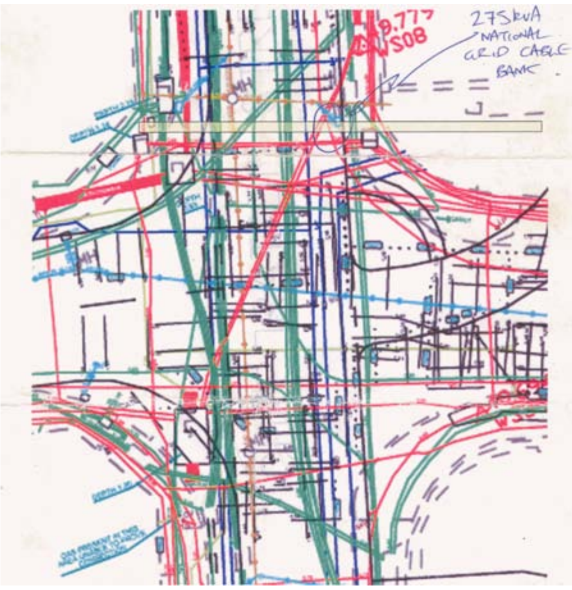

Figure 2: *An example of a multi-service plan*

Section 2 expands on the context of our work. Prior research on aesthetics in information visualization is set out in section 3, which looks in particular at findings from graph depiction. We then discuss the role aesthetics play in support tasks on underground data; section 4 documents the motivation for our efforts to manage detail in service plans. Our work toward a suitable underworld aesthetic emphasises *clutter reduction*, and builds on results from both information visualization and graph theory. We show how the aesthetic could be applied to the problem domain (section 5), before setting out our findings and future work (section 6). We close this paper by reflecting on the link between aesthetics and the information-seeking mantra [Shn96].

2. VISTA Project Background

Every year, in excess of 4 million holes are dug in UK roads to repair assets, provide connecting services to new premises and to lay new cables and pipes, making the 'gap under the road' a scarce resource [MS97]. Prior to invasive works it is normally required that excavators should request and obtain record information from all relevant utilities to identify what is buried where. Digital GIS records can be tailored to these different user group needs (e.g. GIS data views or scaled printouts).

Within the VISTA project [VIS07], we are working within a consortium of private companies providing utility services, civil engineering companies sub-contracted to repair and replace these assets, and government and industry bodies concerned with regulations and the effective management of these services. The Traffic Management Act (TMA 2004), in particular, is designed to reduce congestion and disruption on the road network using a range of different initiatives.

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Of significance for utility assets are those aspects of the act that cover the co-ordination of utility works in the highway. The TMA encourages asset owners to co-operate more effectively on street works. Importantly, the act currently proposes that all utility organisations will provide asset location in digital (GIS) format from June 2008 [Nat06].

Currently, most utility companies provide single-service plans as part of the utility packs they issue to on-site teams or to third parties. The lack of a standard format for exchanging data between these organisations, as well as the many survey techniques used to record the location of services and scales for mapping the different asset types meant that multi-service plans (such as in Figure 2) not only are visually complex but are also difficult to produce. Using multiple plans, necessitates a great deal of visual coordination. If utility companies comply to the TMA then they could supply GIS data to other organisations on request, making it more convenient to issue an integrated view of underground assets in a single plan (in addition to the single-service drawings that on-site teams are used to). The question that arises is whether there are currently suitable tools in place to support the integrated visualization of a congested underworld.

VISTA aims to make asset information more readily available to assist in providing better knowledge of the location of buried assets and help reduce unnecessary holes. This can be achieved by developing an integrated data model for buried assets [BCS*08], and critically for this context, supporting this integration with visualization techniques that adequately reflect the richness of attribute information and the inherent uncertainty in the data.

3. Related Literature

Clutter is 'a collected mass, a collection; a crowded and confused assemblage' [Onl08]. Because of the confused nature of clutter and our inability to comprehend it, it is often seen as undesirable and hence better eliminated. Moreover, we associate visual properties such as balance and symmetry with *positive* or *good aesthetics* that can help us understand an image more easily. Clutter, on the other hand, causes confusion and can be an obstacle to carrying out tasks requiring visual search and accuracy; it is therefore also associated with visual complexity and *negative aesthetics*.

In this short survey, we review efforts in information visualization in general, and in graph theory in particular, to improve the aesthetics of visual representations (section 3.1). There are other methods to reduce clutter that are not directly related to improving aesthetics. We describe some of these methods in section 3.2.

3.1. Survey of InfoVis Aesthetics

The role of aesthetics in information visualization is well documented through the books of Tufte [Tuf06, Tuf83], and, at a more theoretical level, the seminal work of Bertin [Ber83] looks at the link between meaning and layout. A number of user studies were conducted to assess the link between visual features and visual efficiency. A study by Fairbairn [Fai06], for example, showed that a monochrome map where all symbols have the same level of contrast is seen as complex since there is no notion of hierarchy to ease the reading of the map. User studies to measure colour interaction and its impact on 'visual efficiency' [Rob52] (cited by Fairbairn [Fai06]) highlighted that certain colour interactions (e.g. yellow/yellow and yellow/other intersections) could decrease the perceived visual impact.

In the last 20 years, aesthetics have been an important principle guiding the development of algorithms within graph drawing, with families of algorithms intended to preserve particular properties of a graph (e.g. directedness, planarity and orthogonality). The highly influential work on spring-embedder algorithms similarly is intended to draw out symmetries within the structure. The intuitions underpinning these approaches have been given experimental support through the work of Purchase [Pur98] and more recently Ware et al. [WPCM02] who investigated the effect of different aesthetic constraints on user performance with graph-based tasks.

Widely quoted aesthetics criteria concern five visual aspects: bends, crosses, angles, orthogonality and symmetry. Purchase [Pur98] tested and compared these criteria based on the following hypotheses:

- **Bends**: increasing the number of edge bends in a graph drawing decreases the understandability of the graph.
- **Crosses**: increasing the number of edge crosses in a graph drawing decreases the understandability of the graph.
- **Angles**: maximising the minimum angle between edges leaving the nodes in a graph drawing increases the understandability of the graph. 'When edges cross at acute angles, they will be more likely to cause visual confusion when rapid interpretation is important, than when they cross close to 90°' [WPCM02].
- **Orthogonality**: fixing nodes and edges to an orthogonal grid increases the understandability of the graph.
- **Symmetry**: increasing the symmetry displayed in a graph increases the understandability of the graph.

Purchase [Pur98] concluded that edge crossing is by far the most important aesthetic criteria in comparison to the other four. This was then challenged by a later study [WPCM02] which showed that the total number of crossings in a graph drawing is not a significant indicator of response time, as was initially envisaged. The number of lines crossing the shortest path affects its perception negatively. The concept of continuity is, therefore, argued for. The implication of this is that smooth lines are easier to perceive than lines with zigzagging node pattern. On a practical note, they concluded that 'it may be worth allowing for an occasional crossing in a graph layout if it reduces the bendiness

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of paths'. This finding is useful for applications where path finding is important (e.g. when identifying a high voltage cable from a number of close-by services on a service plan).

Aesthetics from graph drawing have been successfully applied to information visualization applications such as route maps. Agrawala et al. [AS01] implemented a set of generalization techniques to improve the efficiency of route maps while preserving readability, clarity, completeness and convenience. They highlighted the effect of rendering style (e.g. choice of colour and line thickness) on the readability and clarity of a map; 'the rendering style can aid the user in interpreting how closely the map corresponds with the real world' [SPR*96]. Duke et al. [DBHM03] further studied the link between rendering and affect.

3.2. Non-aesthetical measures

To reduce clutter, there are methods that do not, or at least not directly, focus on aesthetics. Some of these methods focus on data, others on geometry, although techniques such as semantic lenses [RGE07] combine both.

Data-driven solutions focus on filtering, sampling (e.g. random sampling [DE02]) and statistical models to reduce the amount of objects on the display or to find relevant data clusters. On the latter, work by Holten [Hol06] on hierarchical edge bundling claims to reduce visual clutter in compound graphs. Clutter reduction through data clustering has some drawbacks:

- clusters may not be visually intuitive to the viewer.
- clustering is viewed as lossy data compression and the information that is deleted could be critical.

Geometry-driven solutions focus on simplification of visual objects such as work by Barla et al. [BTS05] on geometric clustering of line drawings. Their method works based on selecting a smaller set of lines to represent the geometry of the original lines. The final image is a simplified version of the original. This non-distortive method is suitable for highlighting morphological structures.

4. Underground Data and Tasks

The scope and extent of underground assets in the UK are massive [Far06]. A naive representation of such complexity results in drawings that serve neither as good overview nor as interface to fine detail. The aim of this section is showcase scenarios from industry where aesthetics have been *manually* applied to deal with visual complexity and detail on plans (section 4.1). These, however, are by no means common practices. We examine the nature of multi-service plans through an example in section 4.2.

4.1. Existing practices to deal with clutter

Multi-service plans are typically complex drawings so sometimes utility organizations adopt simplification or abstraction procedures manually to reduce clutter. Often details are moved or removed for the sake of clarity. In such cases, visual conventions are adopted to mark the areas where simplification has been carried out. We note that these procedures do not necessarily reduce the accuracy of the information presented (e.g. using cross sections).

There are a number of scenarios that illustrate the variety of techniques used to deal with visual complexity that are currently being used. For example:

- valve details will usually be shown by a simple cross line and hydrants as a single filled circles.
- two mains running side by side will usually be shown further apart than reality.
- a congested area will sometimes be shown as a hatched area. This also applies to close-by cables which can be portrayed by drawing the 2D extent of the set and hatching the bounded area as in Figure 3.
- complicated pipe junctions may be shown in an exploded detail view, often with a link to a scale CAD drawing of that junction.
- cable ducts are portrayed using the cable conduit and cross section points placed at a regular interval for high voltage electricity cables and at locations where there are significant deviations such as in depth (Figure 4).

Figure 3: *Cables extent to reduce clutter*

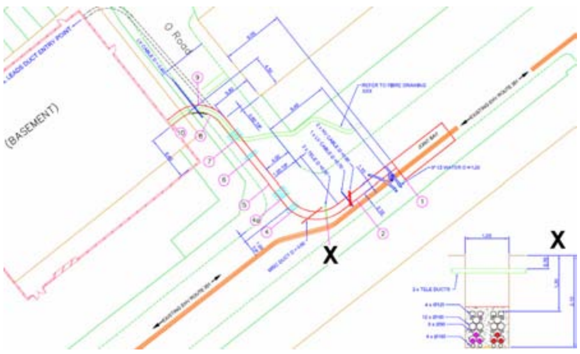

Figure 4: *Cross section (X) to reduce clutter*

4.2. Integrated views: a multi-service plan

Although there are a number of techniques currently used by utility companies to deal with clutter (section 4.1), the problem of clutter is complicated by the lack of standarisation

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through the utility industry; documents describing guidelines for recording and display of utility assets (e.g. STC 25) do not cover methods to deal with detail. Moreover, they are substantially out of date and not necessarily followed.

A visual inspection of the service plan in Figure 2 (issued in July 2006) can reveal dense areas of asset apparatus (e.g cable and electricity in green and red respectively). There are various factors contributing to visual clutter in this drawing:

- close geographical proximity between assets especially for telecommunication and electricity cables.
- line crossings and busy junctions.
- missing 3D information resulting in overlapping or nearly-overlapping objects.
- overlaps between labels (& their anchor lines) and geometric objects on the plan.

Utility companies mostly rely on their GIS and CAD systems to handle visual complexity, for example, by turning layers on and off. This may work for digital displays but paper plans are still the most widely used visual tool for onsite work. There is much potential for improvements; in this paper we suggest areas where aesthetics can help create simpler yet functional plans.

5. Clutter Elimination

This section sets out and reflects on the methods used to encapsulate graph theory aesthetics for application to the problem domain (section 5.1). Other aesthetics considered in information visualization, such as rendering style and colour, are addressed separately in section 5.2. Three design assumptions underlie the details set out below:

- the geographical 'backdrop' lines are ignored when calculating clutter information, as the backdrop has a different status from that of the asset network data and its features are visible on-site;
- no distinction is made between types of assets when generating abstractions, i.e. we will, if visually appropriate, merge features from different networks;
- clutter caused by the overlap between labels and assets, or between the labels themselves, is not accounted for; and
- our clutter calculations do not consider scale variations.

5.1. Graph Aesthetics

Not all graph drawing aesthetics are applicable in the assets domain; although symmetry for example might prove helpful in presenting topological models of service provision, the anchoring of asset data against geographical space means that there is little flexibility to explore or exploit this property. However we have found that four aesthetics that contribute to clutter are relevant: *proximity*, *edge crosses* (their number), *bends*, and *angles*. For each case, we outline how the specific source of clutter can be detected and removed, and the implications for doing so. Data from a utility survey company is used to regenerate the plan in Figure 2 to apply the chosen aesthetics criteria.

We note that certain aesthetics interact with others, both positively and negatively. Bundling together lines to remove proximity clutter, for example, has the beneficial effect of also reducing the number of line crossings. However, smoothing a line by reducing bends may affect the angle at which that line crosses others, impacting the angles aesthetic. This raises a question of prioritisation: does line continuity, for example, take precedence over line crossing? For the present, the potential for interactions means that we examine aesthetic criteria in pairs.

5.1.1. Close Proximity, and Crosses

In order to detect lines in close proximity, we first compute the smallest distance D between any two line segments (D=0 for intersecting lines). A threshold value T is then identified which is the minimum value of D that captures the *spatial proximity Gestalt* [BGG03]. Thus, two lines occurring within distance T are perceived to belong to a visual group.

To determine the absolute proximity threshold for the map in Figure 5 (and the close-up in Figure 6), we used the *staircase-method* [Cor62] in a single subject study. For this case, T = 0.15 of the domain's coordinate system. We also found that over half of the total number of line segments in the plan (57.33%) fall into the category of lines in close proximity. We are aware that proximity thresholds, and clutter in general, are scale-sensitive. Our intention is to conduct a larger study with a pool of participants from different age groups, thus examining the link between scale, visual acuity and proximity thresholds.

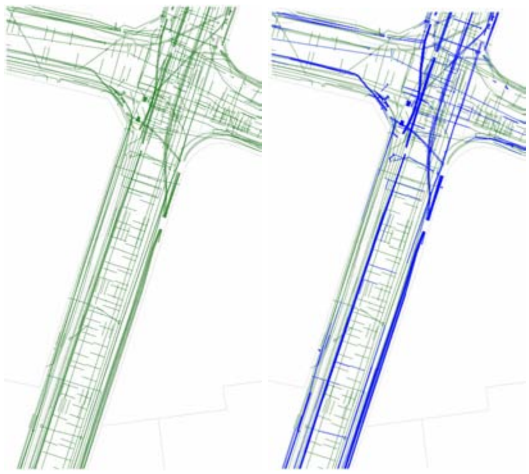

Figure 5: *[left] Reconstructed service plan of Figure 2 showing all assets (indiscriminate) [right] The same plan showing assets in close proximity in blue*

We chose two techniques to reduce clutter caused by close

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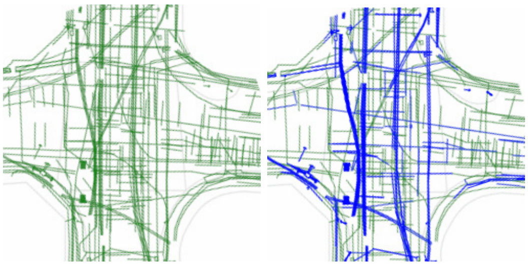

Figure 6: *[left] A close up view of the service plan showing all assets (indiscriminate) [right] A close up view of the service plan showing assets in close proximity in blue*

proximity (Figures 7 and 8). The first method replaces each perceptual group with its convex hull; the second method simply grows the width of close lines to reach the 0.15 proximity threshold, thereby merging the lines into a single feature. For both cases, we used colour intensity to indicate, qualitatively, the density of each perceptual group (Figure 9). When lines are occluded, opacity gives a more truthful indication of asset density than the original line drawing.

The current implementation of the convex hull does not take into consideration the length of intersecting line segments, thus a visual inspection of the results suggests that the second solution is a better match to what users perceive as a group. As a result of increasing the line width of close lines, new 'ticker' line segments are formed, reducing the total number of line crossings in the drawing.

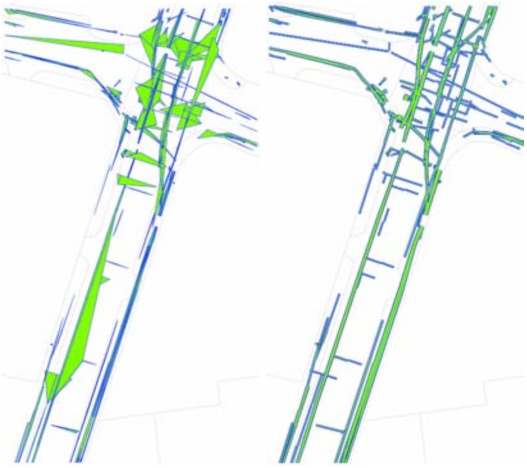

Figure 7: *[left] Drawing the convex hull of each perceptual grouping to reduce clutter [right] Growing line width to colour the perceptual groupings areas*

5.1.2. Bends, and Angles

Ware et al. [WPCM02] defined line bendiness as the average angular deviation from a straight line. We soften this

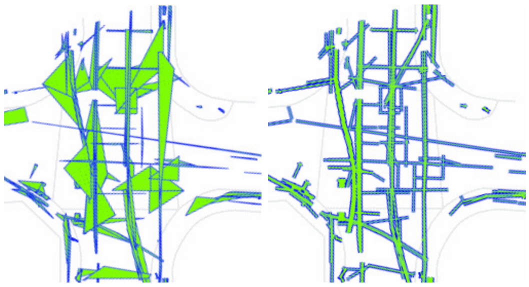

Figure 8: *[left] Close up of the convex hulls of the perceptual groupings [right] Close up of the perceptual groupings areas achieved by growing line width*

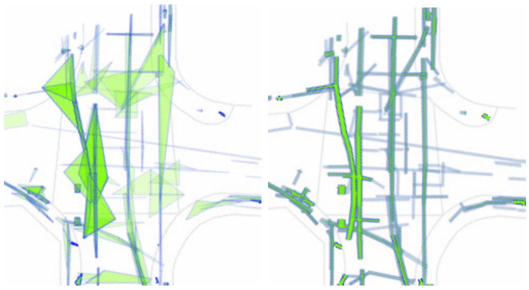

Figure 9: *Clutter intensity in the convex hull areas [left] and 'grown lines' [right] represented by colour opacity*

definition by accepting angle deviations that are 45° (+/-5°) or multiples of this angle, in line with Beck's London underground aesthetics. Similarly, we define clutter angles at asset intersection points where the angle is *different* from 45° or its multiples (again we take +/-5° angle margin).

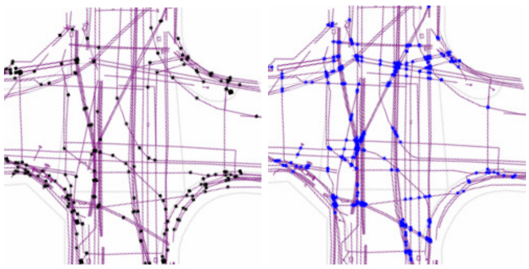

Figure 10: *[left] Clutter bends denoted in blacks [right] Clutter angles at asset intersections are highlighted in blue*

The majority of line segments are clearly affected by clutter bends and angles (Figure 10). It is not possible to completely eliminate this type of clutter without increasing the clutter angle margin (currently set to 5°) or adopting new constraints. Even partial solutions require some feature locations to be adjusted and in some cases a considerable shift can occur, for example, an asset located under the pavement

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may be moved to the road. This is not desirable for excavation tasks requiring accurate information. Other methods to de-clutter busy junctions and zigzagging bends that preserve accuracy need to be investigated.

5.2. Information Visualization Aesthetics

The Ordnance Survey backdrop has a vital role, proving a frame of reference for site teams, and correlating features of the asset network with local geography. It plays a similar role to that of axes and grids within a numerical graph, but in our application this reference layer is also a potential source of clutter, particularly as assets are often laid in close proximity to pavements. As it would be inappropriate to treat reference lines in the same way as asset features, we instead note the recent work of Bartram and Stone [BS07], who explored means of making grids perceivable but not intrusive. Their recommendation, that grids be drawn with an alpha of 0.3, has been adopted within our approach.

A further area of aesthetic concern, and one where work is ongoing, concerns annotations. Service plans carry a wealth of further data, both as textual labels on features, and as geometric annotation, for example transects through ducts carrying multiple assets. Our thought is to generalise from the latter, using transects to reveal internal details where multiple assets have been replaced with single features.

6. Discussion

This paper makes a contribution to establishing an aesthetic view for the underworld. We have implemented methods to detect clutter caused by proximity, crosses, bends and angles. The two methods we adopted to reduce clutter (i.e. line grown and line bundling) can be useful for user tasks requiring access to an overview image showing assets *extent* and *density* in a given geographical area (e.g for a planning job to build a bridge). However, service plans produced using these two methods lack detailed information which makes them less suitable for tasks requiring greater accuracy (e.g. for finding a duct or a single pipe). Because of the diverse range of use-case scenarios of utility data across the utility sector, a one-plan-fits-all solution is therefore not suitable.

Additionally, we have shown how perceptual groupings can be an intuitive basis for repackaging details; and discussed, via examples, how certain aesthetic combinations interact and affect each other. We also hinted towards the prioritisation of aesthetic criteria. This view is in agreement with Purchase et al. [PAC00] that the prioritisation of aesthetics criteria in abstract graphs is different in domain-specific applications where the network has a meaning in real life. There are three main areas for future work and improvements: (1) in-depth investigation of the trade-off between accuracy and clarity (2) incorporation of the notion of salience in the definition of aesthetic criteria (3) evaluation and comparison of service plan aesthetics.

Firstly, there is a trade-off between clarity and accuracy of information. For some planning tasks where centimeter accuracy may not be paramount, asset locations can be moved. In such cases, visual marks need to be placed to describe the positional shift. Such is a common practice in uncertainty visualization. However, the added graphics could also contribute to the problem of clutter. Where greater accuracy is required, non-distortive techniques should be used. Transects, for example, can reveal internal details where multiple assets have been replaced with single features. This however creates a challenge of placing these views so that the result is not further clutter; note that while in principle one might generate transects 'on demand', this is not an option where service plans are (and will continue to be) printed on paper.

Secondly, we would like to further investigate the link between salience and aesthetics. We think that a key part of aesthetics involves how to ensure or encourage the perceptual pop-out of just those elements in the plan that are salient for the task. Some of the clutter criteria we used in this paper helped identify the visual groups that are formed as a result of the close proximity between some of the assets on a 2D plane. There are other factors which can help identify perceptual groupings more accurately, such as line *width*, *length* and *orientation*. Indeed, we can also use these visual properties to prevent unwanted pop-outs of the less salient features by, for instance, visually de-emphasising their appearances.

Finally, there are two types of evaluations that would be useful in this study. First, a comparison between aesthetic and non-aesthetic methods to reduce clutter. This can highlight commonalities and conflicts. Second, the evaluation of usage of the service plans themselves. The difficulty in this is that plans are a specialised representation. A plan succeeds if the task is performed correctly, e.g. an asset is located without other assets being damaged in the process. In practice however, the value of the plan may be compromised by uncertainties within the data - a good plan might none the less lead to task failure. Ideally, one would like to compare task performance with two plans, one with visual clutter, and one respecting aesthetics. It is not straightforward however to arrange a controlled study, and performance in any case may be subject to individual expertise. Our argument is probabilistic - by encapsulating accepted good design practice we hope that the plan will prove useful.

Conclusion

In this paper, we have considered clutter as an important factor in diminishing the aesthetics of the presented image. In our investigation to eliminate clutter in service plans, we took reductionist steps from graph drawing to measure clutter primitives such as proximity, bends, crosses and angles. We implemented proof-of-concept techniques to reduce clutter by repackaging details and using aesthetics from information visualization.

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We argue that '*de-cluttering*' does not mean loss of information, but rather *repackaging* details to make them more accessible. In this respect, aesthetics have a fundamental role in implementing Schneiderman's mantra of 'overview, zoom & filter, details-on-demand' for information visualization. Simplification and abstraction methods, such as line bundling, can provide a good overview; then interaction techniques such as multiple coordinated views and transects can help zoom & filter and provide details-on-demand.

7. Acknowledgements

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