What Hetero-functional Graph Theory Can Do for a Smart City

Wester Schoonenberg and Prof. Amro M. Farid
Laboratory for Intelligent Integrated Networks of Engineering Systems
Thayer School of Engineering at Dartmouth

The Rise of the Smart City

By 2050, the global population is expected to soar to almost 10 billion, and over two-thirds of these people will live in cities. This immense increase in urban population will put a tremendous stress on the urban environment and the delivery of its infrastructure services. Furthermore, most mega-cities are susceptible to natural hazards given their proximity to the coast. Consequently, questions concerning the resilience and sustainability of infrastructure systems are at the core of building a future-proof city.

For many of the largest population centers in the world, the key to success is the affordable and reliable delivery of critical services to their residents. Lowering the cost of basic services such as potable water, transportation, and electricity, increases the financial freedom of residents. This is universally true for all types of cities across the world. For example, in Los Angeles, residents may have to drive 2 hours to and from work; adding 4 hours to an already long workday. In Mexico City, residents may have to work an extra 4 hours to be able to pay for potable water. Improving the design of infrastructure service delivery directly improves the residents' quality of life.

Innovation Siloes Prevent Systematic Improvement

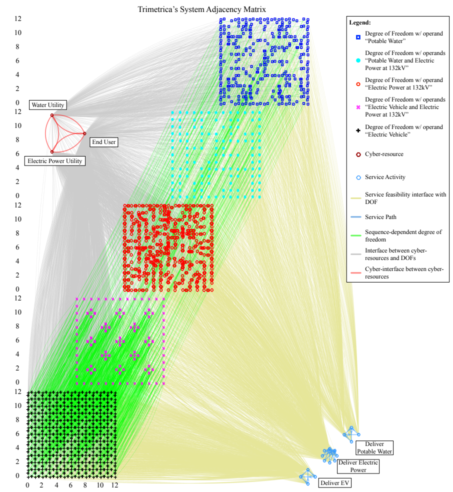
Existing approaches to the planning and operation of urban infrastructure take each infrastructure independently. For example, rarely do practitioners in the electricity, transportation, and water sectors coordinate their efforts. This siloed reality is often further reinforced by the recent emergence of the Internet of Things. Adding intelligent devices to our lives; be they smart meters, solar panels, or intelligent traffic lights is evidently technological advancement. Furthermore, such devices open the door to system-level innovations like smarter ways to collect garbage or deliver packages to houses. Each of these innovations is valuable, but together, they lack a fundamental recognition of the city as a system-of-systems that delivers multiple and often interdependent services to its residents.

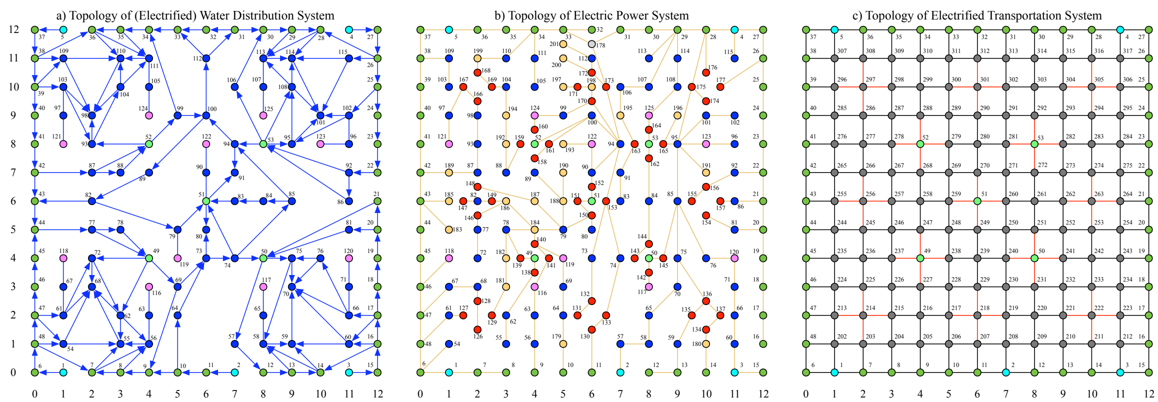
This siloed approach to infrastructure services is consequently problematic. As the urban population increases, infrastructure systems become more interdependent. They simply need to deliver more services while space comes increasingly at a premium. In other cases, the availability of water or electricity creates fundamental trade-offs between the residential, commercial, industrial, and agricultural sectors. These competing demands require increasingly efficient operation and potentially the bundling of service systems. Therefore, the delivery of one service will directly impact the operation of another. In New York City, for example, the interdependence of these services was especially felt during Hurricane Sandy. In the early stages of the storm, widespread outages occurred as a result of the heavy rainfall. These outages disrupted the electricity delivery to the electrically-powered public transportation systems. Consequently, the operation of the public transit system was halted. As people were trying to evacuate, the now highly congested roads became deadlocked by the surge in demand. Electrification of the transportation system reduces carbon emissions, but mobility increasingly relies on the delivery of electric power. The understanding of interfaces across the siloed systems is, thus, critical to the architecture of sustainable and resilient cities.

The use of these siloed planning approaches made sense for a long time, because mathematical models to represent such interactions simply didn't exist. The transportation system engineers have advanced mobility models, the electric power system engineers use power flow analysis, and hydrological engineers rely on fluid dynamics. These experts speak their respective languages and until recently, it hasn't been necessary for them to communicate. Efforts to integrate these models are usually not effective. The interfaces between infrastructure models are often not well studied and their combination often places impractical demands on computational resources. Furthermore, such analytical approaches are often one-off case studies that do not generalize across multiple cities or regions. In the meantime, other network science approaches have abstracted the real-world too much and impose unrealistic limitations on the types of interdependent systems that can be modeled.

Hetero-functional Graph Theory

Recently, however, hetero-functional graph theory has fundamentally transformed our understanding of multiple interdependent infrastructure systems. It is the first theory to successfully model and integrate multiple arbitrarily-coupled cyber-physical infrastructure systems while explicitly retaining their distinctive characteristics. For example, the illustration on the right depicts the hetero-functional graph of the three interdependent infrastructure systems below. The first complete overview of the theory is presented in the book: *"A hetero-functional graph theory for modeling interdependent smart city infrastructure" (2018)*, by Wester Schoonenberg, Inas Khayal, and Amro Farid.





The development of hetero-functional graph theory comes at a time when Big Data is revolutionizing our understanding of how we interact with city infrastructure. Hetero-functional graph theory supports the development of unprecedented data-rich physics-based models of the structure and function of our engineered world. It can be used to support planning and operations decisions, expose likely trade-offs, and highlight undiscovered synergies between infrastructure systems.

The LIINES (Laboratory for Intelligent Integrated Networks of Engineering Systems) maintains an expertise in the enhancement of sustainability and resilience in intelligent engineering systems. We specialize in systems where one physical engineering system with its associated layers of decision-making and control interacts with another fundamentally different physical engineering system with its own layers of decision-making and control. This specialization has consistently produced novel mathematical models, simulation software and optimization algorithms across five relevant research themes: 1.) smart power grids, 2.) energy-water nexus 3.) electrified-transportation systems, 4.) microgrid-enabled production systems, and 5.) interdependent smart city infrastructures. This expertise provides us a unique insight in emerging smart city projects.

1867 THAYER SCHOOL OF ENGINEERING AT DARTMOUTH | LIINES LABORATORY FOR INTELLIGENT INTEGRATED NETWORKS OF ENGINEERING SYSTEMS EMPOWERING YOUR NETWORK