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Constructing hybrid infrastructure: Exploring the potential ecological, social, and economic benefits of integrating municipal infrastructure into constructed environments

Giancarlo Mangone

Azrieli School of Architecture & Urbanism, Carleton University, 1125 Colonel By Drive, K1S 5B6 Ottawa, Ontario, Canada

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ABSTRACT

Centralized infrastructure systems are ineffective infrastructure solutions for a diverse range of contexts, yet they comprise a substantial portion of current and planned infrastructure systems in municipalities throughout the world. The synthesis of a multidisciplinary, two phase review of existing literature on potentially higher performing infrastructure solutions is presented in this paper.

In the first phase, the potential economic and ecological advantages of semi-decentralized and decentralized infrastructure systems are explored. The results of the first phase of the study indicated that innovative infrastructure solutions, particularly hybrid infrastructure, can have substantial economic and ecological performance benefits.

Hybrid infrastructure is defined in this paper as infrastructure systems that are integrated within buildings and landscapes that also provide non-infrastructure uses. In order to be considered hybrid infrastructure, the infrastructure system(s) must provide a greater quantity of infrastructure services than the quantity of services that are required by the individual building or landscape, and their occupants.

Through an analysis of the results of the second phase of the review, the potential ecological, social and economic benefits of hybrid infrastructure are explored, some of which would otherwise be unattainable. The potential effectiveness of several hybrid infrastructure performance assessment methods is also discussed. The results of this discussion have substantial implications for building performance assessment methods and metrics. In particular, refocusing building performance goals and assessment methods to the urban scale can be more effective than current building performance goals and assessment methods. In addition, the results suggest that improving the ecological integrity of ecosystems through building and landscape design can also benefit the economic and social performance of buildings, landscapes, and local communities.

Thus, this paper contributes to deepening the understanding of the maximum ecological performance potential of buildings and landscapes. This is accomplished by investigating potentially effective ways buildings and landscapes can contribute to the development of sustainable cities and regions, in ways that improve the ecological integrity of local natural ecosystems.

1. Introduction

1.1. State of existing municipal infrastructure systems

Existing municipal infrastructure systems within a number of cities throughout the world, particularly those that were developed within western countries decades ago, are currently nearing the end of their service lives, and depending on the context, are in a considerably poor state. These infrastructure systems are in need of substantial repairs or replacement (American Society of Civil Engineers, 2013; Mirza, 2007; New York State Department of Environmental Conservation, 2008; SNC-Lavalin/Dessau-Soprin, 2002; US Environmental Protection Agency, 2009a; US EPA Office of Water, 2002). For instance, at the national scale, the overall condition of existing infrastructure within the US was found to be in a substantially deficient state by the American Society of Civil Engineers (ASCE) in their 2013 Report Card for America's Infrastructure. The state of drinking water, wastewater, and transit infrastructure was found to be particularly negatively performing, in terms of a number of performance metrics: capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation (American Society of Civil Engineers, 2013). In Canada, 59% of the nation's infrastructure is over 40 years old, and 28% of Canada's infrastructure is more than 80 years old. Moreover, 79% of Canada's infrastructure has met or exceeded its life expectancy (CSCE, CCPE, CPWA, & Canada, 2003).

At the city scale, 67% of Montreal's current water distribution pipes will reach the end of their service lives by 2020. Moreover, 33% of these pipes already reached the end of their service lives in 2002

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(SNC-Lavalin/Dessau-Soprin, 2002). In the state of New York, more than 30% of the state's sewage collection systems were found to be over 60 years old in 2004, which exceeds their service life. In addition, 23% of the municipal wastewater treatment plant equipment was older than their projected 30 year service life (New York State Department of Environmental Conservation, 2008).

Moreover, centralized infrastructure systems comprise a substantial portion of existing systems, and are being incorporated into developing urban areas throughout the world (American Society of Civil Engineers, 2013; McCarty, Bae, & Kim, 2011; Tihansky, 1974). Centralized infrastructure systems provide municipal scale system services at a centralized location (Hamilton Booz Allen, Rocky Mountain Institute, & US EPA, 2004; Metcalf & Eddy Inc et al., 2014; US Environmental Protection Agency, 1997). However, semi-decentralized and decentralized infrastructure systems can be more economical in a number of contexts (American Rivers, American Society of Landscape Architects, Water Environment Federation, & ECONorthwest, 2012; Muschalla, 2004), tend to have less adverse effects on local natural ecosystems (Moore, Kissinger, & Rees, 2013; Nico Tillie et al., 2009; Wood et al., 2015), and can be designed to provide opportunities to improve the social performance of buildings and landscapes (Izembart & Boudec, 2003; Mangone & Linden, 2014; Zhang, Piff, Iyer, Koleva, & Keltner, 2014), as discussed in Sections 2 and 3.

The distinction between centralized, semi-decentralized, and decentralized infrastructure systems varies within existing literature. A review of these varying definitions, and identification of potentially effective definitions, are discussed in Hamilton Booz Allen et al. (2004). This paper incorporates definitions similar to those proposed by Hamilton Booz Allen et al. (2004), which focus on distinguishing the system types by the relative scale of service provided, and degree of centralization of the system. From this perspective, a decentralized infrastructure system can be defined as a self-sufficient infrastructure system that provides the total infrastructure services, for that system type, to individual buildings, clusters of buildings, or small scale communities within a larger municipality, without the aid of centralized infrastructure systems (Hamilton Booz Allen, Rocky Mountain Institute, and US EPA, 2004; Wang, 2014). Semi-decentralized systems are municipal scale infrastructure systems that include both centralized and satellite system components (also referred to as distributed system components within existing literature). Satellite system components provide onsite, partial services that supplement the central servicing system (Gikas & Tchobanoglous, 2009; Wang, 2014).

1.2. Economic costs of replacing + repairing existing infrastructure

The economic cost of replacing and repairing infrastructure is considerable, particularly in contexts where maintenance has been deferred. In these cases, replacement and repair costs substantially increase, and can be as much as the construction costs of the system (Mirza, 2007). For instance, the ASCE estimated in 2013 that $3.64 trillion (USD) is needed by 2020 to repair and replace the existing infrastructure systems within the US. Approximately 44.2% ($1.61 trillion) of this funding has not been allocated. Moreover, this lack of investment in repairing infrastructure systems in the US is projected to reduce the personal disposable income per US household by approximately $3100 (USD) annually between 2012 and 2020, which amounts to a total of $27,900 (USD) per household. Failing and obsolete US infrastructure is projected to cost businesses $1.2 trillion (USD) and households $611 billion (USD) by 2020 (American Society of Civil Engineers, 2013). In Canada, the repair of existing municipal infrastructure has been estimated to require $123 billion (CAD), while the construction of new centralized infrastructure to meet new and changing demands of communities has been estimated to be $115 billion (CAD) (Mirza, 2007).

At the state scale, the cost of repairing, replacing, and modernizing New York's municipal wastewater infrastructure through traditional solutions was estimated to be approximately $36.2 billion (USD) over 20 years by the New York State Department of Environmental Conservation in 2008 (New York State Department of Environmental Conservation, 2008).

1.3. Defining infrastructure

Although the term infrastructure has been used to describe typical technical municipal infrastructure systems in Sections 1.1 and 1.2, a number of definitions of infrastructure have been proposed in existing literature from diverse research domains. For instance, a considerably broad definition of infrastructure is the human constructed systems and processes that function to generate and circulate the goods and services needed by a community (Cavalieri, Franchin, Gehl, & Khazai, 2012). Thus, this definition comprises the physical aspects of a community, which includes buildings, social infrastructure, such as hospitals, schools, sports and recreation facilities, and libraries, as well as technical infrastructure, such as water, transportation, waste, data, communications, and energy infrastructure systems, as well as provisioning and regulating ecosystem service infrastructure, such as flood control, air filtration, and food production (Cavalieri et al., 2012; Gabdrakhmanov & Rubtsov, 2014). Some socio-technical infrastructure models, particularly those from the 'urban informatics' research domain, include people, or actors/users, and their social networks and interactions, as social infrastructure components (Lukszo & Bouwmas, 2005; Nik-Bakht & El-Diraby, 2016). In addition, within some urban planning focused definitions of infrastructure, buildings that have a primary function which is not to generate social or technical infrastructure services, such as housing, office, and retail buildings, are not considered to be infrastructure (Chakrabarti, 2013; Gabdrakhmanov & Rubtsov, 2014).

In regard to infrastructure, the focus of this paper is on integrating socio-technical services into buildings and landscapes. Therefore, people and their social networks are excluded from the definition of social infrastructure within this paper. Moreover, buildings that do not provide socio-technical services, such as housing, office and retail buildings, are not considered infrastructure within this paper. On the contrary, these types of buildings provide opportunities to integrate socio-technical services within and adjacent to these building types, as discussed in Sections 3 and 4. Although a detailed discussion of social infrastructure is outside the scope of this paper, Section 3.5 includes a discussion of opportunities to integrate social infrastructure into buildings and landscapes. Thus, the discussions within this paper are primarily focused on technical infrastructure systems.

1.4. Defining the scope of the paper

The technical infrastructure issues discussed in Sections 1.1 and 1.2 demonstrate that there is considerable need by municipalities to develop cost effective, high performing technical infrastructure system design and replacement solutions. To this end, Section 2 provides a review of existing research and infrastructure projects that demonstrate that the economic and ecological performance of various types of existing and new technical municipal infrastructure systems can be substantially improved through the integration of semi-decentralized and decentralized infrastructure components. This is true both in regards to infrastructure system replacement and new development strategies. Although the discussion focuses primarily on wastewater infrastructure systems, with brief discussions of stormwater and district heating and cooling systems, semi-decentralized and decentralized infrastructure strategies can be beneficial to a diverse range of infrastructure systems (Ahern, 2011; Nico Tillie et al., 2009; Rosenberg, 2013). While a review of the application benefits to a broader array of infrastructure system types is outside the scope of this paper, Section 3 includes discussions on the potential benefits of several semi-decentralized technical and social hybrid infrastructure types.

Existing research indicates that innovative infrastructure solutions can be more cost effective and provide additional social and ecological