Smart City Infrastructure: a Hetero-functional Graph Theory Approach
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The central role of cities in our civilization has grown to an unprecedented scale as a result of mass-migration towards urban areas. Currently, over 55% of people live in cities, and another 2.5 billion are expected to move to cities by 2050. Cities will be forced to reconsider the fundamental architecture of their infrastructure, society, and governance. Furthermore, cities will be affected disproportionally by climate change, whether as a consequence of the proximity to ever-rising sea levels or as a result of extreme weather events. These megatrends result in infrastructure that is stressed by crowded populations and that is vulnerable to the effects of climate change. If smart cities are to live up to their promise of a *"better life"* for a city's residents, they will need to ensure the sustainability and resilience challenges of their city's infrastructures.

Traditionally, infrastructures have been designed with a specific purpose, or service in mind. The electric power grid provides power to the inhabitants, whereas the roads that make up the transportation system facilitate movement of goods and people throughout the city. Traditional city planning has assumed these systems to be largely independent. The systems do interface, but they are managed by different institutions that are not necessarily communicating with each other about their current and future needs.

As smart cities become more crowded, systems theory and design theory recognize that a large number of functional requirements imposed on the confined space of a city inherently couples the elements of the systems. Consequently, the infrastructures become interdependent. Even though infrastructures have been designed independently, interdependent city infrastructures already exist. Today's cities contain many examples, spanning all six functional domains of the IEEE smart cities initiative: water, health, mobility, energy, food & agriculture, and waste.

Dedicated water infrastructure is directly related to the power generation capabilities of a region, as water is used for the cooling systems of all nuclear and fossil fuel power plants. NREL has performed a study and found 43 incidents between 2000 and 2015 where water resources have affected power plant operations, either resulting in curtailment or even shutdown incidents. Furthermore, the water infrastructure is intertwined with the food & agriculture industry. Water withdrawals for irrigation is 37% of all US water consumption, second only to the water withdrawals for thermo-electric power at 41%. A shortage in fresh water consequently impacts people directly, and indirectly via the price of electric power and food.

Healthcare is an integral part of a city's infrastructure. Hospitals rely on the electric power grid to operate, and only use local back-up generation to support emergency healthcare during outages. Health also interfaces with transportation, as the ambulances navigate their way through the city to reach patients as fast as possible. Furthermore, by promoting physical activity during the commute, British researchers were able to significantly reduce the BMI (body mass index) of the participants in the study. Consequently, incentives to stimulate cycling to work could have benefits in terms of both health and reduced congestion.

Mobility accounts for 30% of the US energy consumption, and there is a growing recognition that in order to achieve long term sustainability through deep decarbonization, cities will have to invest heavily in electrified transportation. And yet, the experience of hurricane Sandy informs us that it Is impossible to evacuate a city as large as New York City without the electrified subway and commuter rail systems. In other words, whereas electrified transportation can serve to bring about greater sustainability, it may indeed hinder a cities' resilient response to natural disasters.

Waste is the end of many of the aforementioned services. The food and agriculture infrastructure has the goal to deliver food to people and livestock. Food waste is a failure to accurately match supply and demand. A more accurate balance of supply and demand would lower the need for food production and therefore its energy and water footprint. Similarly, by reusing other (non-consumable) products, the need for new products can be reduced. This further reduces both the the supply chain's energy use and the congestion on local roads caused by delivery trucks.

Provided these examples, we can conclude that infrastructure systems, once independent, are now *interdependent*. In order to achieve the goals of a smart city, its infrastructure should be managed efficiently with minimal side-effects and maximal benefits for the city's residents. Consequently, there is a need to design and operate the infrastructure systems synergistically.
Multi-disciplinary infrastructures have been studied in literature from two major angles. First, some work focuses on a combination of two specific systems and their dynamics. These models often represent the interdependencies between the systems accurately, but are not generalizable towards a larger smart city model. Consequently, there is a need for theory that facilitates the integration of more than two systems of an arbitrary type. Second, other work is strongly rooted in graph theory and aims to expand existing graph theory to create a *network-of-networks*. Some limitations of these multi-layer networks include the failure to facilitate networks of arbitrary topologies, and the inability to represent multiple functions within a network. With these limitations in mind, *hetero-functional graph theory* provides an alternative for modeling multi-layer infrastructure systems.

Hetero-functional graph theory has been developed over the past decade. It can be viewed as an intellectual fusion of model-based systems engineering and network science. The development of hetero-functional graph theory originates from automated mass-customized production systems, as these systems can have a nearly arbitrary size, an unlimited diversity of production capabilities, and an almost infinite number of product variants. Other applications of hetero-functional graph theory include multi-modal transportation systems, electric power systems, multi-model electrified transportation systems, microgrid-enabled production systems, and personalized healthcare delivery systems. More recently hetero-functional graph theory has been applied to a *three-layer* interdependent smart city infrastructure system, combining a water distribution system, an electric power system, and a transportation system.

The authors have recently published a book with Springer entitled: "A Hetero-functional Graph Theory for Modeling Interdependent Smart City Infrastructure" which is due to appear October 2018.