Relating Urban Form to Resource Consumption: Analysis and Visualization

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In this paper, we describe a process that is being developed to analyze and visualize the resource efficiency of urban areas at the neighborhood scale. This approach examines patterns in the urban form of neighborhoods, and estimates material and energy consumption measures.

The objective of this analysis is to facilitate simple and repeatable methods of spatial analysis so that comparisons of the resources used by neighborhoods can be made using the same initial assumptions. It does not provide a detailed assessment of individual consumption patterns, but tries to identify ranges of behavior based on some measurements of the urban form.

This paper is structured in two parts. The first part describes analysis that has been performed to identify ranges of resource consumption; the second part focuses on how the results of this analysis are displayed and explores some different strategies to show this analysis.

Contents

Introduction

This research is motivated by the lack of suitable tools available to the planning community to quantitatively analyze the resource consumption of urban areas in a replicable way. This is apparent in the guidelines that have emerged from leading planning and sustainability organizations such as the US Green Building Council, and the New Urbanism design movement. While these guidelines have merit as they focus on sustainability issues, such guidelines are not always based on quantitative analysis, which can make it difficult to assess their benefit when implemented. It is hoped that applying a similar analytical approach to cities and neighborhoods will enable the identification of ranges of behavior.

The identification of ranges of resource consumption from empirical data can provide a means to characterize urban complexity and resource efficiency. Identifying these ranges enables planners and policymakers to develop reasonable targets as they attempt to ensure their cities become as resource-efficient as possible.

Exploring the spatial configuration of cities and general patterns of resource consumption is challenging as there is little published work (either raw data, or results) available. Frequently, aggregated per capita values are used when describing consumption within a city which can conceal the variation that occurs at a higher resolutions of measurement.

There are two intended audiences for this work. It is hoped that the detailed GIS analysis would be more of interest to an expert in the field, such as a planner or engineer. The web-based visualization of resource consumption is intended to be used by non-experts or those who try to gain an understanding of different urban form patterns.

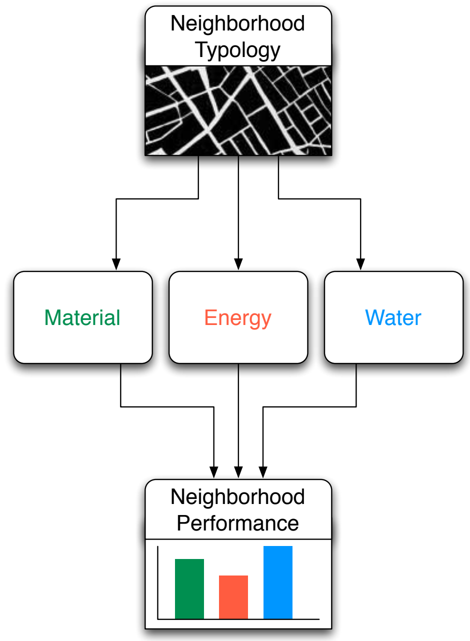

Figure 1: Schematic of tool functioning and data inputs for GIS tool. In this paper, resources are considered to be material and energy measures. Materials consist of construction material required for road and building construction, while only energy for transportation is considered.Water will be examined in a future iteration of this work due to data constraints.

Review of Prior Work

Previous work analyzing cities in a standardized way has typically been done from a high-level perspective (Bettencourt et al., 2007; Decker et al., 2000; Newman and Kenworthy, 1989). Although there is limited relevance for local policy at this level of abstraction, it is a useful approach for identifying macro-behaviors and enabling comparisons. Bettencourt et al. (2007) identify scaling patterns when groupings of cities are examined while Decker et al. (2000) examine energy and material use in megacities. Newman and Kenworthy (1989) explored the relation between population density and energy and suggested that cities with higher population densities used less energy per person for transportation, a conclusion that has been debated often in the literature.

Much of this work has compared the functioning of urban areas to each other, using city-level average measures. Within the city, standardized analysis has been more limited. Although population density gradients have been observed for some time, and more recent work has examined internal mechanisms that result in particular urban patterns (Batty, 2008; Marshall, 2007); the relationship between these patterns and resource usage have not been explored comprehensively. Work by Quinn and Fernandez (2010) describe the general spatial structure of the city with the goal of relating the spatial structure to resource consumption, as well as describing a method to perform the analysis (Quinn and Fernandez, 2011)[1].

[1] This method is a plugin for ArcGIS written in the Python programming language to calculate population density and road density gradients.

Standardized Analysis of Urban Form

This research uses spatial data which describes the location of people, buildings, roads and services. The objective of the analysis is to provide a performance measure of a city that considers a variety of tradeoffs (Figure 1). The analysis is performed using a series of plugins using standard geographic information-systems (GIS) software. For example, this analysis can be used to compare the resource consumption of a sprawling suburban low-density neighborhood and a compact mixed-use high-density neighborhood.

The software used for much of this analysis is ArcGIS. Python scripts were written to perform the analysis. These scripts are available upon request.

This analytical approach tries to overcome the systematic problem that exists in many urban analyses, where it is difficult to compare an urban area in one city to another area in another part of that city, or in another city. Resource consumption measures are examined for a range of different urban typologies that have been identified from existing cities at the neighborhood scale (where a neighborhood is considered to consist of approximately 1,500 people). Understanding tradeoffs between material and energy use is particularly relevant in rapidly growing cities, as short-term planning decisions have long-term consequences for both the quality of life of the inhabitants, and the future energy and material use of the urban area. The tradeoff of developing a set of analysis that are standardized, is that the process must simpler as it must cover a broader range of conditions.

While the US has excellent census data and road network data, one major weakness is the lack of any publicly available datasets for energy consumption at a high spatial resolution. In contrast, the UK publishes residential energy consumption data (split by electricity and gas) for census districts that contain approximately 1500 people.

However, developing a standard set of analysis steps to run on datasets is only part of the challenge. Assembling datasets that represent neighborhoods accurately, at a spatial scale suitable for this type of analysis is still challenging. This data organization is a slow process, but one that is becoming easier with improved technology (digital storage of data, improved computational power). In addition, cities are beginning to realize the benefit of making data available as they realize the potential and benefit of researchers analyzing this data. New York, Boston, Cambridge, San Francisco, Chicago and Seattle are some US cities that have comprehensive spatial datasets available.

In the long term, it is hoped that identifying the critical pieces of information needed for assessing resource consumption performance will be more easy available, and the quality of the data (and consequently analysis) will improve. Inevitably, this process will be iterative as city officials need to understand the benefit of gathering certain types of data that they may not have previously considered, and to release this data in machine readable formats.

Web-Based Visualization

Effective visualization strategies are important for understanding complex systems, and for understanding the performance of systems with multiple dimensions. Batty (Brail, 2008)[p.29] states that visualization is 'drifting toward web-based models', but also observes that there is a lot of software fragmentation associated with *Planning Support Systems*.

While there have been significant improvements in geo-visualization at the global and urban scale[2], much of the improvements have been purely from the visualization side. It seems likely that the next phase of technological innovation will be the development of move intuitive tools that enable quantitative analysis and that the current paradigm of static GIS desktop analysis will be become less relevant.

[2] Google maps, Google Street-View, OpenStreet map, Maquest and Microsoft Bing have all greatly changed how individuals (who have access to a web-enabled device and are computer literate) perceive the built environment.

This advancement in quantitative spatial analysis will most likely be influenced by the software used.[3] It is important that planners (and schools educating planners) start to use GIS tools that are either free or open-source, so that these methods of analysis are accessible to all. This will result in a democratization of spatial analysis similar to the changes that have occurred in the geo-visualization field and will move GIS analysis from being a specialist academic discipline to one that is commonplace. Using web-based visualization and analysis tools that are platform agnostic, enable the user to access these tools on any device. *GeoIQ*, *BatchGeo* and *Walkscore* are three online webservices which either illustrate or provide the ability to perform quantitative analysis.

[3] ESRI were estimated to control approximately 30% of the global GIS market in 2009 (Daratech, 2011) but have been estimated to have a much higher 'mind-share' (Batty, 2009)

Standardized Analysis of Urban Form

In this section I describe two examples of standardized analysis that have been performed on two different datasets. The first example is performed at a city level and examines population density and road density for 40 cities on the continental USA. The second example considers more detailed urban form measurements at the neighborhood level using data for London.

City Level Analysis

Based on the analysis of 40 US cities, certain patterns of behavior have been observed that can relate population density to material and energy demand. Figure 2 illustrates the road length per person for varying population density levels, for the 40 cities examined. Interestingly, there are clear upper and lower ranges of road length per area and per population density, based on these calculations. These measures were calculated on a grid with a cell size of 200m and consist of approximately 8 million observations.

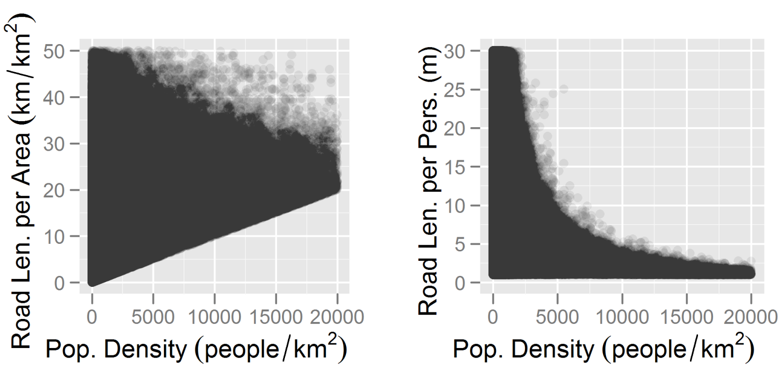

Figure 2: Infrastructure and population density for 40 US cities. This pattern illustrates the amount of infrastructure per person, using empirical data for the US (Data source: US 2008 Tiger road files). Road length calculations were performed using vector data; population values were calculated using the 2000 US census assuming a uniform distribution across the census district.

A more detailed explanation of this analysis is given in a working paper available upon request.

A clear trend can also be observed in empirical Vehicle Kilometers Travelled (VKT) data per person for the state of Massachusetts. Using this empirical data, Figure 3 shows that the upper boundary of VKT per person decreases significantly when the population density increase. Figure 2 and 3 illustrate how these ranges of behavior vary. While the variation is still extremely large, at low population densities the individual behavior cannot be predicted with any great accuracy, at higher density levels the predictive capacity becomes more accurate.

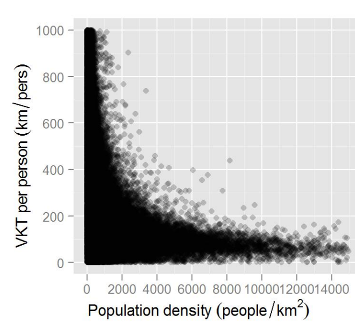

Figure 3: Empirical VKT data and population density for the state of Massachusetts. Data: US Census and Massachusetts Department of Motor Vehicles.

Neighborhood Level Analysis

Neighborhood typologies are identified using parameters that describe the physical environment. Using an approach to categorize the urban form into typologies based on urban form measurements, then material conversion factors for London were used to convert the geometric patterns into material unit measures. Typologies are identified from the existing building stock of London, and their material intensity is analyzed. Material intensity is calculated based on construction materials used in residential buildings and urban infrastructure.

The following work is a collaboration between David Quinn, Daniel Wiesmann (PhD Candidate, Instituto Superior Técnico, Technical University of Lisbon, Portugal) and Juan Jose Sárralde (PhD Candidate, University of Cambridge, UK). More details of this work can be seen in Quinn et al. (2011)

Physical parameters were identified that describe the urban form (Table 1) and these measures were used to identify clusters. The data sources used for clustering in this analysis were a 3D building model and land-use categorizations. After calculating urban form measures for each census area, a statistical clustering technique was used to identify groupings in the data.

Table 1: Clustering dimensions

Category	Description
Plot Ratio	Total floor space / LLSOA area
Green Space Fraction	Total green space / LLSOA area
Built Area Fraction	Total built footprint / LLSOA area
Average Building Height	Average height of buildings in LLSOA

The k-means algorithm was used to identify clusters. This algorithm partitions data into *k* number of clusters (where *k* is chosen based on graphical observation) using *n* observations. In this case, three cluster groups were chosen (k=3, n=5625) and the statistical language R (R Development Core Team, 2011) was used for the calculations.

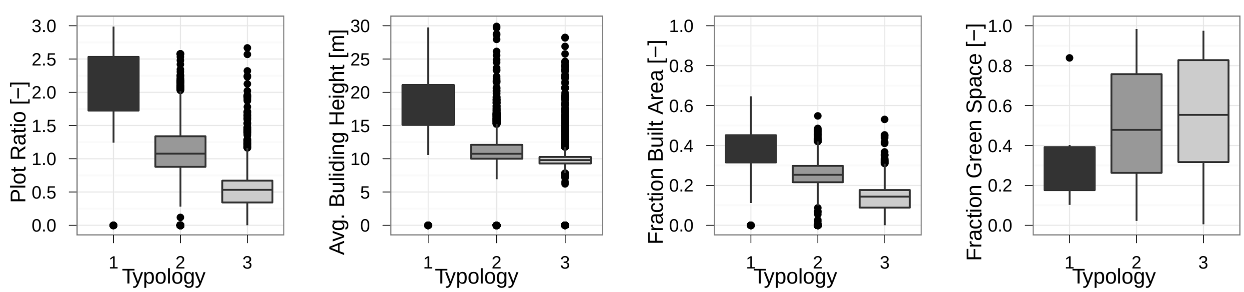

Figure 4: Using geometric measurements, three typologies were identified using clustering. These typologies are shown for each geometric measurement.

The spatial location of each typology is shown in Figure 5. It can be seen that these patterns are in radial bands, following the gradient in building density that decreases from the centre of the city towards the suburbs. The results of this unsupervised clustering process are still general and do not reflect the high level of complexity in the urban fabric, but they show that the structure of the city can be identified using only four general descriptors of urban form, without a prior understanding.

Example clusters are shown in Figure 6 using a 3D model and Google Earth, illustrating the differences in a more intuitive way. We can also observe that there are more single-family homes in Typology 3, compared to Typology 1. These typologies were then used in the web-tool to categorize the urban form.

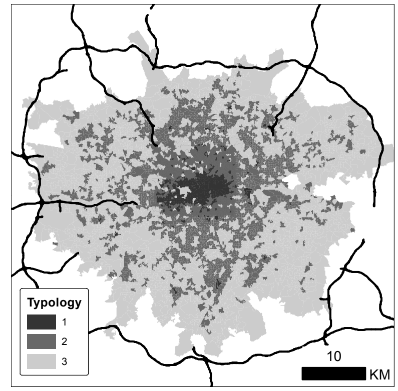

Figure 5: London clusters

Figure 6: Examples of London clusters

Finally, geometric measurements of each typology area shown in Figure 7. Using estimates of material required for road construction and building construction estimates of the material required for infrastructure and buildings are also shown in Figure 5.

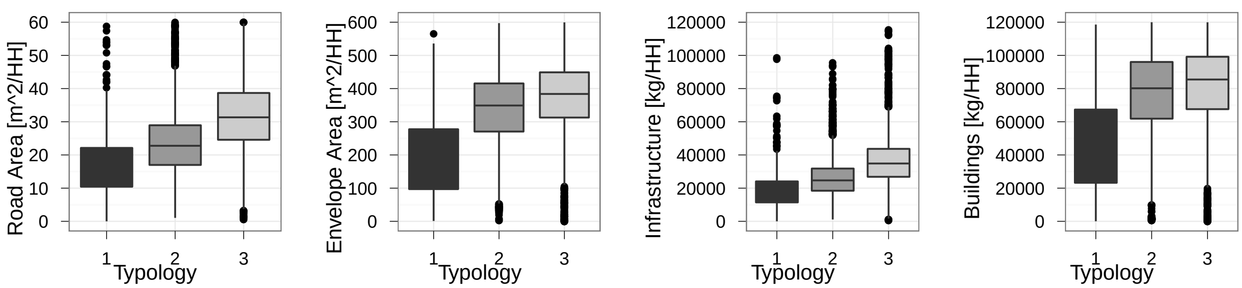

Figure 7: London road and building surface area by typology.

This analysis ilustrates that urban typologies can be identified using geometric measurements at the neighborhood scale. Through comparison, the material intensity of each typology shows significant differences in construction material for the greater London area.

Web-Based Visualization

The objective of developing this tool was to display the results of this analysis in a user-friendly way that works on any software platform with an internet connection. This visualization is intended primarily as a pedagogical method to facilitate discussion about urbanization patterns, and to illustrate differences in resource consumption quantitatively.

The first iteration of this tool was developed using HTML/Javascript on the browser side and PHP/MySQL on the server side. The current development version is using HTML/Javascript on the browser side (with the Javascript OpenLayers library), and PHP/PostgreSQL 8.3 with PostGIS 2.0 on the server side to store vector and raster data. PostgreSQL and PostGIS are both open-source software.

Currently this tool only displays spatial data that has previously been analyzed using other GIS software. It does this by performing a spatial query on the area identified by the user and displaying the results in the browser (Figure 8). The tool is not processing the raw data in real-time; instead it is displaying information that was previously prepared. The connection with the underlying base-map[4] is to calculate the latitude and longitude of the area identified by the user.

[4] In the images in this paper, Google Maps is used as a base-map.

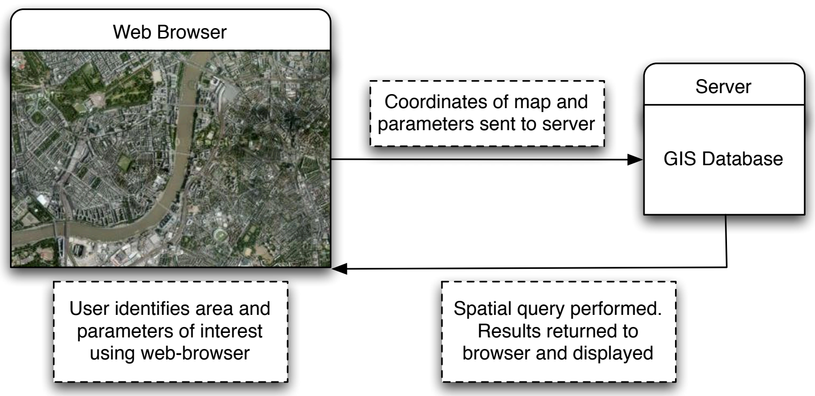

Figure 8: Diagram of browser/server interactions. The GIS database can store vector or raster data which can be displayed in the browser as an overlay on the base map.

Structure of Web Tool

The objective of this visualization tool is to demonstrate some of the tradeoffs associated with specific urban configurations. The interface provides a user-friendly way of exploring these tradeoffs, so that the user can learn what parameters influence resource consumption at the neighborhood scale. The tool focuses on general cases, with some simple scenario-like functionality built in (Figure 9).

The output of the tool illustrates graphically what the resource consumption of the selected urban area is assuming a typical functioning of the neighborhood. A detailed explanation of the structure of the tool is shown in Figure 10 with the corresponding numbers as a key to the red boxes.

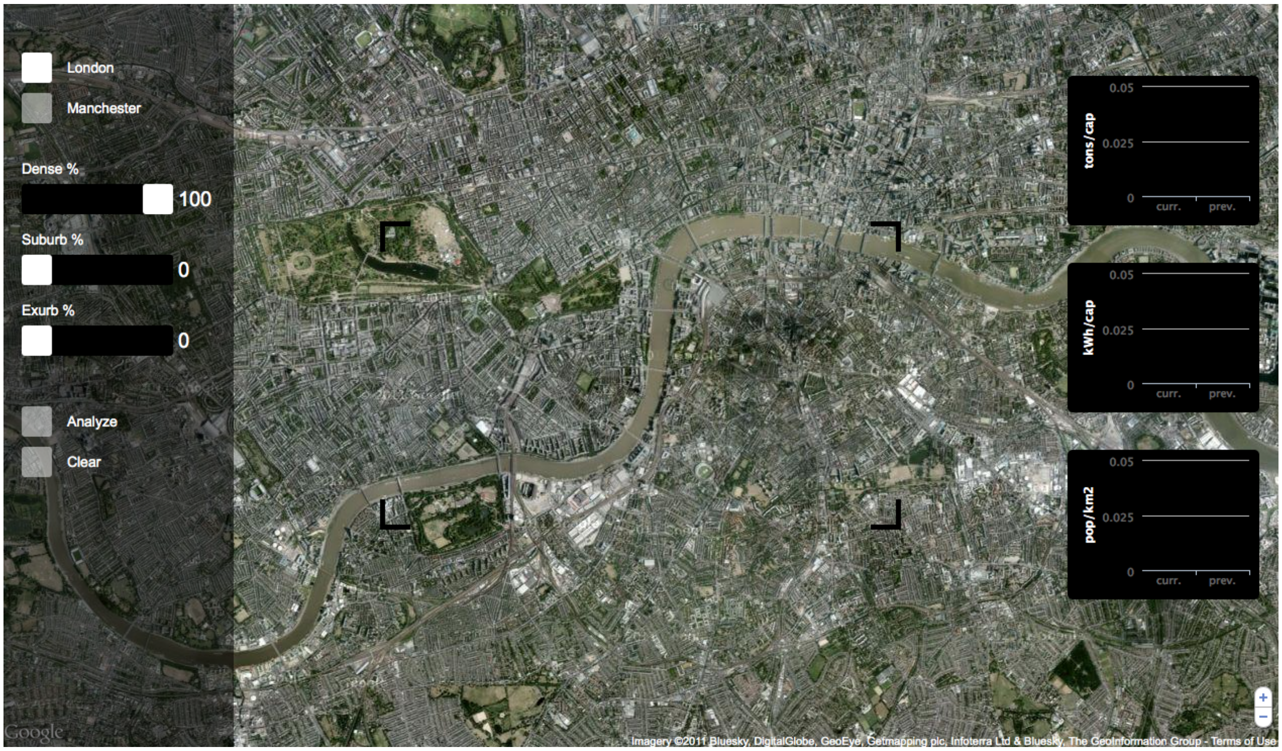

Figure 9: *Neighborhood Analysis Visualizer v0.2* interface. The input parameters on the left-hand side provide the user ways to adjust the mix of urban forms that are present. A working version of the site can be seen at `http://urbmet.org/visualizer/` and a video explaining how it is used: `http://vimeo.com/30348678`

Box 1: The user can choose the city which they wish to examine. Currently only Manchester or London are the options; the 40 US cities described earlier will be included next.

Box 2: Measurements of the urban form are shown on the sliders in this box. When a user examines a specific area, these adjust to explain the mixture of neighborhood types. These groupings correspond to the results of the typologies shown in in Figure 4

Box 3: Two button options are shown here. The user can click *Analyze* which causes the plots in Box 5 to be updated. Clicking on the *Clear* button will result in all values being removed from the screen.

Box 4: This central box identifies the area over which the analysis is performed. The user can pan the map freely, and analyze a second area; both results are shown on the map at the same time. If more areas are chosen for analysis, only the two most recent are shown on screen.

Box 5: These three graphs provide an area for the user to examine the output. The current output measures are KG of material per person (estimated using road and building geometries, housing construction survey data and road construction guidelines), KWh of energy (based on residential consumption of electricity and gas).

Figure 10: Detailed explanation of web-browser interface.

Future Improvements

The underlying goal of this research is to assemble information about the resource consumption of cities, in the most useful format possible. One of the challenges in developing a tool to assist in visualizing this analysis, is identifying what questions people are interested in, and for what purpose. The original intention of this work was to develop a system for showing spatial analysis in a graphically intuitive way and to facilitate learning. The next part of this work is to explore whether planners (or decision makers) are interested in these quantitative measures and the form that this would take. This tool will be tested with users to gather feedback so that we can refine and develop future iterations of it to explore whether it facilitates learning and if the overall format is useful.

The next version of this analysis tool will show users the parameters used to create the groupings and enable users to examine what combination of factors are considered most important for material and energy use. Diagrams of proposed future functionality are shown in Figure 11 and explained in the following list:

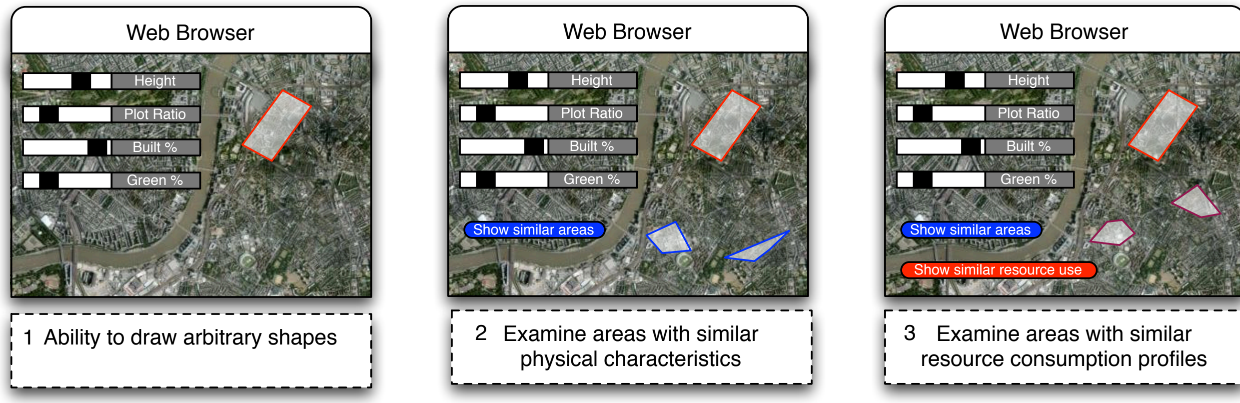

Figure 11: Some proposed functionality for the next iteration of the *Neighborhood Analysis Visualizer* tool.

1. User can define irregular boundaries by drawing on screen. At the moment, only the central rectangular area can be analyzed. Enabling a user to draw an irregular boundary on screen could return more accurate results for the area of interest (assuming that the data is available at the resolution required).

2. Enable user to identify areas that have the same physical characteristics. When a user analyzes a specific area they could chose to examine other areas with similar physical characteristics within a specified distance.

3. Enable user to identify areas that have the similar resource consumption profiles. When a user analyzes a specific area they could chose to examine other areas with similar resource consumption profiles within a specified distance.

We are also considering how to relate this analysis to urban growth models. While the focus of this approach is to gain a better understanding of material and energy consumption, many of the relationships identified could be used to convert the output of an urban growth model into quantitative measures of material and energy which could be useful for scenario analysis.

Conclusion

This paper discusses some methods that have been applied to perform a standardized GIS analysis of cities and neighborhoods, using examples from cities in the US, and London.

The intention of this visualization approach is to enable a holistic and quantitative understanding of the urban system. It is hoped that this approach enables users to learn about some relationships through exploration.

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