A Framework for Transitions in the Built Environment: Insights from Compound Hazards in the COVID-19 Era

David Mendonça[1]; Tracy Kijewski-Correa, A.M.ASCE[2]; Ann-Margaret Esnard[3];
Julio Ramirez, Dist.M.ASCE[4]; and Julia F. Olson[5]

Abstract: The COVID-19 era has witnessed numerous successful and unsuccessful attempts to adapt or reconfigure physical, virtual, and hybrid aspects of the built environment in order to mitigate the risks of co-occuring (i.e., *compound*) hazards. But it has also witnessed major challenges to ensuring that the protections these reconfigurations afford are equitably distributed. Additional theoretical and empirical research is needed to inform transitions (via adaptive reconfiguration) toward short-term goals of health and well-being, as well as to guide transformations (via the establishment of stable configuration) toward longer-term goals of equitable societal function. To this end, this paper presents a framework for conceptualizing adaptation of the built environment as a series of state transitions in response to (or in anticipation of) compound hazards. It draws upon cases from recent experience in the areas of food production, shelter, and education to critique, clarify, and explicate this framework. It concludes with implications for further research on the management of transitions in the built environment under a range of hazard scenarios. **DOI: 10.1061/JITSE4.ISENG-2285.** *© 2023 American Society of Civil Engineers.*

Practical Applications: The COVID-19 pandemic provided a global backdrop for the study of the capacities and vulnerabilities of many aspects of societal function, challenging conventions around the design and operation of wide classes of infrastructure to protect populations from pandemics as well as hazards such as hurricanes and earthquakes. The framework offered by this study, and its application through the associated case studies, reveals how observed adaptations of the built environment can elucidate new potentials to mitigate the risks associated with co-occuring (i.e., *compound*) hazards, as well as areas where our existing conventions are no longer compatible with contemporary uses of the built environment. One such convention challenged by this study is the definition of critical infrastructure in existing regulatory frameworks. The built environment transitions documented by this study suggest that contemporary notions of what infrastructure is critical and what services are essential have outstripped the traditional notions in codes and standards, demanding corresponding realignment of regulatory frameworks to ensure life-safety can still be achieved as usages evolve.

Introduction

The COVID-19 era has proven sufficiently long and far-ranging to yield myriad observations on how society has adapted (or failed to adapt) the built environment to mitigate risks not only of the pandemic itself, but also of other hazards that have overlapped with it. In these and other cases (Nakamura and Kikuchi 2011; Mendonça et al. 2019), multiple hazards have been linked through functional, spatial, or temporal relationships, yielding a class of complex hazards that are typically denoted as *compound hazards* (Gill and Malamud 2014; Tilloy et al. 2019). As is evident in recent research in this area (Catto and Dowdy 2021; Zscheischler et al. 2020), compound hazards may represent something more than the simple sum of individual hazards. Indeed, the individual hazards that comprise a compound hazard may have amplifying, dampening, or no effect on each other's duration, intensity, or other properties (Duncan et al. 2016), raising considerable challenges for how they are conceptualized and modeled (Wright et al. 2023).

Given these and other potential complexities of compound hazards (Tarvainen et al. 2006; Kappes et al. 2010), efforts to adapt the built environment to mitigate risks associated with them may differ markedly from those used for individual hazards (National Academies 2022). Recent work by Nohrstedt et al. (2022) suggests the breadth of adaptation actions, including changes to the configuration and use of the built environment, undertaken to mitigate the effects of individual hazards. For example, among the reported adaptations to the built environment to mitigate the effects of extreme heat are green roofs/walls and cooling centers. [See Supplementary Table 2 in Nohrstedt et al. (2022).] In the case of compound hazards, and as suggested by Kruczkiewicz et al. (2021), reconceptualizations of hazard risks—and therefore of recommended remedial or adaptive actions—should be considered when hazards may be compound. Indeed, any of the built environment adaptations highlighted above could serve to amplify the effects of other hazards: green roofs may increase fire risk in exceedingly dry conditions (Gerzhova et al. 2020), while cooling centers may increase transmission of infectious diseases among sheltering individuals (Salas et al. 2020). In this sense, the adverse impacts of a compound event may be greater than the sum of those of the individual events that comprise it if mitigation actions for one individual event serve to amplify the adverse effects of another.

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[1] Senior Principal Scientist, MITRE Corporation, 202 Burlington Rd., Bedford, MA 01730 (corresponding author). ORCID: https://orcid.org/0000-0001-8070-0960. Email: dmendonca@mitre.org

[2] Professor, Dept. of Civil and Environmental Engineering and Earth Sciences, Keough School of Global Affairs, Univ. of Notre Dame, Notre Dame, IN 46556.

[3] Distinguished University Professor, Dept. of Public Management and Policy, Georgia State Univ., Atlanta, GA 30302.

[4] Karl H. Kettelhut Professor, Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN 47906.

[5] Lyles School of Civil Engineering, Purdue Univ., West Lafayette, IN 47906.

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For other compound hazards, the adverse effects of one event may be mitigated by those of the other (e.g., heavy rains that retard the spread of forest fires). As argued in this paper, understanding the type—as well as the temporal and spatial distributions—of the individual hazards that comprise a compound hazard is needed to increase the likelihood that adaptation actions will contribute to hazard mitigation, not detract from it.

As with other hazard events, adapting plans for preparedness, response, and recovery in relation to compound hazards will remain essential in addressing emerging risks. In the US during the COVID-19 era, for example, private residences (a noncritical infrastructure) were pressed into service as places of work and study for countless workers and students, despite the fact that some of this private infrastructure (and the means to operate it) was desperately lacking (Kennedy et al. 2022), particularly among less-advantaged populations (Goldberg 2021; Saucedo 2021). The move to a highly distributed workforce and educational system also introduced numerous risks, including reduced access for students to essential health services and increased costs for workers associated with providing the services that enabled at-home learning and working. To understand adaptation of the built environment, then, a perspective should be taken that includes but is not limited to designated critical infrastructures.

Recent work (Gibson et al. 2023; Smite et al. 2023) has highlighted challenges in returning to prepandemic modes of working and learning given that countless individuals have adapted to doing so remotely. Thus, while some of the changes to the design and operation of the built environment in recent years may prove transitory, others may persist. And while some changes have been enforced through institutional authority (such as government action), others have happened outside of it, raising questions about the sources of adaptation in society.

During the process of adaptation, individuals, communities or societies in general continue to face threats, thereby calling into question how *transitions* in the design and operation of the built environment can be identified and managed not only to support health and well-being in the present, but also to drive the evolution of the built environment toward greater stability and improved societal function in the future.

Building on prior work in this area (e.g., Steinberg et al. 2004), as well as prior research on transitions management (e.g., Malekpour et al. 2020), this paper develops a conceptual framework for characterizing adaptation in the built environment as a dynamic process of transitions between states of the built environment in relation to the properties of compound hazards. The framework is illustrated and enriched through case studies from the COVID-19 era in the areas of education, food production, and shelter.

The paper concludes with observations and recommendations for future work that frames adaptation as an emergent property of the built environment, one that may originate from top-down policy or bottom-up grassroots initiatives. Indeed, an overarching conclusion of this work is that, as policy and governance move to less centralized models, engineers must be prepared to design for the adaptive use of the built environment by the public at large, signaling a continuation of the transition from prescriptive approaches toward designs that are more performance-based and that have a greater potential to adapt to changing market, sector, and societal demands. An implication of this work is that engineering practice must contribute to the development of mechanisms for capturing, evaluating, and potentially formalizing adaptive use in order to support performance-based design processes.

Background

As suggested by the foregoing observations, compound hazards represent a distinct class of hazards with the potential to induce new challenges for their mitigation through adaptation of the built environment. This section provides a synthesis and analysis of recent work in attempting to define compound hazards, yielding a broader perspective on how to conceptualize their spatial and temporal aspects while also addressing their potential to create adverse consequences, particularly among vulnerable populations.

Given the emerging state of knowledge about how best to model and manage compound hazards, adaptive use of the built environment is likely to be an essential strategy in mitigating their adverse effects. We therefore adopt a very broad view of the built environment—its elements and their interrelationships—and theorize that both conforming and nonconforming uses of the built environment must be considered in developing strategies to mitigate the effects of compound hazards. Finally, we suggest that changes in the configuration of the built environment over time should be expressed in terms of changes in the spatial and temporal properties of the built environment, along with the costs (financial and otherwise) associated with those changes.

Compound Hazards

Although scholarship on compound hazards stretches back some years, there is still considerable debate over how best to conceptualize such events, with many contesting terminologies and perspectives (Gill and Malamud 2014; Duncan et al. 2016; Ciurean et al. 2018; Tilloy et al. 2019). Research in the area of climate change in particular has contributed valuable perspectives on conceptualizing and modeling the phenomenology of compound hazards (including underlying causes) (Zscheischler et al. 2020; Tilloy et al. 2019). Certain other definitions, however, conflate characteristics of the hazard per se (De Angeli et al. 2022; Gill and Malamud 2014) with characteristics of hazard exposure (Pescaroli and Alexander 2018). For example, IPCC SREX7 (IPCC 2012) defines compound events as "(1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined. The contributing events can be of similar (clustered multiple events) or different type(s)." Point (1) emphasizes etiology independent of exposure, while point (3) includes both etiology and the potential for adverse consequences. Clearly, both the phenomenological and impact perspectives must be considered to support effective mitigation. The emphasis here is on adaptation of the built environment to mitigate adverse consequences (as opposed to mitigating the triggering conditions), so the impact perspective is prioritized.

Three features that set compound hazards apart from single hazards are the potentially evolving *spatial* and *temporal* relationships between two or more hazards (De Angeli et al. 2022), as well as complex patterns of *potentially adverse consequences* associated with hazard exposure.

The *spatial attributes* of exposure to compound hazards refer to the relationship between or among the geographic areas put at risk by two or more hazards (Aghakouchak et al. 2020). Over time, this spatial relationship may change in various ways. For example, coastal flooding associated with high wind events is reaching ever inland in many parts of the world due to sea level rise and other factors (including sinking land masses) (Piecuch et al. 2018), so that the spatial relationship of flooding with any other co-occuring hazard may also be evolving over time. In summary, constituent individual hazards may be nonstationary processes, leading to changes in the areas at risk from them [see (Leonard et al. 2014) for a discussion and additional examples].

The *temporal attributes* of exposure to compound hazards typically refer to the proximity of two hazards in time. De Angeli (2022), for example, distinguishes hazard time (when the events are happening) from exposure time (when exposed to risk from the hazard) and resulting damage time. Other temporal aspects of constituent individual hazards may be relevant. For example, periodicity here refers to the extent to which recurrence of an individual hazard can be characterized in terms of an interval of predictable or regular length. The compound hazard analogue would express the joint periodic relationship (e.g., annually in summer for one hazard, monthly in summer for another). This perspective is common in meteorological research but has not fully found its way into studies of other events.

As with individual hazards, the *potentially adverse consequences* of compound hazards may differ significantly and in complex ways across spatial and temporal scales (e.g., micro to global, seconds to millennia). Tilloy et al. (2022) discuss various logical relationships between hazards in terms of exposure over space and time (e.g., whether a compound hazard indicates the intersection or totality of two different spatial extents). Yet although hazard exposure may overlap in space, it might not overlap in time, leading to a temporal framing based on the idea of each hazard's recurrence interval, and whether any two hazards are in or out of phase with each other (a relationship that may itself change over time) (Ridder et al. 2022).

Two infamous examples of amplifying effects include Mount Pinatubo in the Philippines, which erupted in 1991, and Tropical Storm Agatha in Guatemala in 2010. In both cases, a volcanic eruption coincided with the passage of an extreme weather system, leading to violent *lahars* and structural collapses due to the combined effects of ash, volcanic debris, and heavy rain (Gill and Malamud 2014). Of course, two hazards may also mitigate each other's adverse effects. This type of alleviation (or dampening) of one hazard's risk by another is not nearly as widely explored as amplification [but see Duncan et al. (2016), Tilloy et al. (2019), Gill and Malamud (2014), along with an extensive hypothetical example from De Angeli et al. (2022) for examples]. Lastly, the Cameron Peak (Colorado) Fire of 2020 suggests even subtler patterns of combined effects. During the fire, 12 in of snow fell over the wildfire, temporarily halting its expansion—while also hampering ongoing firefighting efforts (Bradbury 2020).

Adaptation in the Built Environment

The notion of adaptation has figured prominently in the hazard mitigation literature, typically as a type of goal-directed, risk-mitigating activity or process in relation to one or more hazards (Smit and Wandel 2006). For example, as defined by the Intergovernmental Panel on Climate Change (IPCC), "Adaptation is the process of adjustment of human or natural systems to the actual or expected climate and its effects, the aim being either to reduce or avoid the negative impacts of climate change or to exploit beneficial opportunities" (IPCC 2014). Additionally, work on community adaptation (Ayers and Forsyth 2009; Forsyth 2013) considers both institutional (Woods 2012) and noninstitutional (e.g., grassroots) sources of adaptation. "Human" systems encompass a wide variety of systems in which humans exhibit some degree of control over the design and operation of the built environment, but also include governance systems (Djalante 2012) and "nature-based" systems (Hamin et al. 2018).

An emerging need for additional research is in identifying patterns of adaptation in the built environment in relation to exposure to compound hazards. Two perspectives on prior research may be taken to describe this need more precisely. The first addresses the extent to which the use of elements of the built environment does or does not conform to the uses for which they were designed. The second, which is motivated chiefly by societal experience with the COVID-19 pandemic, addresses the extent to which these elements are physical, virtual, or some mix of the two (i.e., hybrid).

Conforming versus Nonconforming Use

The history of human response to disaster suggests the depth and breadth of actions that may be undertaken to mitigate hazards through adaptive behavior (Bassett and Fogelman 2013). Adaptation is related to, but conceptually distinct from, the related processes of improvisation (in the short term) and development (in the longer term) (Sherman et al. 2016), both of which imply novel or otherwise creative approaches to the utilization of personnel, material, and procedures (Webb 2004).

The concept of improvisation has been studied extensively in the context of response to more acute emergency events (Hutter 2013; Webb 2004; Mendonça and Wallace 2004), where there is a need for real-time creativity in order to address an unfolding event. Incorporating the lessons learned from improvisations into best practices is one way that individuals and organizations can build capacity for dealing with subsequent events. The latter concept is more difficult to disambiguate from adaptation, particularly due to the fact that it implies adherence to a practice over longer time scales (quite unlike improvisation per se). As noted by Sherman et al. (2016), "While the IPCC's definition of adaptation is widely accepted, in practice it can be difficult to distinguish between adaptation and development." A similar point has been made by Maru et al. (2014), who cite a lack of robust frameworks for characterizing "pathways" to adaptation, particularly in geographic areas that are remote and disadvantaged [also see Shi et al. (2016)]. In a compound hazards context, a transitions-based framing of change to the built environment may be useful in identifying the conditions under which improvisations and adaptations inform development. For example, the successful use of "noncritical" elements of the built environment to mitigate a compound hazard may lead to inclusion of these elements in subsequent hazard mitigation plans (Parks 2017).

Physical, Virtual, and Hybrid Elements

A longstanding strain of research addresses the role of the (physical) built environment in hazard mitigation (Haigh and Amaratunga 2010), including recent research addressing the role of the built environment in the suppression of COVID-19 (Megahed and Ghoneim 2020; Dietz et al. 2020) as well as implications of COVID-19 for the design and operation of the built environment (Mahima et al. 2022; Honey-Roses et al. 2020). A parallel strain of research considers how human-centered information technologies—ranging from social media to virtual and augmented reality (Beroggi et al. 1995; Zhu and Li 2021)—can improve societal capacity for hazard mitigation. During the COVID-19 era, these two strains have begun to join, sometimes in unexpected ways.

At the height of the COVID-19 pandemic, millions of individuals worldwide were in the midst of perhaps the largest hazard-related evacuation in human history. A key difference from "normal" evacuation was that this particular "movement to safety" (Yang et al. 2019) was often toward safe *virtual* spaces as opposed to traditional physical ones. For many individuals, work and education (at least in those communities with access to the necessary physical infrastructure) shifted online, with individuals undertaking a wide variety of activities from their personal residences. In considering how best to mitigate the adverse effects of compound hazards, not only traditional physical resources but also virtual and mixed (or hybrid) resources therefore may be considered.

To this end, related work has begun to explore the integration of physical and virtual (i.e., *hybrid*) spaces in support of comprehensive hazard mitigation, building on earlier research on so-called mixed reality approaches (e.g., Lochhead and Hedley 2019). Rather than viewing virtual spaces as contingent spaces for use when physical spaces are unavailable, work along these lines views physical and virtual spaces holistically (Salama 2020; Carvalhaes et al. 2020), in ways that are similar to the design of hazard mitigation policies governing shelter-in-place, use of secure shelters, and evacuation. For example, recent work by Mouratidis and Peters (2022) considers the relationship between characteristics of the built environment and the type and extent of tele-activities (such as remote work) before and during COVID-19. Koohsari et al. (2023) consider the conditions under which risky decision making in a computer-simulated environment (e.g., a "metaverse") may contribute to or detract from the quality of decisions in a real-world environment. In both studies, the relationship between virtual and physical environments is theorized as not necessarily symbiotic but almost certainly inevitable. An emerging challenge for hazard mitigation, then, is to consider how best to manage and support transitions between real and virtual worlds in ways that improve safety and well-being.

Finally, it should be noted that adaptation through the use of virtual and hybrid spaces for hazard mitigation is mirrored in adaptation of so-called noncritical infrastructures for supporting the continuance of essential societal functions. As discussed more fully below, physical infrastructures designated as critical (such as the physical installations of educational institutions) may be supplanted by noncritical infrastructure if they themselves present a risk. In the case of education, for example, physical facilities designed to accommodate large numbers of students in close proximity represented an unacceptable risk to those students (and a liability to educational institutions), resulting in the adaptive use of online instruction and virtual learning spaces. The mitigation of hazard-related risks through adaptation may therefore no longer be necessarily restricted to the management of established institutions and designated critical infrastructures. Instead, hazard mitigation may now be viewed as the responsibility of potentially hegemonistic forces, some formally recognized, others not.

The proposed framework and the cases used to exemplify it adopt a broad view on adaptation to compound hazards in the built environment, one that encompasses but is not restricted to critical infrastructures, that considers contrasts between conforming and nonconforming uses of the built environment, and that admits the possibility that nonphysical (i.e., virtual) or mixed physical/virtual (i.e., hybrid) spaces may be used to craft adaptive behaviors.

Transition Management and Adaptation

Transitions have been described as "the process of change from one system state to another via a period of nonlinear disruptive change" (Loorbach et al. 2017). As summarized by Hölscher et al. (2018): "Transition has been mainly employed to analyse changes in societal sub-subsystems (e.g. energy, mobility, cities), focusing on social, technological and institutional interactions (Loorbach et al. 2017). Transformation is more commonly applied to refer to large-scale changes in whole societies, which can be global, national or local, and involve interacting human and biophysical system components (Brand 2014; Folke et al. 2010)." This paper adopts the perspective of Hölscher et al. (2018), focusing on how transitions can be conceptualized and measured in a way that enables progress toward transformations to be assessed [see Ernst et al. (2016) and Fekete et al. (2022) for further discussion].

The field of transitions management identifies four short-term activities—reflecting, activating, orienting, and agenda setting—directed toward achieving "a longer-term vision of transformation" (Malekpour et al. 2020). Transitions management chiefly concerns undertaking these activities in order to craft policies that will drive transitions. Recent research in this area (Malekpour et al. 2020) has sought to characterize and explore these transitions, and to examine implications for planning and operations (Tyler and Moench 2012). Related work has applied a state-based approach for characterizing the resilience of critical infrastructure (Hémond and Robert 2012).

In contrast to policy-driven transitions are those transitions initiated by individuals, households, and others, not in conformance to top-down directives, but in response to local needs and capabilities (Forsyth 2013; Ayers and Forsyth 2009). Similarly, Lachman (2013) notes the relative lack of attention in the transitions management literature to transitions made by consumers in how they use services afforded by the built environment. It may be, for example, that consumers, through their approach to use of the built environment, enable or inhibit transitions in the built environment [see Wilson (2012) and Hans de Haan and Rotmans (2011) for additional discussion]. In line with seminal work by Rotmans and Loorbach (2009), this "grassroots" level may represent a niche within which may be found (and perhaps cultivated) innovative approaches to achieving appropriate transitions in the design and use of the built environment [see Wahlund and Palm (2022) for additional discussion].

As suggested by the foregoing discussion, transitions may arise due to a wide variety of forces and result from a wide variety of behaviors. The emphasis of this paper is on adaptive behavior. As described in highly influential work by Smit and Wandel (2006), "Adaptation in the context of human dimensions of global change usually refers to a process, action or outcome in a system (household, community, group, sector, region, country) in order for the system to better cope with, manage or adjust to some changing condition, stress, hazard, risk or opportunity." Prior research (e.g., Geels 2011) suggests that societal adaptations to potential or actual hazards must be conceptualized at multiple spatial and temporal scales if the transitions induced by adaptation are to be managed effectively. A complicating factor is the likelihood that adaptations will be driven by some combination of top-down policy and bottom-up (local) behaviors (Switzer et al. 2022), associated with which are the financial or other costs of transitions. The following section presents a framework that captures these and related aspects of the problem of managing transitions for compound hazards.

State Transition Framework to Support Designing for Adaptation in the Built Environment

The framework presented in this section is ultimately intended to support modeling and analysis of transitions between states of the built environment in relation to exposure to compound hazards. Building on the foregoing discussion, the fundamental elements of the framework are first described, and then elaborated upon, in the following section through an analysis of case studies from the COVID-19 era.

As shown in Table 1, the framework characterizes each state of a *built environment* in terms of its elements (physical, virtual, or hybrid) and the extent to which its observed use conforms with its designed or intended use. A *compound hazard* is described in terms of the spatial properties, temporal properties, and adverse consequences associated with exposure to the individual hazards that comprise the compound hazard. *Transition dynamics* between a

Table 1. State transition framework for compound hazards

Dimension	Aspect	Description
Built environment	Element	A distinct *physical*, *virtual*, or *hybrid* component or meaningful collection of components.
	Observed use	The extent to which the observed use of an element of the built environment is *conforming* or *nonconforming* in relation to its designed use.
Compound hazard	Temporal relationship	The difference in the *temporal aspects* of the relationship between two or more hazards.
	Spatial relationship	The difference in the *spatial aspects* of the relationship between two or more hazards.
	Adverse consequences	The difference in *potential harm* to human, technological, or natural systems due to exposure to two or more hazards.
Transition dynamics	Spatial distribution	Changes in how one or more elements of the built environment are *distributed or configured physical, virtual, or hybrid space*.
	Temporal frame	Changes in *temporal relationships* among one or more elements of the built environment.
	Transition costs	*Financial or other costs* associated with spatial and/or temporal changes to one or more elements of the built environment.

sequence of any two states of the built environment are described in terms of changes in the spatial and temporal distribution of elements of the built environment, as well as the costs associated with the transition. The remainder of this section further describes the elements of this framework.

Built Environment

The first dimension of the framework characterizes two aspects of the *built environment*. The first aspect identifies whether an *element* or some set of elements of the built environment is *physical*, *virtual*, or some mix of the two (i.e., *hybrid*). Physical elements encompass distinct or interconnected structures and services that occupy physical space. Virtual elements encompass online environments, which may range from telework spaces to virtual reality, while hybrid elements blend both physical and virtual aspects (e.g., virtual reality-based learning in a physical classroom). Each set of elements imposes its own constraints and enables different capabilities. For example, physical elements introduce spatial constraints (e.g., on the capacity of rooms or buildings), while the capacity of virtual elements is essentially tuneable (e.g., the size of a virtual meeting room can be adjusted at will).

The second aspect addresses the extent to which the *observed use* of an element or elements of the built environment conforms to or departs from the use for which it was designed. In certain cases, the designed use is established by law or policy. For example, building codes impose constraints on how a structure may be used, in addition to specifying minimum standards for safe operation. In other cases, the designed use may not completely constrain activities, as with private homes that were designed as residences but that, during the pandemic, were repurposed to support distance work and learning.

Compound Hazard

The second dimension of the framework characterizes hazard exposure in terms of the *attributes of the compound hazard*. Given that exposure to a compound hazard is the product of exposure to two or more hazard events, we propose attributes that reflect differences between or amongst the individual hazards.

The first attribute is the *geographic relationship* between the individual hazard events comprising the compound hazard. This attribute may be used to capture a difference in the areas exposed to them. It will likely be useful or convenient to conceptualize this dimension in relation to jurisdictional or similar boundaries. For example, a tornado may threaten a few square miles of a given state, while a hurricane may threaten most of a state or indeed multiple states.

The second attribute is the *temporal relationship* between the individual hazards. This attribute may be used to capture a difference in cycle times (which may be orders of magnitude when comparing pandemics at a centennial scale to, say, hurricanes at an annual scale), or, essentially equivalently, the number of times one hazard is likely to recur before the second one does (in the foregoing example, a given area might experience 100 hurricanes between one pandemic and another), or other relationships.

The third attribute is the relationship between the potential *adverse consequences* of the individual hazards that comprise the compound hazard. This attribute may be used to capture differences in the potential harm to human, technological, or natural systems as a function of two or more hazards. For example, slower-onset events (such as hurricanes or coastal floods) may represent potential harm to technological systems, such as physical public infrastructure, as humans are more likely to be able to evacuate from them than from, say, rapid onset events such as earthquakes. It should be emphasized that, consistent with prior literature (Cutter et al. 2008; Mendonça and Wallace 2006), understanding of potential adverse consequences of a hazard must be informed by salient characteristics of the resistive and adaptive capacities of the human and technological systems exposed to it.

For all three attributes, and as suggested by Tilloy et al. (2019), various relationships among the individual hazards that comprise a compound hazard may be of theoretical and practical interest. For example, a difference-type relationship for geographic extent may reflect the extent to which two or more hazards overlap spatially. More fine-grained perspectives might consider whether two or more hazards are merely circumscribed by the same geographic area (e.g., a single municipality), but do not themselves overlap.

Transition Dynamics

The third and final dimension of the framework addresses *transition dynamics* through a conceptualization of three attributes that characterize the process of change in the built environment. These are changes in the *spatial distribution* and *temporal frame* of one or more elements of the built environment, along with the *transition costs* associated with those changes.

The *spatial distribution* attribute refers to changes in the configuration of physical or virtual elements of the built environment. Notions such as density, dispersion, and connectivity are all relevant to this attribute. Changes in configuration to a physical element (e.g., a structure) are said to occur when the geographic coordinates of an element are altered, as may occur when an element is relocated, installed, or taken out of service. Changes in configuration to a virtual element are analogous, with a network or similar address replacing geographic coordinates.

Of course, an element's location may also change from physical to virtual, an example of which would be the shift from colocated instruction (i.e., in which a school building is one element) to distributed instruction (i.e., in which online learning spaces are one element). This example also highlights the potential role of interconnected supporting elements of the built environment. For example, students who are learning via distributed instruction continue to occupy physical space (which, not uncommonly during the COVID-19 era, changed from the school building to the private home).

The *temporal frame* attribute refers to changes in temporal relationships among individual and interconnected elements of the built environment. Notions of duration, frequency, sequence, and cycle time are all relevant to this attribute, as are notions of synchronization, phase shift, and interruption. To the extent that human interaction with elements of the built environment drives or supports the function of the built environment, such interaction is relevant as well. In the education example given above, classroom interactions in a colocated setting are synchronous: as the instructor lectures, students take notes and ask questions. In a distributed setting, in contrast, interactions can be asynchronous, so that there may be an appreciable lag between, say, the instructor's lecture and any questions asked by a student. In some sense, in many educational settings this transition between colocated and distributed is ongoing, with some schools transitioning multiple times between synchronous and asynchronous regimes.

The *transition costs* attribute refers to the financial or other costs associated with undertaking a change of state of the built environment, including the bearer of those costs. Notions of material and immaterial costs and benefits are relevant here. An example of material cost in the education example is the money spent by at-home learners in configuring their homes (and computing equipment) to support online learning. An example of an immaterial cost is the time spent by caregivers (such as parents) in supervising or otherwise facilitating online, at-home learning for young learners. Construing these costs broadly—in terms such as time, money, and political or social capital—will enable broader theorizing about the forces that dampen or enable adaptation. For example, in the education example, the shift to large-scale online learning involved far more modest costs than, say, constructing new schools that would incorporate better ventilation as well as physical spaces that could accommodate social distancing. Meaningful costs were, however, incurred in terms of social capital (particularly as protests grew over protracted at-home schooling) as well as time (as the inefficiencies associated with the growing pains of large-scale online learning became apparent).

Summary

The foregoing framework provides a means for characterizing transitions in the built environment in relation to temporal, spatial, and impact-related factors associated with compound hazards. The aspects of time, space, and cost are used to characterize the transitions between states of the built environment, as described in terms of its configuration and use. The following section explores the expressive potential of this framework through exploratory cases drawn from the essential sectors of education, food production, and housing, beginning with an overview, followed by a description of the cases in relation to the framework, and concluding with observations and implications.

Built Environment Transitions in the COVID-19 Era

To illustrate the framework and explore its implications, we develop a number of case studies centered on the role of the built environment in the education, food production, and housing sectors during the pandemic period. (For simplicity and clarity, the term *pandemic compound hazards* refers to compound hazards involving exposure to the COVID-19 pandemic and one or more other hazards.) Related research in this area is emergent and largely confined to implications for the design of the built environment subsequent to COVID-19, and not to compound hazards. For example, Mahima et al. (2022) address implications for the design of buildings and urban public spaces to afford physical distancing. Scholz et al. (2022) address changing notions of criticality in the provision of essential services as implicated by COVID-19. Megahed and Ghoneim (2020) discuss construction strategies to improve spatial buffering capacity. And Megahed and Ghoneim (2020) discuss the need for further work on the interactions between activities in the built and virtual environments. None of these works address compound hazards.

As explicated in the remainder of this section, the case studies illustrate both top-down and bottom-up approaches to transitions in the built environment. It is important to note, however, that the presentation of the cases is not intended to be an authoritative analysis, but rather a set of initial observations that can support further theory-building through enrichment of the framework. The case studies therefore illustrate the various elements of the framework, while also indicating the expressive potential of the framework and suggesting some of the challenges and opportunities associated with modeling transitions in the built environment.

K-12 Education

The COVID-19 pandemic challenged and transformed the delivery of education and related services in the K-12 sector. A snapshot of students who were enrolled in distance learning in February 2021 provides evidence of this forced transition: in the spring of 2020, 77% of public schools reported moving to online distance learning formats, compared to 21% of public schools that offered any classes entirely online during the 2017–2018 school year (US Department of Education and National Center for Education Statistics 2022).

Policies that rightly prioritized mitigating the spread of COVID-19 also motivated engineering and physical adjustments within school environments. In contrast, the response of school systems to destruction and damage from natural hazards and climate-related disasters has been characterized by school closures of varying lengths of time (Esnard et al. 2018). This case study focuses on the adjustments that were made to accommodate safe in-person use of school facilities in the midst of the pandemic and up to one year after housing and public schools in Iowa were damaged by the August 2020 *derecho* (Hannon 2020; Rogers 2021).

Built Environment

In a sector where physical spaces (classrooms, labs, cafeteria, gyms, etc.) and interaction are fundamental to teaching and learning, the rapid and widespread transition to virtual spaces was a significant departure from the norm. The adoption of teaching and learning platforms for virtual instruction during the height of the pandemic in fall 2020 is well-documented for the K-12 sector (Bonderud 2021; National Education Association 2021). As schools prepared for a potential return to the classroom in fall 2021, several elements of hybrid learning remained as some families opted for at-home learning due to the pace of vaccine rollouts for children, or because schools provided the option for a partially hybrid model to reduce classroom overcrowding and improve one-on-one interaction

(Abril 2021; Bonderud 2021; National Education Association 2021).

Also observed were transitions to nonconforming observed uses of the built environment in order to sustain delivery of services typically offered to school children in person (e.g., access to technology; access to meals and nutrition assistance programs; after-care; and medical, counseling, and psychological resources). For example, when schools suddenly shut down during the height of the pandemic in fall 2020, these adaptations facilitated delivery of prepackaged meals in school parking lots and other open spaces on school grounds. Delivery of other nontangible services (such as counseling) entailed a shift to virtual instruction environments to a hybrid form of service largely based on phased schedules.

Pandemic Compound Hazard

A total of 13 *derechos* have been recorded in Iowa since 1980 (Joens 2021). The August 2020 *derecho* is the most costly thunderstorm in US history to date, with more than $11 billion in damage to homes and crops in multiple states (Alexander 2021; Joens 2021). In the state of Iowa, six million acres of crops were either damaged or destroyed; more than 4 million trees were lost; and, in Cedar Rapids, 90% of homes sustained some type of damage (Alexander 2021). The August 2020 *derecho* also caused widespread power outages for up to two weeks in Cedar Rapids, and damaged or downed more than 7 million trees (Eller 2020; Fischels 2021).

The combination of the *derecho* and the COVID-19 pandemic created further complications for those households with students, as the *derecho*'s timing in August 2020 coincided with the beginning of the 2020–2021 academic school year—a moment when school districts thought that they had taken the necessary precautions to return to in-person learning. This case highlights some of the dilemmas faced by school administrators in communities impacted by compound hazards with very different cycle times.

Transition Dynamics

Transitions in the built environment during the period of exposure to the combined effects of the *derecho* and COVID-19 were observed with respect to both spatial and temporal aspects. Associated costs were diverse.

Impacted Iowa school districts transitioned from traditional centralized and synchronous instruction to distributed and synchronous instruction. The Benton, Iowa, school district relocated its students to different (physical) spaces and settings in order to offer in-person learning (Hannon 2020; KCRG News Staff 2020). Yet as cases in the community increased, unanticipated absences of students and staff prompted the district to shift to the distributed and asynchronous instruction.

The transition from colocated instruction (i.e., in school buildings) to distributed virtual instruction (in multiple private homes or community facilities) did not follow a prescribed plan, at least not in the early stages of the pandemic. Key drivers included the phase of the pandemic, the number of COVID-19 cases, and the known sources of community spread. Nonstructural adaptations were focused on enhancing the flow of movement within and among school buildings and outdoor facilities. When learning took place in a building, student movement between classes was minimized; desks were used instead of regular tables in the cafeteria to better enforce social distancing, and alternative community facilities and shared sports fields were used. Band teachers improvised by rolling carts of supplies to grade-level classrooms to limit contact between groups of students in hallways (National Education Association 2021), in what can be characterized as swapping from colocated, synchronous instruction in dedicated band and equipment rooms designed for music and band instruction to a scheduled distribution of equipment to specific classrooms. In addition to in-person learning in school buildings, another form of colocated, synchronous use by schools and school districts was offering in-person learning at hubs and other remote learning labs for those students who needed additional help or supervision (King 2020; Graham 2020).

Costs were incurred for purchasing school supplies, plastic shields, and other temporary barriers to facilitate social distancing, as well as for purchasing and upgrading learning platforms and related technical support. In some cases, stabilization of Internet was necessary, as well as the purchase of additional computers to loan to students or families. Private schools were able to return to in-person learning at a quicker pace given the available financial resources to retrofit their existing buildings, spaces, and equipment as previously noted. Specifically, installation and retrofit of ventilation and air flow systems enabled safe in-person attendance and instruction. According to the US Government Accountability Office, more than 41% of school districts needed to update or replace their heating, ventilation, and air conditioning systems in at least half of their buildings to prevent the spread of the coronavirus inside schools (National Education Association 2021). Maintaining a healthy school environment with frequent hand-washing and sanitizing has associated costs and implications for school budgets of underfunded schools. School nurses and facilities for screening for COVID-19, conducting contact tracing, and managing isolation rooms (some physical improvisation needed) for potentially infected students became essential (National Education Association 2021).

Discussion

A signature feature of this case study is the involvement of unofficial personnel in unconventional settings using newly deployed technology to deliver an essential service—education—to children, a protected population. Indications are that underresourced families and communities struggled with the transition to these new ways of educating, and that children bore some of the negative consequences associated with the attempt to make the transition. The many individual deleterious effects of the pandemic on education are of immediate importance, yet it must also be recognized that students are embedded within individual schools, each of which is in turn embedded within a school district, broader community, region, and state. These are governed by their own missions, regulations, and policies. An appropriate extension of the proposed framework, then, would provide mechanisms for building theory concerning these multiscalar dependencies (e.g., impacts that flow from schools to the broader communities in which they are embedded).

Of course, many private homes were converted to education outposts, as the digital divide between well- and under-resourced homes came into clearer view. In an attempt to support the shift to online learning, impacted families in the Cedar Rapids community school district switched between mobile hotspots and student Internet hubs at area churches and libraries (Holt 2020). The negative impacts on educational achievement and learning loss for students (both academically and in their social-emotional progress) continue to emerge, particularly among Black and Hispanic students and among students with disabilities (Dickler 2021; National Education Association 2021).

It remains unclear, both from student and school institution perspectives, whether the effectiveness of the transition from in-person to virtual learning diminished or improved over time in terms of perceived value, and also whether efficiency increased in terms of reduced cost for maintaining virtual versus physical spaces. On the positive front, many districts have now invested millions of dollars in infrastructure to support virtual instruction, so that technology is likely to play a more prominent role in education, even when everyone returns to the classroom (National Education Association 2021). The ability to switch to virtual instruction, while not ideal, can be seen as a positive in improving schools' ability to recover "virtually" if (1) children are displaced and if access to electrical power or Internet is impacted in affected and host communities; and (2) the ability of schools and teachers to return to the physical classroom is impeded.

Food Production

The industry of meatpacking, and of meat production in general, remains largely invisible to the general public, despite its centrality to food production. The majority of floor workers in meatpacking plants are immigrants and/or people of color who come from lower-income households (Fremstad et al. 2020). As of 2020, 44% of floor workers were of Hispanic descent and 25% were African-American (Fremstad et al. 2020). Additionally, 51% were immigrants, of which roughly one quarter lived in households with limited English proficiency (Fremstad et al. 2020). Of the total factory workforce, 45% were in low-income families and one in eight lived below the federal poverty line (Fremstad et al. 2020). All of these factors contribute to the vulnerability of the meatpacking workforce, both in mitigating exposure to COVID-19 and in seeking relief from work-related exposure to it.

Built Environment

Meatpacking plants are factories that range in size from a handful to hundreds of workers on the floor. These individuals work shoulder-to-shoulder to slaughter, process, and package nearly all the meat sold in grocery stores throughout the nation. This industry was deemed essential by the Federal government at the onset of the pandemic (Bogage et al. 2020), forcing these workers to continue to work despite potentially fatal health hazards. Generally speaking, meatpacking plants are not designed to essential business criteria, but rather they are designed to support maximum production efficiency (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021).

As COVID-19 spread in the spring of 2020, a Presidential Executive Order compelled meat processors to remain open to head off shortages in the nation's food supply chains (Trump 2020), despite mounting reports of plant worker deaths attributed to COVID-19. The Executive Order invoked the Defense Production Act to classify meat plants as essential infrastructure that must remain open (Bogage et al. 2020). As noted in this paper, meat processing plants were prepared to address power shortages; however, until these plants were declared essential facilities during COVID, managers and owners were not required to follow building code requirements for essential facilities (which would have included requirements for mitigating risks from tornadoes). Section 423 of 2021 International Building Code (IBC), which specifies shelter requirements, is essentially the same as in the 2015 edition, with the exception of new criteria regarding additions to existing schools. Hence, in terms of current IBC, meat processing plants are not required to have an ICC 500-compliant shelter. The compound hazard of COVID-19 coupled with tornadoes has thus highlighted the need to revisit IBC code for this type of food processing infrastructure going forward.

As of April 2021, about 334,000 COVID-19 cases were directly attributed to meatpacking plants as the source of infection, with the actual number likely much higher (Preidt 2021). As of 2020, approximately 18,000 COVID deaths were attributed to the spread of COVID in the nation's meatpacking plants (Grabell 2020). The top five meat production companies—JBS, Tyson, Smithfield, Cargill, and National Beef—had an estimated total of 59,000 workers infected with the virus, at least 269 of whom subsequently died (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). Overall, the total impact of COVID-19 on the industry cost the world economy more than $11 billion (Preidt 2021).

Pandemic Compound Hazard

The meatpacking industry is notoriously secretive and reluctant to share information about its facilities and operations, especially when the information is related to COVID-19 (Narea 2020). Data made public in October 2021 showed that within the five largest meatpacking companies (Tyson Foods, JBS, Cargill, Smithfield Foods, and National Beef), official notice was given of only one-third of the total COVID-19 cases among workers (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). Within those five companies, nearly 90% of their plants recorded multiple COVID-19 cases over the time period, and at National Beef the figure was 100% (Douglas 2022). A US Congressional subcommittee formed to look into the COVID crisis in plants concluded that the five companies should have acted more quickly, and indeed that they often pushed back against public health recommendations and requirements (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). Moreover, there was little to no oversight into plants' compliance with Occupational Health and Safety Administration guidelines and Department of Health regulations (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). With the Biden Administration signing an Executive Order to protect the workers in plants, including increasing federal regulation and plant inspections, many of the meatpacking unions are optimistic that conditions will improve (Krebs 2021).

The high case rates in meatpacking plants had their parallel in the communities in which they were located. In beef and pork packing plants, for example, the COVID-19 infection rates were doubled in counties with plants compared to those without them (Preidt 2021). Similarly, in counties with chicken processing plants, infection rates were 20% higher than in counties without them (these figures were recorded within only the first 150 days that COVID-19 was first detected within a given county) (Preidt 2021). Local Health Officials in Black Hawk County, Iowa, saw COVID-19 rates skyrocket 900% in April 2020, and they attributed more than 90% of those cases to the local Tyson plant (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). Overall, the mortality rate due to COVID in counties with meatpacking plants was 37%–50% higher than in counties without a plant (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021).

Two different joint-hazard situations illustrate some of the dynamics of hazard exposure in this setting. The first occurred when a tornado storm passed near a Tyson Foods plant in the state of Tennessee (Shaffer 2021). The plant briefly lost power due to the impact of the storm, but there was "no indication of any significant impact on Tyson operations" due to the availability of on-site electrical generation (Shaffer 2021). The second occurred when Hurricane Ida struck one of Sanderson Farms' processing plants in Louisiana and five others in Mississippi. Operations were briefly stopped due to power loss at some locations (Demetrakakes 2021) but recovered due to on-site generators. In contrast to COVID-19, for other natural hazards, there were plans in place owing to prior experiences in these regions with high wind events (Shaffer 2021; Demetrakakes 2021).

Transition Dynamics

The act of meatpacking is, inherently and inescapably, one that requires making physical changes in the raw materials in order

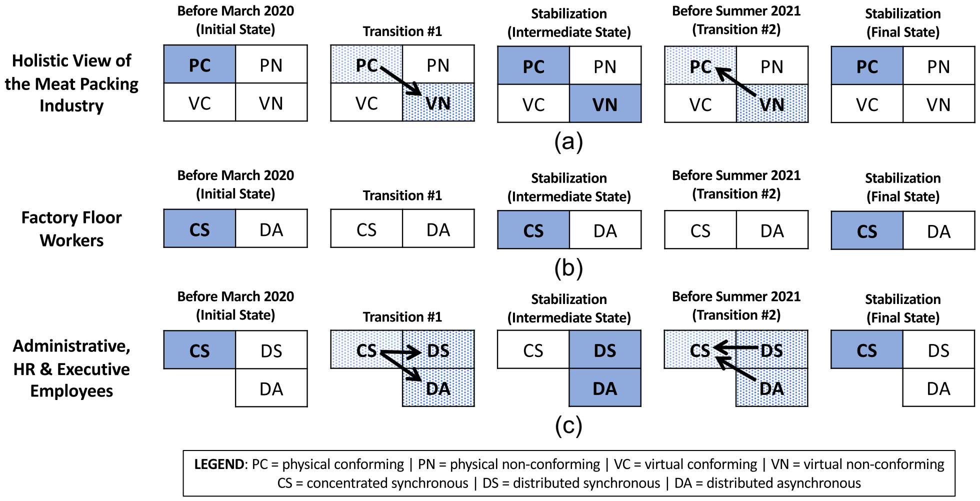

Fig. 1. Transitions in meatpacking plants.

to yield a consumable product. Opportunities for manipulation of the spatial distribution of elements of the meat processing system were therefore confined to changes in physical configuration, with no opportunities for switching to a virtual/remote or hybrid mode for workers on the production line. Other pressures and circumstances yielded few changes in the physical configuration of the processing system, including the close proximity of workers. Thus, it may be said that no transition along the spatial dimension was observed, so that workers continued to use physical elements in a way that conformed to designed use (we abbreviate this state of the built environment as PC). In comparing this system pre-COVID to post-COVID, then, no significant change was detected in the spatial distribution (i.e., it remained concentrated) or in temporal frame (i.e., it remained synchronous), here abbreviated as CS, as shown in Fig. 1.

In contrast, while workers on the factory floor remained onsite, certain supporting systems (e.g., administrative, human resources, and upper management) experienced multiple transitions, including transitioning from physical/conforming (PC) to virtual/nonconforming (VN) at the height of the pandemic. This transition similar to the one shown in panel C of Fig. 1. Administrators often operated both synchronously (DS) and asynchronously (DA) from their homes. In the so-called stabilization period shown in Fig. 1, which occurred before the summer of 2021, many of those workers transitioned back and operated under the physical conforming (PC) modality (Fig. 1, panel A). Before the pandemic, these workers operated in concentrated synchronous (CS) mode in office spaces (Fig. 1, panel C), and the at the height of the pandemic they worked in distributed asynchronous (DA) and distributed synchronous (DS) modes. As the pandemic appeared to steady, many of the workers transitioned back to concentrated synchronous work (Fig. 1, panel C). The meatpacking industry as a whole experienced a transition from PC to both PC and VN at the initial onset of the pandemic, then transitioned back to PC before the summer of 2021 (Fig. 1, panel A) (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021).

During the pandemic, the December 2021 tornadoes that struck Kentucky and surrounding states highlighted the importance of assessing and mitigating the extreme-wind vulnerability of existing essential facilities and improving the tornado damage resistance of new essential facilities. In addition to widespread property damage, the tornado outbreak resulted in numerous injuries and deaths, demonstrating the importance of providing easily accessible tornado storm shelters or safe rooms to ensure life-safety protection for the occupants of essential facilities (Federal Emergency Management Agency 2023).

Tornado storm shelters and safe rooms are specifically designed for life-safety protection during strong and violent tornadoes. Storm shelters meet the requirements in the International Code Council (ICC) 500 standard, while safe rooms meet both the requirements in the ICC 500 standard and the more stringent FEMA Funding Criteria of FEMA P-361. Through field investigation and research, FEMA developed these Funding Criteria to provide near-absolute life-safety protection during extreme-wind events. Essential facility storm shelters and safe rooms are typically multiuse; hence, during normal times, the space may function as a meeting room, restroom, or other similar purposes. Section 423 of the 2015 International Building Code (IBC) (ICC 2018) for the first time included the requirement that 911 call stations; fire, rescue, ambulance, and police stations; and emergency operation centers be ICC 500-compliant storm shelters, as these were deemed essential facility buildings when constructed in 250-mph tornado shelter design wind speed zones.

With respect to guidelines and building code requirements, going forward, ASCE/SEI 7-22 (ASCE 2022), Minimum Design Loads and Associated Criteria for Buildings and Other Structures, and the forthcoming 2024 International Building Code (IBC) define "essential facilities" as "buildings and other structures that are intended to remain operational in the event of extreme environmental loading from flood, wind, tornado, snow, or earthquakes." It is important to note that previous editions of ASCE 7 and IBC defined "essential facilities" with the same language but did not include "tornado" because a tornado load determination had not yet been addressed until the publication of ASCE 7-22. Its forthcoming reference by the 2024 IBC will be the first edition to do so.

Discussion

The lack of transition within meatpacking plants in the case of the floor workers had deleterious consequences. There was little impact on production levels due to COVID-19 unless a plant was shut down by the Center for Disease Control and Prevention (CDC) for a mass outbreak. In the case of closures by the CDC, any deficiencies in production were remediated through increased production within other plants in the area. There was little impact on the consumer side of the supply chain since the production levels were consistent (Select Subcommittee on the Coronavirus Crisis 2022).

The negative impact on floor workers was amplified for racial minorities and for low-income and immigrant workers (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). Not only did COVID-19 cause repercussions for floor workers, but it also affected their greater communities (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021). Counties with large meatpacking plants had disproportionately high infection rates, thus impacting individuals who were unrelated to the meatpacking industry (Select Subcommittee on the Coronavirus Crisis, United States House of Representatives 2021).

In terms of policy, the impacts of COVID-19 within meatpacking plants led to a congressional subcommittee investigation into the industry, and it is possible that this will result in positive change for the workers in order to protect them now and in future pandemics. The Biden Administration is working to ensure an increase in plant investigations to enforce regulations from the federal government on the meatpacking industry as well as expanding protections for meatpacking plant workers (Krebs 2021).

Housing

The US housing sector is composed of approximately 139 million individually managed, largely nonengineered units. It is thus guided by millions of potentially different usages, configurations, and adaptations (Abbou et al. 2022). Thus we first situate the US housing inventory in general within the framework, examining the distribution of units to establish norms in intended and adapted uses at different points during the current pandemic, then turning to the specific example of housing transitions in the state of Louisiana during a period of simultaneous exposure to the pandemic and to multiple hurricane landfalls.

Built Environment

As discussed previously, the normal venues for work and school activities were largely shuttered during the initial COVID-19 surge, followed by a transition to telework and telelearning. Given the closures and insufficient supply of private or low-density spaces (such as coworking facilities), personal residences emerged as the answer if these activities were to continue. This example highlights how state transitions were interdependent across many sectors: one physical element of the built environment (private homes) transitioned from conforming (in terms of conventional use as a place of habitation) to nonconforming observed use (i.e., as improvised infrastructure to support work and learning). In the remaining discussion, we therefore emphasize state transitions in the built environment in which physical elements put to conforming observed use transitioned to states in which physical elements were put to nonconforming use. These two states are respectively denoted States 0 and 1 (see right panel of Fig. 2).

Pandemic Compound Hazard

Given that housing is pervasive, managing its exposure to a compound hazard is feasible only for hazards with a confined geographic extent and seasonality (e.g., Gulf and Atlantic Coasts in hurricane season). Managing hurricane risk thus demands that surges in pandemic risk be out of phase with the peaks in hurricane activity. However, the extended cycle time over which a large proportion of homes supported productive activities in state State 1 (PI in yellow in Fig. 2) increased the potential for exposure to joint occurrence. The 2020 and 2021 Atlantic Hurricane seasons provide a case to exercise this aspect of the framework.

The sustained decentralization of productive activities into homes challenged the long-standing societal approach to minimizing the risks associated with natural hazard events. While the state transition in housing minimized pandemic risks, it actually elevated hurricane risks. Mitigation of hurricane impacts is founded on hardening a handful of buildings in each community (i.e., those deemed essential to recovery and preservation of life), with building codes reflecting the assumption that residences would not be expected to fill this role during and after a natural hazard event. Accepting significant damages to residences in design-level windstorms, the ensuing potential for injury and life loss was historically mitigated by evacuation mandates that concentrate residents in hardened community storm shelters, with the expectation of long periods of displacement while damaged homes are repaired.

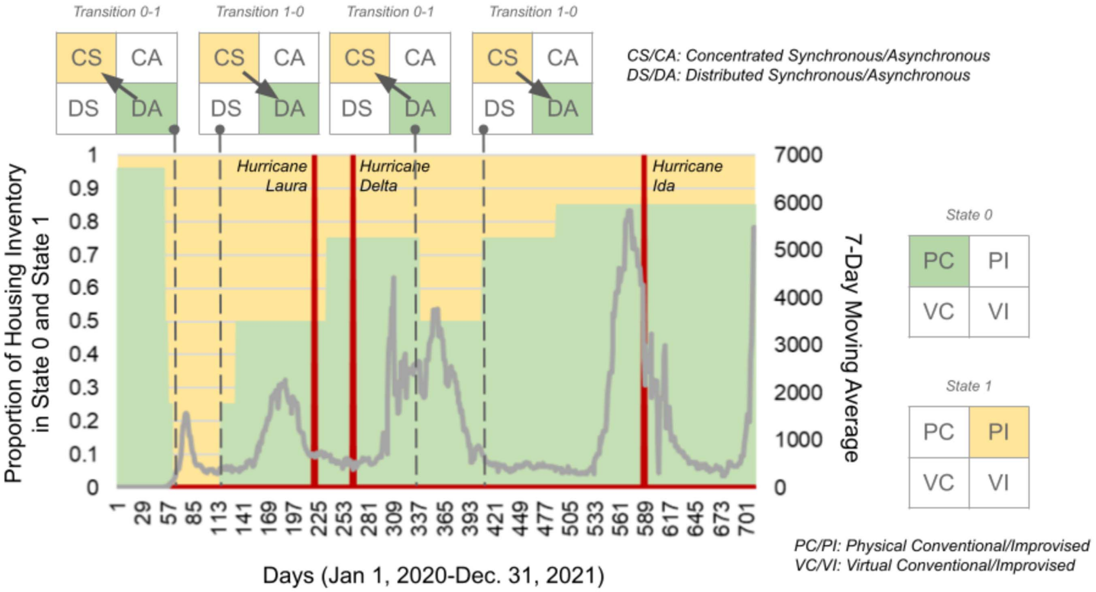

Fig. 2. State Transitions of Housing in Louisiana during 2020–2021. Proportions of State 0 and 1 derived from Louisiana reopening phases (data from Coronavirus Resource Center 2022) and 7-Day Moving Average of Daily Case Counts (data from USA Facts 2022) against landfall dates of notable hurricanes in 2020 and 2021 Atlantic Hurricane Seasons.

Transition Dynamics

The risks associated with pandemic-induced adaptations were revealed with the onset of the 2020 hurricane season and a pair of strong hurricanes (see Laura and Delta in Fig. 2), not only disrupting a home's support for productive endeavors but even forcing homes to take on new societal functions such as disaster sheltering. The approach of Hurricane Laura in August of 2020 prompted Louisiana (and Texas as a state preparing to receive Louisiana evacuees) to adapt their evacuation protocols and direct evacuees to "noncongregate" shelters such as hotels and motels to mitigate the risk of public hurricane shelters becoming superspreaders in two states with high levels of community spread (Haines 2020; Feuer 2020). The limited supply of hotel rooms (Haines 2020; McCullough and Garnham 2020) combined with inefficiencies of busing evacuees while maintaining social distancing (Karlin and McAuley 2020; Feuer 2020) ultimately transferred yet another critical service—sheltering logistics and financing—to households. The prospect of absorbing the forced transition of emergency management under compound pandemic hazards resulted in an many households sheltering-in-place during the hurricane's passage (Natario 2020), despite the fact that their homes were not constructed to survive this design-level hurricane. Surveys suggest an overwhelming majority sheltered in their homes in the 2020 hurricane season, weighing the risk of the pandemic more heavily than that of the hurricane itself (Collins and Polen 2022).

Hurricane Delta's landfall on October 9, 2020, brought strong winds and rain to some of the same areas. It further strained the state's evacuation capacity, with hotel rooms occupied by the 6,000 still displaced from Laura and the thousands more unable to shelter-in-place as their homes were among the more than 500,000 properties previously damaged by Laura (BBC 2020). A year later, during the fourth surge of COVID-19 (Fig. 2), Hurricane Ida forced even higher rates of shelter-in-place both because of the number of COVID-infected individuals unable to transfer to congregate shelters and the storm's rapid intensification that made evacuations of New Orleans and other major cities infeasible (Holahan 2021). However, in stark contrast to the prior hurricane season, public shelters were not only open but even accepted COVID-19-positive evacuees (Durkee 2021), a signal that society was prepared to accept the pandemic risks in the face of the life-safety risks of a potentially Category 5 hurricane, even in a state with vaccination rates hovering around 40%.

In Louisiana, the period March 13–22, 2020, marked the rapid transition from State 0 to State 1, as reflected in the proportion of housing inventory in each state (Fig. 2). This rapid and forced transition away from the conforming or intended use of housing required, at times, significant material deviations and arguably the highest levels of adaptation. And while businesses and schools continued to reopen in 2021, many of the physical adaptations of homes are anticipated to persist. Indeed, just as the 1918 Influenza pandemic introduced staples of the modern home such as powder rooms and closets (Lerner 2021), the COVID-19 pandemic is pushing the housing industry to deliver designs away from open concepts and toward more partitioned and acoustically friendly spaces that better support in-home activities associated with working and learning. Among these are more flexible floorplans, with features such as adaptive learning/working spaces, outdoor entertaining spaces, and even dedicated quarantine rooms (Lerner 2021). However, there is a need for cost-effective strategies to extend these potentials to private residences across the economic spectrum, lest the capacity to adapt and absorb joint pandemic hazards remains confined to higher-income households.

In State 1 (Fig. 2), the decentralization of productive endeavors from office buildings and schools into housing units prompted the temporal frame of housing to dramatically transition from phase-limited usage during evenings and weekends to continuous usage of the home. The rates of homeschooling in Louisiana more than doubled in 2020, consistent with national trends (Eggleston and Fields 2021). Similarly, the number of workers preferring to remotely work has doubled since the pandemic (Parker et al. 2020), and Louisiana's weak broadband infrastructure has been less conducive to remote work (Cohn 2021), creating barriers to sustaining the state transition long-term. Daytime hours, where the house was typically unused, were not only now in service but also forced to modify their spatial distribution of activities to achieve a higher density of parallel services than envisioned in their design. In other words, individuals in households had little choice but to work and study from home using shared or weakly-partitioned spaces.

In terms of *transition dynamics* from State 0 to State 1, *spatial distribution* and *temporal frame* shifted, respectively, from distributed/asynchronous (where limited productive activities in the home were informally distributed and phased, mostly in evening hours) to concentrated/asynchronous (where activities unfolded throughout the day, often in parallel and demanding a greater concentration of activities in *ad hoc* spaces). The dynamics of the shelter-at-home and reopening orders in Louisiana—together with surging case counts—dictated the proportion of homes in these respective states over time, with four broad transitions between 2020 and 2021 (Fig. 2). More recently, some homeowners have argued that State 1 should be the "new normal" due to its perceived benefits (e.g., greater flexibility, reduced commutes/environmental impacts, reduced overhead costs, and reduced COVID exposure).

Finally, regarding *transition costs*, and unlike a discrete school or office building, the decentralization of essential services into private residences implied that an entire inventory of the least formalized, lowest regulated, least equipped, and least supported elements of infrastructure was forced to simultaneously improvise to provide safe learning and work environments in the absence of formal regulations. These nonconforming uses arose as *ad hoc*, self-directed, and self-financed, largely achieved by adapting spaces that were not designed for these services. Individual transition costs and transition efficacy varied with the owner's degree of disposable income and the property's underused space, resulting in inevitable disparities.

Discussion

The building sector is moving away from performance goals of life safety and toward enhanced performance objectives to achieve functional recovery, defined initially in earthquake engineering as providing a building that is "maintained to safely and adequately support the basic intended functions associated with the preearthquake use or occupancy of a building" (FEMA 2021). The question then becomes what are those intended functions? Will a family's primary venues for productive endeavors such as education and employment continue to be assumed as external to the structure itself (see State 0: PC in Fig. 2), in which case functions are confined to less critical demands such as recreation, restoration, and socialization? Or have these functions permanently expanded in the wake of the pandemic to include more productive activities such as home schooling and remote work given to offer more flexibility and robustness to absorb forced transitions triggered by lockdowns of workplaces and schools in future pandemics? In such cases, the failure to achieve functional recovery would have high stakes as the loss of a home's use could equally imply disruptions to education and livelihoods. More critically, will these escalating functional demands expand even further to encompass disaster sheltering?

Once unthinkable, the function of a home as a disaster shelter became far more realistic given the hazards described here. Challenges with evacuation protocols—forcing households to shelter in highly vulnerable homes, consistent with aversions to evacuation and especially public congregate sheltering noted in other locales (Collins et al. 2021, 2022; Hill et al. 2021)—created demand for hardened residences with off-grid services (power, water) supporting shelter-in-place. A notable case, Florida's Babcock Ranch, demonstrated how off-grid communities could not only be environmentally sustainable but also remain fully functional (Ramirez 2002). Creating more hardened, off-grid communities would not only absorb the consequences of joint occurrence of pandemics and hurricanes, but also mitigate the pandemic-independent threats of fast moving hurricanes in overdeveloped coastal areas with insufficient egress infrastructure to evacuate the entire population in 24–48 h, a lesson also tragically learned in Hurricane Ian (Allen 2022). In short, the pandemic has underscored the fractures in our approach to relying on evacuation to maintain the historical life-safety design requirements for housing as supposedly noncritical infrastructure.

Discussion and Conclusion

This paper introduces and expands upon a transitions-based framework for describing adaptation to compound hazards in the built environment. The framework is cast largely in relation to the risks posed by compound hazards to the built environment during the COVID-19 era and, implicitly, to the individuals who live and work within that environment. At a conceptual level, the framework adopts an inherently functional perspective concerning these relationships. In so doing, it opens the possibility for theorizing broadly about the form, function, and timing of reconfigurations of the built environment in response to (or in anticipation of) exposure to compound hazards. The exploration of case studies from the COVID-19 era demonstrates that adaptive behavior in relation to hazards may involve marshaling a broad variety of elements of the built environment, including those that are not classified by policy as "critical," in order to preserve the flow of essential services.

The remainder of this section addresses three potentially productive approaches to enriching and extending the framework.

Exploring Issues of Scale

The case studies illustrate the relevance of multiple spatial and temporal scales in understanding transitions in the built environment. In terms of spatial scale, decisions were made at levels ranging from isolated, privately controlled structures to entire portfolios of buildings, based on their assumed significance to a community. The cases explored transitions ranging from the level of individual, specialized commercial buildings (i.e., meatpacking plants) to that of entire school systems. Notable across this sampling of community assets is the varied approach to regulating building design against natural hazards and the delivery of services contained therein. Schools represent an extreme case, with a design process that hardened them against hazards (in their role as critical infrastructure) and a policy process that introduced high levels of regulation into daily operations, including those operations that were adaptations to the pandemic. In contrast to schools were commercial constructions, such as meatpacking plants (likely not engineered with high importance factors), and nonengineered constructions, such as homes (whose level of regulation in their pandemic transitions mimicked the same degree of regulation governing their design, despite their increasing criticality in the pandemic).

Transition Dynamics

The transition dynamics perspective of this work is expressed in terms of evolving spatio-temporal relationships between different configurations of the built environment, as well as the associated costs of moving from one configuration to another. Starting with this level of abstraction has the advantage of encouraging the exploration of different approaches to expressing space, time, and cost. It also raises questions about the conditions under which ongoing shorter-term changes eventually cease, yielding states of the built environment that either are resistant to further transitions or that represent the target state (e.g., a transformation). The food production case study suggests a built environment that is in part characterized by such stasis, while the housing case study suggests a built environment that is in the midst of a potentially long-term series of transitions. Further research on the framework ought to yield implications for the measurement and modeling of transitions in a way that enables broader observations on the evolution of the built environment to be made.

An emerging area of research highlighted by recent work (Carvalhaes et al. 2020) and by the case studies is the role of virtual spaces in comprehensive approaches to hazard mitigation, including through hybrid approaches that mix physical and virtual elements. Work in this area is expected to continue to address traditional themes associated with technology-based support and training, but also the longer-term effects of the use of hybrid spaces on risk perception and decision making.

These preliminary observations suggest one obvious implication—that multiscale models of transitions will be needed—and one pressing question: that is, what are the spatial and temporal scales at which different approaches to adaptation are likely to occur given the properties of joint hazards and the populations exposed to them? In the educational system, for example, household-level adaptations—while not necessarily desirable or even effective—appeared preeminent. Less visible than spatial scale in the case studies is temporal scale: or, rather, differences between the temporal scale of the pandemic and that of hazards occurring concurrently. Further work is needed to characterize adaptation to compound hazards over longer time horizons.

Revisiting Criticality

It is perhaps not unreasonable to consider the last two decades of research on critical infrastructure as emphasizing the pursuit of system stability, security, and functionality through improved operations of infrastructure systems designated as critical (Mendonça and Wallace 2006; Ouyang 2014; Rinaldi et al. 2001). The examples offered here, and the framework itself, suggest that a different view is equally meritorious—namely, that adaptive capacity to ensure safety and essential services may reside outside the traditional means and materials that produce those services. The housing example in particular shows that private housing—underregulated, diffuse, and certainly not "critical"—represented an essential slack resource in the provision of a broad range of services given closures and failings in infrastructures designated as "critical." Additionally, for a broad range of learners and workers, the virtual environment enabled by networked computers yielded new virtual spaces, some home-grown, others official, within which learning and working could continue with little risk of exposure to COVID-19. Of course, the education and housing examples also suggest that, absent appropriate practices of risk management (e.g., in housing construction), this type of "virtual evacuation" could engender its own risks.

In technological terms, the potential (and, in some cases, the reality) exists for situating adaptive capacity within advanced technologies: that is, by endowing tools and technologies with an ability to adapt their form and function in response to actual or anticipated changes in exogenous conditions (e.g., Alanne and Sierla 2022; Alani et al. 2022). Extending this concept to the systems level would represent a logical progression of this work. For example, the food production case study considered here concerns one activity in a much more extensive system, in which questions of equitable access to healthy food are raised alongside questions of operational efficiency. Risks of compound hazards, considered at the systems level, should naturally lead to quantification of equity/efficiency trade-offs, and the role of adaptive capacity in negotiating those trade-offs.

The proposed framework is essentially agnostic in identifying which aspects of the built environment should be viewed as critical. Instead, it enables characterization of transitions in (arbitrary) elements of the built environment in relation to actual or potential hazards. The question of which "infrastructures" to examine in the case studies is therefore driven not by the question of criticality as defined by policy, but by a broader one: what are the essential needs that the built environment should help fulfill, and how is it utilized do so? The case studies suggest a broad range of possible answers to this question:

- The need to educate the populace was addressed through a large-scale, largely decentralized, and unregulated process of distributed instruction, enabled through the efforts of individuals and organizations not only inside but also outside the formal educational system;
- The need to maintain levels of food production led the federal government to declare meatpacking plants as essential facilities, thus requiring them to function at prepandemic levels, producing higher risks for floor workers than for those who could work virtually; and finally,
- The need to house the populace was addressed through comparatively routine approaches, but these had to coexist with new functions, including not only at-home education but also emergency shelter—both of which engendered their own risks.

As discussed here and elsewhere (Carvalhaes et al. 2020; Clark et al. 2018), a wider perspective on criticality is needed, one that is tied intimately to questions of demand (in terms of essential societal needs and functions) and supply (in terms of sources of security and stability, but also adaptive capacity). Research in this direction is expected to yield new, more holistic, perspectives on questions of societal resilience to individual and compound hazards. Indeed, in contrast to traditional, highly centralized approaches to pursuing resilience, COVID-19 has shown that the capacity for adaptation resides in many and varied sources. A promising role for the field of engineering is to bring these sources into our purview, manage their risks accordingly, and seek to leverage them for the greater societal good.

Data Availability Statement

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

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