Optimizing Demand Density with Carrying Capacity to Create Resilient and Future-Ready Cities in Times of Crisis and Beyond

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Abstract

As the novel coronavirus moved like a wave across continents in early 2020, most operations were reduced to emergency levels, or even ceased altogether. Governments everywhere implemented essential services to ensure survival and recovery. Yet, even in this state of shock, certain supply chains became critically important as demand for virtual activities – such as online shopping – skyrocketed. Suddenly, the carrying capacity of the operations supplying and distributing all those Amazon purchases had to increase and be supported, despite the surrounding crisis.

The intricate balance of demand density and carrying capacity is challenging to manage even in "normal" times. What is the optimum carrying capacity? How can demand density be predicted? Within an urban context, this question is more complicated still: cities consist of numerous delicately linked infrastructures, each with its own demand density and carrying capacity.

So, as urban centres around the world struggle to right themselves after each wave of the pandemic – and future crises – this white paper offers an important look at the significance carrying capacity and demand density have in successful cities, the importance of adaptability when it comes to creating balance between them and why it's necessary to map for all infrastructure dependencies in an urban model that optimizes the delicate relationship between carrying capacity and demand density without compromising the inherent value of the community.

Contents

Introduction

The rapid shift in consumer behaviour, work routine and economic output caused by the coronavirus pandemic presents a unique learning opportunity for urban planners everywhere. The sudden shutdown has shown us how critical it is for systems to be flexible, and that a city's ability to react to change in a timely manner is key to its future success.

Foundational to this is a dynamic urban planning process and the relationship between carrying capacity, the ability to support an operation, and demand density, the measure of demand in a given area, that underscores it. Optimising the two ensures that cities will continue to grow and thrive under both regular and crisis operations. Misalignment between them can cause a city to fail.

Of course, demand density and carrying capacity are not standalone measures. Rather, they are defining parameters of an operation or function, like the provision of food and energy or services like health care. In turn, those functions are generally dependent on others, and together they form a complex system of operations with upstream and downstream dependencies.

The coronavirus pandemic exposed critical connectivities in this complex system of interdependent operations. The state of emergency declared to curb the spread of COVID-19 reduced normal operations to "essential services". Decision makers had to weigh possible anti-infection measures and their assumed outcomes against the consequences that reduction or stoppage of services would bring. Essential services were deemed those, whose absence would prevent stability and the recovery of the whole operation.

Every essential service is enabled by critical infrastructure. Public Safety Canada (2009, 2018) has identified 10 critical infrastructure sectors:

ENERGY + UTILITIES   INFORMATION + COMMUNICATION TECHNOLOGY   FINANCE   HEALTH   FOOD

WATER   TRANSPORTATION   SAFETY   GOVERNMENT   MANUFACTURING

A deserted Boulevard René-Lévesque, Montreal, Quebec.

While all these sectors had been protected and supported by the government to ensure continuity and the ability to recover, upstream and downstream dependencies impacted the operations of all sectors.

The COVID-19 crisis has severely changed carrying capacity and demand density in all sectors within a short period. While this crisis seems a worst-case scenario, it would be imprudent for planners and decision-makers to focus future decisions solely on mitigating the effects of a pandemic. Instead, they should focus on the individual operations they control. This reduces the inherent fragility of the operation to a component failure, rather than to a specific hazard. Focussing on what you can control increases resilience against any foreseeable and unforeseeable threat and protects from any secondary or tertiary effects caused by the initial shock.

Resilience is certainly part of the answer. But a careful review of the fundamentals of resilience reveals an important fact, a fact that can be overlooked by planners: in an extreme event, individual citizens need to be able to self-recover. They must be able to meet their needs for food, water and other essentials for the first 72 hours after a shock without relying on the municipality. Why? Simply put, if individuals have prepared for an emergency and can look after themselves, then the city as a whole can focus its resources on self-recovery and is much more likely to survive.

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Demand Density and Carrying Capacity: Critical Pieces of the Resilience Puzzle

The Balance Between Them Can Determine Survivability

Demand density is the measure of how demand for an operation is concentrated in a given area. Hay (2019) defines carrying capacity of an operation/infrastructure as the "amount of demand it can support under different conditions."

Demand density and carrying capacity are linked through the operation; one cannot exist without the other.

The catch is, carrying capacity and demand density are not constant; they vary over time. In the short term, this can be due to normal peak operations or an emergency. In the long term, slow changes in demand or capacity will always occur.

To account for their variability, carrying capacity and demand density are described by three measures (Hay, 2019):

PEAK

Normal, recurring operations, for a short period. Non-sustainable.

An upper limit

SUSTAINABLE

Normal operations. Sustainable (zero net revenue for operations)

EMERGENCY/ESSENTIAL

System failure. Possible operation under system failure (capacity through backup systems, emergency supplies).

A lower limit

Perfect alignment between these measures is not generally possible. But the below example shows how an infrastructure operation might adjust demand density (DD) and carrying capacity (CC) to ensure sustainable operations:

ESSENTIAL DD > ESSENTIAL CC

• Add alternative standby or base supply

SUSTAINABLE DD > SUSTAINABLE CC

• CC needs to increase to sustainable DD levels but not above, as the net revenues from the enabled service need to cover infrastructure operating costs

SUSTAINABLE DD < SUSTAINABLE CC

• Infrastructure is unsustainable, new markets are required for excess CC (establishing supplementary demand cluster)

• Reconfigure the infrastructure laydown to focus on local [burden-sharing] demand clusters, rather than monolithic supply of commoditized services (electricity, water, gas, etc.)

• Decommissioning or managed deterioration in the infrastructure capacity, which is typically irreversible without a significant capital investment

• Increase net revenue from services through increased tariff, though this is not a socially sustainable option.

PEAK DD > PEAK CC

• Adjust sequencing of operations to reduce peak demands (especially useful with clustering of demand groups)

• Add supplementary direct and latent (storage) supply, which is a possible use for essential CC

For planning purposes, it makes sense to establish an operation's short-term and long-term measures for both carrying capacity and demand density. Figure 1 shows an example of how they can align in an operation.
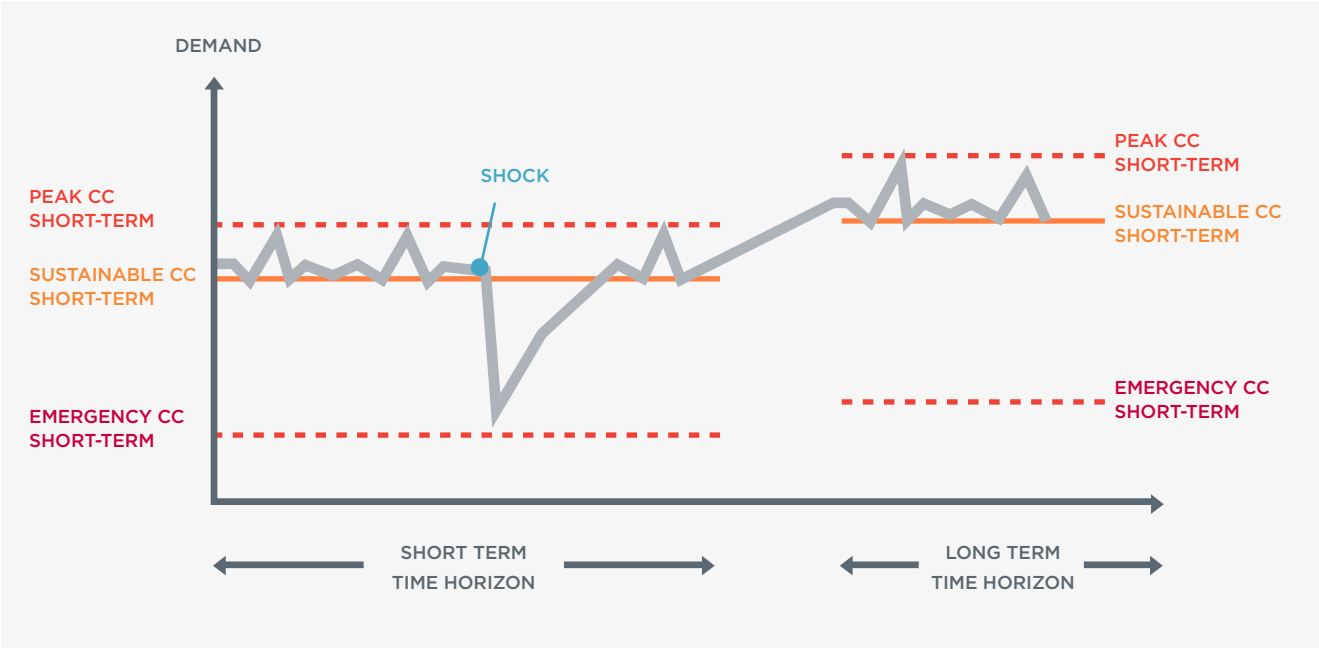

Figure 1. Operational demand and capacity over short and long-term time horizon

Adapting to Build Synergy – and Better Cities

Understanding Dependencies Can Create Synergy and Ultimately Increase Resilience

Increased flexibility in carrying capacity allows us to adapt an operation to changes in both short- and long-term demand. It is difficult to change built infrastructure due to financial constraints and long lead times. Instead, our focus should be on adaptive infrastructure (Chester and Allenby 2019) and, as part of it, virtual infrastructure (Hay 2019). Together, they make it possible for an operation to perceive and react to changes, enabling long-term survival and growth.

Adaptive infrastructure is characterized by two different structures:

Focus on adaptive infrastructure and, as part of it, virtual infrastructure.

TECHNICAL STRUCTURE

Compatible, connected and modular, software-focused and directed towards resilience. Smart grids in electrical distribution networks are a perfect example.

INSTITUTIONAL STRUCTURE

Organic, with a culture of change and a trans-disciplinary education and outlook.

The management style of adaptive infrastructure is networked and decentralized with less adherence to authority and control. There are fewer rules and regulations, and loyalty is towards the project, not the organization. They afford a high degree of flexibility and discretion.

A trans-disciplinary outlook that overcomes operational boundaries is important. It allows the various functions that contribute to the main operation to understand and work with each other, and focus on a unified purpose leading to synergy within the organization.

Most operations are not standalone and thus depend on outside infrastructure to supply them with resources and services. That's why it is important to extend this trans-disciplinary outlook to every function your operation depends on, as well as those that depend upon you. Here is just one example of what that looks like:

> *Cooperation between an energy provider and its clients enables staggered operations to decrease peak demand density. This reduction in peak demand allows for a concurrent reduction in peak carrying capacity and thus reduces energy costs.*

This stability and synergy benefits all consumers, but it can come at a cost: reduced resilience and *frisson*. Frisson – the creative impulse that promotes progress – is a cornerstone of innovation and successful cities. Every city requires a certain amount of frisson – of instability – to evolve and grow. Even negative instability from intrinsic or extrinsic pressures or events can lead to an improved routine performance post-recovery.

On the other hand, an imbalanced system comes with increased inherent risk, and that means every decision-maker has to determine their operation's risk tolerance.

Apple Park, corporate headquarters of Apple Inc., Cupertino, California.

Urban Systems: A Complex Balancing Act

You Must Accept a Certain Risk to Preserve the Fluidity of Modern Life

A city has been described as a vitae ("of life") system of systems (V-SoS) (Okada 2004, Hipel et al. 2011). A V-SoS is a concentration of dynamic independent operations. Each operation develops individually but also as part of the whole (Bristow et al. 2013). The main goals of each V-SoS are the following functions (Okada 2006):

TO LIVE (SURVIVAL)
Depends on shock recovery and risk avoidance. Cannot be ensured if the treatment causes a breakdown in growth and community

TO LIVE LIVELY (VITALITY)
Cannot be at the expense of security

TO LIVE TOGETHER (CONVIVIALITY)
Community needs to be supported by economic growth and safety

None of these functions exists in a vacuum, and any measure supporting one needs to address the effect it will have on the others. You cannot have complete security if you are to maintain vitality.

What's more, communication and connectivity between a city's many elements is vital. Each element needs to know how and to what it is connected, as any action impacts other elements both directly and indirectly. Let's look at the shelter function within a city:

> *New dwelling units increase available shelter but also raise demand for energy, water, transportation and more. Existing operations may see this as a stress, yet additional sustainable demand allows infrastructure to grow as its carrying capacity can be supported by increasing revenue. Competition for resources seems like a negative, but it also drives synergies, cooperation and diversification.*

Each piece of infrastructure within an urban system has its demand density and carrying capacity, and the balance between them will determine if a city fails or prospers. A central task for any city infrastructure planner is to optimize carrying capacities. This task begins with knowing the impact, both upstream and down.

Mapping the Dependencies:
Creating an Urban Model for Planning Purposes

Chart Every Element and a Complete Picture Emerges

Figure 2. Dependencies for a small subset of elements/operations within a city
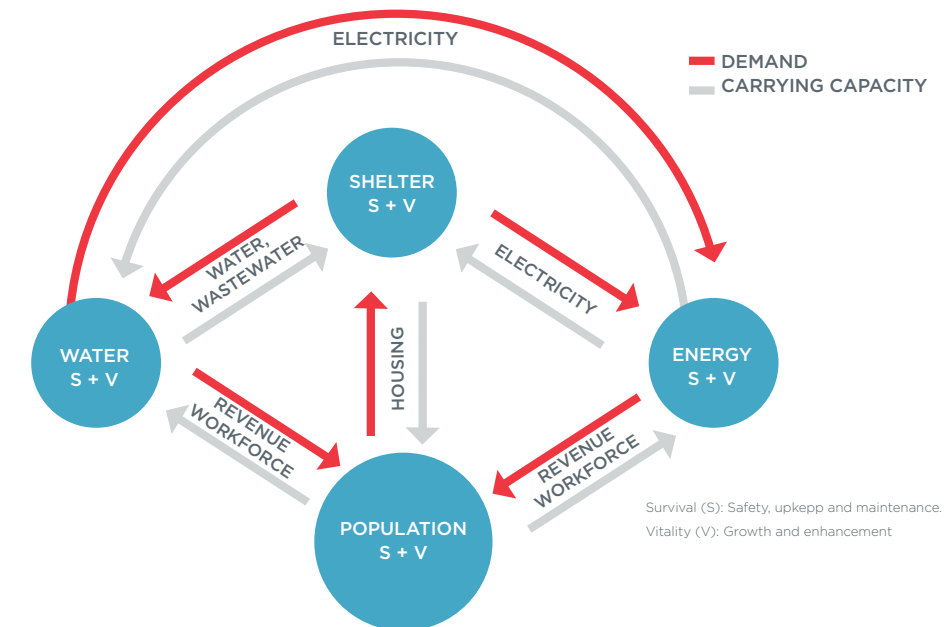
A city model needs to be seen in context and include dependencies.

Figure 2 shows the upstream (demand) and downstream (carrying capacity) relationships between a small subset of operations within a city. Total demand and carrying capacity for each element needs to be balanced to ensure the survival and vitality of the element itself and the city as a whole. Keep in mind that, while most elements would be inherent parts of the city, others – commerce, legislation, food chain, water and energy – are often highly dependent on outside operations. Thus, a city model needs to be seen in context and include dependencies to neighbouring cities, provinces and countries, as well as their infrastructures.

ELEMENTS OF THE URBAN MODEL

Numerous studies use three categories to describe the various types of carrying capacity within an urban environment (Li and Lian 2012, Li and Ma 2014, Oh et al. 2005):

**RESOURCE
(NATURAL OR BIOLOGICAL)**
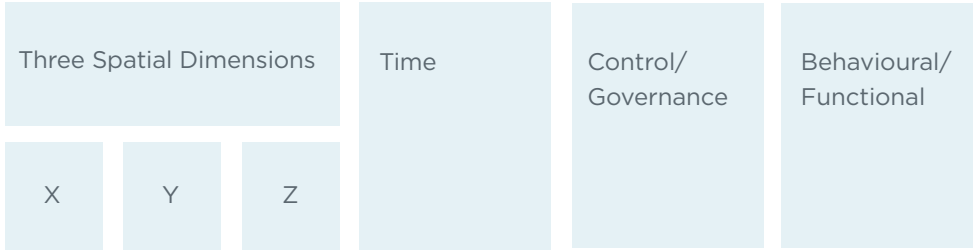
ECONOMIC

SOCIAL

Hay (2019) describes the numerous operations within a city system as being enabled by infrastructure that influences and is influenced by the population; the demand densities on the services which the carrying capacity of the infrastructure enables. The infrastructure is represented by three of the four V-SoS domains and operates in six dimensions:

INFRASTRUCTURE DOMAINS

Natural	
Built	Interacting with the Human Domain
Virtual	
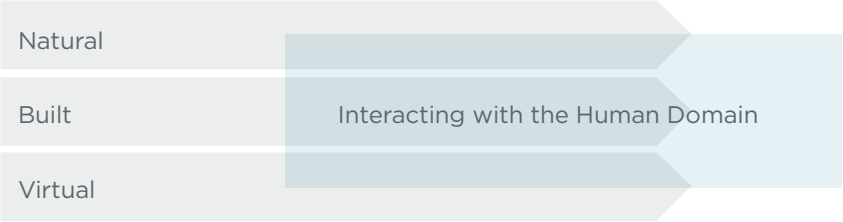
INFRASTRUCTURE DIMENSIONS

| Three Spatial Dimensions			Time	Control/ Governance	Behavioural/ Functional
X	Y	Z			

This approach works from first principles and is not restricted by previous models. By incorporating the six dimensions into the systems model, spatial distribution (required for allocating carrying capacity and demand density), as well as the variability over time, becomes part of the model.

As an example, the mapping of carrying capacity through spatial analytics and the visualization through geographic information systems (GIS) has proven to be an essential tool for the city of Arlington, Texas (Dennehy et al. 2014). The information from the GIS study helped establish the current baseline for the existing built and natural environment. Coupled with a study on social aspects, economy and policy, this will aid informed decision-making.

Creating an urban model for planning purposes is necessarily unique. Each city has a unique location, culture, population, social fabric and economic laydown. Model granularity should reflect the focus and purpose of the user's organization. However, the granularity of the model is driven by the decisions to be informed by the model.

The previously mentioned essential services – energy and utilities, health, food and water – can be used as a first step towards the urban model. These services are needed in every city as they support the survivability of the population (Survival Goal of the V-SoS). They are only an enabling part of a lively and prosperous city, and the model needs to include the operations that are curtailed as the survival of the whole is prioritized over vitality. Cultural, educational (Vitality Goal of V-SoS), and community-building operations (Conviviality Goal of V-SoS) come to mind, as well as operations in the service and commercial industries. These operations are unique to every city and give character to the urban environment.

Creating an urban model for planning purposes is necessarily unique.
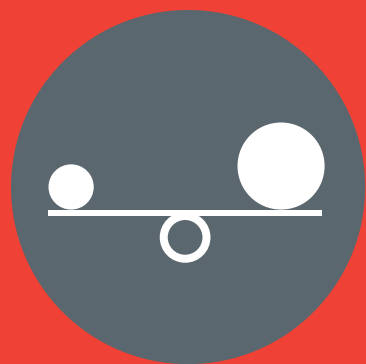
Planning Factors

*Balance Demand Density and Carrying Capacity to Ensure Sustainability–
and the Ability to Recover From Shocks*

1 | DETERMINE THE UNIFYING PURPOSE FOR THE URBAN INFRASTRUCTURE

The ultimate optimization of the elements of urban planning in terms of
carrying capacity and demand density within a city requires a unifying
purpose for the urban infrastructure. Answer the following questions to
steer decisions around carrying capacity and demand density:

WHAT IS THE ULTIMATE GOAL OF A CITY?

A city needs to serve a purpose, just as each element within has a purpose.

WHO OR WHAT SHOULD BE THE ULTIMATE BENEFACTOR OF THE CITY?

Historically, economic growth has been the main benchmark of successful cities
but the requirement for a unifying purpose can also be reflected in more than
just economic metrics.

The government of Iceland recently published indicators for measuring
wellbeing (Government of Iceland 2019) that are highly aligned with the United
Nation's Sustainable Development Goals (UN General Assembly 2015). Therein,
the welfare and prosperity of the country are defined beyond the usual economic
factors generally applied. Instead, the focus is on the population and its wellbeing.

The concept of wellbeing can be expanded to Quality of Life (QoL), as described
by Lindström (1992). The World Health Organization defined Health as, "A state of
complete physical, mental and social wellbeing and not merely the absence of
disease or infirmity," (1948). Based on this definition, Lindström's model uses QoL
as a global concept that encompasses QoL for an individual, a group and a society.

QoL is defined by these spheres and dimensions, e.g.

PERSONAL
Physical, mental
and spiritual

INTERPERSONAL
Family – intimate,
extended

EXTERNAL
Work, economy,
housing

GLOBAL
Macro environment,
human rights policies

Lindström proposes the definition of base levels of QoL for each variable/dimension as the lowest acceptable level. Expanding on this idea, the use of base and sustainable levels for each QoL variable can provide the planning factors for demand density and carrying capacity. Each base level is thus connected to the purpose of health on a personal, interpersonal, external and global level. Ensuring that a city can guarantee both base levels (during crisis) and sustainable levels of QoL (during normal operations) should guide decision makers on appropriate investment and regulatory decisions.

2 | QUANTIFY THE INPUTS AND OUTPUTS

This makes it possible to compare demand density with carrying capacity. Different infrastructures use different units of measure. By using a ratio of the two, the various units within an urban model will be eliminated. This allows a single urban model to include a multitude of infrastructure types.

3 | REMEMBER THAT THE RELATIONSHIP BETWEEN CARRYING CAPACITY AND DEMAND DENSITY IS TEMPORAL

Demand density and carrying capacity have to be based on the same time frame. This way, a model includes staggered operations of dependent elements, which more accurately reflects the dynamism of peak demand on the supplying infrastructure. The total demand on a supplier is the sum of the demands of each dependent element at a specific time. If the peak demand of the various dependent elements occurs at different times, the peak demand on the supplier is less than the sum of the peak demands of dependent elements.

4 | CONSIDER ACCESSIBILITY

A population without timely access to the city's infrastructure and amenities will not thrive or contribute to the overall resilience and success of the community (Hay and Willibald 2017). Accessibility really speaks to the conviviality goal of the urban system. Also, location and control determine accessibility, and refer to the spatial and control dimension of infrastructure.

5 | APPLY SHOCKS AND STRESSES

Shocks are sudden events – an earthquake, accident or terrorist attack – while stresses are characterized by slow, cumulative effects on the system – decay, climate change or social inequality – as described by Yanga et al. (2018). Both should be applied to the urban model as they influence demand density and carrying capacity over both the short and long terms.

6 | TAKE AN ALL-HAZARD APPROACH

This allows for the combination of shocks and stresses, and takes into account how a shock or stress can change the probability and impact of other shocks or stresses, either due to direct and indirect effects (a power outage) or by merely reducing resources in the system.

7 | AIM FOR A FAST POST-SHOCK RECOVERY

Shocks or stresses can affect the system as a whole or only specific operations. The downstream effects will generally be noticeable over larger parts of the model, and can sometimes be separated by time and space. Nevertheless, these hazards should not be applied to the model with the goal of hardening it. Unforeseeable events are not part of hazard scenarios, and only a resilient operation will be able to adapt and recover. We cannot undo a shock or stress, but we can influence how an operation reacts to it by focussing on the purpose of our operation.

Conclusion: Towards an Adaptable Urban Model that Helps Cities Succeed

Optimizing demand density with carrying capacity for each piece of city infrastructure is a critical task for any city planner because it can create resilient, future-ready cities – especially in times of crisis.

Of course, infrastructure is never standalone. It links directly or indirectly to numerous other operations that make up the urban system, as well as operations that are beyond the physical and legal realm of the city. By mapping the dependencies between all these elements over the space, time, control and human/functional dimensions, a full picture emerges that informs both short- and long-term decision-making. And while every urban planning model is unique – a city planning department will need to construct a different model than the provider of a specific infrastructure within a city – both need to go beyond immediate operations and show the dependencies to the other operations within the city.

As recent events have shown, hardening against a specific threat is not always the best response. Even using an all-hazard approach is not sufficient to protect yourself, as a black swan event can strike anytime. Instead, managers at all levels need to focus on the elements of their operations they can control, and especially on the purpose of their operations, to ensure sustainability and resilience. Knowledge of both upstream vulnerabilities and downstream dependencies will enable the developer to understand how both shocks and stresses travel through the system. This understanding of a systems view can generally be translated into a depiction of the daily carrying capacity and demand density relationships between the supporting operations.

The use of adaptive infrastructure, with its modular technical components and decentralized management structure, will allow the infrastructure system and, in turn, the city it supports, to adapt to changing demands, both short and long term. Roadmapping a culture of change and a resilience focus ensure adaptability.

Ultimately, there is no one-size-fits-all model to determine the perfect carrying capacity for each element within a city. Cities vary in their geography, resources, climate and economy, but more importantly, in their population and culture. Perfect alignment between carrying capacity and demand density in all operations will ensure stability and sustainability over the short term as well as minimizing a city's required budget. However, complete stability will prevent a city from evolving, as there are no incentives or additional resources/investments for change. Unchanging stability can lead to an inability to recover from unseen stresses and unexpected shocks.

Therefore, decision-makers will have to decide their level of risk tolerance in allowing a certain dissonance in demand density and carrying capacity. This tolerance will have to be addressed at the system level, as both too little and too much dissonance can ultimately lead to failure.

Adaptive infrastructure will allow the infrastructure system and the city it supports to adapt to changing demands.

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