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COMMENTARY

Resilient by design: the case for increasing resilience of buildings and their linked food-energy-water systems

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The resilience of buildings and food, energy, and water systems (FEWS) to natural or manmade disruptions are closely linked. The resilience of a building goes beyond the safety of its structural elements and must include the resilience of its supporting systems and the services they supply. The resilience of FEWS, in turn, can increase through design elements of a building that affect generation and storage of FEW resources. In this commentary, I discuss increasing the resilience of buildings and their linked FEWS—improving their resistance, absorption, restoration, and adaptive capacities—through new integrated systems design practices. I begin with a discussion of the current state of building design at the FEW nexus. I then use the prior establishment and current use of sustainability design objectives as an analogue to developing and implementing resilience design objectives. I review progress and limitations of specific drivers for increasing resilient design practices, including economic incentives, regulations, extralegal programs and initiatives, and societal incentives. My recommendations for leveraging these drivers to increase resilient design include: for economic incentives, quantify the costs and benefits to make the business case for resilience; for formal regulations, specify increased building requirements with performance-based resilience objectives; for extralegal initiatves, integrate these resilience objectives with existing certification programs and award designs that address FEWS as an integrated network rather than as disparate systems; and for societal incentives, demonstrate public benefit to shift societal perceptions of resilience. Together, these actions will motivate the design of more resilient building and FEW systems to increase their longevity, performance, and robustness.

Keywords: Resilience; buildings; food-energy-water systems (FEWS); design objectives; integrated systems; performance-based design; design practices and incentives

Introduction

Food, energy, and water systems (FEWS) are essential for the functioning, safety, and security of society. They provide critical resources and services for the population of a community. They are also characterized by interconnections and interdependencies, which can both support the performance of these systems, e.g., if outputs from one system can be leveraged for use in multiple systems; or expose the systems to additional vulnerabilities, e.g., if failures in one system cascade into losses for connected systems.

Buildings are also critical to daily life. We live the majority of our lives in buildings, with Americans spending on average 87% of their time in enclosed buildings (Klepeis et al. 2001). Buildings and FEWS are inextricably linked, particularly for energy and water systems. Buildings serve as the final distribution points for most municipal energy and water systems. Once energy and water resources are generated, treated, and transmitted, buildings – including residential, commercial, government, school, and hospital buildings – are where we consume these resources.

In terms of resource consumption, buildings account for 41% of total energy and 74% of electricity use in the U.S. (U.S. Department of Energy 2012). About 12% of freshwater withdrawals in the U.S. are for public supply, which includes delivery for commercial, industrial, and domestic use. The largest share is domestic, accounting for about 60% of public-use withdrawals or 23,800 Mgal/day (Maupin et al. 2014), which includes use for buildings.

Buildings have direct or indirect linkages with broader FEWS. For energy and water, most buildings are connected to the electricity grid and municipal water supplies, and rely on the physical links to these networks to function. For food, occupants of buildings typically rely on transportation systems and complex food supply chains to obtain their food. Buildings as secure sites to store, prepare, and consume food are particularly important in a disaster scenario, where a building can serve as an emergency shelter if it is powered, has water services, and is able to provide access to food for its occupants. On-site production of food could partly mitigate dependence on potentially disrupted transportation and supply chains during a disaster. Food (arriving from off-site or produced

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on-site) additionally requires on-site energy for refrigerated storage, and both water and energy for food preparation, consumption, and cleanup. Thus, multiple ties between buildings and FEWS all intersect at the building site. Thinking about these systems as an integrated network creates the opportunity to build systems that are more robust and able to persist in function, particularly during and after disaster scenarios.

Resilience of buildings and their linked FEWS

This article focuses on increasing the resilience of buildings and their linked FEWS through new integrated systems design practices; and on opportunities and drivers to motivate these changes. Resilience is a term that is used in many fields, from psychology to characterize the "process of, capacity for, or outcome of successful adaptation despite challenging or threatening circumstances" (Masten et al. 1990), to ecology as "a measure of the persistence of systems and of their ability to absorb change and disturbance" (Holling 1973). Recent work has expanded this latter definition to social-ecological systems (Walker et al. 2004). The notion of absorbing disruptions and persisting despite potential challenges and threats is adapted to the built environment and critical infrastructure to signify "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" (White House 2013). The performance of infrastructure systems, including buildings and FEWS, then has a corresponding impact on the health, safety, and security of communities (Johansen et al. 2017).

The resilience of critical infrastructure has four components: resistance, absorption, restoration, and adaptive capacities (Johansen and Tien 2017). Resistance is the ability of infrastructure systems to prevent and avoid potential hazards. Absorption refers to lessening the immediate damage caused by the hazard event, including taking actions to accelerate decision making in the case of an emergency and utilizing system redundancies (Ouyang 2014). Restoration refers to activities to support recovery after an emergency, including community notifications and optimized sequences of response. Adaptive capacities include increasing the strength of infrastructures and installing monitoring for the states of systems to decrease vulnerability to future disasters.

Two factors make it a national imperative to increase the resilience of our critical infrastructure to disasters (National Academies 2012). First, the modern design approach emphasizes code compliance and minimum cost projects (Loosemore and Richard 2015). While it is true that many buildings, and even water systems such as ancient aqueducts, have existed for centuries, these were designed at the time with excess capacities. Such capacities would be designed out in modern times to reduce cost. Instead, buildings and FEWS are now designed to meet minimum safety requirements and maximize efficiency, with a low-bid mentality constraining innovation (Miozzo and Dewick 2002).

Second, buildings and their linked FEWS are increasingly subjected to hazards. These include natural disasters and manmade, deliberate attacks (DHS 2015). Increasing frequencies and intensities of natural hazard events (Flato et al. 2013) and accelerated degradation of structures (Saini and Tien 2017) due to climate change are of particular concern. Recent events, such as earthquakes and hurricanes (Hines et al. 2009; Mukherjee et al. 2014), have shown the vulnerability of buildings and critical infrastructure to damage and failures cascading across networks (Duenas-Osorio and Vemuru 2009). Therefore, there is the need to increase the resilience of these critical systems (National Research Council 2010).

Integrated design practices consider the intersection of a building and FEWS. This offers the opportunity to increase resilience of these interlinked systems, where the resilience of one is coupled with the resilience of the other. For example, if, after a disaster, a community's energy system is functioning, however, the buildings are not safe to occupy, then there is no place for the community's residents to shelter and be able to utilize those resources. If, on the other hand, the building survives, but it has no energy, water, or food supply, its ability to serve a community's population is severely diminished. Assessing a building's resilience goes beyond the safety of its structural elements and must include the resilience of its supporting systems and the services they supply. This includes utility services when assessing post-disaster building performance (e.g., Mitrani-Reiser et al. 2012). Increasing the resilience of FEWS that exist within and link to a building increases the resilience of that building.

Building design offers opportunities to increase the four components of resilience of FEWS – resistance, absorption, restoration and adaptive capacities – through integrating the design of distributed FEW resources generation and storage systems into the operations of the building. Examples include on-site power generation, water storage, and food production. Increasing the structural strength of rooftop solar panels and greenhouse structures for urban farming, for example, would increase the systems' resistance capacities and abilities to withstand and continue functioning after a hazard event. Having both municipal water supply connections and a rainwater retention system would increase absorption capacity through increased system redundancies. The ability to utilize on-site battery backups to power local water distribution repair activities would facilitiate recovery for the water network and increase restoration capacity. A new system to dynamically predict conditions and change energy supply for the building across a diverse range of sources from external utilities to on-site solar or wind would increase adaptive capacity. Local generation of resources and on-site supply systems would be independent of, and therefore not vulnerable to, potential widespread failures on the network after a disaster. If the resilience of a FEW system is measured by its ability to provide FEW resources to members of the community after a disruption, then these adaptations increase resilience of the system. In these cases, resilient buildings and designs of their linked FEWS increase the resilience of FEWS overall to be able to provide minimum levels of service to the population during larger-scale disruptions.

In this commentary, I discuss opportunities for increasing resilience of buildings and their linked FEWS. I begin with a discussion of the current state of building design at the FEW nexus. Then, I examine specific drivers for changing practices in building design, including economic incentives, formal regulations, extralegal programs and initiatives, and societal incentives. I focus on the role of each driver in motivating higher-performance building design. First, I review, as an analogue, progress and limitations of these drivers towards adoption of sustainability-based design practices; then, I recommend ways each driver might help to introduce resilience design objectives. The recommendations will lead to new design practices to increase resilience of buildings and their linked FEWS.

Sustainability design for buildings has had many more years of development and can inform development of the resilience design objectives. I draw on the growth of sustainable design as an analogue for increasing resilient design, given that both sustainability and resilience design objectives move beyond safety and code specifications to achieve additional performance goals for buildings and their linked FEWS. In the discussion of sustainability, I focus on the limits principle of sustainability (Quental et al. 2011) because it has been the focus of building and system design. Specifically, the objective is to minimize the use of limited natural resources so that current needs can be met without compromising the ability of future generations to meet their own needs (Brundtland 1987). For buildings, this has meant decreasing the resources used during construction and consumed over the lifetime of the building. In the discussion of resilience, the objective is to maximize the likelihood that the systems will be able withstand and recover quickly from any potential disruptions. This includes increasing the resistance, absorption, restoration, and adaptive capacities of the building and corresponding FEWS. Assessing the ability of varying drivers to achieve these four components of resilience forms the basis for my recommendations for more resilient building design at the FEW nexus to increase the longevity, performance, and robustness of these critical systems for the future.

Current building design at the FEW nexus

Current building design at the FEW nexus emphasizes minimizing a building's use of energy and water resources. For energy, there is a recent movement towards automated building controls to more efficiently manage building energy (e.g., Agarwal et al. 2010, Klein et al. 2012). From an overall building design point of view, improvements in the building envelope, e.g., window-to-wall ratios, insulation of the walls and roof, air tightness, and window characteristics, are most effective in reducing building energy use (Harvey 2009). For water, installation of water-conserving devices and appliances, including showerheads, toilets, and clothes washers, reduces household water usage in the first few years of adoption (Lee et al. 2011). Landscaping and irrigation improvements decrease water usage outside the buiding (e.g., Syme et al. 2004, Haley et al. 2007). In all of these studies, energy and water systems are treated separately. Studies that do treat energy and water systems together focus on activities at the industrial generation and municipal distribution scales (e.g., Stillwell et al. 2010, Ackerman and Fisher 2013, Nair et al. 2014). Few studies focus on how to integrate these systems for more efficient and effective operation at the building level.

In recent years, there has been growing activity in urban agriculture, mostly on municipal lands close to buildings, and increasingly on rooftops (Mok et al. 2014). Urban agriculture occasionally considers the larger FEW nexus. For example, rainwater harvesting systems can be designed to water rooftop crops (Astee and Kishnani 2010), enabling crop cultivation without increasing building water usage. Another example involves combining building and greenhouse structures to reduce heating enegy requirements compared to standalone structures (Delor 2011). Vertical farming inside buildings or on their exterior walls has also been tried (Despommier 2011) but is far from routine, with only 44 vertical farming projects identified in all of North America as of a few years ago (Thomaier et al. 2015).

Building design elements for sustainable resource use, i.e., to decrease outside energy and water use in buildings and increase on-site generation and storage of FEW resources, also offers the potential to increase resilience. For energy and water, it results in decreased dependence on the utility services supplied by outside sources. The decreased vulnerability to outages on those networks increases the absorption capacity of the system. Using on-site generated energy and water resources to facilitate system recovery increases restoration capacity. For food, building-integrated food production has the potential to increase absorption capacity for resilience with an increased ability to withstand external disruptions such as weather extremes and certain pests (Specht et al. 2014). Integrating FEWS designs into a building enables it to be more self-reliant and maintain the functionality of the building and connected FEWS during and after disruptive events.

Changing design practices, however, can be complex. In the design process, many considerations come into play. Designers balance client demands, legal requirements, physical constraints, and cost. Economic drivers often prevail, with lowest cost designs that meet minimum codes and specifications chosen (Loosemore and Richard 2015). This is especially true for public projects, which are legally bound to accept the "lowest bid that meets the spec" (Heylin 1981). Many private owners similarly seek lowest cost designs and contractors (Rankin et al. 1996).

In the last few decades, however, there has been a growing recognition of the importance of designing for objectives beyond minimum codes and specifications. This has been particularly evident in designing for sustainability objectives to reduce the use of limited resources. Several sustainability-focused programs have emerged, such as LEED (Leadership in Energy and Environmental Design), Living Building Challenge, Green Globe, and EarthCraft. The number of LEED-certified buildings in the U.S. has steadily increased over this time period (U.S. Green

Building Council 2016a), reflecting shifting design norms and a movement towards more sustainable design.

Compared to the growth in sustainable design, however, resilient design is in the beginning phases of development. There is a growing national conversation around resilience (White House 2013). Programs to encourage construction of more resilient buildings include the Integrated Resilient Design Program from the National Institute of Building Sciences (NIBS 2016a), sponsored by the High Performance and Integrated Design Resilience Program of the Department of Homeland Security. Most of these efforts, however, focus on increasing resistance capacity through increasing the strength of structural elements to withstand and resist hazards. NIBS (2011) and NIBS (2016b) address this, as do retrofit design guides such as those from the International Code Council (ICC 2016) for earthquakes and Federal Emergency Management Agency (FEMA 2010) for wind. While the structural elements are important, the functioning of a building after a disaster goes beyond its structural or even non-structural components. Particularly with the connection between buildings and FEWS, it important to look at a larger scale beyond the structural elements. The Resilient Design Institute is moving in this direction to look at buildings combined with landscapes, communities, and regions (Resilient Design Institute 2016). Within this larger context, consideration of the FEWS on which a building depends is needed to fully assess and improve resilience.

Drivers for integrating resilience practices into design of buildings and their linked FEWS

Four drivers of change offer opportunities to integrate resilience practices into design of buildings and their linked FEWS.

Economic incentives

In building construction, economic drivers, i.e., a "lowest price mentality," most often prevail (Wong et al. 2000). Owners began to adopt and become willing to pay for more sustainable designs only after being able to make the business case for these higher priced designs (Von Paumgartten 2003). For example, costs are typically higher to furnish and install more advanced energy and water systems that use energy-water resources more efficiently. The client will expect a return on this additional investment, such as energy savings and decreased utility bills over the lifetime of the building. Additional economic benefits include increased market value and increased employee productivity for commercial buildings (Von Paumgartten 2003).

Examples of additional investment to create a more resilient building include installing redundancies in the building systems to increase absorption capacity. Constructing a backup water system supplied from an alternative source, for example, will minimize reliance on utility-provided water service that may be disrupted after a disaster (e.g., Porter et al. 2011). Codes require buildings to have a functioning water source to supply fire protection systems for occupancy. If a disaster results in damaged fire service lines, even if a building is structurally sound, it cannot be reoccupied. In this case, a redundant water system would supply code-required fire protection capabilities, facilitate reoccupancy of the structure, and decrease building downtime. Another example would be to integrate a greenhouse or a cool and dry area for food storage into the building design. This would provide food on-site that would otherwise have to be delivered in on transportation networks that may be down after a disaster. The water and energy resources required for these systems, such as for irrigation or refrigeration, would be powered from on-site backup sources. Such resources would increase the absorption capacity of the building. In general, clients who invest in a more resilient design expect the building to incur less damage and be able to maintain essential building functions during a disaster event. The decreased likelihood of damage translates into decreased costs for repair, the ability to maintain operability, and a faster return to full functionality, e.g., for the economic benefits of maintaining business continuity.

For sustainability, economic incentives have been effective in changing investment behaviors to reduce resource use. The most straightforward example is in the purchase of Energy Star products. Consumers are willing to pay higher prices for products with the Energy Star label due to anticipated energy cost savings (Ward et al. 2011). Similar results exist for buildings, with owners willing to pay for sustainable building attributes due to the anticipated energy saving benefits (Banfi et al. 2008, Kwak et al. 2010). Part of the success of this driver is the relatively straightforward quantification of costs and benefits associated with sustainable building practices. Building designers can estimate a sustainable building alternative to cost a certain amount more than a conventional design. They can also anticipate that the design will perform at a given level that will lead to a specific value of decreased resource use. For energy, for example, multiplying energy costs with the decreased energy use for each window, façade, and ventilation system option (Banfi et al. 2008), results in a certain value of cost savings. Designers then compare those savings with the potential increased costs for initial construction and subsequent maintenance of the sustainable design element. They can make a direct cost-benefit analysis to select the desired building design option. If the calculated benefits exceed expected increases in cost, it is an economically viable solution.

In comparison, resilience savings are more difficult to quantify. Cost savings associated with a more resilient building design are closely tied to risk. This introduces uncertainty into the problem with economic savings based on unknown damage values due to an uncertain event that may or may not occur in the future. For example, analysis of the economic benefits of investing in an on-site backup power generation system requires estimating the likelihood of a disaster event, predicting the probability of loss of utility-provided electricity service due to the event, and accounting for the probability that the backup system itself will function after the event. Building designers have to then convert the ability of the building to maintain operability through the outage to an economic benefit. They would calculate this based on business continuity or other measure to compare it to the initial additional cost.

Each step of this analysis has significant uncertainty that is difficult to quantify (Goulet et al. 2007). The analysis must be probabilistic to adequately account for risk and impact (Tien and der Kiureghian 2016, Tong and Tien 2017). In an environment of price competition and choice of lowest cost designs, it can be difficult to justify paying more now for cost avoidance later, particularly uncertain future costs. The lowest price mentality of the industry has over time removed from building designs exactly the kinds of system redundancies that might increase resilience, e.g., elements that can resist higher loads than originally anticipated or backup components if one fails in a disaster. It is important to demonstrate returns on resilience investments to motivate increased investment in resilient building design (Jennings et al. 2013). Potential methods to do this are long-term studies that track costs over building lifetimes, simulations over multiple impact scenarios to comprehensively assess risk, and historical studies comparing actual costs after a disaster with predicted costs from potential different system designs. Each of these would quantify the expected economic benefits of more resilient design to incentivize investment.

Formal regulations

Formal regulations, including building codes at the national, state, and regional levels, are the most important factors affecting building design. The U.S. has widely adopted the International Building Code (IBC), with states and municipalities adding amendments to these codes for their particular locations. Code compliance is legally required and extensive permitting and inspection practices enforce these codes. However, codes generally represent minimum standards of building performance. In the absence of additional drivers, builders or owners have little incentive to exceed the minimum requirements with design attributes that would likely increase overall costs. Thus, code provisions must become stricter or additional incentives must exist to drive changes in design.

Building codes regulate energy and water use in buildings by treating them as independent systems rather than as they actually are: a connected, integrated FEWS. Codes do not explicitly consider interactions at the energy-water nexus. For example, the electrical code is separate from the gas code, which is separate from the plumbing code. The building code has its own regulations for energy efficiency, which are separate from the regulations governing the mechanical energy systems themselves (Laustsen 2008). In consideration of the FEWS triad, food system regulations reside in separate governmental branches, including local health departments and state health codes governing food transport, storage, and preparation. These siloed regulations limit the ability of codes to regulate integrated systems designs across the FEW nexus.

The plethora of design codes can make merely navigating all existing regulations a challenge. Designers have minimal incentives to move beyond these codes to think about FEWS in new ways while still operating within the legal boundaries of the regulations. Instead, to maintain price competitivity and limit liability, most will follow standard design codes and customs of the trade. Miozzo and Dewick (2002) found that the common practice of awarding contracts through lowest cost selections constrains innovation. Traditionally, buildings have been designed for safety and efficiency. The former discourages designs beyond prescribed safety factors; the latter encourages omission of redundancies. This means that the excess capacity, additional reinforcements, or redundant elements that would contribute to increased resilience are designed out of projects in practice.

Within a code-driven design environment, increasing mandatory requirements is one potentially effective method to drive advances in design. This would create an even playing field such that more expensive designs that meet increased resilience design objectives would not be at a competitive disadvantage based on price. This would be applicable both for new construction and retrofits of existing buildings.

Further, the recent movement towards performance-based design offers additional opportunities. Traditional design codes specify particular methods or design parameters in a prescriptive approach. In contrast, performance-based design requires buildings to meet certain performance criteria. As long as the building meets those objectives, the designer is free to choose the method and details. This enables flexibility in the building design and provides space for creativity in the development of new solutions.

Among the most successful implementations of performance-based design are in seismic engineering (Priestley 2000, PEER 2010), e.g., for buildings to withstand maximum considered earthquakes with less than 10% probability of collapse (ASCE 2013). Extending the notion of performance-based design to resilience would be to create new performance measures related to resilience. For example, suppose a resilience requirement existed to be able to maintain minimum operations for the building, including providing minimum power, water, and food resources for occupants, for a certain number of days after a disaster. Performance-based seismic design required the creation of seismic performance measures. Similarly, establishing measures to meet desired resilience goals at the FEW nexus would support the development of new methods to meet those goals. Buildings would be required to meet the resilience performance-based requirements. Designers would be free to innovate to meet those requirements rather than merely following prescriptive design codes. Best practices would be shared in the industry to facilitate new designs.

With such a performance-based approach, the incentive would be to meet resilience objectives through an integrated system solution. For example, the building could include a greenhouse design element that allows occupants to cultivate crops for food production. The greenhouse could have a photovoltaic roof for distributed solar power generation (Cossu et al. 2014) combined with on-site battery storage as a backup in case of outages. Such a system would increase resilience for both food and energy systems for the building. Or, the design could include an integrated wind-solar hybrid renewable system with rainwater retention (Chong et al. 2011) to provide on-site power generation and water resources. A portion of the rainwater collected could supply building-based farming for food production. This integrated approach would likely be more cost-effective than designing three completely separate systems to provide backup power, water, and food. It would enable designers to leverage the outputs of one system as inputs to another to meet both sustainability and resilience goals. Rather than enforcing prescriptive codes, a performance-based approach allows flexibility in developing new solutions to meet FEWS goals. It enables designers to think in innovative new ways to meet performance objectives, increasing the resilience of buildings and the FEWS on which they depend.

Extralegal programs and initiatives

The rise, in the last few decades, of many extralegal programs and initiatives to support design and construction of more sustainable buildings offers the possibility of integrating resilience objectives into these design practices. Numerous "green building" initiatives support designs to achieve sustainability objectives, including LEED by the U.S. Green Building Council, the Living Building Challenge certification program by the International Living Future Institute, Green Globes ratings through the Green Building Initiative, the National Association of Home Builders Green Building Guidelines, and EarthCraft (Retzlaff 2008). Of these, LEED has become one of the most popular. Despite some objections (e.g., Lstiburek 2008), owners and designers have effectively adopted LEED as a standard for sustainable building design and construction.

The number of LEED-certified buildings in the U.S. is in the hundreds of thousands (U.S. Green Building Council 2016a). The Living Building Challenge, with more ambitious sustainability goals and establishment about 10 years after LEED, has a lower level of adoption: just over 100 projects in the U.S. and Canada are pursuing certification, with less than 30 certified projects worldwide as of this writing (International Living Future Institue 2014). For LEED, many high-profile buildings have certifications at silver, gold, or platinum levels, with prominently displayed LEED plaques at their entrances. The more widespread adoption of LEED, which began as a private extralegal program, has been due to a combination of factors: society's increasing emphasis on sustainability overall, specific economic incentives, and acceptance and adoption by public agencies.

Broader society now associates a certain cachet with LEED certification. Many public buildings seek LEED ratings at a level of silver or above. Officials communicate the ratings to the public to indicate a community's commitment to sustainability and clearly display the markers of achievement in the building. Private corporations similarly seek certification to demonstrate the organization's investment in sustainability efforts, often within the larger context of increasing corporate social responsibility (Smith 2007).

Accompanying such social and reputational gains, LEED has benefited from specific economic incentives and formal regulations for support. Economic incentives have been mostly tax-based, including property tax exemptions and tax credits for LEED-certified buildings in particular cities or counties. Formal legislation at the state level requiring LEED certification for public construction has further driven growth in the LEED program (Simons et al. 2009). Some states have also broadened previously LEED-centric incentives to include any "high-performance buildings." For example, the State of Maryland passed a bill in 2014 recognizing any building that "complies with a nationally recognized and accepted green building code, guideline, or standard" to meet state legislative requirements (State of Maryland 2014). Such adoption of these sustainability initiatives by public agencies has facilitated the growth of LEED and other programs.

In terms of contributing to reducing the use of limited resources to increase sustainability, studies have found LEED builidngs to use less energy per floor area compared to conventional construction, though improved performance is not necessarily correlated with certification level (Newsham et al. 2009). This shows an extralegal program, such as LEED, to be a viable mechanism to achieve sustainability design objectives. In terms of FEWS, of the points awarded in the LEED system for various building design elements, the original credits for water efficiency and energy use now extend into food systems, with site credits given for urban food production in the place of watered landscaping (U.S. Green Building Council 2014a). In addition, LEED has now moved beyond buildings to include certification for neighborhood development. Ratings for FEWS include credits for energy efficiency and water management. Local food production has its own point category at the neighborhood level (U.S. Green Building Council 2014b).

With the LEED credits separated across FEW categories, building elements are necessarily designed to gain credits within each category. For example, self-supplied renewable energy production will gain credits under the energy category. The opportunity exists, however, to design integrated systems that score well under the LEED framework by simultaneously gaining points in multiple categories for a single system. For example, an urban agriculture system may require additional water. If water can be cycled through the building using on-site renewable energy sources, such a system would gain credits across three categories: for self-supplied renewable energy generation, water reuse, and urban food production, incentivizing design of an integrated system compared to three disjointed systems addressing energy, water, and food. Similar incentives exist within other programs, such as achieving imperatives across multiple Living Building Challenge categories, including imperatives for "urban agriculture," "net positive energy," and "net positive water." This type of integrated system, while receiving points to increase sustainability under the LEED framework, would also increase absorption and restoration resilience capacities across linked FEWS.

Integrated systems designs would more effectively increase resilience across absorption, restoration, and adaptive capacities. Holistic design approaches would promote the positive interactions between the three components of FEWS and take advantage of systems-level effects, e.g., by leveraging outputs from one system as inputs to another to decrease overall resource requirements and use. Adding credit multipliers is a way to incentivize these integrated system designs to increase resilience. LEED could be modified, for example, as follows: If a designer can show that a building or FEWS design element scores credits in multiple areas across FEWS, a multipler could give that element 1.5 (or 2) points instead of 1 point if it connects two (or three) systems. Alternatively, an integrated systems design could receive a 2- or 3-point bonus overall. With 10 points separating each LEED certification level, this could prove significant enough to motivate innovative new integrated systems designs that leverage linkages among inputs and outputs across FEWS, with point values adjusted as needed. It would increase absorption, restoration, and adaptive resilience capacities by moving towards the notion of a building or neighborhood as a more self-contained system capable of providing essential life-support services to its occupants and residents during emergencies. Such a system that is less reliant on outside resources is better able to withstand disruptions that may occur at regional scales and sustain function under those conditions.

New programs are under development to support resilient building design. For the residential sector, this includes Resilience STAR, an initiative from the Department of Homeland Security (DHS) to build and retrofit more disaster-resistant homes (U.S. Department of Homeland Security 2013). The program is run in cooperation with the Insurance Institute for Business and Home Safety (IBHS), and its name derives from the widely adopted Energy Star designation for reduced energy use products. A home achieves a Resilience STAR designation if it meets the standards of the IBHS FORTIFIED Home program through a third-party verification process. The FORTIFIED program provides standards for new construction and retrofits to reduce damage and losses due to hurricanes, high winds, and hail (Insurance Insitute for Business and Home Safety 2012). DHS piloted Resilience STAR in 2014 for single-family homes in hurricane-prone communities (U.S. Department of Homeland Security 2014). However, since the conclusion of the pilot program, little impetus was offered by DHS, IBHS, or other parties to similarly certify additional homes, whether as new construction or for retrofits, in hurricane-prone areas or for other hazards such as tornadoes or floods.

The U.S. Resiliency Council (USRC) has created a building rating system that rates buildings on three measures: safety, damage, and recovery (U.S. Resiliency Council 2017). The current focus is on resilience to earthquakes. Safety refers to the ability of people to exit the building unharmed after an earthquake. Damage is measured by the repair cost as a percentage of replacement cost. Recovery is estimated as the time required to regain occupancy and basic use of the building. The USRC building rating system is currently in the promotion phase to encourage adoption by owners, tenants, lenders, and insurers.

Thus far, neither program has established itself as a standard for resilient design. The growth of the original Energy Star program and its ability to affect consumer behavior was partly due to its status as a government-supported initiative, contributing to its credibility, stability, and long-term viability (Banerjee and Solomon 2003). In that sense, Resilience STAR is well positioned, originating from DHS. However, consumers are willing to pay higher prices for products with the Energy Star label due to both anticipated energy cost savings and perceived public environmental benefits (Ward et al. 2011). As previously discussed, similar cost savings for resilient designs are more difficult to quantify.

Considering the resilience of buildings and their linked FEWS and the importance of considering them as an integrated system, a limitation for both programs is the focus on structural building elements. Resilience STAR focuses on the roof, windows, doors, walls, and foundation of the building, without consideration of linked FEWS. In the USRC building rating system, structural and architectural elements account for the safety and recovery time to basic occupancy of the building. The rating does not consider the ability to provide critical services, e.g., water or power, to a bulding. The scope of these programs would need to expand from only the building to their linked FEWS to comprehensively consider resilience, thus moving beyond resistance capacities to also include absorption and adaptive capacities.

In their current states, programs for evaluating building resilience have not yet been sufficient to incentivize a movement towards increasing resilient design. One proposal by the Resilient Design Institute is to integrate new resilient design credits into existing building design programs such as the LEED framework (Resilient Design Institute 2015). LEED recently adopted these credits in a pilot (U.S. Green Building Council 2015) and the U.S. Green Building Council established a new LEED Resilience Working Group to implement the project (U.S. Green Building Council 2016b). This is a promising avenue to integrate resilience into an established structure for improving building design.

In general, however, the combination of social, economic, and legal factors that led to the growth of initially informal standards such as LEED for sustainability are as of yet lacking for resilience programs and initiatives. The social conversation about resilience has not yet reached the levels as that on environmental sustainability. Current economic incentives, such as decreased insurance premiums for resilience-certified homes or tax credits for undertaking retrofits to increase resilience according to specific program guidelines, have been insufficient in motivating change (Kunreuther et al. 2013). In terms of legal support, certain jurisdictions have passed legislation in the wake of major events, such as the States of New York and Rhode Island after Hurricane Sandy (State of New York 2014, State of Rhode Island 2014). These acts support increasing the resilience of communities, particularly to climate risk. However, they do not lay out detailed legislation related to more resilient building or FEWS design. They are also independent of any common nationally or internationally recognized resilience standards or programs.

Societal incentives

The final element towards changing practices in building design is the influence of societal incentives. Studies have shown that social drivers such as perceived public environmental benefits affect purchase decisions for sustainable products (e.g., Ward et al. 2011). The general growth of the environmental movement in the U.S. (Gottlieb 2005) has made additional investments in sustainable designs palatable, and often desirable. Both public and private entities tout their signature green buildings among constituents and highlight their sustainable design features.

Designing for resilience, however, has a longer timeline to see benefits than does designing for sustainability. While sustainability does address long-term objectives in resource availability for future generations, benefits of a sustainable building option are immediately evident. For example, as soon as the building becomes operational, its occupants experience the designed energy savings. A rainwater retention system is activated after the first rain. Depending on the crop, a food system may take at most a year or two to reap the first harvest.

In contrast, the public benefits of increasing building resilience, e.g., in decreasing losses and facilitating recovery after a disaster, may take years or even decades to become evident. In some cases, a building owner may never experience the benefits, as its improved performance is shown during the occurrence of an uncertain future significant disaster event such as a 100-year storm or infrequent large-magnitude earthquake. In fact, in considering societal incentives for investing in resilient design, a parallel can be found in medicine. Increasing resilience during the building design phase is to undertake a preventative action to minimize future losses rather than spending to repair later damage. This is akin to a preventative medicine approach that focuses on preventing disease rather than treating future illness. Preventative approaches, ofcourse, are more effective for some diseases than for others. Similarly, more resilient design will be more effective at mitigating damage for some buildings compared to others. This is particularly true for buildings and systems that have increased vulnerabilities to damage based on building type, material, or location in areas with higher exposure to disasters or extreme loads.

Key to the adoption of preventative medicine was showing its public cost effectiveness benefits (e.g., Herman et al. 2005). Demonstrating the cost effectiveness of more resilient design can similarly show its public benefits to reduce losses and the economic burden of disasters. For example, Hurricane Sandy resulted in damages of $19 billion (Rosenzweig and Solecki 2014) and economic losses of $65 billion (Kunreuther et al. 2013). More resiliently designed buildings would decrease the costs for rebuilding and recovery after a disaster, thus benefiting the public (e.g., Rose 2009). Increases in human survival and availability of FEW resources would be additional public benefits and could increase social incentives to invest in more resilient design. Nevertheless, just as there were challenges in transitioning preventative medicine from theory to practice (Weingarten et al. 1995), building designers have been slow to adopt resilience practices.

Recommendations for more resilient design of buildings and their linked FEWS

The current state of incentives and the progress and limitations of various regulations and initiatives in promoting sustainable and resilient design leads me to recommend specific steps on economic incentives, formal regulations, extralegal programs, and societal incentives. Acting on these recommendations would further drive change in resilient system design.

In terms of economic incentives, further research in demonstrating the economic viability of resilient design would help make the business case for resilience. This includes the clear calculation of the costs and benefits of investments to increase resilience. This will necessitate quantifying several uncertain parameters, including frequency and impact of disruptions and disaster events. It will also require an understanding of the longer time scales associated with receiving the benefits of resilient design. This can be done through studies that track long-term costs over building lifetimes through failures and disruptions, perform multiple simulations to capture the uncertainty and risk associated with assessing resilience, or compare historical building costs after disasters with potentially reduced costs from other system designs. With the lowest price mentality of the construction industry, it is important to be able to show evidence of monetary returns to motivate increased investment in resilience.

In terms of formal regulations, increasing minimum standards required by building codes would raise the performance of buildings without putting higher-performance designs at a competitive price disadvantage. In addition, specifying standards on a performance basis rather than through prescriptive codes is a way to encourage innovation in the design of buildings' systems to meet required resilience performance objectives. This would require establishing new performance measures related to resilience. A performance-based approach would also incentivize design of integrated building and FEW systems as a more effective way to meet multiple performance objectives at once compared to individual designs to meet separate system code requirements.

In terms of extralegal programs and initiatives, building rating systems currently award points for each of the food, energy, and water categories. Adding credit multipliers or bonus credits for systems that address multiple categories simultaneously would incentivize the design of more integrated systems to leverage positive interactions across FEWS. Integration of resilience objectives with existing, established programs to improve building design such as LEED for sustainability design objectives is a promising option. This would facilitate adoption by public agencies and potential legislation to stimulate more resilient design. It is also important to develop a standard for resilient design and certification that recognizes not just the resistance of structural components but also the reliance of buildings on FEWS to increase absorption, restoration, and adaptive resilience capacities.

Finally, in terms of societal incentives, the general public will need to have a shift in mentality from commending those who manage to bounce back after suffering losses to celebrating stories of superior planning and precautionary actions. Valuing the undertaking of preventative measures before a disaster occurs will help create societal incentives for motivating more resilient design. Demonstrating the public benefit of more resilient design will increase the social impetus to make these changes in design practices. This can be done through cost-effectiveness studies to show decreased losses and reduced economic burden of disasters with more resilient design, as well as increased human survival and availability of FEW resources through any disruptions that may occur.

Buildings and FEWS are closely linked, and both are critical to the continued survival and growth of our communities. Through designs and retrofits that better integrate buildings and their linked FEWS, we have the potential to create buildings and systems that perform more positively in the face of disruptions, particularly after a disaster event to continue provision of services to the community. Drivers involving economic incentives, legal regulations, and social incentives exist to motivate more resilient design. Work in any one of these areas would help support these efforts, but coordination among all three would significantly impact the creation of integrated buildings and FEWS to increase the resilience of our communities and these critical systems on which they depend.

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