Civil engineer for urban livability, sustainability and resilience

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ABSTRACT
Urban infrastructures, to fully take advantage of future investments, must first be recognized as interconnected complex systems of systems. This forum paper describes research and education needs that, if properly addressed, could prepare the civil engineering profession to meet the new challenges of urban infrastructure renovation. Among the needs, the objective documentation of the life-cycle performance of constructed systems could leverage novel sensing systems and advances in computer science, tools often untapped by civil engineering programs. Other needs and opportunities involve the design process, perhaps the most important milestone in the development of civil engineers. The topics and needs discussed in this paper could become core curriculum areas in newly developed postgraduate and eventually in undergraduate programs. The authors hypothesize that, if the integration of such topics is successful, civil engineers could become true protagonists of the rejuvenation of the US urban infrastructures and future stewards of cities and megacities.

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1. Introduction

In 2020 as the Nation is dealing with the impacts of the Coronavirus pandemic, there is also motivation for significant investment into infrastructures as a vehicle for economic recovery (Tomer et al., 2020). Such a need has been promoted by the civil engineering and construction industry since 1998 (ASCE Committee on America’s Infrastructure, 2017). One of the writers’ motivation is to discuss the pressing need to resolve fundamental gaps that remain in our understanding, policy and domain knowledge related to the built environment in order to assure a meaningful long-term return on infrastructure investments.

An earlier paper by the writers (Aktan et al., 2016) and a more recent Brookings report (Tomer et al., 2019) touched on some of these gaps. One barrier to infrastructure reform is the state-of-civil engineering education and practice, ‘especially in regard to knowing and acknowledging what we do not know.’ There is a need for a new advanced graduate level degree, integrating engineering, urban design, and government policy together with the critical knowledge needed from natural and social sciences before civil engineers may justify the stewardship of the urban built environment. Building on the domain knowledge of the constructed and engineered systems, a new civil engineer, educated by a cross-domain curriculum and in partnership with a group of critical stakeholders, may grow to claim this role.

Writers have dedicated many decades of their careers for observing, understanding and solving the organizational, financial, operational and structural aspects of asset management concerns of various infrastructures, both in the realm of research and as consultants in partnership with other practicing engineers, as well as federal, state and city engineers. Living through hazards, security threats and increasing daily service demands in a dense urban metropolitan area and its suburbs, they experienced many forms of infrastructure disutility and disruptions directly impacting livability. These experiences demonstrated that the livability concerns in dense urban regions and their suburbs may be very different from small towns in rural areas. Further, many aspects of daily life in an urban region is shaped by urban and transportation planners with little input from civil engineers experienced with infrastructure utility, performance and asset management.

Given that the urban population accounts for over 80% of the Nation’s population and a significantly greater share of the economic output (United Stated Census Bureau, 2010), the importance of urbanization to the national economy has been the subject of many discussions including by Khanna (2016), Alberti (2017)
2. Urban livability, sustainability and resilience

The gaps in urban designers’ approach to the concepts of livability, sustainability and resilience, and civil engineers’ approach to sustainability and resilience while often ignoring livability is due to the significant gaps which remain between various civil engineering domains and urban planners as well as social and information sciences. Today in North America, urban livability, sustainability and resilience remain in the custody of somewhat separated communities; – Livability as a beacon for planners, architects, public health officials and social sciences (AARP (2018), Chatterjee et al. (2012); Sustainability as a beacon for environmentalists (World Commission on Environment and Development, 1987)); and the contemporary environmentalism following Elkington and Zeitz (2014) based on balancing the social, environmental and economic (triple) bottom lines. After Hurricane Sandy (National Academies, 2012) Resilience emerged as a beacon for environmentalists (ecological resilience), urban planners and social scientists (community resilience), economists and insurers (economic resilience) and, elected officials, public security officials, emergency managers, first responders and civil engineers specializing in multi hazards risk mitigation (disaster resilience).

Unfortunately, various communities researching and practicing Livability, Sustainability and Resilience (LSR) in the US have not yet come together for developing a common language and exploring the integration of LSR as the performance goal of the overarching complex system-of-systems within which each discipline functions. Further, there are many cities and urban regions that have not yet experienced major livability concerns or natural disasters and have not yet learned about the challenges of recovery. Consequently, their elected officials, industry and community leaders may not fully recognize the significance of and payoff in investing in resilience. We now recognize that disasters are not only due to natural hazards, and many slowly occurring intertwined ecological, economic and social disasters may not even be recognized in a timely manner.

For example, the current COVID-19 pandemic we are living through in 2020 may be considered as a 100-Year hazard (following the Spanish Flu pandemic of 1918), while at the same time, the nation is affected by widespread demonstrations regarding the recognition and elimination of racism and the need for inclusiveness. Meanwhile, the federal, state and local government responses have been highly political. The interactions between these public health and social hazards demonstrate some of the dichotomies as well as the interdependencies between L, S and R that often lead to a cascading of various secondary hazards.

3. Objectives and scope

The broader objective of this FORUM paper is to discuss the origins and current principal stakeholders of urban LSR, and how the civil engineering education and practice may benefit by reforming itself and taking a leadership role in striving towards coordinating an integrated LSR in urban U.S.A.

The specific objectives of the paper are:
To discuss and thread a plethora of societal concerns regarding the built environment and especially regarding infrastructure performance that current civil engineering education and practice has not been able to address, pointing to a need for reforming civil engineering education and practice. There are too many examples of how infrastructure disutility has been impacting livability, sustainability and resilience especially in dense urban regions even during low-demand periods let alone during hazards. The question is whether we clearly understand the reasons so that we may formulate effective solutions to mitigate these performance failures.

To discuss some of the knowledge, skills and insights required of future civil engineers, which include:

- Understanding and identifying complex systems and decision-making for managing risk to complex systems due to infrastructure disutility; and, recognizing and guiding elected officials for mitigating known as well as yet unknown hazards,

- The differences between risk and risk perception for different classes of hazards are especially important given the increasing complexity and associated uncertainty of cascading hazards,

- Understanding the distinctions between reductionist and holistic approaches to defining problems, especially when associated with complex systems, and most importantly, leveraging creative, cross-disciplinary design-thinking for solutions;

- Resolving the pressing need for describing the condition and performance of constructed systems in terms of rational and quantitative (measurable) metrics that incorporate uncertainty;

- The necessity of partnering as equals and coordinators to integrate contributions by planners, architects, policy makers, social and health scientists and other engineering, science and art disciplines for designing infrastructure solutions that promote and do not adversely impact urban LSR.

The third objective is to discuss the importance of an integrated cross-disciplinary approach to the planning and management of the built environment in the context of LSR. The three concepts of urban livability, sustainability and resilience are not yet precisely described or threaded in many civil engineering applications although they construe the ultimate goals of urban planning, design and management. This paper is hoped to serve as a step towards crystalizing LSR and the need for their integration as an objective function in the challenges facing the civil engineering and urban design community.

Civil engineering and reality

Today, civil engineers are expected to reliably evaluate, monitor and maintain the performance and condition of constructed systems in terms of objective and meaningful metrics; develop effective lifecycle operations and preservation strategies; identify and promote policies for securing funding mechanisms for sustainably managing various sectors of the built environment and infrastructures as assets; mitigating and managing especially emerging multi-hazards risks; and, intelligently renew and replace these systems with resilient systems while causing minimum disruption to day-to-day urban functions. Civil engineers are expected to identify, adapt and integrate innovative technology tools for accomplishing the above. In spite of many research papers we cannot claim that the profession has advanced meaningfully towards these expectations.

Experienced engineers know that testing scaled physical models of constructed systems as well as computer modeling and analyses may result in observations and predictions significantly detached from those of the actual, prototype systems (Bertero et al., 1985). Meanwhile, monitoring structures over several years or observing structural performance following earthquakes have revealed how constructed system and soil behavior and performance may be dramatically affected by distance, time and environmental changes (Barrish et al., 2000). The differences between the actual capacity of decommissioned systems as opposed to predictions of capacity may reach as large as 20 times on the conservative side while the failure modes may be strikingly different depending on how design and construction errors, and/or deterioration and damage affect failure mode (Miller et al., 1994). Forensic studies of failed structures, even by highly experienced engineers, some at government agencies such as the National Transportation Safety Board (NTSB), can seldom offer a complete and reliable explanation of all the reasons for failure. Further, such experiences generally remain in the realm of heuristic knowledge and are not yet fully synthesized or fully incorporated in education or codes.

While many constructed systems may have significant reserve capacity, we cannot claim that the current practice of civil engineering have led to satisfactory performance for many constructed systems, especially given the fast-changing construction practices increasingly relying on the quickly erected, prefabricated, prestressed and post-tensioned systems. Field testing and
long-term monitoring of operating prototype structures with their foundations and soil; and structural identification of physics-based, 3D geometric replica FE models offer perhaps the only way to catch a glimpse of reality regarding the actual characteristics, behavior and performance of constructed systems (Catbas et al., 2013). Yet only a handful of programs in the US can be trusted to possess knowledge and capability for instrumentation, monitoring and structural identification in the laboratory let alone in the field.

5. Objective and meaningful metrics for measuring performance

Architecture, civil engineering and urban planning were integrated under military engineering millennia ago (e.g., Hammurabi’s Code, 1750 BC) until after the 1789 French revolution, making this the oldest engineering discipline. After the 1800’s and until the mid-20th Century this integrative discipline separated from its military roots, renamed itself ‘civil’ engineering, and evolved as an art-form learned through apprenticeship. Following the 2nd World War, civil engineering completely detached architecture and planning arts, and started to envision itself as a ‘science’ as opposed to art. Disciplines such as structural, geotechnical, water resources, environmental engineering, transportation engineering have specialized in an unintegrated manner.

Unfortunately, while electrical, mechanical, chemical and many other engineering disciplines are able to maintain control over the performance of their manufactured products by extensive testing and quality control, as a result of which they could offer long-term warranties for their products, constructed systems are integrated with soil and each may exhibit vastly different and unique properties. Even side-by-side identical pairs of bridges constructed at the same time may have significantly different long-term performances due to the local variations in soil, exposure to sun and UV, weather conditions and oversight during construction, curing, early age loading and many other reasons some of which are not fully understood or accounted for during design, construction and preservation.

It is well known that design should be based on providing the stiffness and load distribution, load paths and the corresponding capacities at different limit-states, considering cracking, fatigue, yielding and other material failures at the local levels while the system will remain stable, dissipate ample energy before it may fail in a mode that is not life threatening (stability of failure). Analysis results from idealized 2D models and even 3D finite-element models during design are associated with such significant uncertainty that design analysis can be meaningful only for estimating trends and bounds. Successful designs rely on experience and heuristics that can only be gained by apprenticeship. Further, code design often fails to recognize many of the utility and functionality as well as serviceability and durability limit-state performance criteria. For example, few buildings and bridges are designed for dynamic response at the serviceability limit state and for some buildings and bridges dynamics has been observed as a major influence for lack of serviceability, deterioration and fatigue. Table 1 offers a ‘qualitative’ but comprehensive definition of lifecycle performance for most constructed systems based on four critical limit-states of performance (Aktan et al., 2007).

Today many civil engineers actually believe in the results of their analyses. Many students may graduate without seeing a moderate-scale reinforced concrete beam failure or column buckling let alone learn about the distinctions between material, element, connection and systems performance. Figure 1 provides a graphical illustration of performance described in Table-0, accentuating the uncertainty and disutility probability which increases with each consecutive limit-state. It is important to distinguish between random and epistemic uncertainty, as the measures to mitigate each type of uncertainty may be quite different. Performance requirements are not constant and evolve with time and social change.

6. Urban regions and infrastructures as complex systems

Aktan et al. (2016) offered a civil engineering perspective on infrastructures and their services. A complete and holistic perspective on infrastructures should recognize the significance of the political, regulatory and legal processes which influence infrastructure policy, ownership (corporate, utility, Federal, State, Local), and lifecycle financing mechanisms; subjective and objective performance metrics (at the utility, functionality, serviceability, durability, safety, failure and resilience limit-states), economics and utility, and the organizational and socio-technical aspects of infrastructures; as well as the principal actors and processes that provide services – to infrastructures and their stakeholders.

Any perspective on infrastructures would inevitably be associated with a scale (geometry and time) and resolution (a network with nodes vs pipes and manholes, or, a regional highway system vs all of the physical engineered, constructed and natural components, along with organizations, institutions, cultural influences and stakeholders). In addition to a broad systems engineering
intuition, we would also need domain knowledge in the financing, revenue, ownership, operations, preservation and interdependency between various elements of different urban infrastructure systems. As discussed earlier, in many academic programs in the US, civil engineering sub-domains remain highly fragmented and civil engineers seldom interact with urban planners. Meanwhile, in Great Britain, municipal engineering remained as a special domain of civil engineering for addressing urban challenges, and for collaborating with urban planners. In Japan, urban planning remains within the scope of civil engineering education and practice, and one cannot deny the Japanese accomplishments related to LSR of even mega-cities such as Tokyo. If we envision an urban region as the intersection of ecology, economy, society, the built environment, infrastructures and government services, we may then conceptualize it as a complex, intertwined, social-technical-natural system-of-systems.

Sussman (2005) identified urban transportation systems as 'Complex, Large-Scale, Interconnected, Open, Socio-Technical (CLIOS) Systems.' Based on the CLIOS systems concept, Figure 2 offers a schematic view of the systems impacting LSR of an urban region, and zooms further on the infrastructures. In complex systems the whole (system) is more than the sum of its components and the collective behavior of components cannot be inferred from the individual properties of the parts. Recognition of the properties of complex systems

### Table 1: Definition of lifecycle performance and asset management.

| Limit State Return Period | Utility and Functionality | Serviceability and Durability | Life Safety and Stability of Failure | Safety and Resilience at Collapse Limit States |
|---------------------------|--------------------------|-------------------------------|-------------------------------------|---------------------------------------------|
| Operational Management    | Everyday throughout the lifecycle | 5-25 years | 50-750 years | 1000 years |
| Maintenance Management    |                          | Multi-Hazards Risk Management | Assurance of Life-Safety, quick recovery of normal operations following any Hazard | Minimizing Casualties Protection of escape routes, evacuation, search and rescue needs Assuring economic Recovery |
| Performance Criteria      | Operational efficiency, safety and security; Robust and predictable revenue stream During Lifecycle | Effective & Economical Inspection, Maintenance, Repair And Rehabilitation During Lifecycle | Assurance of Life-Safety, quick recovery of normal operations following any Hazard | Minimizing Casualties Protection of escape routes, evacuation, search and rescue needs Assuring economic Recovery |

**Figure 1.** Graphical representation of performance, return period and uncertainty.
(such as emergent behaviors, non-stationary internal structures, adaptation, evolution, and uncertainty) and the need for a new methodology to study them started in the 2000’s. An Interagency Working Group, with members from various US Government agencies issued a position paper Interagency Working Group on the Engineering of Complex Systems (2013): ‘Transforming the Practice of Engineering for Large Complex Systems,’ indicating that ‘a fundamental rethinking of engineering methodologies is urgently needed if our nation is to ensure that the large complex systems critical to our national security, economy, and quality of life are resilient in the face of natural disasters, creative adversaries, and an unforeseeable future.’

The foundational and complex (CLIOS) systems that make up urban LSR therefore point to a need to recognize the challenges in ‘the engineering of complex adaptive systems’ and that cross-disciplinary research for new knowledge and tools for reliable simulation of such systems has emerged as a paramount concern. Rinaldi et al. (2001), Sussman (2005), (Dodder et al., 2004), and DOE’s LANL Researchers Toroczkai and Eubank (2005) have contributed to our understanding of adaptive complex systems as an emerging research and application area. In addition to common systems engineering tools, a number of mathematical tools (e.g., Pareto optimization, graph theory, chaos theory, game theory, Markovian filters, Bayesian networks and agent-based models to name but a few) have been proposed for the data-driven modeling and analysis of various natural and multi-domain complex systems. Future civil engineers are expected to understand and design infrastructure solutions within complex systems, discussed further in the following.

7. Traditional civil engineering design versus design-thinking

The ability to design is what distinguishes engineers from scientists. According to Accreditation Board for Engineering and Technology (ABET): ‘Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert
resources optimally to meet these stated needs.’ The related ABET program criterion for civil engineering is ‘an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.’ Meanwhile, the concept of design-thinking has significantly expanded the practice of design from a linear, stepwise to a holistic, circular and innovative user-oriented approach that is much more suitable for addressing complex systems problems (Liedtka, 2018).

Civil engineering faculty teaching design are expected to have experience in designing constructed systems as licensed practicing engineers. Many programs hire retired professionals with a P.E. license for teaching design. Some programs search and recruit part-time ‘professors of practice’ from amongst experienced and practicing design professionals to teach design. Unfortunately practicing professionals who are qualified to teach design-thinking at a university are quite few. Academic researchers who have accumulated a sufficient level of design experience through consulting are also very few. Consequently, most design faculty end up encouraging students to design a new or replacement system of their choice, and most students choose to design a hypothetical new building or bridge or one that has been designed with blueprints available. The primary resource used for such designs is codes and regulations.

Without an owner(s) and user’s describing their hard and soft requirements from the product, and a public official overseeing the permit requirements for land-use; the soil, foundation, architectural and structural systems; water, mechanical, electrical, energy and HVAC systems; and, communication, internet, fire safety and security systems; hypothetical design exercises fall way short of reality. Design faculty should mentor students to go through a complete and realistic design by shadowing an actual project, or team with a local government to understand and solve some of their concerns related to the inspection, assessment, maintenance, reuse and renewal or replacement of an existing constructed system. This requires the design faculty to appreciate and be knowledgeable about actual societal concerns in the context of LSR of the built, engineered and natural environments. Most importantly, design faculty should mentor students in using design-thinking for infrastructure problem-solving by taking advantage of the real-life infrastructure concerns in their vicinity as opposed to design of a new constructed system.

It follows that teaching conventional code-based approaches to civil engineering design, especially if we wish to learn designing solutions for enhancing the performance of urban infrastructures, may be insufficient and/or unsuitable as infrastructure problems are very different and complex as opposed to the design of new constructed systems by following empirical code provisions. In design problems related to renewing and managing a built environment, we have to reconcile multiple conflicting objectives, different types of hard and soft constraints and significant uncertainty in the impacts of policy and decisions that shape life in dense urban regions. Design-thinking in the most creative context is essential for leveraging engineering design for solving problems within complex system-of-systems envisioned in Figure 2.

### 7.1. Hazards and resilience

Resilience has now become a guiding concept for civil engineers engaged in civil infrastructure and lifeline systems, multi-hazards characterization, natural disasters, risk assessment, hazards mitigation, infrastructure protection and emergency response. However, an overarching identification of hazards (natural and man-made, Table 2), and given the complexity of how the resilience of urban regions may be impacted under interacting natural and man-made hazards need to be explored and further understood. Recent advances in understanding and mitigating high impact low probability risks (UK Government Office for Science (2012)) need to be recognized by the US researchers, especially in the case of regions that have not experienced major disasters retained in collective memory.

Government efforts seem to be focused on community resilience under natural hazards without making distinctions between midsize cities and dense urban regions (such as the Boston-Washington D.C. (Northeast) Corridor, Los Angeles, San Diego or the San Francisco

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**Table 2. Summary of man-made and natural hazards.**

| Man-made Hazards                      | Natural Hazards                        |
|--------------------------------------|----------------------------------------|
| Climate Change                       | Hurricanes and Tropical Storms         |
| Radioactivity Release                | Earthquakes                            |
| Chemical Threats and Bio-Weapons     | Major Wildfires and Forest Fires       |
| Radiological Emergencies             | Tsunamis                               |
| Hazardous Materials                  | Extreme Heat                           |
| Terrorist Attacks                    | Drought and Water Shortage             |
| Cyber Attacks                        | Landslide and Debris Flow              |
| Power Disruption, Blackouts          | Damaging Wind and Tornadoes            |
| Civil Unrest                         | Winter and Ice Storms                  |
| Infrastructure Disutility; Dam and Levee Failures | Floods and Flash Floods |
| Epidemics, Pandemics                 | Hail and Damaging Storms               |
| Ignorance, Incompetence and Corruption | Thunderstorms and Lightning Storms     |
| Agricultural Diseases and Pests      | Sinkholes                              |
Bay Area). Department of Homeland Security (DHS)'s infrastructure protection program seems focused on protecting infrastructure assets against manmade hazards. No other federal agency except the NAE and NSF seem to have embraced the significance of considering LSR of a dense urban region as a critical integrative urban planning and engineering design problem involving complex systems, and how LSR are closely linked. Rather than fragmenting the resilience of various urban systems, we should be focusing on urban resilience as the capacity of individuals, communities, institutions, industry and businesses within a city or region to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience.

Recently, we have observed how climate change induced cascading weather anomalies, such as frequent super-storms, and extreme droughts and temperatures followed by brush-fires; which may be followed by mudslides. Other long-term, slowly-increasing and socially driven hazards include infrastructure and organizational failures leading to service disruptions; ignoring proactive, preventative maintenance leading to early deterioration and infrastructure disutility; accidents due to weather compounded by infrastructure inadequacy; long-term economic disruptions such as loss of manufacturing jobs leading to increasing disparity of income and wealth between the residents of a dense urban region; blight, etc. which are usually ignored in considering resilience. Such socially driven hazards, especially when coupled with others listed in Table 2 need to be fully recognized and incorporated under the umbrella of LSR by planners, multi-hazards experts, engineers and public health specialists during resilience planning.

Urban LSR planning would provide a great opportunity to consider all of the man-made and natural hazards with their inter-relationships and cascading potential in order to design mitigation as well as emergency response in an integrated, coordinated manner. We have to recognize that our experiences in multi-hazards mitigation and response planning has been mainly driven by earthquake, hurricane and flood, and yet the risk of human-caused hazards at dense urban regions (especially those that have not yet experienced a natural disaster) may be far greater for communities especially if they have NOT experienced and learned from natural hazards.

7.2. Risk

In the broadest sense risk is defined as the probability of an event occurring multiplied by the resulting cost or benefit associated with the event (van Dantzig, 1956). In disaster planning, risk is a subjective and relative concept depending on the uncertainty, scale, return period and nature of hazard, past experiences and the culture of a community, including leadership, vision and rigor in the planning, mitigation and preparation for risk. In many cases risk perception rather than risk may govern decision-making for resilience.

Renn (2008) developed a new system of risk categorization and evaluation described by the German Advisory Council on Global Change (Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveraenderung, WBGU, 2000). In order to achieve a balanced and reasonable judgment on the acceptability of risks, a more comprehensive set of attributes were sought to reflect public concerns and acknowledge the inherent uncertainty and assumptions in risk assessment. As a result, the WBGU report outlines nine criteria for hazards classification (UK Government Office for Science, 2011, 2012; Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveraenderung, WBGU, 2000).

While the writers agree with the need to characterize risks in different categories, they propose to classify hazards into only three distinct groups, based on perception, the associated uncertainty, cause and the return period of hazard:

1. Risks due to “Black-Swan” events with very high uncertainty and very low probability of occurrence but with extremely high consequences, with return periods of 100-500 years;

2. Risks due to the occurrence of natural hazards such as hurricane, flood and earthquake expected with return periods of 75-500 Years (may be characterized as White Swan events);

3. Risks due to frequent “Neon-Swan” events that are obvious but immensely important and with near statistical certainty, as further illustrated in Figure 3. Some of the man-made hazards in Table 2, such as cyber-attacks, civil unrest, ignorance, incompetence and corruption may fall into this category.

While the above classification is less granular than Renn (2008)’s, it may help guide elected officials as well as emergency planners to begin to recognize the hazards that fall under the Neon-Swan category. Some of these hazards which may lead to cascading failures due to interdependencies are especially critical for planning and preparation. The LSR of a region requires proper functioning and performance of infrastructures and their services; however, the planning, engineering, and managing of an urban region as a complex system and with the objective of LSR should be considered as the actual parent ‘design’ problem that demands the collaborative efforts of engineers, architects, planners and scientists. Properly trained civil engineers by going through the proposed post-
graduate study on urban LSR would be perfectly suited for leading such an effort.

8. Discussion and conclusion

8.1. Summary of research and education needs for urban LSR

In this position paper the authors offer an overview of some recently emerged or evolving concepts that are not currently fully recognized and incorporated in civil engineering education and practice in North America while becoming essential for civil engineers to claim stewardship and coordination of urban LSR:

(1) The need for observing and documenting lifecycle performance of constructed systems in terms of rational, objectively measurable metrics—such as actual permissible strains, displacements, drifts, settlements, vibrations and dynamic amplifications at difference limit-states over the lifecycle; and, the coordinated efforts required for structural-identification of statistical samples of actual operating systems for quantifying such characteristics and recommending metrics for performance. Existing heuristic knowledge about how constructed systems that are constructed by different approaches on different soils (cast-in-place, prefabricated, pre-stressed, post-tensioned, segmental, sliding formwork, mixed and on rock or various types of deep or shallow foundations, etc.) are actually behaving, performing and failing at various limit-states along their lifecycle need to be collected, sorted and archived. How recent and emerging construction materials and systems as well as technology may impact performance at various limit-states should also be recognized during the design process.

(2) Authors and their colleagues participated in research on reforming civil engineering education, (The Learning Bridge; NSF Award 0855023; 2009-2011: Drexel, Purdue, TX A&M and NE Universities). The Final Report of this project offers a list of recommendations for improving the content and pedagogy of civil engineering education by transforming constructed systems, complete infrastructures and even entire communities and urban regions into field laboratories. Leveraging real-time sensing, imaging, communication and computing (i.e. creating cyberinfrastructures), events in a field laboratory may be viewed from any classroom, helping improve the understanding of reality of civil engineering and urban infrastructures (Drexel, Purdue, TX A&M and NE Universities, 2014). Transforming operating infrastructures into living field laboratories requires academe-government-industry partnerships and especially the support of the owners/stewards of the infrastructure systems to be transformed. The field laboratories would become the sources of projects in the context of project-based learning (established as a most effective pedagogical approach to learning) and leveraging design-thinking for infrastructure problem solutions.

(3) Civil engineering design cannot be meaningful without recognizing and fully conceptualizing the complex systems influencing the built and natural environments of dense urban regions. Civil engineers should learn about engineered systems as well as complex systems and how to apply design-thinking within a complex urban environment. Urban universities have an important role to play by partnering with their city and county to understand their infrastructure concerns and take these on as their design projects. It is not fathomable for students especially at urban colleges to learn civil engineering without leveraging an urban region as a living laboratory.

(4) Civil engineering design should recognize that an integrated LSR is essential at urban regions and such an integration is a critical objective that need to be satisfied in any infrastructure planning, design, operations, renewal and risk management or intervention project. For
accomplishing this, civil engineers should work closely with urban planners and architects. Some additional disciplines that need to be included are: Environmental Sciences, Social, behavioral and information (computer) sciences; Economics, Finance and Organizational systems; Health Sciences; Infrastructure and Social Services; Homeland security, Emergency management and first response experts. Convincing elected officials to form such cross-disciplinary groups for urban planning rather than leaving planning in the hands of one profession is needed.

(5) New interdependent and cascading hazards are emerging, affecting larger populations. Many natural hazards such as forest and brush fires are being affected by climate change. Regions of Texas and Florida are being subject to hurricanes as they are also hot-spots for Covid-19. Civil engineering knowledge regarding hazards were founded on earthquake, wind or blast, leading to different specializations for each type of hazard. We now understand that our knowledge is not sufficient to understand the linkages and likely cascading between human-caused and natural hazards. We need to consider climate change not only as a hazard for coastal areas, but as a significant enabler of many other natural and human caused hazards anywhere. Civil engineers have to rethink the interdependence of not only infrastructures but also the cascading of hazards caused by infrastructure failures. The concept of cross-sector infrastructure asset management is becoming increasingly important in urban areas especially for managing the cascading of risk to many infrastructures due to the failure of any one infrastructure system.

9. Conclusions

- Urban regions are complex systems of systems that often straddle multiple states, political districts, local governments, a multitude of public and private infrastructure agencies with different organizational systems, varied public and private enterprises, and multiple shared natural and built environmental assets. In the US, where ‘home-rule’ is a cherished tradition, a consistent integration of urban and infrastructure planning is a particularly formidable challenge. The concept of urban infrastructure ownership and stewardship requires rethinking.
- While urban planners and policy-makers currently lead the efforts for providing LSR, they cannot/should not function without involving qualified and experienced civil-systems engineers who have domain knowledge in the design, maintenance and management of critical infrastructures and infrastructure services. However, only a few civil engineers are trained in systems, and fewer can understand complex systems. Engineers who are engaged in the management and renewal of the built environment are currently being trained in reductionist approaches with little or no background in complex systems and/or multidisciplinary design-thinking for addressing complex systems problems. This should be urgently rectified by curriculum reform at least by a select subset of leading civil engineering and urban design programs. The graduates of the vast number of programs in the country have the risk of serving as technicians as ABET accreditation is becoming the measure of success for the majority of civil engineering programs.
- LSR are closely coupled goals that are influenced by natural and built environments, society, economy, infrastructure services, information and government. Unless LSR of a city is explicitly recognized within the planning activities in an integrated and holistic manner, long-term success may be compromised since there is evidence that disconnected, piecewise, or loosely connected plans for urban revitalization or hazards mitigation often render them ineffective. In many cities LSR is effectively under the stewardship of planners. In the case of large metropolitan areas federally supported regional planning commissions lead in planning, however these are seldom coordinated by engineers.
- Any investment into hazards mitigation, emergency response and resilience planning needs to consider all hazards and their probable combinations as well as their cascading – and not separate natural hazards from human-caused hazards. What we consider as a hazard changes as society and economy change over time. It is recommended to seriously consider identifying and mitigating the Neon-Swan hazards, occurring several times each day/week/month/year with statistical near-certainty; Emerging hazards such as climate change, infrastructure disutility, economic and demographic shifts, and the resulting human-caused hazards, as well as many variables related to history and culture should impact how we approach an integrated LSR planning and multi-hazards mitigation in the 21st Century.
- The authors suggest that a graduate discipline including integrative planning and engineering for the design and management of LSR at urban regions is urgently needed and could be hosted in the future by urban universities in civil engineering programs with the support of ABET and ASCE. Experts within this graduate discipline would be coordinating and integrating the products of architects and planners, social scientists and engineers and scientists from many other disciplines towards LSR of the built and natural environments at dense urban regions. The creation of such a graduate discipline is an ambitious goal and a seamless integration of complex
concepts such as ‘Livability (including inclusivity),’ ‘sustainability’ and ‘resilience’ and their interdisciplinary constructs is a significant undertaking. One way to eventually reach such an ambitious goal, is to encourage cross-disciplinary PhD programs to embed these concepts to train the next generation of educators needed to make future civil engineering students true protagonists of the rejuvenation of the US urban infrastructures and stewards of cities and megacities as was envisioned in ASCE’s Vision 2025.

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No potential conflict of interest was reported by the author(s).

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Data availability statement
No data, models, or code were generated or used during the study.

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