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The State-of-the-Art of Geographic Visualization in Urban Planning

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Abstract

Urban planning is a technical and political process concerned with the use of land and design of the urban environment, including economy, environment, transportation and distribution networks, etc. It helps policy makers to shape a sustainable future of our cities, and thus very relavant to our everyday life and long-time prosperity. Geographic visualization has always been of significant importance in urban planning, as majority of data collected for urban planning purposes are geo-referenced and can be naturally handled by geographic visualization techniques.

In this state-of-the-art report, we present current situation in utilizing geovisulization in urban planning research, survey newly achieved improvement in geovisualization, and interview three urban planning experts, one of whom has geovisualization background. We also summarize several challenges in the intersection area of geovisualization and urban planning to conclude the report.

1. Introduction

Urban planning is a general term for a very wide range of research or practical activities. It includes a variety of technical and political processes concerned with the use of land and design of the urban environment, including economy, environment, transportation and distribution networks, etc. The ultimate goal of urban planning is to enlighten policy making so that cities can be designed and improved to be more sustainable.

The political aspects of urban planning is out of the range of this state-of-the-art report. The technical aspects of urban planning involve the technical consideration, processes and features that are involved in planning for land use, urban design, natural resources, transportation, and infrastructure. Urban planning includes techniques like predicting population growth, zoning creating, geographic mapping and analysis, analyzing park space, water supply, identifying transportation patterns, food supply demands, allocation of healthcare and social services, the ability of citizens to use the urban environment and the impact of land uses, etc.

Visualization, or more precisely, geographic visualization (geovisualization) has been a very important part of urban planning for a long time [MK01]. Geographic visualization refers to processes, techniques and tools that support geospatial data analysis through the use of interactive visualization. Geovisualization integrates approaches from information visualization, cartography, image analysis and geographic information systems (GIS) to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data, which refers to any data that with some kind of geo referencing. This referencing ranges from precise geographic coordinates, through street addresses, to codes for administrative or other types of regions, such as zip codes and drainage basin indices.

In this report we conduct a survey of recent advances in techniques of geovisualization and in urban planning research. We also present interviews to three urban planning researchers. Dr. Tilahun and Dr. Ai are both from the Department of Urban Planning and Policy at University of Illinois at Chicago (UIC) and work on urban transportation related research and urban environmental planning, respectively. Dr. Derrible is from the Department of Civil and Material Engineering at UIC. He works on applying complex theory and data visualization techniques in civil systems. We hope this work lead to further discussion in the intersection region of urban planning and geographic visualization and promote collaboration between the two communities.

This report is organized as follows. In Section 2 we briefly describe urban planning tasks and the geospatial data they used, followed by a dicussion about common techniques that are used in urban planning in Section 3. We then present some of recent research efforts in improving the utilization of visualization in urban planning tasks in Section 4, and followed by a list of challenges that should be tackled in the future in Section 5. In Section 6 I draw some conclusions. We put the record of interviews to domain scientists at the end of this report as Section 7.

2. Tasks and Data in Urban Planning

2.1. Tasks

The process of urban planning is systematically formulated as "survey - analysis - plan". Survey stage is where data collection happens. This stage is important because without proper acquisiton of adequate and accurate data, no (or even wrong) conclusion may be made during analysis stage. Analysis stage is where urban planning researchers perform conversion, storage, synthesis, calculation, simulation, etc, to collected data in order to find insights from the processed data such as relationships between events, patterns in phonomena, or trends in development. Plan stage is where the result of analysis make influence in policy making to build more sustainable and resilient cities.

2.2. Data Types

Urban planning is a very general term. It includes a variety of aspects of planning a sustainable and resilient urban areas. These aspects varies from transportation, education, employment, to economy, environment and safety. Therefore, massive heterogenous data needs to be collected. The only common property of this sets of data is that all data can be geo-referenced, which makes geovisualization techniques a good fit for accelerate and escalate tasks in analysis stage.

Major types of data that urban planning researchers make use of include but not limited to cartographic data, geographical data, demographic data, transportation data, and environmental data.

2.2.1. Cartographic Data

Cartographic data refers to static maps (mainly used in traditional urban planning tasks) and map tiles for interactive maps (mainly for geovisualization).

Commonly used map tile services include: Mapbox, OpenStreetMap, MapQuest, Google Maps, Bing Maps, etc. Commonly used online mapping frameworks to support browsing a tiled map include Google Maps API, Mapbox API, Leftlet.js, etc.

2.2.2. Geographical Data

Here geographical data refers to any data with geographic coordinates. In old days these types of data were usually integrated directly to static maps. Since 1994, the foundation of the Open Geospatial Consortium (OGC) started the trend of using standardized formats to store geospatial data digitally.

Commonly used geographical data format include:

- GML (Geography Markup Language), XML based open standard for express geographical features developed by OGC;
- Shapefile, a popular geospatial vector data format for GIS software developed by Esri (Environmental Systems Research Institute);
- KML (Keyhole Markup Language), an XML notation that complements GML for expressing geographic annotation and visualization developed by Google.
- GeoJSON, an open standard format based on JSON for encoding collections of simple geographical features along with their non-spatial attributes.

2.2.3. Demographic Data

Demographic data refers to the Decennial Census and other surveys of individuals and households administered by the Census Bureau or other government agencies.

Demographic data is usually not stored in standardized geographic format. Instead, general-use file formats such as CSV or other tabular format are used. The geo-reference of this type of data is usually not geographic coordinates but codes for administrative or other types of regions. It is also common to store demographic data together with geographical data, such as storing as associated attributes of geometric shapes in shapfiles, or storing in GeoJSON files.

2.2.4. Civil Data

Civil data refers to data that relevant to citizens every day life. Some example in this data type include transportation data, employment data, crime data, land use data, economic data, etc. One expert we interviewed uses economic data a lot, while another expert uses travel behavior data extensively (see Section 7).

Like demographic data, civil data is usually collected by government agencies. For example, Longitudinal Employer-Household Dynamics (LEHD) is one of the major sources for employment data, and Census Transportation Planning Products (CTPP) is a major source for transportation data.

2.2.5. Environmental data

Environmental data refers to data collected for events and phenomena that have impact to our urban environment. This type of data includes data for climate, air emission, groundwater, wildlife and so on.

3. Technical Foundations

Despite of the heterogenous nature of urban planning tasks and geospatial data they handle, there are some techniques appear in many different directions of urban planning and thus can be considered technical foundations of this field.

In this section we discuss some of the most commonly used geovisualization techniques across the urban planning context, including geographic information systems, urban modeling techniques and urban simulation software.

3.1. Geographic Information Systems

Geographic Information System (GIS) is probably the most popular and the most famous technique that is used by urban planning scientists and also known by researchers from other research areas.

A GIS is an integrated platform for capturing, storing, editing, analyzing, managing and presenting all types of geospatial data to understand relationships, patterns, and trends.

GIS has become a more and more popular aspect of urban planning in the past few decades. One of the early contributions in the progress of contemporary GIS was the development of the Canada Geographic Information System (CGIS) in 1963 [Tom98]. It had some basic functionalities that are included in almost every GIS software, including area calculation and spatial statistical information summarizing. Another significant milestone in the history of GIS occurred in 1970. At that time, Harvard Laboratory for Computer Graphics and Spatial Analysis, a pioneering in GIS development, created the first general-use GIS and used it for analyzing the US population census [MGPG11]. More recently, another milestone that took place in 1995 is that United Kingdom, for the first time, covered its whole territory with standard-scale digital maps [Lon05]. These early milestones pushed GIS technology into its current state, called 'the era of ubiquitous GIS' by Maliene et al. [MGPG11]. Today, commonly available GIS software products include ESRI's ArcGIS [ESR15], Intergraph's GeoMedia [Int15], MapInfo's SpatialWare [Min98], and GRASS GIS [GRA15].

Due to its nature of being general-use, GIS software is often used as cornerstone of many specific-use tools. Software developers usually take a specific subset of GIS software's functionality as start point to add features to fit their own needs.

One use case of GIS is for accessibility analysis. Accessibility is a measure of the ease of reaching valuable destinations. Accessibility analysis helps urban planners to understand the relationship between transportation and land use and provides reference for them to improve the equality of the residents.

For accessibility analysis, useful subset of GIS functionality includes its capability of collecting, storing, and manipulating spatial data, including geometric data and demographic information, of calculating shortest paths between places, of modeling transportation networks and of visualizing the calculated accessibility values [Mil91] [vEDJ99]. However, as accessiblity analysis is a very active and fruitful subfield in urban planning, in which numerous advanced measures of accessibility have been proposed, no GIS software is able to handle all cases, and extensions or plug-ins to built-in functionality are necessary for a GIS software to fit a specific need of a specific task.

3.2. Urban Simulation

The term urban simulation has two general definitions in urban planning context. One common use of this term by domain scientists in urban planning is to describe 3D rendering of urban landscapes, like in [FZ03] [Mer07] [MWH*06] [MZWVG07] [PM01] and [RWF02].

Another broad meaning of urban simulation is the attempt of using operational models to represent dynamic processes of changes of urban activity and landscapes, and of interactions of urban development and transportation.

Urban simulation models and the visualization of their results have been increasingly used by planning agencies in city, county, and regional scopes to assess alternative transportation investments, land use regulations, and environmental protection policies.

There are two major challenges in urban simulation. The first and fundamental one is to adequately model and predict the complex socio-economic interactions that determine the growth of an urban space in order to simulate the change of this urban space over time. The future structure of a city is governed by both deterministic rules (e.g. population capacity of the city must grow) and organic rules (e.g. social, cultural, and economic interactions strongly influence how a city grows). Because of the intricate nature in urban simulation, a simulation model will usually generate an overwhelming amount of data when running over a long period of forecasting time in a large geographical scale (e.g., one or more decades for a large city with a several million population). This makes it difficult for researchers, planners, or policy makers to interpret the data.

This is where the second challenge in urban simulation lies. An effective and intuitive visualization is essential to extract useful information from the large mass of data generated by such simulations. In fact, visualization has played an integral part in the development and use of urban simulations of different types for quite a while. Batty introduced various approaches that relate urban modeling, GIS, and computer graphics in [Bat93] and described the impact of virtual reality and 3D visualization to GIS and demonstrated it in a variety of examples [Bat97]. Cartograms, which use map shape warping to visualize relationships and values of urban and geospatial datasets, is widely used [DBN06] [HJO*01]

[PSKN06] and [PDBB00]. Dykes and Brunsdon [DB07] introduced geowigs, a series of geographically weighted interactive graphics, to provide large-scale geographical environment visualization. Some approaches also make use of choroplethic maps, generated by exporting simulation results to GIS for rendering.

3.3. UrbanSim

One of the most widely used tools for urban simulation is UrbanSim. UrbanSim is a software-based simulation system for supporting planning and analysis of urban development, incorporating the interactions between land use, transportation, the economy, and the environment. Overviews about UrbanSim can be found at [Wad02] [Wad11] and [WU04].

There are multiple research projects ongoing that utilizes or extends UrbanSim, here we list some of such projects that are of particular importance:

- **SustainCity Project** (http://www.sustaincity.org). This project is funded by the European Research Council and is seeking to develop an European-adapted version of UrbanSim (called UrbanSim-E) to make it more suitable for the context of European cities. The system was then tested in three European case studies: Brussels, Paris and Zurich.
- **FHWA: Modeling the Urban Continuum** (http://urbanmodel.asu.edu/intmod.html). This project is funded by the Federal Highway Administration, and focuses on 'Modeling the Urban Continuum in an Integrated Framework: Location Choice, Activity-Travel Behavior, and Dynamic Traffic Patterns'.
- **NSF: Robust Intelligence Project**. This project focuses on melding artificial intelligence techniques with discrete choice econometric methods to develop dynamic models of activity and routing behaviors.UC ITS Multi-Campus Research Program on Sustainable Transportation.

These projects, among some others, are part of a initiative that is intended to develop common data structures for urban modeling and 3D visualization.

4. Survey of Recent Research

In this section, we present some of the recent research trends that are either urban planning studies that utilize, expand or build geographic information systems, or geographic visualization research towards better spatial data analysis.

4.1. Geographic Information Systems

Geographic information systems has always been attracting research efforts due to its importance in the urban planning, civil engineering and geographic visualization.

Research work around GIS can be categorized into two categories: one category is to extend current general purpose GIS systems to fit for specific purposes, and the other one is to build new GIS systems for areas that GIS does not serve well.

In 2004, Liu & Zhu [LZ04] presented an integrated GIS tool for accessibility analysis in urban transportation planning, called Accessibility Analyst, built as an extension to desktop GIS software ArcView. Accessibility Analyst incorporates a number of accessibility measures, contains several travel-impedance measurement tools for estimating the travel distance, time, or cost by multiple travel modes, and interoperates with GIS data-management and data-integration, spatial-analysis, network-analysis, surface-modelling, and spatial-visualisation functions. It also included two visualization functions, integrated with built-in ArcView visualization functionality, to visualize accessibility profiles in 3D. Figure 2 and Figure 3 shows snapshots of visualization of accessibility measures.

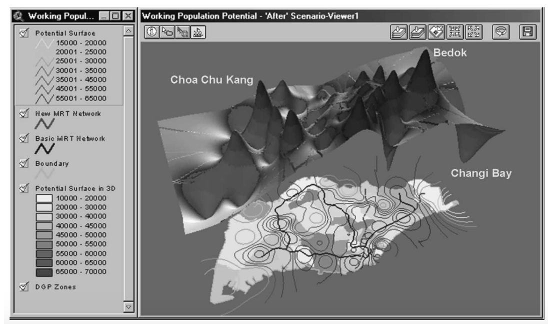

Figure 2: *Visualization of accessibility surface. (Taken from [LZ04])*

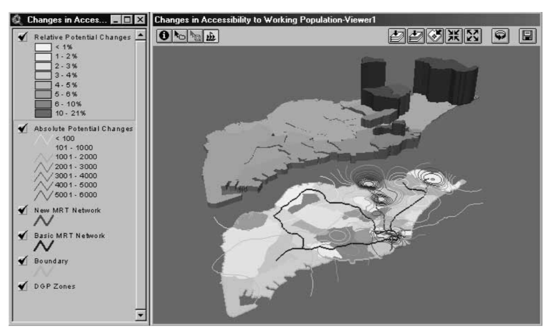

Figure 3: *Visualization of changes in accessibility. (Taken from [LZ04])*

One of the efforts to build customized GIS is made by Gahegan et al., who desicribed their experimental environment, GeoVISTA *Studio*, in [GTWH02]. *Studio* is a Java-based visual programming environment that allows for the rapid development of complex data exploration and knowledge construction applications to support geographic analysis. *Studio* contains full 3D rendering capability and other functionality

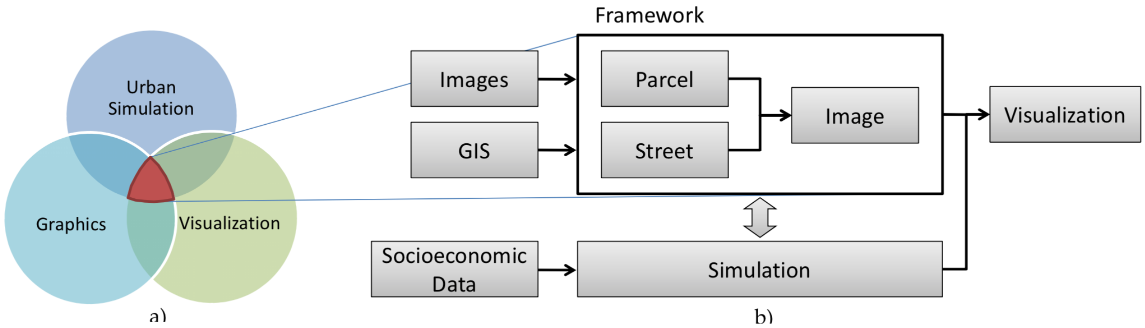

Figure 1: *(a) This method is built upon the combination of urban simulation, urban visualization and computer graphics. (b) The processing pipeline completes an urban simulation with visualization. Images and GIS data, together with simulation results data, are fed into the framework to generate parcels and streets, which are then be used as basis for generating urban layout images. (Taken from [VABW09])*

such as interactive parallel coordinate plots, scatterplot, visual classifier, 2D map and image viewer, sophisticated color selection, and supervised and unsupervised neural networks. The contribution of *Studio* is it provides capability for induction reasoning and abduction reasoning, while other GIS only supports deduction reasoning. Figure 4 shows a snapshot of using Parallel Coordinate Plot (PCP) for exploring multivariate data.

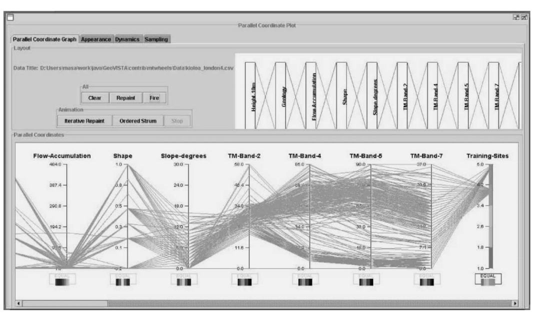

Figure 4: *An interactive PCP used to study suitability of a training sampl. (Taken from [GTWH02])*

4.2. Urban Simulation

As an attempt to tackle the challenges in urban simulation brought by the increased amount of data generated by urban simulation tools, Vanegas et al. [VABW09] introduced a method that automatically and interactively infers geometry and image content of urban layouts using the input data and output data of an urban simulation. The major contributions of their work are:

1. A methodology for enhancing the visualization of the result of urban simulations by using inferred higher-level structural information.
2. A set of automatic and interactive algorithms for generating a visually plausible urban layout from the data generated by an urban simulation.

The input of this method consists of three components: the first one is a set of parcel and street geometries obtained from shapefiles from ArcGIS; the second is the high-resolution geo-referenced aerial imagery of the targeted area, in this case GeoTIFF files containing coordinates information; and the last is the socio-economic data of this area, which is used as input to an urban simulation engine, this case UrbanSim, that predicts the future value of several state variables of the urban space. These intermediate results of the simulation will then be used by the visualization tool to generate detailed urban layouts for any point in the simulation. The overall process of the pipeline is illustrated in Figure 1.

The automatic layout generation process consists of three steps: parcel generation, street generation and parcel-content generation. In parcel generation step, an recursive algorithm is used to partiion an existing city block or a large parcel to multiple based on empirical rules (see Figure 5). In street generation step, the system makes decisions about whether to convert subdivision line from last step to a new street segment (see Figure 6). In the last step, paarcel-content generation step, plausible image content for each of the newly generated parcels are generated. The system uses some similarity metric to reuse existing aerial image fragments of parcels in the new ones (see Figure 7).

4.3. Integration

Another direction of research is towards the integration of different systems, techniques from both urban planning context and geovisualization context.

Recently, Opach & Rød [OR14] conducted a study on whether choropleth maps that are linked with parallel coordinates would facilitate understanding of multivariate spatial

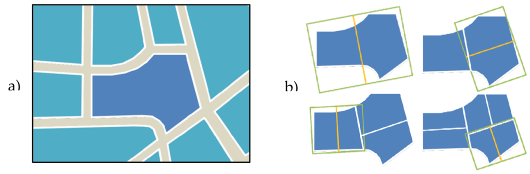

Figure 5: *(a) A candidate large parcel corresponding to a city-block is divided into smaller parcels (beige=street, light blue=parcels/city-blocks, dark-blue=parcel to subdivide). (b) First four subdivisions of the original parcel yield to parcels with egress (green=oriented bounding box). (Taken from [VABW09])*

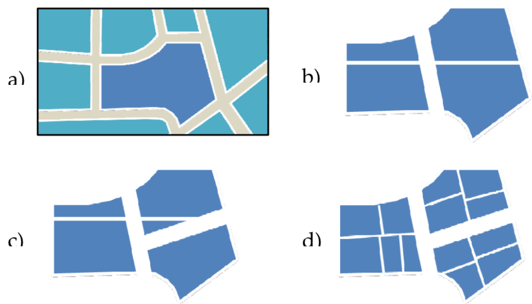

Figure 6: *(a) An initial parcel (from Figure 5). (b-c) First two subdivisions are chosen to be streets. (d) In further iterations, only more parcels per city-block are produced. (Taken from [VABW09])*

Figure 7: *(a) An original urban area from where parcel image fragments are extracted; (b) The newly generated area, with some of reused image content highlighted. (Taken from [VABW09])*

characteristics by building a tool called ViewExposed (see Figure 8).

Another work to integrate different systems and techniques is [Wan05], where an attempt was made to integrate GIS, simulation models, and visualization techniques in traffic impact analysis (see Figure 9).

5. Challenges

The challenges in applying geovisualization tecniques to urban planning tasks lie in four aspects: *representation* of geospatial information, *integration* of visual with computational methods of knowledge construction, *interface design* for geovisualization environments, and *cognitive/usability* aspects of geovisualization.

Although visualization has been playing an important role in urban planning for a long time, urban planning is not acutally take advantages of a large portion of advanced techniques in information visualization. Good news is that advanced visual encoding techniques is starting to be used in some of the research work. Although there aren't too many such studies, the influence will be more and more obvious.

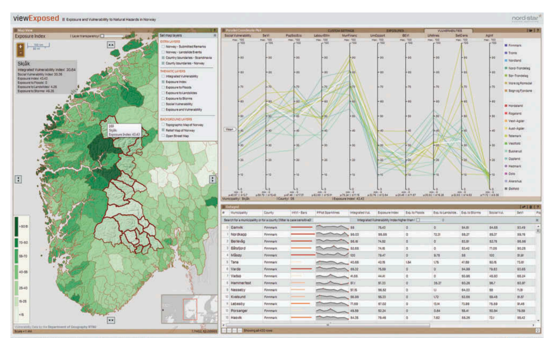

Figure 8: *The GUI of ViewExposed. It is composed of a map view, a parallel coordinate plot, and a datagrid with sparklines embedded into its cells. (Taken from [OR14])*

As the hardware improves very fast in recent years, plenty of possibilities for urban planners to make use of new technologies are now open. Most of the systems and tools for urban planning tasks are still for desktop computers or for the web. GIS is one of the best examples of how visualization-computation integration happens today. Efforts could also be made in taking advantage of state-of-the-art hardware

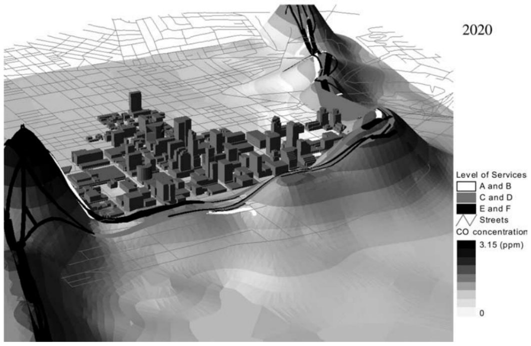

Fig. 5. Perspective views of CO concentration surface.

Figure 9: *Perspective views of carbon monoxide concentration surface. (Taken from [Wan05])*

achievement, such as immersive environments, large-scale displays, to solve. With the powerful computing ability of graphic clusters, new theory of visualization-computation integration for urban planning data of visualzation should be proposed. Also, geographic information science community should adapt or propose new design paradigms for these new forms of interfaces.

6. Conclusion

Urban planning is relavant to almost every aspect of our life. As a process of collecting data for analysis to suggest policy making, it has huge space in analysis phase for geovisualization to demonstrate its capability.

In this state-of-the-art report, we provided a brief overview of urban planning and geographic visualization, including background information, data collected, tasks to perform, and techniques used. We then surveyed recent research progress in geovisualization as well as in utilizing geovisualization in urban planning. We also summarized some challenges in applying geovisualizaiton techniques in urban planning that of great importance and should be tackled soon. At the end of the report we recorded interviews we conducted to three urban planning researchers (see next section).

7. Interviews

In this section we record three interviews we had with domain scientists to get first-hand information about their research work and how geographic visualization helps in their research.

7.1. Interview 1

Dr. Nebiyou Tilahun is an Assistant Professor from the Department of Urban Planning and Policy at University of Illinois at Chicago. He works on urban planing stuides related to tranportation system.

Q: What are the main research project(s) you work on?

I work on questions of travel behavior, access, and the economic outcomes for people that are linked with the provision of transportation.

Q: What would be an ideal result from the project(s)?

The ideal would be to be able to influence transportation policy that is consistent with travel behavior and decisions that allow for equitable access to opportunities.

Q: What kind of data do you work with most often in your research?

I work with Census data, travel behavior data (such as Travel Tracker collected by CMAP, or Travel Behavior Inventory collected by Metro Council (Minnesota)), LEHD, Census CTPP. I have also collected data through surveys when needed.

Q: How do you gather or generate this data?

Most are available through online portals by the collecting agency.

Q: How is this data used/analyzed?

The data is used to do empirical work. Questions of choice are analyzed as a function of cost, service availability, land use, and other variables.

Q: What visualization tools/techniques do you use to help make sense of this data?

Mostly statistical software to do plots and graphs. Another example is what we did for the accessibility project.

Q: What visualization tools/techniques do you use to display the data and/or communicate with other experts in your field?

Mostly figures and plots done in R. On occasion made in Excel. They are presented using Powerpoint or Keynote.

7.2. Interview 2

Dr. Ning Ai is an Assistant Professor from Department of Urban Planning and Policy at University of Illinois at Chicago. She works on projects related to urban environmenetal planning.

Q: What are the main research project(s) you work on?

A: In general, my research focuses on urban environmental planning. I have three ongoing projects: (1) modeling the sustainability, resilience, and stability of urban systems in a metabolism framework (e.g., categorizing inputs and outputs of urban systems); (2) modeling food waste generation volume and recovery/reuse opportunities in urban neighborhoods; (3) investigating how healthcare sector can reduce greenhouse emissions through sustainable transportation programs.

Q: What would be an ideal result from the project(s)?

A: Ideal outcomes would be deliverables that can benefit researchers, practitioners, and general public. That means the results should be publishable, transferable and replicable in other studies and regions, and accessible to the public.

Q: What kind of data do you work with most often in your research?

A: Most often we use data on demography, land use, economy, ecology, and environment at various geographic and temporal scales.

Q: How do you gather or generate this data?

A: We collect data from various government agencies, industry/market reports, as well as research publications, through online data/ literature reviews, formal surveys, and personal communications.

Q: How is this data used/analyzed?

A: Data may be aggregated or disaggregated using spatial and statistical analyses. Advanced models may also need to be developed for environmental and socioeconomic impact analyses.

Q: What visualization tools/techniques do you use to help make sense of this data?

A: ArcGIS Spatial Analyst/Network Analysis, MS Excel and Access.

Q: What visualization tools/techniques do you use to display the data and/or communicate with other experts in your field?

A: ArcGIS, Photoshop, Adobe suites.

7.3. Interview 3

Dr. Sybil Derrible is an Assistant Professor from Department of Civil and Material Engineering at University of Illinois at Chicago. He works on applying complexity theory and data visualization techniques to civil systems to build sustainable and resilient cities.

Q: What are the main research project(s) you work on?

A: Application of complexity theory to civil systems to uncover emerging and inherent properties that will ultimately lead to recommendations for more sustainable and resilient cities.

Q: What would be an ideal result from the project(s)?

A: Depiction of clear complex properties that impact energy use and that can be actuated to reduce overall energy consumption.

Q: What kind of data do you work with most often in your research?

A: Spatial data on infrastructure systems, climate data, and behavior / consumption data by individual / households or aggregated by zones.

Q: How do you gather or generate this data?

A: Relevant authorities including city open data portals (e.g., Chicago Open Data), federal government agencies (e.g., Census Bureau, Energy Information Administration), open access platforms (e.g., openstreetmap), international organizations (e.g., World Bank).

Q: How is this data used/analyzed?

A: Displayed as GIS maps, turned into networks (e.g., using python igraph library), analyzed statistically.

Q: What visualization tools/techniques do you use to help make sense of this data?

A: Mainly: ArcGIS, Gephi, matplotlib (python), JavaScript (D3 library).

Q: What visualization tools/techniques do you use to display the data and/or communicate with other experts in your field?

A: Same as question 6.

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