Implications of COVID-19 for Future Research and Education on Engineered Structures and Services

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Abstract

While there may be a tendency to characterize COVID-19 as exclusively a public health issue, engineered structures and services have both mitigated and exacerbated the pandemic's march around the globe, raising questions about the role of engineering in controlling pandemics. Any attempts to answer these questions implicate not only the tools, techniques and problems which we define as within the province of engineering, but also the means by which we arrive at this definition. As described here—in settings ranging from nursing homes to prisons to Brazilian *favelas*—the COVID-19 crisis has upended a number of foundational notions associated with the practice of hazard mitigation through the design and operation of engineered structures and services. It has revealed the need to examine the conditions and assumptions that characterize the models we construct and the data we collect. We do so through a number of case studies collected during the COVID-19 crisis, leading to implications for the conduct of research and education to support not only further advances in our field but to improved prospects for improved mitigation of pandemics and other hazards.

Index Terms

COVID-19, Systems Engineering, Civil Engineering, Hazard Mitigation, Natural Hazards Policy

INTRODUCTION

We, along with many others throughout the world, surely felt a looming sense of dread early in the COVID-19 crisis when obviously essential supplies (e.g., masks) and services (e.g., tests) were described as being in perilously short supply in storehouses in the United States and elsewhere [1][2]. We watched as the demand side of this crisis spun wildly out of control, marked by rampant and desperate purchasing of essential store-bought goods, precipitating immediate and profound shortages in households worldwide (and, it would seem, disproportionately among less advantaged households). And we took part in the massive evacuation from places of work and learning that had, in effect, been transformed into vectors for disease transmission. Private residences have now been re-purposed to take on multiple uses—school, daycare facility, place of work, even health care facility—thereby stretching our definition of *critical* in understanding the facilities needed to produce and deliver vital services in the time of pandemic.

Throughout this paper, we take an inclusive and flexible view of the term "engineered structures and services" (ESS). The reasons are twofold. First, evidence from the field in the COVID-19 era has revealed manifold, even heretical uses of the constructed aspects of our built environment (hospitals, prisons, schools, and private dwellings among them) and the services (such as health care, education and communication) enabled by and through the built environment. Second, we wish to explore the implications of the boundaries we construct to differentiate these aspects as “critical” vs. “non-critical,” particularly as a function of the hazards we face and our capacity to deal with them.

The nature of coronavirus—highly contagious, invisibly spread—is of course a key driving force behind this paradigm shift: if we are not careful, our “designed” physical proximity—achieved through highly spatially (and economically) efficient workplaces and similar facilities—could literally kill us. Thus, while there may be a tendency to characterize COVID-19 as exclusively a public health issue, the built environment (and the engineered systems that links its elements) has both mitigated and exacerbated the pace of COVID-19’s march around the globe, calling into question the role of engineering in the mitigation of pandemics. Included among these factors underlying our current capacity to respond to COVID-19 is the long-standing desire of many for-profit entities–supported by decades of research done in academia and elsewhere–to reduce operating costs by maximizing efficiency, thus further reducing slack in essential systems. And at a fundamental, essentially philosophical level, we see in the current situation a challenge to explore (and defend) the intellectual and practical boundaries of our field.

The COVID-19 crisis suggests that engineering ought to have a prominent voice in this discussion: after all, the work of engineers is fundamentally concerned with the organization of space and time in order to serve people—and it is precisely this organization which strongly determines the spread of pandemics [3].

Given the expected long duration of pandemics, other hazards are likely to occur, raising questions about whether measures to control those hazards will strengthen or dampen the efficacy of measures taken to control the pandemic. Indeed, prior disasters arising from joint hazards (i.e., those involving two or more spatially and temporally co-located hazards [4] may offer compelling examples of incompatibilities that can emerge in real-time among the response plans for individual hazard events. With rising COVID-19 case counts, record wildfires in America’s West, and what is on pace to be a historic hurricane season for the Gulf Coast, 2020 is already providing ample illustrations of the challenges now posed by pandemic joint-hazards. For example, social distancing requirements and the economic impacts of the pandemic delayed response and recovery and Hurricane Laura [5], while the storm’s impacts in turn impaired the ongoing COVID-19 response in Texas and Louisiana, two of the country’s hotspots for the virus [6], [7].

This paper explores such evidence from the field, considers it in relation to current practice in our disciplines, and develops recommendations for research and education that we believe have the potential to advance basic science and engineering while improving society's ability to prepare for, respond to and recover from exposure to such hazards.

HOW DID WE GET HERE?

At present, and despite the fact that the threat of pandemics had been well documented, too many of the engineered structures and services supporting personal and institutional health have been driven to extreme dysfunction (and even near-collapse) by COVID-19. The current worldwide crisis therefore represents an opportunity to ask two questions of ourselves and of our field: *How did we arrive at the situation?* and, equally importantly, *What can we do to fix it?*

Research in systems engineering on methodologies to support the delivery of various services has been overwhelmingly dominated by a cost minimization paradigm, particularly for private sector operations. We see precious little evidence of engagement of problems in the public and non-profit sector when compared with those in the private sector. Despite various contemporary bright spots (e.g., [8], [9]), as well more historical exemplars [10]), problem formulations which seek to engage social good, equity and health—including trade-offs among these and other factors—remain underexplored relative to their importance to society.

It may be argued, however, that the analytic formulations which typify work on engineered services address societal concerns indirectly, through the implicit mechanisms that link the systems under study to particular societal outcomes. For example, research on performance improvements in pharmaceutical supply chains is tied implicitly to societal well being through the sale and consumption of prescription drugs. However, with COVID-19 (as with other disaster or even non-disaster settings [11]), assumptions about the demands on these supply chains may fail spectacularly. Regulatory regimes may also change, as government and industry seek to control the flow of supplies [12], or as prescription drug prices rise due to compromises in the supply chain which threaten manufacturing output (cf., Hurricanes Irma and Maria in Puerto Rico [13]). These and other disruptions in context may be so profound as to threaten the validity of the tools and techniques embedded within them.

Structural engineers' approach to design has always been focused on delivering the most efficient design that preserves human life under extreme events, with *life safety* established as the minimum performance objective, enshrined in codes and standards. Emerging trends like Performance-Based Design are now further elevating design objectives not only to prevent injury and loss of life, but to ensure that buildings remain safe and functional after major hazard events [14]. Yet as discussed below, tensions remain between the intended and actual use of structures, as well as between risks avoided and induced by structures.

If we continue to assume that the context within which our engineered structures and services are embedded is equitable and benevolent (or at least benign), we lose the possibility of understanding the impact of contextual factors—including corrupt and dysfunctional economic and political systems [15]—on the validity of our models and on approaches to design. Indeed, as the cases and situations discussed in the next section suggest, COVID-19 has raised the possibility that too many of our claims and results with respect to ESS design and operation hold only over a narrow, perhaps even tangential, set of operating conditions. As Carvalhães et al. have noted, "In a future defined by acceleration, increasing uncertainty, and increasing complexity, COVID-19 provides a glimpse of how best practices that were developed under past conditions that focus on efficiency and stability are becoming increasingly insufficient" [16] (see also [17]). It is therefore essential that we develop methods for characterizing these conditions, the extent to which our results are contingent upon them, and subsequent normative guidance for ESS design, operation and assessment.

OBSERVATIONS FROM THE FIELD

The ongoing COVID-19 crisis has exposed a number of fault lines in the engineered structures and services that our disciplines have helped to construct over the years. We reflect on three of these—*food distribution networks*, *crisis and risk communication*, *private housing* and *personal safety*—in order to discuss our role in the social construction of this particular reality, as well as to speculate on why some elements of these systems may be viewed as marginal or even taboo. We argue that, pragmatically, the challenges exemplified by the cases described here illuminate two tightly coupled sets of opportunities: first, to conduct research oriented towards identifying and testing the boundary conditions of the knowledge that we claim characterizes our field; second, to develop new tools and techniques, embedded within our curricula, that enable ongoing exploration of these boundaries and the expansion of the core skills that characterize our profession.

Food Networks

In retrospect, the U.S. National Science Foundation's program on "Innovations at the Nexus of Food, Energy and Water Systems" was prescient. The program addressed the highly interdependent and critical nature of food, energy and water networks, including the role of governance within and across them. The impact of COVID-19 on food networks in particular is rapidly coming into sharp and alarming focus, demonstrating at once the immense size of the food production system, but also—paradoxically—its lack of agility.

As the economic situation of many households throughout the world worsens, the need for food assistance is becoming urgent [18]. Relatively small scale, local, *ad hoc* solutions are springing up throughout the U.S. (e.g., [19]), but massive gaps and dysfunctions remain [20]. Despite the pressing (and expanding) need for food, however, the U.S. is dumping vast quantities of food into an already overburdened waste stream because restaurants and other shuttered food dispensaries are not buying them [21]. The problem, in short, is not a lack of food, but a means to redirect the distribution of this food to other destinations.

The state of Kentucky [22] and the city of New York (NY) [23] are recent examples of the consequences of this network dysfunction. In New York City, the city's mayor projected an approximately three-fold increase in the number of school-related meals, from 4.5M per month to approximately 10M-15M per month by May. Beyond the U.S., the United Nations has warned of a global famine of "biblical" portions, precipitated by major factors such as ongoing conflicts and exacerbated by COVID-19 [24]. Indeed, a major recent report on hunger in the U.S. has noted that the country faces a predicted shortfall of eight billion meals in the next 12 months [25]. The issue of profound food shortages is likely to be exacerbated worldwide by a substantial increase in global poverty levels [26].

The collapse of the food supply chain in the U.S. in particular represents a catastrophic, even unimaginable failure–the blame for which (we might quickly conclude) ought to be placed squarely at the feet of "the regulators" for failing to mandate performance standards which will enable food systems to withstand the effects of pandemics. Yet the situation also implicates the steady drive in the U.S. towards large-scale, highly centralized food production systems, linked via global supply chains to massive sinks, and thence to smaller distributors. As researchers in systems engineering seeking to have an impact on practice, this situation highlights the need for systems engineering models and results which can influence policy, legislation and industry standards in this domain.

Crisis and Risk Communication

Classic risk communication paradigms are based on the notion of the broadcast of authoritative information by trusted, often institutional, sources. In our current era of many-to-many communications, over networks rife with errors and disinformation, this hegemonistic view is no longer wholly representative. In other words, the frame for risk communication has changed, so that we must now deal not only with contested meaning [27], but also—to a much greater extent than previously possible—with the spread of disinformation undertaken in order to create instability [28] and not merely to undermine the true, correct or socially accepted point of view [28][29].

Public institutions now have very limited influence in using information to shape public perceptions and, by extension, to induce target behaviors (e.g., towards conformance with directives to stay at home) [30]. Instead, with the monetization of information through advertising and other sources of revenue, the incentive is to generate greater uncertainty and, thus, a greater need to resolve that uncertainty through further consumption of information. While standard Public Service Announcements (including for COVID-19 [31]) must and will continue, at present it seems overly optimistic to base models of risk communication on the assumption that such traditional messaging will be enough.

In a sense, then, we have come full circle, to the point where we are again asking basic questions about how to induce particular behaviors among at-risk and other populations based on our current (and likely future) situation. Our information systems (including but not limited to social media) are now highly resistant to single point "failure" (i.e., a collapse in their ability to generate an ever-growing demand for information). As a consequence, they are highly resistant to centralized control. Crucial messages either may not get through or may be distorted [32]. It seems clear that, if correct, risk-relevant information is to be heeded, we shall need a new basis from which to proceed.

Private Housing

In the U.S., private companies' ability to fire employees at will and without cause—even in the midst of a global pandemic—has helped create the largest number of unemployed individuals in the country's history[33], precipitating important concerns about the ability of these individuals to cover housing costs.

Concurrently, widespread quarantine measures have also required countless individuals to work and study from home, thereby shifting some direct and indirect costs associated with running a business from employers to employees. A loss of housing therefore will, for some, also represent the loss of a platform from which to work and learn.

The current U.S. hurricane season has provided glimpses of additional housing-related risks to the population introduced by hazards co-occurring with COVID-19. Due to quarantine rules active during Hurricane Laura, for example, emergency shelters could not operate safely, leading to busing of evacuees to "non-congregate" shelters such as hotels and motels [34]. Some individuals concerned with infection risk due to "congregate" transportation elected to shelter in place—despite facing the prospect of a Category 4 hurricane [35] and its attendant effects on critical infrastructure[36].

Looking ahead to the COVID-19 recovery period, it is not altogether unreasonable to admit the possibility that economic deprivation induced by mass unemployment, loss of access to employer-provided health insurance [1] and reduced ability to meet monthly bills will lead to a massive scramble for jobs.

Perhaps an enterprising engineer will then develop a Lyft- or Uber-like platform for "aligning" unemployed individuals with jobs in a wide variety of locations. *Yes, that would be super cool!* But the onus will then be on employees themselves to abandon their current location and "ramp up" to their new positions: in other words, the start-up risks will be transferred to employees from employers. Framing this problem (or, "the app") in employee-centric terms has the potential to create a more equitable solution.

Safety at the Margin

At the margin of society, many effects of COVID-19 have been amplified and twisted. We consider three settings—in the U.S., prisons and nursing homes; and in Brazil, *favelas*—all of which are governed, regulated and regarded in ways that differ radically from those of the public at large, raising important issues regarding the design of engineered structures and services to ensure the safety of those who reside within or use them.

Prisons. Based on a recent (2018) report from the U.S. Bureau of Justice Statistics [37], "nearly 2.2 million adults were held in America's prisons and jails at the end of 2016. That means for every 100,000 people residing in the United States, approximately 655 of them were behind bars" [38]. The 2015 incarceration rate in the U.S. (698 per 100,000) put it, worldwide, second only to that of Seychelles [39]. As of 2018, the number of incarcerated individuals in the U.S. is roughly ten times the number of individuals holding "executive" positions in the country [40].

Reports of coronavirus transmission within the U.S. prison system continue to filter into the popular press. As in the general population, the prison population has been dramatically under-tested, particularly in light of the risks inherent in the close confines of a prison system. Indeed, at the time of once recent report [41], the Cook County (Chicago) jail was "the nation's largest-known source of coronavirus infections." Perhaps not surprisingly, these conditions are thought to have contributed to recent reported riots [18]. Other factors, whether precipitating or amplifying, are also implicated, such as serious overcrowding [24].

The ongoing privatization of the U.S. prison system has presaged a drive towards monetization of incarceration coupled with a strong emphasis on cost containment [42]–[44]. A pre-COVID- 19 (2009) meta-analysis found no major benefits of private (for-profit) prisons over public ones [45]. That study did not, of course, consider the resilience of the prison population to hazards at the scope and scale of COVID-19. It seems appropriate to ask, then, whether the failure of prisons to protect their prisoners is due to a failed economic model, an over-constrained physical environment, failed regulation and oversight, the prisoners themselves, or other factors.

Nursing homes and long-term care facilities. As of 2016 (the latest year for which reliable figures are available), approximately 1.35M individual resided in nursing homes, and another 0.81M in residential care communities [46]. As of 23 April 2020, there had been over 10,000 COVID-related deaths in U.S. nursing homes (including both residents and staff) [47]. Approx- imately one week later, that number had doubled, "with more than 1 in 6 facilities nationwide now acknowledging infections among residents or staff" [48]. Perhaps not surprisingly, numerous individuals—both inside and outside these nursing homes—have expressed frustration with the slow release of accurate information on the health of patients and staff [48] [49].

The vast majority of U.S. nursing homes (69.3%) are for-profit entities [46]. And recent articles note intense lobbying by the industry for indemnification against future lawsuits [50]. While nursing home residents are not captives within their environments, it is certainly worth asking whether the current approach to monitoring and regulation sufficiently compensates for their real lack of mobility. For example, is it appropriate to view the services of nursing homes and residential care facilities as existing in an open, competitive market? If yes, then is the current dysfunction best viewed as a market failure, or, if not, as a regulatory one?

The U.S. hurricane season has placed another layer of risk atop this particular at-risk population. Hurricane Laura further exposed the regulatory gaps threatening those senior and disabled populations with limited mobility. Nursing homes and senior living facilities in the Lake Charles (Louisiana) area, a number of which were subsequently damaged by Hurricane Laura and rendered uninhabitable, struggled to evacuate their residents [51] and even failed to communicate evacuee whereabouts to concerned family members [52]. Public housing is not required to have an evacuation plan, resulting in some vulnerable residents being abandoned in the hurricane [53]. These reports powerfully demonstrate the pandemic's exposure of flaws in both the physi- cal design of facilities that house vulnerable populations and the regulatory gaps that further compromise residents' safety under pandemic joint-hazards like hurricanes. More broadly, such pandemic *joint hazards* [4] present a number of potentially unique challenges, including the likelihood that mitigation efforts for one event (e.g., evacuation) will undermine those of another (e.g., isolation to reduce contagion).

Favelas. According to the Brazilian Federal Government's Institute of Geography and Statistics [54], approximately 12 million people live in the country's *favelas* (shanty towns), representing approximately 6% of the entire Brazilian population [54]. The ongoing economic crisis in Brazil, begun in earnest in 2016, has only served to increase this population and, more recently, to erect considerable barriers to the effective management of the coronavirus pandemic within them.

Due to the extreme marginalization and lack of political power in the *favelas*, each one operates as a country within the larger country of Brazil, with *de facto* laws which are imposed by drug traffickers and other criminals. As in impoverished and at-risk communities in the U.S., this marginalization has been manifested in lack of care and attention to the spread of coronavirus within them. Indeed, the response to COVID-19 in the *favelas* has been carried out outside established Federal, State, and City government authority—most notably by drug cartels and other criminal elements. The motivations are likely complex, but probably not altogether altruistic. In any case, the result has been a highly disorganized response, albeit one that has included elements of the World Health Organization's recommendations (this in stark contrast to the anti-WHO posture of Brazil's Federal government). Reported efforts include supplying alcohol gel and imposing a night-time curfew in order to avoiding possible agglomerations that would facilitate contagion [55].

Despite the efforts within the *favelas* to slow the spread of the virus, recent reports indicate an increasing rate of infected individuals as well as deaths due to the virus, a situation that is only exacerbated by the government's poor performance in removing corpses [56]. These deleterious effects are only magnified by the ongoing degradation of other state-sponsored services for poor families, such as health and financial aid, the effects of which are beginning to impact even formerly stable and large Brazilian cities.

Summary

The discussion of *food networks* calls into question not merely the obvious notion of diminishing slack and supply chain brittleness, but also the need to address flawed assumptions about the policy and other contexts within which the food network operates and with which it interacts. The discussion of *crisis communication* raises the prospect (and not for the first time) that our approach to warning and preparing at-risk populations ought to anticipate information competition, rather than cooperation, particularly in online environments. The discussion of *private housing* reveals the speed with which workers' and learners' places of residence have been appropriated to business and education uses. The discussion of *safety at the margin* suggests the incompatibility of approaches to hazard mitigation for mainstream *vs.* marginalized populations. We view these problems as proceeding from a particular value system, just as those which typically occupy our time do. Expanding our vision to accommodate problems and issues which lie beyond the current boundaries of our discipline will doubtless engender conflict and consternation within it, but we view this as healthy, natural and essential. Indeed, given the observations here and in the burgeoning literature on societal response to COVID-19, resolving the problems is essential to the maintenance of a just and fair society; however, and as discussed in the following section, if our field is to contribute, doing so will require revisiting the envelope of contemporary engineering research and education, as well as some of our most cherished assumptions.

We argue that, as systems engineers, we must be prepared to ask three fundamental questions on an ongoing basis, and as a condition of laying claim to making advances in our discipline:

Q1 What is the nature and scope of the advances in basic science and engineering that bring "our" systems into being?

Q2 How do we agree, as a community of systems engineers, on the rules for deciding which elements define a given system (or lie outside of it), as well as on the context within which a given system is embedded?

Q3 What deeper assumptions—about societal values, the efficacy of regulation and the function of our economies and institutions—have we made or tacitly affirmed, and are these assumptions reasonable or merely convenient?

Implications and Recommendations

This section explores the foregoing three questions by arguing for innovative, even contrarian, perspectives in addressing the following five themes:

- Tensions of scope arising from discontinuities between the *temporal frames* that our methods and data are prepared to handle and those which characterize the target phenomena observed in the world (Q1);
- Conflicting notions of *criticality* induced by discontinuities between the intended and actual uses of engineered structures and services (Q2);
- Uncertainty concerning the observed vs. expected (or perhaps hoped for) *societal impacts* that result from our work on ESS design and operation (Q3);
- Contested roles and responsibilities of public vs. private *governance networks* in ensuring quality of life under threats from hazards (Q3); and
- The ambiguous role of *regulatory frameworks* in the midst of rapid decentralization of formerly centralized services (Q3).

Through this section, we suggest potential avenues for productive, novel and useful *research and education activities* that, taken together, can help spur fundamental discoveries and the intellectual capacity to address them. We must, however, acknowledge two very real challenges to progress in these areas. The first is that, despite rising calls for research approaches that engage the disciplines implied by our three focal questions, the methodological and empirical points of connection between different disciplines are frequently insufficiently constrained or even ignored. The second is that, as a consequence of accreditation and licensing requirements for professional engineers, any discussion of wide-scale curriculum revision is likely to engender not only practical difficulties (e.g., in budgeting credit hours) but also professional angst (e.g., reconsidering what it means to be a particular kind of engineer).

Temporal Frames and Time Scales of Adaptation

Engineered structures and services are expected to provide the means and physical spaces through which communities may thrive and prosper. As evident in the discussion of food networks, pandemics occupy a middle ground between frequent, fairly predictable events (such as hurricanes in the southeast U.S.) and rare, stubbornly unpredictable ones (such as earthquakes in mid-America). Designing for pandemics will require more than simply adding another limit state to existing frameworks, given how dramatically the performance objectives and even functional demands at the limit states of pandemics vary from the operating conditions in typical service (or even during other extreme events).

For a variety of reasons, including continued human intrusion into formerly isolated ecosystems [57], there is obvious and urgent need to model pandemic etiology and onset. Less widely recognized, particularly in the literature on community resilience [58], is the need to understand the consequences of choice of temporal frame in assessing how societal interaction with ESSs can contribute to or detract from societal resilience.

As evident in the discussion of private housing and, relatedly, of safety in marginalized populations, the evolution of institutions, economies, policies and technologies may call into question the validity of the measures and data used to assess a community's capacity to mitigate hazards ([59], [60]). Moreover, the physical environment in which a community is situated may itself change significantly over a relatively short period of time. The prospect of other hazard events that overlap with pandemic regimes adds a further impetus to focus on timescales of planning.

Historical studies that examine societal interaction with ESSs offer prospects (as well as considerable methodological challenges) for understanding and supporting mitigation capacity [61], particularly by testing the boundaries of contemporary theories against historical data [62]. A further need (amplified by the current pandemic) is for the development of methods that can be used to estimate the extent to which communities learn (or fail to learn) as a function of exposure to hazards. So-called scenario planning or futures thinking [63], both of which are common in policy and planning domains, may be used to explore the impact of different timescales on anticipated societal outcomes of mitigation activities.

Research: analytic methods and open data to support longitudinal and comparative modeling of societal interaction with ESSs in the context hazard mitigation and community adaptation. *Education*: exploration of historical data on the antecedents and consequences of changes in ESS design and use, to include collaborations with other disciplines such as archaeology and ethnography; student/practitioner collaborations across multiple disciplines, focusing on the temporal framing of spaces and places.

Revisiting Criticality

As evident in many of the cases reviewed previously (e.g., private housing), widespread adaptive behavior in response to COVID-19 has upended established notions of ESS criticality in various ways. For example, as discussed by Carvalhães et al. [16], the U.S. Department of Homeland Security (DHS) defines critical infrastructure as, “systems and assets that are so vital to the United States that their incapacity or destruction would have a debilitating impact on our physical or economic security or public health or safety.” Defining which systems are critical results in a prioritization of resources during the response to extreme events [64], but what if the response to extreme events causes non-critical structures and services to fulfill a critical role, or critical ones to become liabilities?

Purpose-built facilities have yielded mixed results in mitigating the adverse impacts of COVID-19, and indeed have sometimes exacerbated those impacts. It would therefore be an error to exclude the role of *ad hoc* services and *non-traditional facilities* in mitigating pandemic hazards. We therefore recommend the study of ESS systems *wherever they may be found*. While this may lead to systems already designated as critical and used in standard ways, it may also lead to purpose-built facilities (such as sports arenas, hotels and even parking lots) used in *ad hoc* ways, as well as to otherwise innocuous structures and services that suddenly become essential to the preservation of human life. A striking example of the former are the many virtual spaces which have been pressed into service for commercial, governmental and even spiritual uses. These virtual artifacts of design differ in fundamental ways from the tactile artifacts that are emblematic of the field of engineering.

Regulatory standards have sought to manage risk and costs by classifying the importance of structures based on criticality. This “importance factor” is closely aligned with the concept of highly centralized infrastructure, meaning that a small number of critical facilities bore the responsibility for (and thus derived value and investment from) potentially significant loss of life and or community disruption. Occupant vulnerability as a result of dislocation or displacement was not considered, despite the possibility of "transfer trauma" [52]. Nor was it ever imagined that the vast inventory of private residences would introduce a new model of distributed yet critical infrastructure, responsible for mitigating the spread of COVID-19 as well as for support- ing healthcare, education and livelihoods during months of quarantine. These *de facto* critical facilities were largely non-engineered with low importance factors, the implication being that they were highly vulnerable to damage and disruption from hurricane and other events [5].

Research: further exploration of the relationship between adaptive behavior and criticality, as well as design frameworks that enable the quantification of tradeoffs inherent in this relationship; techniques and technologies to support the design of adaptive ESS.
Education: exploration of methods for quantifying ESS criticality as a function of societal adaptive capacity; design methodologies for adaptive reuse; training in systems thinking for ESS design and operation.

Societal Impacts

When possible we should learn from other efforts to re-design in light of other performance outcomes beyond cost and efficiency. This may include design to support use of adaptive capacity in potentially diverse populations, as well as assessment of longer-term impacts of hazard mitigation measures. An example is the U.S. National Institute of Building Sciences framework that, in seeking to monetize mitigation investments, encompasses psychological trauma, disruption of livelihood, and other factors that equate to measurable societal impacts [65].

In the way that our desire to achieve engineered structures at the lowest minimum cost gave way to a more balanced approach—where sustainability from the standpoint of energy efficiency came to be not an afterthought in the design process but an equal partner—now our design must evolve to accommodate health and continuity of service during pandemic times. More fundamentally, a more robust and transparent approach to ESS design and analysis will include tools and techniques not only for incorporating the norms and values of a society—its ethos—into engineering artifacts, but also for extracting and analyzing the ethos implicit within engineering artifacts.

Research: methodological work on alternative formulations for measuring ESS performance, particularly to capture concerns of equity; methods and data to support the study of tipping points in a community's ability to prevent or adapt to different hazards, particularly through ESS design and use.

Education: methodological integration of equity-related concerns into techniques for ESS design and analysis; ability to incorporate ethical stances *into* models, and to understand the ethical stances *of* models; continued exploration of methods for human-centered design.

Governance Networks

As illustrated through many of the foregoing examples (and their anticipated aftermath), we are witnessing internal and external fragmentation of the various levels of public and private organizations that comprise the *de facto* governance network for many engineering structures and services. And it is no exaggeration to say that there is a real implosion of the systems used in the provision of many essential public services. What is unprecedented about this implosion is that it has been endorsed for decades by public officials themselves—and on an large, even industrial scale [66]. For private organizations and companies, business continuity plans are far from adequate to address the large scale disruptions created by COVID-19. Furthermore, public- private partnerships once seen as a panacea for a range of challenges, including supplementing limited public sector capacities, will have to be re-imagined as part of a more dynamic public governance and governance networks (local, national and global).

How and when society enters its post-COVID recovery phase is an open question. Among the many challenges for recovery is examining and perhaps revising the role of government (and other institutions) in ensuring societal stability and equity. It is therefore appropriate to raise these challenges in the face of the emergence of the dysfunction widely seen in developed and developing countries [67],[55]. Among developing countries, Brazil offers a dramatic example of friction, disharmony and lack of coordination in intra-governmental policies. As has been well documented, the Brazilian federal government has not only understated the severity of the COVID-19 pandemic, but has also suppressed the development of policies to combat it. Recent examples include exporting vital respirators to Italy and suing the Brazilian State of Maranhão for having bought respirators and other equipment directly from China. Therefore, a country of almost 6,000 municipalities, 27 states, 214 million inhabitants—the ninth-largest economy on the planet–is collapsing [68].

It is also appropriate to ask ourselves what role the field of engineering can play in the redesign of government systems at federal, state and municipal (local) levels. This may include initiatives to renew systems engineering approaches to supporting improved understanding of the role of government in the suppression of large-scale crises. An essential element of this effort will be in building modeling approaches that can explain (and predict) the interactions between engineered systems and the societal context in which they are situated. This is in marked contrast to the notion of engineered systems as largely separable from their context. Indeed, we would go further and say that it is precisely the context of a system that imbues it with meaning and produces its value (or cost) to society.

Research: empirical research on emergent roles and types of governance networks at federal, state, and municipal levels; frameworks and indicators of citizen participatory governance in the context of ESS design.
Education: project-based courses that introduce strong dependencies in the workflows that connect the members of multidisciplinary student teams; educational experiences that explore the consequences of actual and alternative regulatory and governmental structures on ESS design and operation.

Regulatory Frameworks

While COVID-19's extreme impacts could serve as an accelerator for large-scale re-design of our regulatory frameworks, it is more likely that pure inertia and the lack of political will inhibit sweeping regulatory reform, as in many other prior disasters. We must also accept the reality that we are living in a time of highly decentralized and on-demand delivery of services, so regulatory regimes that leverage societal acceptance of centralized control are going to be met skeptically in countries like the U.S. What then can we learn both from regulatory reform following past disasters and such understanding of attitudes toward regulation in contexts like the U.S.? We must use caution when doing so, as COVID-19 has further amplified the detrimental impacts posed by relying on concepts, frameworks, data, and models that lack the context of inherent conflicts in policy and regulation arising from interactions among different actors (e.g., private and public sector) across multiple scales (e.g., structures to systems, local to regional) and different operating points (e.g., typical to extreme conditions). Adaptive responses to these conditions only heighten the need to explore alternative regulatory frameworks that can ensure continued societal function.

At a minimum, regulatory frameworks that enable and even encourage higher levels of performance-based design will be critical to more resilient engineered structures and services in pandemic contexts. However, while consumers with means are likely to pay more for facilities and services that avoid future disruptions, the same is not true for ESSs serving the most vulnerable, creating an important space for regulatory action that ensures similar protections for the low-income populations reliant on government facilities and services. Further, recognizing the inherent tension between efficiency under normal operating conditions and resilience under extreme operating conditions, regulatory control will provide a vital safety net, establishing an appropriate definition of extreme or "design-level" events for ESSs that formally mandate minimum performance standards.

At the same time, *ad hoc* solutions will inevitably emerge in response to sudden and extreme dysfunction and loss of meaning [69]. Regulatory schemes must themselves have sufficient agility to accommodate and even accelerate the emergence of promising ESSs, particularly those which serve marginalized populations, while not compromising minimum performance expectations necessary for public safety. Such a delicate balance is essential at a time when structures, systems and even regulatory environments require unprecedented agility.

Research: Exploration of agile regulatory systems; methods for defining minimum performance objectives for diverse ESSs.
Education: Enhanced capacity for risk communication; training in policy advocacy; understanding of interaction between regulatory and ESS design processes.

Closing Remarks

We are not alone in arguing that our fields ought to advocate for better (or at least different) social outcomes—we are simply being obvious about it. Implicit in much of contemporary research and practice in engineering is a belief–even a dream–that the forces of market-based capitalism will lead to a just and fair distribution of costs and benefits. COVID-19 has shattered those dreams; we must find a new way.

Expanding the scope of our work is both a practical necessity and an ethical one, bound inextricably to the quality of the work we produce. We do not assert that a concern with these problems is absent in the research literature. Rather, we ask why have these and related problems–all of which bear directly on issues of social good and equity–have not become "classic" problems in our curricula, publications and the way we talk about our field.

We sometimes fail to account for the slow and steady evolution of the basic underpinnings of society, including value systems, economies and social fabrics, thus making historical relics of our models. As one of us has said, *Estamos em prisão domiciliar por causa do ilusionismo científico que nós construímos*. That is, we find ourselves in a domestic prison as a result of the scientific illusion which we ourselves have constructed. We can and we must question the degree to which this illusionism figures into our scholarship and our practice—and why.

And yes, we are taking positions here, or at least arguing for the relevance of a set of problems which appear incompatible with the current paradigm. We see no great difference in doing so than in, say, arguing that greater efficiency will benefit a particular subset of private enterprises. After all, the problems we and others have articulated are real, with real lives and livelihoods at stake. We emphasize that COVID-19 has revealed some of our most cherished assumptions to be hopelessly outmoded. We need an engineering discipline that is ready to learn from the errors of the past, respond to the challenges of the present, and shape the designs of the future.

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