Improving the resilience of urban buildings: an integrated approach to measuring optimum demand density

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Abstract

Despite extensive literature on the linkages between sustainability and resilience, conceptual understanding of the capacity of urban infrastructure systems to support higher population densities remains unclear. In response, this paper presents a framework to illustrate the fundamental relationship between infrastructure capacity and density at the building scale. We explore the density and resilience paradigm by developing the "Infrastructure Carrying Capacity" (ICC) framework to calculate the concentration of resource demand (or consumption) that can be "carried" by the building envelope and supporting infrastructure systems i.e. the demand density. In this regard, the ICC framework can be used to calculate the building's natural carrying capacity. Furthermore, applying the ICC framework at the building scale provides a strong foundation for potential replication and scale-up to the neighborhood or city scale. Overall, our research develops a basis for re-thinking urban sustainability and resilience in the context of rapid population growth and changing demand pressures.

Keywords:

Infrastructure Resilience; Urban Density; Carrying Capacities; Demand Management

1 INTRODUCTION

Over half of the world's population lives in cities today [1]. This trend is expected to continue, and by 2050, it is projected that over two thirds of humanity will reside in urban areas [1, 2]. Much of this growth will take place in developing countries whose cities are often located in areas of high risk and vulnerability to disasters [1]. Rapid urbanization will stimulate the emergence of new risks, especially when growth is unplanned and occurring in the context of other socio-economic vulnerabilities such as widespread poverty [2, 3]. Furthermore, higher population densities will also increase demands on urban infrastructure systems, potentially beyond the thresholds of their carrying capacities. This will ultimately compromise the resilience of systems, prohibit equitable access to vital services, and impede response and recovery processes during disaster scenarios. Against this backdrop, what is the capacity for urban infrastructure to support rapid population growth and higher density? What are the impacts on system resilience and performance? And what are the thresholds or limits beyond which resilience is compromised? These are questions that researchers have struggled to address, and where the novelty of this paper resides.

It is widely acknowledged that resilience is essential to sustainable development in cities [2]. Resilience, as it relates to infrastructure, is the ability for systems to respond to and absorb the effects of shocks and stresses, and to quickly recover to normal capacity and efficiency [4]. Therefore, resilient infrastructure can support dynamic urban environments and enable socio-economic well-being in urban communities [3]. For these reasons, the interplay between infrastructure resilience and socio-economic development has been emphasized in existing academic research and policy discourse on sustainable cities. Proponents of the two interrelated concepts have recommended strategies to optimize the efficiency of infrastructure networks and reduce overall demand on systems [1, 5]. Fundamentally, the focus has been on decoupling economic growth and resource use by reconfiguring systems to be more efficient and able to withstand rapid global changes and demand pressures [1].

At the same time, current research on infrastructure resilience generally aligns with social-ecological perspectives that view systems as complex, interconnected and adaptive [6, 7]. For example, some studies have investigated the interactions between different system components to determine cascading impacts and areas for reducing risk [6, 7]. Other works further describe infrastructure as complex socio-technical systems that are not only interacting with each other, but also with the surrounding social and natural environments [9, 10, 11, 12]. While some studies also argue that high-density urban growth or "compact cities" can make greater use of infrastructure services and reduce the overall cost of services – for example, the total road surface area, length of electrical cables, water pipes or number of petrol stations that service a particular neighborhood [13]. Therefore, planning and operating infrastructure for higher density can lead to more efficient use of services and solutions that may be impossible to achieve in lower density neighborhoods [13]. Compact cities can also increase social benefits by increasing the availability of adequate housing options and basic infrastructure services to meet diverse population needs, including for low-income groups [14].

Ultimately, ongoing research on sustainable cities has stimulated discourse for more innovative approaches to urban planning and development; focusing on more integrated solutions that leverage synergies between natural, social and built systems (see [2] for some case study examples). Yet, the dialogue has not explicitly considered the performance and recoverability of infrastructure systems against changing densities or demand pressures over time; and in this regard, infrastructure resilience in the face of disruptions. Furthermore, existing approaches to urban density measurement often rely on spatial measures (e.g. in terms of people, number of residential units or floor-to-area ratios [15, 16]), and do not offer a true reflection of resource use within urban environments. It is therefore difficult to compare across existing density indicators or metrics, and there is limited consensus among researchers on approaches to improve infrastructure performance for different resource use profiles at the building, neighborhood or city scale.

In response, this paper aims to address the aforementioned research gaps. We develop the *Infrastructure Carrying Capacity* (ICC) framework as a tool for calculating the optimum *demand density* to be carried by the building envelope. Essentially, the demand density describes the concentration of resource use at the building scale. Fundamentally, we estimate that for building operations to be resilient, the demand density should be within the carrying capacity of the building envelope and its supporting infrastructure systems i.e. water, energy, waste, telecommunications and transportation (Table 2).

Therefore, the main objectives of this paper are to:

- Develop a conceptual framework to calculate a building's optimum demand density;

- Develop metrics for measuring building resource consumption (or use);
- Describe potential applications of the ICC framework and opportunities for future research.

2 METHODOLOGY

We hypothesize that when an imbalance between demand density and carrying capacity exists, vulnerabilities can propagate within the building envelope and weaken the ability for operations to rapidly recover and maintain function during disruptions or disaster events. In this regard, we develop the ICC framework as an essential tool for urban density planning and demand management. We describe the process for developing the ICC framework in three phases.

2.1 Demand density concept

Firstly, drawing from the social-ecological perspective on resilience thinking [6, 7], the building operation can be described as a collective system-of-systems that consists of the building envelope and its supporting infrastructure systems of water, energy, waste, telecommunications and transportation. Therefore, we use the term "demand density" as to describe how resources are used within the building envelope over a specified time period i.e. the concentration of resource consumption. For example, this can be the volume of water or electricity consumed within the building during peak or off-peak hours over the course of a day.

2.2 Building scale metrics for resource consumption

Secondly, we develop metrics for resource consumption to better understand how resources flow within the building envelope. Data sources would vary depending on the type of metric and infrastructure system being assessed. In essence, Table 1 illustrates that the demand density should not exceed the available capacity of the building's supporting infrastructure. The resource consumption within the building envelope is shown as a "demand" metric e.g. the net water and electricity use per day. These demand metrics are compared against the available capacity within the building (shown as the "availability" metric). The building owner (or manager) would usually have information on the building's available capacity. Therefore, data collection should be completed in collaboration with building owners, as well as with the utility companies that service the building and the local transit authorities.

Table 1: *Resource consumption flows: building scale metrics*

DEMAND	AVAILABILITY *(i.e. available capacity of building operations)*
WATER	
▪ m^3 per day	*Known by building owner*
ENERGY *(Electricity or Natural Gas)*	
▪ kWh per day ▪ MJ per day	*Known by building owner*
WASTE *(Liquid or Solid)*	

▪ m^3 per day ▪ tonnes per day	*Known by building owner*
TELECOMMUNICATIONS *(Landline, Cellphone or Internet)*	
▪ Number of subscriptions ▪ Percentage connectivity (offline vs. online) ▪ Frequency of use (Hours per day per occupant)	*Known by building owner and local telecom companies*
TRANSPORTATION	
▪ Kilometers travelled per day (per occupant) ▪ % of occupants driving (including vehicle type), using mass transit, carpooling, walking, biking ▪ hours per day per occupant	*Known by building owner, occupants and local transit services*

2.3 Framework for Infrastructure Carrying Capacity (ICC)

Thirdly, we represent the ICC framework as a table (Table 2). Using the "Resilience Planning Framework" developed by Hay (2016) [4], there are three levels of operating performance that are essential to infrastructure resilience planning: routine, minimum sustainable capacity (MSC) and minimum operating capacity (MOC) [4] (Figure 1). The ICC framework builds on the resilience framework by assessing the demand density that can be supported by buildings at each of these operating levels.

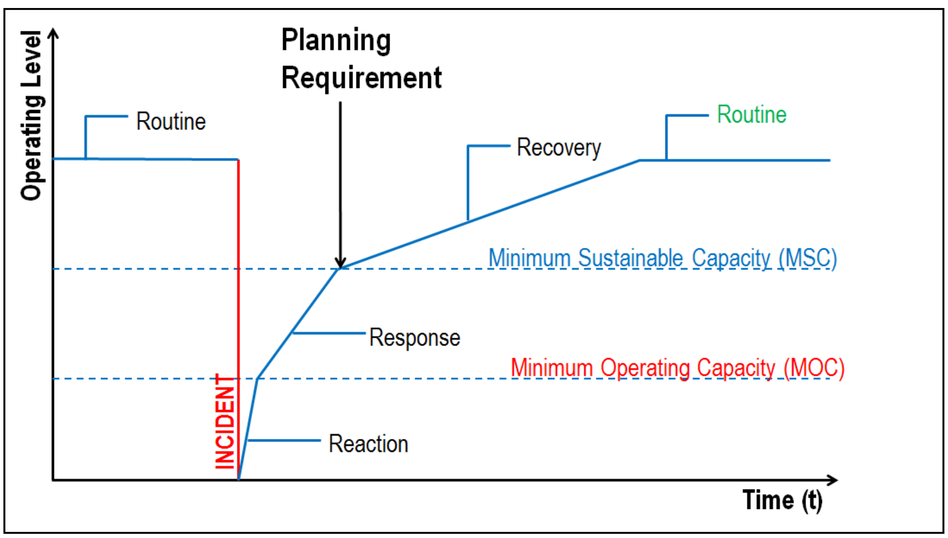

Figure 1: *Resilience Planning Framework (Adapted from Hay, 2016) [4]*

Table 2: *Structure of the Infrastructure Carrying Capacity (ICC) Framework*

OPERATING LEVEL (see Hay, 2016)	**Building's supporting infrastructure System** *(e.g., water, energy, waste, telecommunications, transportation)*
Routine	[Demand density]
Minimum Sustainable Capacity (MSC)	[Demand density]
Minimum Operating Capacity (MOC)	[Demand density]

(**Note:** The carrying capacity is defined as the demand density that can be supported at Routine, MSC and MOC)

Resource consumption flows can enter and leave buildings through various pathways. For example, potable water and energy can be supplied to buildings through a public network. Once available to individual buildings, water and energy resources are further distributed within the in-building supply network to different appliances for end-use. Similarly, wastewater is normally discharged through a public sewer system that is also linked to the building's in-house waste management system for recycling or disposal.

Therefore, when building operations are at *Routine* (Figure 1), the building is operating under a business-as-usual scenario and servicing normal demand patterns (including periods of peak demand). The optimum demand density at this level is the concentration of resource use that can be supported to sustain routine operating levels. Similarly, when building operations are at *Minimum Sustainable Capacity* (MSC), only the essential building operations are running – for example, when waste water from sewerage is being treated, while other waste services typically associated with routine service are not available (e.g. solid waste collection) [4]. Therefore, the demand density when building operations are at MSC refers to the concentration of resource use that can be supported at this level of operation. And finally, the *Minimum Operating Capacity* (MOC) is the level that describes the building's minimum survival level of operation, particularly after an incident occurs. The MOC is therefore critical to system resilience and should be quickly restored following any interruptions or shut-downs [4]. In this respect, the demand density when systems are at MOC describes the concentration of resource use that can be supported immediately following any disaster or emergency situation.

Overall, we estimate that if the demand density exceeds the carrying capacity of the building operation at Routine, MSC and MOC, then resilience is compromised, especially during periods of disruption. Also, the process will vary depending on the type of building assessed. For example, a critical operation at MOC for a hospital may be to ensure back-up electricity generation for the intensive care unit; while for a financial institution, this would be for the trading floor.

3 DISCUSSION

This paper introduces the ICC framework as a contribution to the growing literature on infrastructure resilience by elucidating the challenges of urban densification as it relates to the physical or built environment. Specifically, the ICC framework can be used to determine the optimum demand density that can be carried by building operations. Fundamentally, we argue that density should not be too high as to overwhelm infrastructure capacity, or too low as to constrain its optimum use. Therefore, the carrying capacity is defined as the demand density that can be supported by the building at routine, MSC and MOC (Table 2). Also, data availability and collection would be critical to the successful implementation of the ICC framework. Data can be collected from utility companies, as well from building owners or managers. Some data such as energy and water consumption are collected for different billing periods, and as such, weather normalization could be required to account for seasonal variations and allow for direct comparisons over time.

4 FUTURE WORK

Simply, the ICC framework offers a starting point for building owners to assess the carrying capacity of their building operations against different resource use profiles or demand pressures. However, as previously mentioned, meaningful data is essential to the application and validation of the framework. Therefore, the second phase of the research will be to apply the framework to an existing building in the City of Toronto. At a later stage, the framework will also be applied in the context of developing countries where cities are growing rapidly, and governments are challenged with the duty to provide adequate and affordable infrastructure services to increasing urban populations.

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