A CONSTRAINT-BASED DECISION SUPPORT SYSTEM FOR CAPACITY PLANNING IN INTERDEPENDENT EVOLVING URBAN SYSTEMS

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INTRODUCTION

As urbanization continues at a rapid pace, there is a corresponding need for tools that can aid urban planners in predicting impacts on municipal infrastructure. One of the most salient issues arising from urbanization is the strain that population growth places upon existing infrastructure systems.[1] Since planning decisions – including zoning – can alter land use patterns, they have a direct impact on legacy infrastructure. For example, densification imposes additional demands that can propagate through infrastructure systems in myriad ways. At present, urban planners and other stakeholders have limited means of estimating the impact of planning decisions on the ability of infrastructure systems to reliably deliver resources.

This paper describes a simple decision support system (DSS)[2] intended to aid urban planners in visualizing the impacts of planning interventions on urban infrastructure systems. It demonstrates a means by which urban planners can visualize the impact of zoning decisions or analyze the effects of growth. The software provides users with a district-level model in which each infrastructure system is represented as a network that delivers resources to buildings. Interdependencies between individual infrastructure systems allow demands from one system to propagate to another, providing the user with the ability to visualize changes across the entire set of infrastructures.

Capacity Constraints in the Evolving City

Residents of cities rely upon a variety of infrastructure systems to supply not only resources such as electricity and water, but also essential services such as health care, emergency response, and transport. These systems are typically dependent upon each other in a variety of ways, such that a failure in one system can cause cascading failures in others.[3] For instance, a broken water main may cause problems for co-located infrastructure (e.g. gas lines) and transport (e.g. roadways), which in turn may impact emergency response times.

Disruption to infrastructure systems can arise from numerous causes, including natural disasters, component failures, and sabotage. While these issues have been treated extensively in the research literature,[4] less attention has been paid to risks arising from the adaptive and evolutionary nature of cities.[5] Evolution and adaptation create challenges for legacy infrastructure systems, potentially introducing new risks that have far-reaching consequences for the city and its residents.

Population growth is a good example of an evolutionary driver that can impose additional demands on urban infrastructure. For instance, the London sewer system was originally designed to carry both rainwater and waste products; in order to avoid overflow, it contained a set of outlets that vent material into the Thames river. The system worked well, at least until the growing population started to push the capacity of the system well past its design parameters. The Thames Tideway project was eventually created to provide a solution to the problem, albeit at substantial cost.[6]

The adaptive nature of cities also has significant implications for infrastructure systems.[7] Urban planning can be viewed as an adaptive mechanism by which municipal governments influence the development of cities. Strategies of densification, for instance, are often pursued in order to achieve economies of scale and other desirable outcomes;[8] however, the addition of new residential units on top of entrenched legacy infrastructure systems can result in significantly elevated demands.

There are several capacity-related issues that arise when demand patterns are radically altered through either evolutionary or adaptive mechanisms. In the worst case, the average demands made of an infrastructure system may exceed its capacity. However, it is more common for problems to arise during *peak demand periods*. In Toronto, which has the highest rate of high-rise construction in North America, electrical power grids are already nearing peak capacity.[9]

Another major issue concerns *dependencies* between infrastructure systems. For example, the power required to pump water up into commercial and residential high-rises constitutes Toronto's largest single source of demand for electricity. [10] Electricity outages will cascade into the water system, effectively stalling water delivery in this type of building. Unfortunately, land-use planning, water planning, and energy planning are typically conducted by separate groups that do not share information.[11] This can result in significant risk, since the potential for cascading failure is not analyzed explicitly.

Planning Support Systems and Infrastructure

One method of mitigating the issues described above is to provide urban planners with software tools that allow them to visualize alternative *scenarios*. This paper describes one such approach, providing users with the ability to construct a model, visualize a baseline scenario, and then create alternative scenarios that explore the impacts of population growth or zoning decisions on the capacity constraints imposed by legacy infrastructure. Such a tool would be classified as either a *planning support system* (PSS) or a *spatial decision support system* (SDSS).[12]

As in other domains, the praxis of urban planning should be reflected in the design of the software. Planners are often incentivized to focus on actions with short-term impacts, [13] and they are often burdened with a multitude of demands, ranging from the mundane (e.g. code enforcement, permit processing) to the political. [14] Alongside these burdens are challenges arising from the complexity of urban processes, as well as the multi-dimensional (often wicked) problems that arise in crafting 'plausible futures' for cities.[15]

Provision of useful decision support is made more difficult by the relatively ossified nature of urban infrastructure systems. For instance, transportation, electricity, water, and sewage systems are capital intensive, expensive to maintain, and difficult to modify once in place. Infrastructure systems tend to grow slowly, subject to influence from decision makers with bounded rationality and short time preferences.[16] Interdependencies between systems mean that analysis of key issues such as infrastructure resilience[17] is inherently multi-disciplinary, beyond the scope of a single team of planners.

MODEL DESCRIPTION

Accurate modeling of urban infrastructure is a difficult task on account of heterogeneity. As a result, we make several simplifying assumptions. First, the major infrastructure systems (i.e. gas, electricity, sewage, water) are abstracted as flow networks that carry resources to consumers, and no attempt is made to model domain-specific physical processes.[18] Second, resource demands are represented on an hourly basis, matching the sampling rate found in typical data sets. Third, social systems (i.e. health care, education) are modeled using catchment areas. Fourth, transportation demand is modeled in a simple manner for reasons that will be described below.

The resulting model provides a view of an urban district at the level of individual lots/parcels and buildings. It focuses explicitly upon *demands for resources*, showing how the various infrastructure networks satisfy those demands in the presence of *constraints* – namely, supply limits and capacity limits associated with infrastructure components (e.g. pipe diameters, classroom sizes).

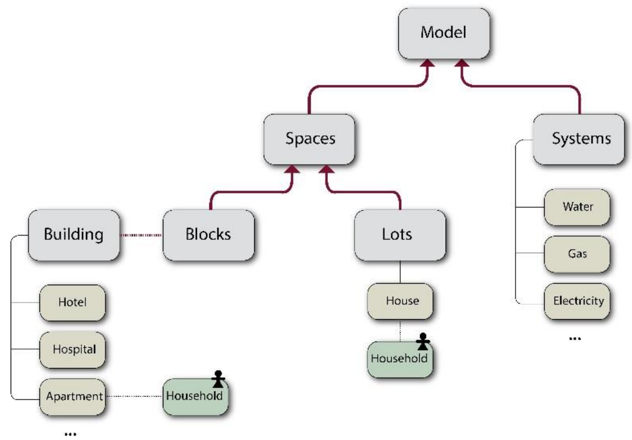


Figure 1. Model Entities

Figure 1 shows the basic entities in the model. The area of interest contains a spatial region – the most important elements of which are *blocks* (containing buildings of various types) and *lots* (containing low density housing). Households are allocated to lots and buildings as a function of building type. In future, household information will be drawn from either an internal or external demographic model.

Demand Curves and Propagation

Demands for resources are computed separately for residential and non-residential buildings. The latter are assigned demand profiles for each resource type according to empirical data.[19] As mentioned above, demand data is sampled on an hourly basis over a 24-hour `average day' cycle. Figure 2 shows (normalized) water demand curves for buildings:

Figure 2. Demand curves for two types of buildings

For residential buildings, aggregate demands are calculated by summing up the demands for each household in the building, as well as the demands from the building itself (i.e. the basic resources required to keep the building operating, even if no people are present). Figure 3 shows a schematic of this computation:

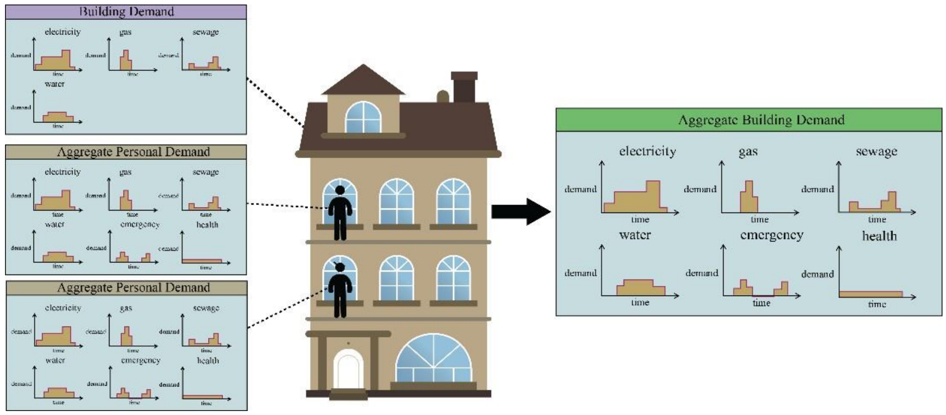


Figure 3. Demands for residential buildings

Once the demand curves for the buildings are established, a probabilistic algorithm is used to propagate those demands onto the infrastructure networks. Figure 4 illustrates how water demand is pushed onto a fragment of a water distribution network:[20]

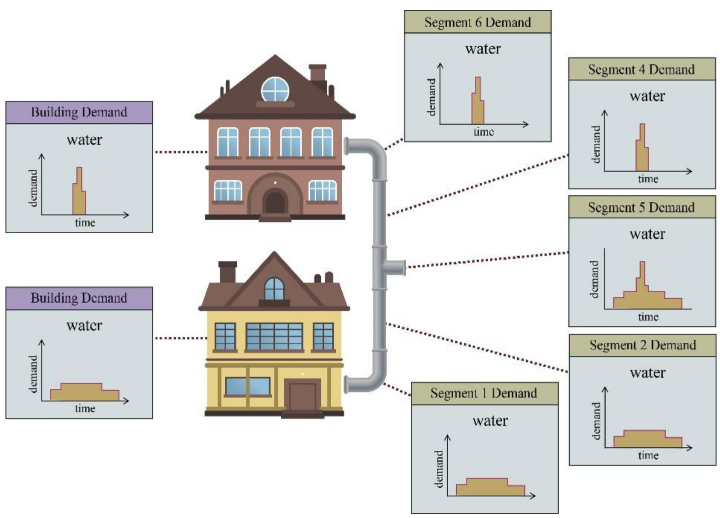


Figure 4. Demand propagation

Transportation

Transportation is the one major exception to our representation of infrastructure systems as flow networks. Typically, a comprehensive activity-based transport model would be used to generate travel episodes; however, most do not operate at the block/lot level.[21] In this simple prototype, transportation demand is generated by selecting a set of random nodes from the street network for each household. Figure 5 illustrates this approach for a single lot:

Figure 5. Generating transportation demand

Data Sources

Figure 6 shows the data flow. Road network information for a district-scale area is exported from OpenStreetMaps and loaded into ESRI CityEngine, where it is edited manually to remove artifacts. [22] Building shapes, block/lot geometry and road network data are exported from CityEngine to a custom application in which the user may define infrastructure networks and assign data to buildings.[23]

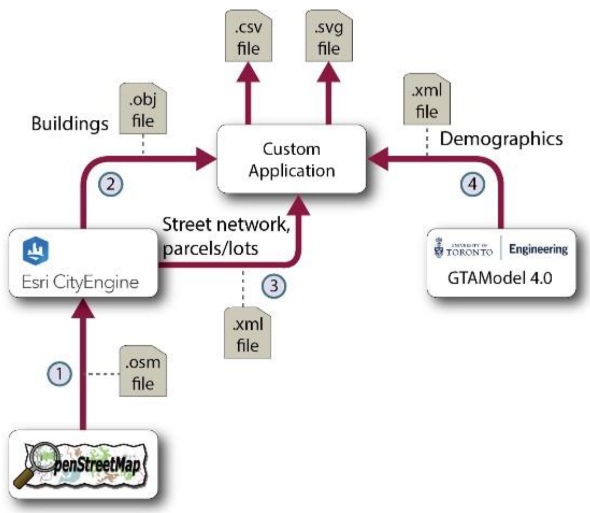


Figure 6. Dataflow

While the application supports 3D rendering (Figure 7), a 2D view is more convenient.

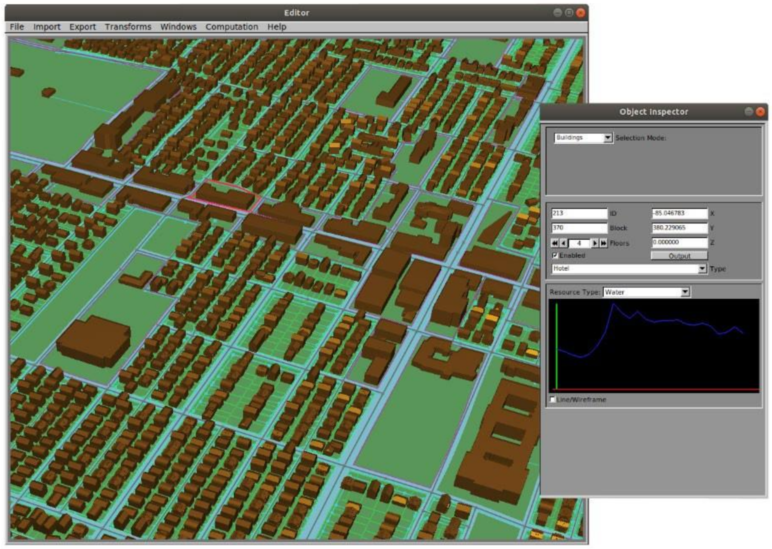


Figure 7. User interface in 3D mode

Infrastructure Modeling

Infrastructure systems are created by the modeler within the custom application. Nodes and links are added in order to create a flow network for each major infrastructure system (e.g. water). Each link (directed or undirected) has a *capacity constraint* indicating the maximum amount of resource that can flow through it. Figure 8 shows a basic water network, using a overhead view that is more manageable than 3D. White circles correspond to demand nodes for buildings/lots, while blue circles are transmission nodes.

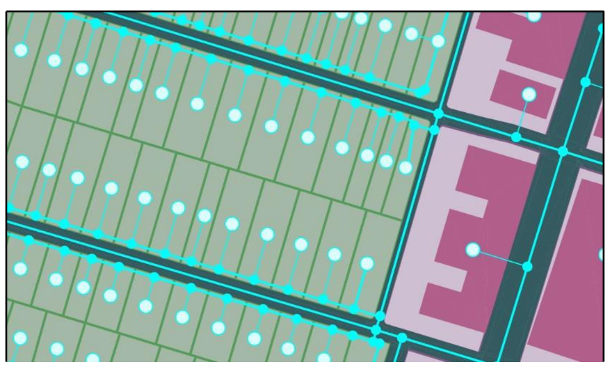


Figure 8. Creating a water network

Multiple infrastructure systems are added to the model in separate layers. Each layer has a single flow network with source nodes, transmission nodes, and demand nodes. Figure 9 shows manual editing of infrastructure layers:[24]

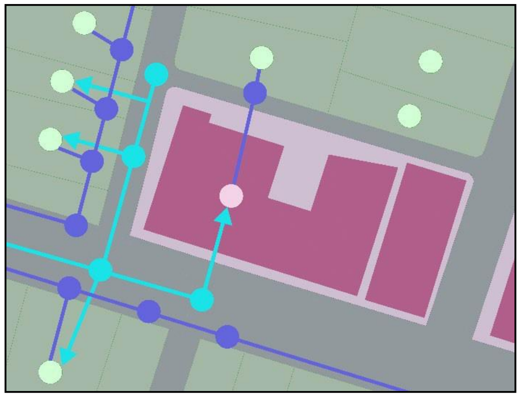


Figure 9. Editing multiple networks

Modelers may also designate *interdependencies* between infrastructure systems by adding them manually. Various forms of dependency have been discussed in the engineering literature, including physical, geospatial, informational, social, and financial. [25] The current model supports *physical dependencies*, in which a resource flowing through system A is required by components of system B. Figure 10 shows a schematic of two infrastructure layers connected with interdependencies.

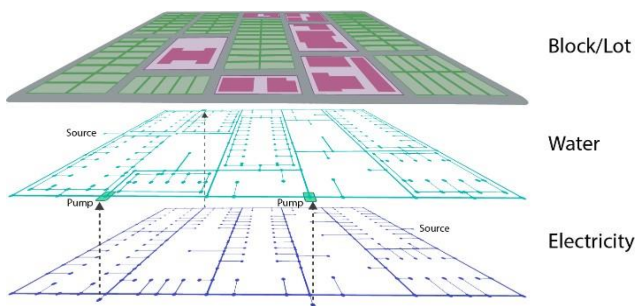


Figure 10. Dependencies between subsystems

Figure 11 shows a large model of downtown Toronto, augmented with water and electricity networks. Models of this size are quite difficult to display in print, so close-ups are used.

Figure 11. A large model of downtown Toronto

Visualizations

The user can visualize data in each scenario in several ways. Figure 12 shows two examples: (A) a heat map of demand levels for buildings, color coded from green (low demand) to red (high demand); (B) a representation for a given building (red) of the infrastructure components that supply it with resources.

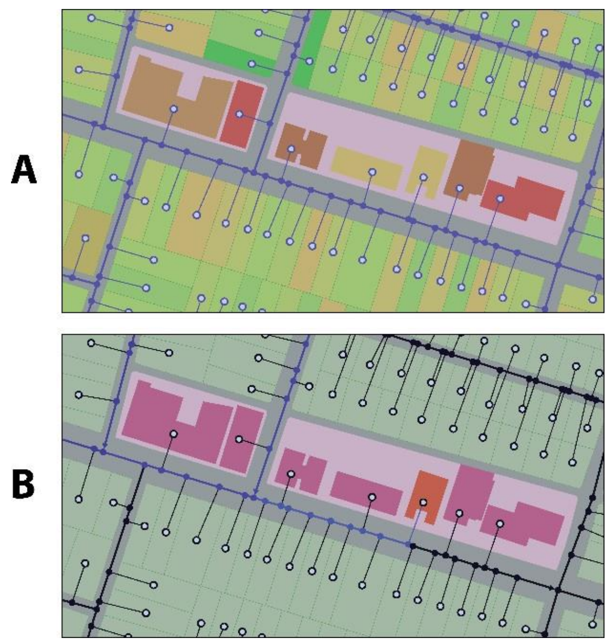
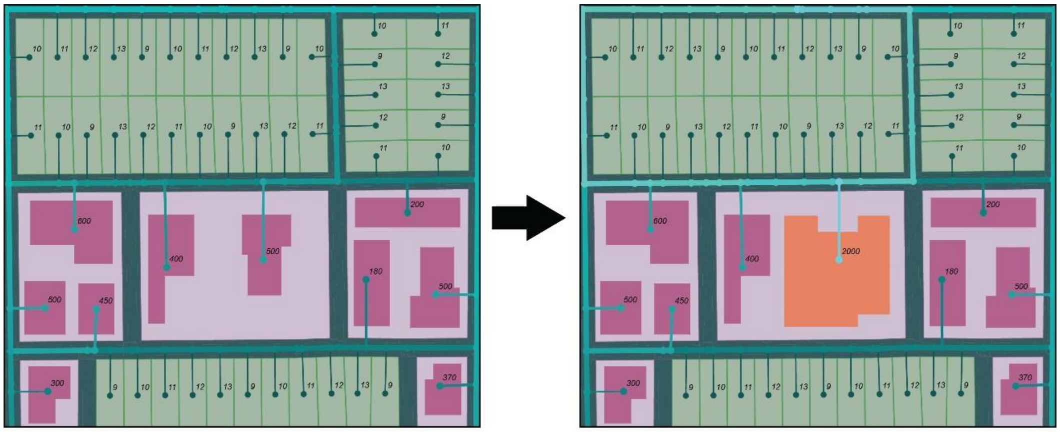


Figure 12. Interactive Visualizations

Comparative analysis can be performed by constructing: (1) a baseline model; (2) one or more variants, in which demand values, capacities, building types, and network components are altered. Figure 13 shows a baseline scenario (A), and a variant where high density residential housing has replaced a commercial building (B); demands are in italic font, and pipe edges are color coded from black (no demand) to light turquoise (high demand).



A B

Figure 13. Baseline scenario (A) and alternative scenario (B)

Instead of viewing demand values, the user can opt to view a heatmap showing *load levels* – that is, the percentage of a component's capacity that is being used in the scenario. Figure 14 illustrates this option, with load colored from green (low) to red (high), showing how the alternative scenario pushes a subset of pipes towards their full capacity. Since demand data is given over a daily 24 hour cycle, those components most heavily utilized during *peak demand* periods can be identified.

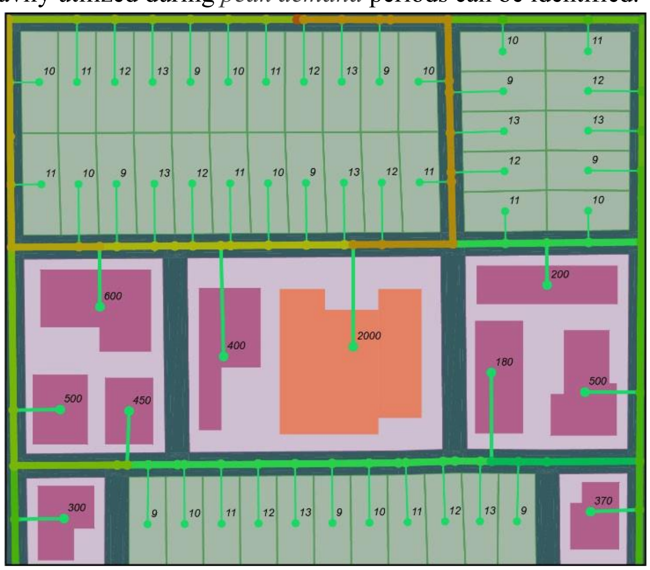


Figure 14. Heat map of load levels for the scenario in Figure 13(B)

Many additional forms of visualization (including statistical analysis) are supported but not shown due to space limitations. For instance, demands imposed on schools and on roadways can easily be visualized using heat maps, histograms, or animations.

CONCLUSION

The prototype presented in this paper is preliminary work, intended to show one possible means by which a DSS system could be developed to aid urban planners in thinking about the impacts of interventions on infrastructure systems. Coupled with an appropriate demographic model, the software could also be used to show how infrastructure is stressed by evolution – namely, population growth and changing land-use patterns.[26]

There are several major challenges with this type of DSS. First, *user interface* (UI) design is a significant problem, given the complexity involved in presenting multiple layers of infrastructure systems. 3D visualization turned out to be confusing, hence the use of 2D graphics that are more suitable for use in *geographic information systems* (GIS). Visualizing physical dependencies between different infrastructure layers is particularly difficult.

The second major problem concerns data availability. Municipalities often lack information on their infrastructure systems; even where such data exists, it is often in inconvenient formats, scattered between different organizations, or subject to security restrictions. [27] As a result, researchers are developing proxy methods for inferring the presence of infrastructure.[28] With district-scale models, it is feasible to assemble a combination of real and synthetic data to approximate real-world infrastructure at an appropriate level of abstraction.

The preliminary DSS outlined in this paper could be expanded to include full demographic modeling. Instead of generating demand from a library of empirical datasets, demands for resources could be a function of activities undertaken by agents. This would allow integration with common land-use models, albeit there may be few that operate at the lot/parcel level.

Finally, the real test of a DSS is whether it meets the needs of urban planners. Researchers have long criticized offerings in this domain on various grounds, including maturity, user-friendliness, and compatibility with actual praxis.[29] Any tool for analyzing complex infrastructure systems faces the burden of representing a tangled set of systems in as simple a manner as possible. Methods for doing so are sorely needed and should be a subject of future research.

NOTES

[1] For a recent work discussing the consequences of growth in a variety of systems, including cities, see (Smil 2019).
[2] (Burstein and Holsapple 2008) (Power 2008) (Keen 1978; Keen and Morton 1973)(Sprague 1980) Old thesis p.71 has a ton of material.
[3] For more on cascading failures, see (Zio and Sansavini 2010) and (Buldyrev et al. 2010).
[4] Disruption to infrastructure systems has been studied in several research communities, including Critical Infrastructure Protection.
[5] Numerous scholars have argued that cities should be viewed as open-ended, complex systems subject to evolution – see, for example, (Bettencourt 2011) and (Desouza and Flanery 2013).
[6] The rationale for the Thames Tideway project is ably covered in (Stride 2016, 2019).
[7] A discussion of cities as complex adaptive systems can be found in (Batty 2008, 2013).
[8] See, for instance, (Le Néchet 2012).
[9] For a detailed exposition of the challenges facing downtown Toronto, see (Kishewitsch 2015).
[10] Ibid.
[11] Ibid. See also (O'Looney 2001), in which the author notes that transportation planning and local `comprehensive' planning take place in silos, resulting in a set of policies that are not cohesive.
[12] There is no consensus on terminology. For an overview of planning support systems, see (Geertman and Stillwell 2009b). A later volume from the same publisher contains articles focused on urban planning (Geertman, Toppen, and Stillwell 2013).
[13] See (Klosterman 2013).
[14] For a discussion of the various demands on planners, see (Geertman and Stillwell 2009a), (Barnett 2009) and (Klosterman 2011). The connections between urban planning, politics, the legal system and other socio-technical aspects of cities are discussed in (Levy 2017).
[15] See (Crooks, Castle, and Batty 2008) for a discussion of the major challenges facing planners, including demands for participative policy-making. The distributional issues (allocation of resources) involved in planning are discussed in (Levy 2017), while wicked problems are introduced in (Rittel and Webber 1973).
[16] See (Andersson 2008) for a discussion of bounded rationality and short time preferences, as well as (Bettencourt 2011) on the topic of the growth of infrastructure.
[17] For a recent discussion of resilience in cities and the importance of considering the various dimensions of cities as socio-ecological system, see (Esteban 2020)
[18] This is in keeping with a network approach to cities, as described in (Batty 2013). The use of domain-specific modeling techniques would drastically increase the complexity of an integrated model.
[19] Empirical data for building demands is obtained from public sources, such as (Aquacraft 2011).
[20] Details on the computations are beyond the scope of this paper. See (Sadeh and Fox. 1989; Sadeh and Fox 1996)
[21] For more on activity based models, see (Miller 2018). The data from transportation surveys is typically collected at the census track level. Note that our initial model omits pedestrian traffic and public transit.
[22] OpenStreetMap, online at https://www.openstreetmap.org/. ESRI CityEngine, online at https://www.esri.com/en-us/arcgis/products/arcgis-cityengine/overview.
[23] Integration with a standard transport model is an optional step that was not undertaken in this paper.
[24] Each layer is identified by a unique color. Demand nodes corresponding to lots are light green, those corresponding to buildings are light violet.
[25] For a classification of infrastructure dependencies, see (Kröger and Nan 2014).
[26] Used to analyze future states on the basis of demographic projections, the tool would be a method of *projection*, per (Isserman 1984).
[27] (Mair et al. 2017).
[28] Ibid. Also see (Sitzenfrei, Möderl, and Rauch 2013).
[29] See (Geertman and Stillwell 2009a) and (Klosterman 2013).

BIBLIOGRAPHY

Andersson, Claes. 2008. "Ontogeny and Ontology in Complex Systems Modeling." In *The Dynamics of Complex Urban Systems: An Interdisciplinary Approach*, edited by Sergio Albeverio, Denise Andrey, Paolo Giordano, and Alberto Vancheri, 43. Springer.

Aquacraft. 2011. "Embedded Energy in Water Studies, Study 3: End-Use Water Demand Profiles."

Barnett, Jonathan. 2009. "The Way We Were, the Way We Are: The Theory and Practice of Designing Cities since 1956." In *Urban Design*, edited by William S. Saunders and Alex Krieger. University of Minnesota Press.

Batty, Michael. 2008. "Cities as Complex Systems: Scaling, Interactions, Networks, Dynamics and Urban Morphologies." 131. *Working Papers Series*. ———. 2013. *The New Science of Cities*. MIT Press.

Bettencourt, Luís M.a. 2011. "The Kind of Problem a City Is." 2013-03–008. *17th International Symposium on Electronic Art*. http://isea2011.sabanciuniv.edu/paper/kind-problem-software-city.

Buldyrev, Sergey V, Roni Parshani, Gerald Paul, H Eugene Stanley, and Shlomo Havlin. 2010. "Catastrophic Cascade of Failures in Interdependent Networks." *Nature* 464 (7291): 1025–28. https://doi.org/10.1038/nature08932.

Burstein, Frada, and Clyde Holsapple. 2008. *Handbook on Decision Support Systems 1 : Basic Themes*. Springer. https://doi.org/10.1007/978-3-540-48713-5.

Crooks, Andrew, Christian Castle, and Michael Batty. 2008. "Key Challenges in Agent-Based Modelling for Geo-Spatial Simulation." *Computers, Environment and Urban Systems* 32 (6): 417–30. https://doi.org/10.1016/j.compenvurbsys.2008.09.004.

Desouza, Kevin C., and Trevor H. Flanery. 2013. "Designing, Planning, and Managing Resilient Cities: A Conceptual Framework." *Cities* 35: 89–99. https://doi.org/10.1016/j.cities.2013.06.003.

Esteban, Theresa Audrey O. 2020. "Building Resilience through Collective Engagement." *Architecture_MPS* 17 (1): 1–15. https://doi.org/10.14324/111.444.amps.2020v17i1.001.

Geertman, Stan, and John Stillwell. 2009a. "Planning Support Systems: Content, Issues and Trends." In *Planning Support Systems Best Practice and New Methods*, edited by Stan Geertman and John Stillwell. Springer. 2009b. *Planning Support Systems Best Practice and New Methods*. Springer. https://doi.org/10.1007/978-1-4020-8952-7_9.

Geertman, Stan, Fred Toppen, and John Stillwell. 2013. *Planning Support Systems for Sustainable Urban Development*. *Springer*. Vol. 195. https://doi.org/10.1007/978-3-642-37533-0.

Isserman, Andrew M. 1984. "Projection, Forecast, and Plan On the Future of Population Forecasting." *Journal of the American Planning Association* 50 (2): 208–21. https://doi.org/10.1080/01944368408977176.

Keen, P. G. W. 1978. *Decision Support Systems: An Organizational Perspective*. Reading, MA: Addison-Wesley.

Keen, P. G. W., and S. Morton. 1973. *Decision Support Systems*. Reading, MA: Addison-Wesley.

Kishewitsch, Stephen. 2015. "Toronto's Unique Energy Challenge." *IPPSO Facto* 29 (4). https://magazine.appro.org/news/ontario-news/3872-torontos-unique-energy-challenge-.html.

Klosterman, Richard E. 2011. "Planning Theory Education: A Thirty-Year Review." *Journal of Planning Education and Research* 31 (3): 319–31. https://doi.org/10.1177/0739456X11413601. 2013. "Lessons Learned About Planning." *Journal of the American Planning Association* 79 (2): 161–69. https://doi.org/10.1080/01944363.2013.882647.

Kröger, Wolfgang, and Cen Nan. 2014. "Addressing Interdependencies of Complex Technical Networks." In *Networks of Networks: The Last Frontier of Complexity*, edited by Gregorio D'Agostino and Antonio Scala. Springer.

Levy, John M. 2017. *Contemporary Urban Planning*. 11th ed. New York, NY: Routledge.

Mair, Michael, Jonatan Zischg, Wolfgang Rauch, and Robert Sitzenfrei. 2017. "Where to Find Water Pipes and Sewers? - On the Correlation of Infrastructure Networks in the Urban Environment." *Water* 9 (146). https://doi.org/10.3390/w9020146.

Miller, Eric J. 2018. "Integrated Urban Modeling: Past, Present, and Future." *Journal of Transport and Land Use* 11 (1): 387–99. https://doi.org/10.5198/jtlu.2018.1273.

Néchet, F Le. 2012. "Urban Spatial Structure, Daily Mobility and Energy Consumption: A Study of 34 European Cities." *CyberGeo. European Journal of Geograph*, no. 580.

O'Looney, John. 2001. "Sprawl Decisions: A Simulation and Decision Support Tool for Citizens and Policy Makers." *Government Information Quarterly* 18 (4): 309–27. https://doi.org/10.1016/S0740-624X(01)00088-0.

Power, Daniel J. 2008. "Decision Support Systems: A Historical Overview." In *Handbook on Decision Support Systems 1 : Basic Themes*, edited by Frada Burstein and Clyde Holsapple. Springer.

Rittel, HWJ, and MM Webber. 1973. "Dilemmas in a General Theory of Planning." *Policy Sciences* 4 (December 1969): 155–69. http://link.springer.com/article/10.1007/BF01405730.

Sadeh, Norman, and Mark S. Fox. 1989. "Preference Propagation in Temporal/Capacity Constraint Graphs."

Sadeh, Norman, and Mark S. Fox. 1996. "Variable and Value Ordering Heuristics for the Job Shop Scheduling Constraint Satisfaction Problem." *Artificial Intelligence* 86 (1): 1–41. https://doi.org/10.1016/0004-3702(95)00098-4.

Sitzenfrei, Robert, Michael Möderl, and Wolfgang Rauch. 2013. "Automatic Generation of Water Distribution Systems Based on GIS Data." *Environmental Modelling and Software* 47 (May 2014): 138–47. https://doi.org/10.1016/j.envsoft.2013.05.006.

Smil, Vaclav. 2019. *Growth From Microorganisms to Megacities*. Cambridge, MA: MIT Press.

Sprague, R. 1980. "A Framework for the Development of Decision Support Systems." *MIS Quarterly* 4 (4): 1–25.

Stride, Phil. 2016. "Super Sewer: An Introduction to the Thames Tideway Tunnel Project in London." *Proceedings of the Institution of Civil Engineers - Civil Engineering* 169 (2): 51–51. https://doi.org/10.1680/jcien.2016.169.2.51. 2019. *The Thames Tideway Tunnel: Preventing Another Great Stink*. The History Press.

Zio, E., and G. Sansavini. 2010. "Modeling Failure Cascades in Critical Infrastructures with Physically-Characterized Components and Interdependencies." In *ESREL 2010 Annual Conference*, 652–61.