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Integrated assessment across building and urban scales: A review and proposal for a more holistic, multi-scale, system-of-systems approach

Chenyang Bi, John C. Little *

Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, United States

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ABSTRACT

Humanity is facing major societal challenges that are complex and systemic in the nature of their drivers, interactions, and impacts. Because buildings and cities play a substantial role in these societal challenges, we need reliable approaches that can be used to assess their resilience and sustainability. Given that building and urban systems are usually tightly coupled, we critically review nine building-scale assessment frameworks and seven urban-scale assessment frameworks, ranking them from high to low in terms of the causality among component systems. We identify four major knowledge gaps that, to varying degrees, span the entire range of assessment frameworks: (1) causality among component systems and their subsystems is limited; (2) sustainability and resilience are too narrowly defined; (3) social systems are inadequately addressed; and (4) building- and urban-scale assessments are poorly connected. To address these limitations, we briefly introduce several closely-related fields of research including integrated assessment and modeling, social-ecological systems research, land systems science, socio-environmental systems modeling, modeling of human behavior, multi-scale modeling, and multi-fidelity modeling. Building on these rapidly emerging research domains, we conclude by proposing a more holistic, multi-scale, system-of-systems approach that connects across building and urban scales using several common systems.

1. Introduction

Many of the world's greatest societal challenges, including those associated with climate change, interdependent infrastructure systems, coastal and inland flooding, renewable energy, and disaster management, are complex and systemic in the nature of their drivers, interactions and impacts. Often framed in terms of resilience and sustainability, these challenges require integration across a wide range of environmental, economic, and social systems (Little, Hester, & Carey, 2016).

Many assessment frameworks have been developed in an attempt to integrate data and knowledge in buildings and cities. Examples include green buildings, building rating systems, building information modeling, urban resilience, and urban metabolism. Many of these frameworks have been the subject of detailed reviews (Alyami & Rezgui, 2012; Ribeiro & Pena Jardim Gonçalves, 2019; Seyis, 2020; Zhang et al., 2019; Zheng, Yuan, Zhu, Zhang, & Shao, 2020; Zhou & Williams, 2013), but existing reviews typically focus on comparisons within a single framework (e.g., comparing one rating system to another) and comparisons among the different approaches are limited. Many of the frameworks are interrelated with considerable overlap, and the building and urban environment are intimately connected, but are usually considered entirely separately. Overall, there is no overarching review that categorizes and compares the various frameworks and discusses their collective strengths and limitations.

In this critical review, we compare nine building-scale assessment frameworks and seven urban-scale assessment frameworks, ranking them from high to low in terms of the causality among component systems, as shown in Fig. 1. We then identify four major knowledge gaps that, to varying degrees, span the entire range of assessment frameworks. Finally, to address those gaps, we briefly outline a more holistic, multi-scale, system-of-systems approach that could be used to connect across building and urban scales to more systematically inform the policy and decision-making process.

* Corresponding author.
E-mail address: jcl@vt.edu (J.C. Little).

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2. Assessment frameworks at building and urban scales

2.1. Ranking of assessment frameworks

It is increasingly recognized that a building or a city can be conceptualized as a system of systems (Bašić, Strmo, & Sladoljev, 2019; Jin, Gubbi, Marusic, & Palaniswami, 2014; Schoonenberg, Khaya, & Farid, 2019; Sharifi, 2019). Thus, a building or a city may have systems that interact with multiple other systems based on complex, dynamic, and causal relationships (Iwanaga et al., 2021; Little et al., 2019). Additionally, building-scale systems can strongly interact with urban-scale systems because buildings are among the most important components of a city. The complex dynamics and interdependencies among the systems mean that realistically assessing either sustainability or resilience is extremely challenging. These complex problems are usually related to multiple social, environmental, and economic systems that are tightly coupled, constantly changing over space and time, and governed by feedbacks (Reyers, Folke, Moore, Biggs, & Galaz, 2018), and it is usually the case that our understanding of those problems is overwhelmed by their complexity. For example, seemingly obvious solutions to problems involving such complex systems frequently create unintended consequences that worsen the situation (Bray & McCurry, 2006; Homsy & Hart, 2019).

Many assessment frameworks at the building and urban scale divide the overarching goal (for example, achieving sustainability or resilience) into multiple independent goals with corresponding assessment criteria. The criteria are typically used to identify indicators, which are then used to quantify the gap between desired and existing conditions. By dividing a complex problem into smaller domains of knowledge, experts then work to close the gap between desired and existing conditions in their respective knowledge domains. However, when considered within the context of the societal challenges listed above, the systems within a building or a city are almost always highly interdependent. Changes to one system may negatively or positively impact other systems. Negative impacts are referred to as trade-offs, while positive impacts are referred to as synergies or co-benefits, assuming the impacts can even be identified in advance. Negative impacts are generally referred to as unintended consequences when they cannot be identified in advance. Identifying synergies and trade-offs without causing unintended consequences is a significant challenge for decision-making across multiple complex systems.

The multi-purpose nature of buildings, which satisfy the needs of occupants for safety (Böke, Knaack, & Hemmerling, 2018), functionality, comfort (Iwaro & Mwasha, 2013), and aesthetics (Winters, 2007), while maintaining high efficiency in resource consumption (IEA, 2008), will inevitably create opportunities for synergies and trade-offs among the various systems. For example, goals in the building energy system can potentially be in conflict with those in the health and comfort system. Room air recirculation is beneficial to achieve high energy efficiency in buildings, but the strategy may reduce the amount of fresh air brought into the indoor environment, thus worsening indoor air quality. At the urban scale, the building sector is an important factor in climate change mitigation because buildings contribute about 40 percent of greenhouse gas emissions globally (United Nations Environment Programme, 2020). On the other hand, buildings are one of the most crucial aspects for adapting to climate change because structurally reliable and resilient buildings are necessary to shelter occupants from extreme weather. The important role of buildings in mitigating and adapting to climate change requires that building construction, operation, and maintenance are optimized for multiple goals. Nevertheless, this considers climate change alone, while other potentially interdependent societal challenges are ignored.

Given the complexity of the societal challenges described above, assessment across building and urban scales cannot simply rely on assigning scores to indicators. In many cases, these indicator scores are so aggregated in nature that it is not clear how an engineer can intervene to positively improve the indicator score. Assessment frameworks should instead focus on establishing causal relationships between the systems in a building or a city and on the desired measures of performance and effectiveness (Group, 2015). Such causal links are established either by a data-driven or a model-based approach (Schoonenberg & Farid, 2020). In the former, input data is tied to measures of

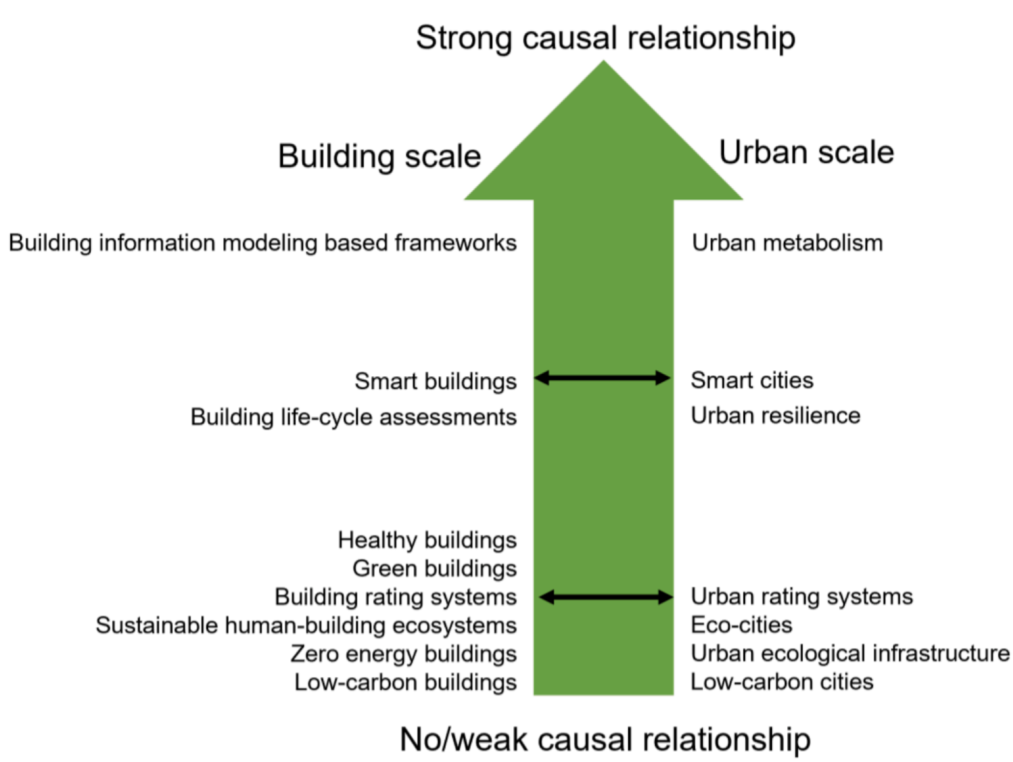

Fig. 1. Ranking of building- and urban-scale assessment frameworks based on the degree of causality among systems of a building or a city.

performance through statistically derived functions that describe how the building and/or urban area behaves. In the latter, the statistically derived functions are replaced with mechanistic models. Interventions that seek to change a system's structure ultimately require the causal relationships found in model-based approaches whereas interventions that seek to change only the system's behavior can rely on either data-driven or model-based approaches. Assessment frameworks that rely on indicators without causal relationships describing how the building or city behaves do not enable engineering interventions (Schoonenberg & Farid, 2020).

We therefore roughly rank the assessment frameworks based on the degree of causality among the systems and/or indicators within the framework (Fig. 1), although we acknowledge that we are unable to comprehensively examine each framework in this brief overarching review. Nevertheless, our review clearly identifies four major knowledge gaps that, to varying degrees, span the entire range of assessment frameworks:

1) Causality among component systems and their subsystems is limited.
2) Sustainability and resilience are too narrowly defined.
3) Social systems are inadequately addressed.
4) Building- and urban-scale assessments are poorly connected.

2.2. Assessment frameworks at the building scale

Buildings serve many purposes that are associated with building systems. For example, building envelope systems protect occupants from outdoor weather; water and energy systems support basic building operations; economic systems are associated with building operation and construction costs; and social systems involve occupant behavior and human comfort. Given that those building systems are likely to be interdependent, achieving goals at the building scale requires the integration of multiple systems to minimize trade-offs and maximize synergies. Although there has been considerable progress in developing approaches to holistically evaluate complex problems at the building scale, the specific boundaries and areas of application are not well-defined, and in some circumstances, the approaches are essentially interchangeable. In an attempt to compare existing approaches, we briefly review low-carbon buildings, zero energy buildings, sustainable human-building ecosystems, building rating systems, green buildings, healthy buildings, building life cycle assessment, smart buildings, and building information modeling.

2.2.1. Low-carbon buildings

Low-carbon buildings are designed and engineered to reduce carbon emissions and improve energy performance, including the use of low carbon materials, low carbon techniques, and renewable energy during the entire building life cycle (Zhang, Li, & Zhou, 2017). By definition, the assessment of low-carbon buildings is constrained to a single indicator (greenhouse gas emissions) although this is one of the most important factors contributing to climate change. It is reported that the building sector represents 28% of global energy-related CO_2 emissions, rising to 39% when construction industry emissions are included (IEA & UNEP, 2019). Since the two main methods to reduce greenhouse gas emissions are to decrease total energy consumption and to increase renewable energy use (IPCC, 2014), low-carbon buildings focus heavily on energy.

Although the low carbon concept is straightforward to understand, there is no consensus on the detailed framework and methodology to assess and evaluate low-carbon buildings. Luo, Tan, Langston, and Xue (2019) identified five main themes in low-carbon building research focusing on policy and practice, life cycle assessment, building design, technology innovation, and building material. They also found that those themes were investigated separately and rarely studied in a connected and systematic way. Additionally, the energy-centric focus on low-carbon inevitably overemphasizes the influence of energy consumption and greenhouse gas emission, but energy saving is not the only goal, even within the context of climate change. For example, resilient buildings are needed to withstand more frequent extreme weather events (Charoenkit & Kumar, 2014), and socio-economic impacts of building energy retrofits need to be included in assessment frameworks (Amini Toosi, Lavagna, Leonforte, Del Pero, & Aste, 2020). Overall, the low-carbon framework clearly targets energy in buildings, but the definition of sustainability is limited to climate-related aspects.

2.2.2. Zero-energy buildings

The International Energy Agency defines zero-energy buildings as buildings that do not use fossil fuels, while the building should obtain energy from solar and other renewable resources (IEA, 2008). Hence, zero-energy buildings focus on minimizing energy consumption and maximizing energy produced by renewable energy systems (Li, Yang, & Lam, 2013). While more details are provided by Marszal et al. (2011) and Sartori, Napolitano, and Voss (2012), zero-energy buildings are not substantially different from low-carbon buildings, which also focus on energy, and share the drawbacks discussed above.

2.2.3. Sustainable human building ecosystem

Due to the lack of socio-economic systems in earlier building assessment frameworks, a sustainable human building ecosystem framework was developed to blend occupant comfort and behavior with social and monetary sciences and the design, engineering and meteorology of buildings (Talele et al., 2018). Although at an early stage, the framework improves the understanding of occupant behavior (energy-related occupant behavior, thermo-physical behavior related to thermal comfort (diet, clothing, movement) and energy usage patterns) and also contextual factors which directly or indirectly influence all behavior (Talele et al., 2018). However, similar to low-carbon and zero-energy buildings, the sustainable human building ecosystem framework remains energy-centric. The social and economic dimensions are included in the framework only when they directly impact building energy consumption or vice versa.

2.2.4. Building rating systems

Rating systems are closely associated with green buildings and are commonly used to evaluate building sustainability. There have been extensive developments in integrated building assessment rating systems such as the Building Research Establishment Assessment Method (BREEAM), Sustainable Building Tool (SBTool), Leadership in Energy and Environmental Design (LEED), and Comprehensive Assessment System for Building Environment Efficiency (CASBEE) (Alyami & Rezgui, 2012; Kajikawa, Inoue, & Goh, 2011). The rating systems assess building sustainability based on a list of evaluation criteria with "water", "material", "energy", "indoor environment", "site", "land and outdoor environment", and "innovation" as the most popular criteria (Shan & Hwang, 2018). Many broader criteria contain a subset of criteria that enables assessment of construction phase or building type. For example, LEED includes LEED Building Design and Construction (BD + C), LEED Interior Design and Construction (ID + C), LEED Building Operations and Maintenance (O + M), and more (Zhang et al., 2019). Multiple indicators are used to evaluate each criterion of interest and calculate an overall score based on the summation or weighted summation of credits in each category (Cordero, Melgar, & Márquez, 2019; Shan & Hwang, 2018; Wen et al., 2020).

In contrast to low-carbon buildings, zero-energy buildings, and sustainable human building ecosystems, which all focus strongly on energy, building rating systems cover more aspects of sustainability by dividing a building into many independent criteria for which indicators can be established and quantified. The indicator-based rating systems divide a complex assessment framework into a series of simple evaluation criteria thus creating a semi-quantitative method to evaluate sustainability. However, there is no causal relationship among the individual building criteria. Because the linear combination of indicators, either weighted or not, is a fixed aggregation method, the assessment framework cannot capture the dynamic relationships among constituent systems. Additionally, rating systems are typically designed based on expert judgment that is context specific, and the applicability of the approach depends on whether the rating system design aligns with the context of a specific country, region, or city. In this case, rating systems are not generalizable and it has been suggested that every country needs to develop rating systems that are best suited to their specific conditions (World Green Building Council).

2.2.5. Green buildings

Green buildings are closely associated with, and typically certified by, building rating systems. Although building rating systems are developed to assess green buildings, in this review we assume that green buildings include, but are not limited to, the green building certification programs using rating systems as the assessment framework. Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle, from siting to design, construction, operation, maintenance, renovation and deconstruction (US EPA). Green buildings cover a wide range of sustainability dimensions such as reduced life-cycle cost, reduced use of energy, water, and other resources, enhanced occupant health and comfort, improved productivity, and better aesthetic appearance (Darko, Chan, Owusu, & Antwi-Afari, 2018).

Nevertheless, the major portion of green building practice only evaluates the environmental dimensions of sustainability (Darko, Chan, Huo, & Owusu-Manu, 2019). Although the political (e.g., disruption to existing regulatory frameworks) and social (e.g., public acceptance of new technology) dimensions of green building assessments received more attention recently and are integrated into a framework (Franco, Pawar, & Wu, 2021), their assessments are conducted separately from the environmental dimension of sustainability (Olukoya & Atanda, 2020) and/or remain as qualitative analyses (Franco et al., 2021). Moreover, although green buildings are considered important components of urban-scale assessment frameworks (Liu, Sun, Sun, Shi, & Liu, 2019), building-scale assessments ofter overlook the influence of urban policy on building management.

2.2.6. Healthy buildings

A healthy building is one that adversely affects neither the health of its occupants nor the larger environment (Levin, 1995). Although there are initial efforts investigating health aspects of green buildings, Allen et al. (2015) suggest that those studies rely on self-reported and subjective measures of health. To address the lack of health indicators in green buildings, the concept of green buildings was expanded to healthy buildings by defining health performance indicators that are quantifiable measures of human health and can be used to identify drivers of negative and positive impacts of buildings on health, productivity and well-being of occupants. Allen et al. (2017) summarized the nine foundations of healthy buildings as air quality, ventilation, lighting and views, noise, water quality, safety and security, dust and pests, moisture, and thermal health. Additionally, Kim and Todorovic (2013) proposed a healthy building sustainability index, which is a weighted rating system with three levels of aggregation, to evaluate the sustainability of healthy buildings. Since current healthy building frameworks were built on building rating systems by adding health performance indicators, they share the same drawbacks as those of building rating systems.

2.2.7. Building life cycle assessment

Life cycle assessment (LCA) can be defined as the assembly and estimation of resource inputs, outputs and the potential environmental impacts of a product system, including their processes and designs, throughout its life cycle (Grant, Ries, & Kibert, 2014; Iso, 2003). Nwodo and Anumba (2019) reviewed life cycle assessment of buildings and found that current studies focus on the embodied and operational energy/carbon in the building life cycle including product, construction, use, and end-of-life stages. Therefore, LCA has the advantage of causally representing the flow of energy and carbon associated with building materials and activities throughout the building life cycle. LCA has also been used in combination with other assessment frameworks such as building rating systems (Alshamrani, Galal, & Alkass, 2014) and building information modeling (Lu, Jiang, Yu, Tam, & Skitmore, 2021). While most LCA studies use carbon emission or energy consumption as a single environmental indicator, others cover multiple environmental indicators such as ozone creation potential and human health respiratory effects potential (Lu et al., 2021).

Current LCA studies are subject to some limitations. Although LCA was used in combination with life cycle cost analysis and social LCA to integrate the environmental dimension with economic and social dimensions (Finkbeiner, Schau, Lehmann, & Traverso, 2010), it was found that social LCA was limited to thermal comfort, human life risk, and social feasibility (Amini Toosi et al., 2020). Moreover, the bottom-up nature of LCA requires the user to aggregate resource consumption and pollutant production of individual materials and operations of a building throughout its life cycle. However, materials and operations may differ significantly between buildings and doing such analysis for every building is costly and sometimes impossible due to the lack of data. Even if the required data are available, building LCA only allows the comparison of specific products or processes without taking a systems approach and does not fully capture dynamic causal relationships among building systems over space and time.

2.2.8. Smart buildings

Smart buildings use smart service systems to optimize the use of resources and goods and increase the quality of life of residents and users (Bašić et al., 2019). Smart buildings feature technology-driven sensing and control of building systems such as energy management system, HVAC system, lighting system, water system, waste management system, air quality system, and health monitoring system (Verma, Prakash, Srivastava, Kumar, & Mukhopadhyay, 2019; Vijayan, Rose, Arvindan, Revathy, & Amuthadevi, 2020). Since nearly half of building energy is consumed by HVAC systems (Shi, Yu, & Yao, 2017), smart control strategies for energy-efficient HVAC systems are an important part of smart buildings (Gholamzadehmir, Del Pero, Buffa, Fedrizzi, & Aste, 2020). Beyond technology-driven smart building strategies, occupant-centric control needs to be developed to holistically integrate technologies, policies, and industrial processes for smart buildings and satisfy the needs of occupants (Stopps, Huchuk, Touchie, & O'Brien, 2021).

While building LCA is useful at estimating embodied carbon, energy, and other environmental impacts of building materials, smart buildings have advantages in capturing the operational consumption of materials in real time through deployment of sensors. Sensors can monitor quantifiable physical parameters (e.g., occupancy, temperature, pollutant concentration, sound volume, and air/water flow rates) that can be used for systemic modeling (Stopps et al., 2021). However, existing smart building frameworks emphasize data collection more than transforming the data into a decision-support strategy. Additionally, parameters that are not directly measurable by sensors (e.g., human behavior, cost of consumer products, and the concentration of specific organic contaminants) are difficult to integrate into the current smart building frameworks.

2.2.9. Building information modeling based framework

BIM is a digital representation of the physical and functional characteristics of a facility, and a shared knowledge resource for information about a facility, forming a reliable basis for decisions during the life cycle, which extends from earliest conception to demolition (National BIM Standard-US). We note that BIM is generally considered a tool instead of a framework (Lu, Wu, Chang, & Li, 2017), but due to its advantages of managing information across multiple building systems, we review BIM-based frameworks separately from others in this work. Some of the early attempts to implement BIM focused primarily on a particular aspect of a building such as construction (Lopez, Chong, Wang, & Graham, 2016), energy-saving (Gao, Koch, & Wu, 2019), and safety management (Martínez-Aires, López-Alonso, & Martínez-Rojas, 2018). Although those efforts helped to inform the sustainability of buildings to some extent, it was only recently that researchers began to incorporate sustainability assessment criteria into BIM standards and guidelines (Chong, Lee, & Wang, 2017). For example, Yahya, Boussabaine, and Alzaed (2016) proposed including eco-indicators in BIM to quantify the sustainability of building construction products.

Since data-driven assessment approaches rely on the availability of data, an advantage of BIM is the integration of physical and functional characteristics into a software platform. In this case, approaches such as LCA, requiring the quantity and type of building materials as input variables, can be used based on information provided by the BIM platform to accelerate the evaluation process (Lu et al., 2021). Besides the embodied cost and environmental impacts assessed in LCA, building operational costs and impacts monitored in smart buildings have the potential to be stored in real-time with BIM, further enhancing the availability of data in the software (Ang, Berzolla, Letellier-Duchesne, Jusiega, & Reinhart, 2022; Ang, Berzolla, & Reinhart, 2020). Although BIM is still at an early stage of development and mostly used in the construction industry, it has the potential to become a software platform that connects building systems in a causal way and that integrates other assessment frameworks such as LCA and smart buildings.

2.3. Assessment frameworks at the urban scale

A city, from both ecological and societal perspectives, can be represented as a collection of coupled human and natural systems (Marcotullio & Solecki, 2013). The coupled systems include social, technological, and environmental dimensions which may evolve over time and space, making urban-scale sustainability assessment even more challenging than at the building scale. Clearly, the increase in complexity for urban-scale assessment means that existing attempts are mostly at a conceptual and qualitative level. Here, we briefly review assessment frameworks including urban ecological infrastructure, eco-cities, low-carbon cities, urban rating systems, smart cities, urban resilience, and urban metabolism.

2.3.1. Urban ecological infrastructure

Urban ecological infrastructure is defined as the organic integration of blue (water-based), green (vegetated), and grey (non-living) landscapes, combined with "exits" (outflows, treatment, or recycling) and "arteries" (corridors) at an ecosystem scale (Li et al., 2017). In contrast to a classic definition of infrastructure, which refers mainly to the built environment, urban ecological infrastructure includes earlier "urban nature" concepts such as green infrastructure and urban green space and emphasizes the non-built urban environment (Childers et al., 2019). Although previous work on impacts of urban ecological infrastructure has covered a wide range of topics including human and environmental health, climate, stormwater management, urban planning, social behavior, and urban economy (Parker & Zingoni de Baro, 2019), only a limited number of studies mentioned causal influence (Venkataramanan et al., 2019). Tzoulas et al. (2007) provided conceptual and experimental evidence to show that there are causal interactions between ecosystem and human well-being in a city. Felappi, Sommer, Falkenberg, Terlau, and Kotter (2020) further qualitatively identified synergies and trade-offs between wildlife support and mental health based on green infrastructure indicators. However, those studies mostly focus on connections between two components (e.g., nearby trees visible from apartment buildings are associated with mental fatigue reduction of residents) and more holistic assessments integrating multiple components involving ecosystems, technological systems, and socio-economic systems are lacking.

2.3.2. Eco-cities

Eco-cities were developed based on earlier neighborhood planning movements, including garden city, neighborhood units, modernism, and neo-traditionalism (Sharifi, 2016). An eco-city is built on the principles of living within the means of the environment. The ultimate goal of many eco-cities is to eliminate carbon waste (zero-carbon city), to produce energy entirely through renewable resources, and to incorporate environmental health (Amakpah, Larbi, Liu, & Zhang, 2016). Zhou and Williams (2013) summarized eight major eco-city indicators including energy and climate, water, air quality, waste, transportation, economic health, land use and land form, and social health. The concept of eco-city is widely promoted in China leading to the creation of multiple world-first eco-city projects that were later questioned over whether ecological goals were achieved (Ghiglione & Larbi, 2015). Prominent eco-city projects include Abu Dhabi Masdar City project (Grey, 2018), Japanese eco-town projects (Van Berkel, Fujita, Hashimoto, & Geng, 2009), the Sino-Singapore Tianjin Eco-city project (Caprotti, 2014), but each project has its own assessment criteria and no consensus on a general assessment approach has been reached (Dong et al., 2016).

2.3.3. Low-carbon cities

A low-carbon city focuses on curtailing the anthropogenic carbon footprint of cities by minimizing or abolishing the use of energy from fossil fuels (Abubakar & Bununu, 2020). Low-carbon cities have emerged as the latest sustainable urban strategy in response to climate change impacts, particularly for China, where low carbon city planning was treated as one of the most important goals of city development with three batches of low carbon pilot cities established (Hunter, Sagoe, Vettorato, & Jiayu, 2019). A variety of indicators were developed to assess the pilot low-carbon cities (Lin, Jacoby, Cui, Liu, & Lin, 2014; Tan et al., 2017; Zhou, He, Williams, & Fridley, 2015).

However, low-carbon city development has been biased towards economic and technological innovations (Hunter et al., 2019). Additionally, while the building sector contributes 40% of carbon emission (IEA & UNEP, 2019) and may impact the urban environment in many ways, the low-carbon city framework often overly simplifies the building sector. In addition, a limited number of indicators such as the number of energy-efficient or green buildings per capita are used (Harris, Weinzettel, & Levin, 2020; Zhou et al., 2015), which may not reflect actual building energy use. The influence of buildings on other urban-scale indicators such as air quality and human health is rarely considered.

2.3.4. Urban rating systems

During the last two decades, a number of well-known building-scale assessment frameworks, including LEED and BREEM, have been expanded to the community scale (Sharifi & Murayama, 2013). Early-stage implementation of those rating systems was usually limited to the development of a single city block or multiple collective blocks with publicly accessible spaces (Tam, Karimipour, Le, & Wang, 2018), while recent work has scaled up the frameworks to city-wide assessment (Ali-Toudert, Ji, Fährmann, & Czempik, 2020; Pedro, Silva, & Pinheiro, 2018). In addition, other indicator-based urban rating systems have been proposed to tackle the challenges in cities from a variety of perspectives (Ameen & Mourshed, 2019; Huovila, Bosch, & Airaksinen, 2019; Lützkendorf & Balouktsi, 2017; McDonald & Patterson, 2007; Verma & Raghubanshi, 2018). Similar to building rating systems, urban rating systems rely on assigning scores to pre-defined indicators and aggregating indicators using a weighting system (Ameen, Mourshed, & Li, 2015). Additionally, while those rating systems cover a wide range of sustainability-related dimensions, their focus on energy, water, recycling, and other environmental aspects is stronger than on social and economic aspects, which represent an essential part of urban communities (Ameen, Mourshed, & Li, 2015).

2.3.5. Smart cities

A smart city utilizes information communication technology and other technologies to improve quality of life, competitiveness, and operational efficacy of urban services, while ensuring the resource availability for present and future generations in terms of social, economic, and environmental dimensions (Farid, Alshareef, Badhesha, Boccaletti, Cacho, Carlier, Corriveau, Khayal, Liner, Martins, Rahimi, Rossett, et al., 2021; Farid, Alshareef, Badhesha, Boccaletti, Cacho, Carlier, Corriveau, Khayal, Liner, Martins, Rahimi, Rossetti, et al., 2021; Kondepudi et al., 2014). The foundation of a smart city is the extensive use of information communication technology that enables the collection and analysis of big data from urban services. The collected information can be used to improve quality of life with a focus on sustainable and efficient solutions for energy management, transportation, health care, and governance (Silva, Khan, & Han, 2018). However, the notion of a smart city, despite some promising attempts to include citizen participation (Malek, Lim, & Yigitcanlar, 2021), has not been adequately conceptualized, mainly due to perceiving the "smart" in smart cities as technological smartness rather than human smartness (Yigitcanlar, Han, Kamruzzaman, Ioppolo, & Sabatini-Marques, 2019). The technological-smartness approach typically focuses on the use of smart technologies in cities while the relationship between sustainability and those techniques is sometimes overlooked (Bibri & Krogstie, 2017).

A conceptual framework has been developed to model a smart city as a system of systems. For example (Naphade, Banavar, Harrison, Paraszczak, & Morris, 2011) proposed to integrate and optimize a set of interdependent public and private systems to achieve a new level of effectiveness and efficiency. Measurable information in different urban systems can be monitored through smart technologies and the integration of information models across multiple systems allows a monitor-control-optimization cycle to plan and manage urban operations (Cavalcante, Cacho, Lopes, & Batista, 2017). While this approach has the potential to establish causal connections among systems, it may overlook important information that is difficult to monitor (e.g., specific pollutant levels or human behavior). In other words, achieving the proposed urban-scale integration of information models relies on the collection of massive amounts of data in physical environments by deploying smart devices throughout the various urban systems.

2.3.6. Urban resilience

Urban resilience is the capacity of a city and its urban systems (social, economic, natural, human, technical, physical) to absorb strong perturbations, to reduce the impacts (changes, tensions, destruction or uncertainty) from a disturbance (shocks, disasters, changing weather, crises or disruptive events), to adapt to change and to improve systems that limit current or future adaptive capacity (Ribeiro & Pena Jardim Gonçalves, 2019). While applications of urban resilience to climate change have attracted most attention (Tyler & Moench, 2012), other areas such as urban planning (Masnavi, Gharai, & Hajibandeh, 2018), urban infrastructure (Liu & Song, 2020), energy (Sharifi & Yamagata, 2016), and human or natural disasters (Cariolet, Vuillet, & Diab, 2019) have also been investigated. While some quantitative assessments still use weighted indicators (Zhang et al., 2019; Zhang, Yang, Li, & van Dijk, 2020), other studies couple models across multiple urban systems, usually limited to water, electricity, and transportation systems, to connect model variables that are associated with civil infrastructure resilience as summarized by Bozza, Asprone, and Fabbrocino (2017). A further attempt to include human behavior (Cavallaro, Asprone, Latora, Manfredi, & Nicosia, 2014) and quality of life (Renschler et al., 2010) in coupled system modeling was made to understand the perception of urban stakeholders on civil infrastructure systems.

2.3.7. Urban metabolism

Urban metabolism refers to "a complexity of socio-technical and socio-ecological processes by which flows of materials, energy, people and information shape the city, service the needs of its populace, and impact the surrounding hinterland" (Currie & Musango, 2017). Ferrão and Fernandez (2013) present a conceptual framework through a multi-layered examination of (i) urban bulk mass balance, (ii) urban material flow analysis, (iii) product dynamics, or life cycle assessment, (iv) material intensity by economic sector, (iv) environmental pressure of material consumption, (vi) spatial location of resource use, and (vii) transportation dynamics. Kennedy, Stewart, Ibrahim, Facchini, and Mele (2014) introduce a multi-layered and standardized indicator set for collecting urban metabolism data in megacities.

As reviewed by Zhang, Yang, and Yu (2015), multiple causal accounting and modeling approaches have been used in urban metabolism research, including substance- and material-flow analysis, input-output analysis, and ecological network analysis. Those approaches can integrate internal mechanisms of urban systems and consider their interactions with the surrounding environment at scales ranging from local to global. Zhang, Yang, and Yu (2015) further suggested that a systems engineering approach should be introduced to unify and integrate the methods from different fields of research and to design approaches that will provide solutions for specific social policy problems. Based mostly on material flow analysis, urban metabolism studies intend to capture the interlinkage and interdependence among different aspects of urban networks, represented by indicators within a weighted matrix (Ko & Chiu, 2020; Maranghi et al., 2020). Finally, Cristiano, Zucaro, Liu, Ulgiati, and Gonella (2020) designed a circular arrangement of production and consumption by integrating recovery of resources such as solid waste, wastewater, and food residuals.

3. Gaps in existing assessment approaches

3.1. Causality among component systems and their subsystems is limited

Due to the complexity of causally integrating multiple systems and the affordability of simulating a complex, coupled problem, many assessment approaches at building and urban scales, including green buildings, healthy buildings, low-carbon buildings/cities, eco-cities, and rating systems, simplify the integration and use indicators that are integrated based on a simple summation of credits, weighting systems (Shan & Hwang, 2018), or an analytical hierarchy/network process (Ding, Niu, Liu, Wu, & Zuo, 2020). Those multi-criteria assessment methods are simple and easy to use, but rely on expert judgment in a specific context (e.g., a type of building or a geographic region) and cannot account for implicit causal relationships among indicators. For example, building energy consumption, indoor particulate matter concentration, and filtration efficiency of filters in HVAC systems are treated as independent indicators in some building rating systems. Nevertheless, the indicators are causally connected because better filtration efficiency may simultaneously result in higher energy consumption and lower particulate matter concentration. Aggregating the credits assigned to the indicators may, to some extent, capture quantitative relationships among the indicators for a specific building at a given operating condition, but cannot represent the change in causal relationships when the scenario changes. In these out-of-context situations, applying weighted approaches will likely result in unintended consequences.

The lack of causal connections among indicators in assessment frameworks has received growing attention and some early attempts have been made to quantitatively describe the interdependence among indicators. Approaches based on material flow analysis including building life cycle assessment and urban metabolism have advantages in linking multiple systems using mass and energy balances. By tracking the consumption of resources and emission of pollutants along the life cycle of a product or a process, these approaches incorporate the mechanisms by which resources are consumed and enable the inclusion of feedback loops, but may have limited temporal and spatial resolution (Hester & Little, 2013).

Although establishing causal relationships among coupled systems (often hindered by the interoperability of models) is more challenging than a rating framework, some pioneering work has been conducted to couple models at the building scale. Recent work has sought to bring building-level energy models to the neighborhood scale (Buckley, Mills, Letellier-Duchesne, & Benis, 2021; Buckley, Mills, Reinhart, & Berzolla, 2021; Cerezo Davila, Reinhart, & Bemis, 2016; Reinhart & Cerezo Davila, 2016). Another recent example couples building energy (e.g., EnergyPlus model) and indoor air quality systems (e.g., contaminant transport model (CONTAM)) (Underhill, Dols, Lee, Fabian, & Levy, 2020). In addition, an asthma risk model was coupled to assess building energy retrofits on asthma outcomes (Tieskens et al., 2021). At the urban scale, smart city frameworks advocate the monitoring of physical information and integrated information models to treat a city as a system of systems (Jin et al., 2014), and urban resilience frameworks apply coupled systems models to predict model variables in civil infrastructure (Bozza et al., 2017; Liu & Song, 2020). However, despite moving towards more causally connected building and urban systems, the application of those approaches are constrained to a limited number of systems.

3.2. Sustainability and resilience are too narrowly defined

Many frameworks such as low-carbon buildings/cities and zero-energy buildings heavily emphasize the impact of greenhouse gas emissions on sustainability, while other important aspects of buildings and cities are ignored. Although one of the biggest societal challenges is climate change, and reducing greenhouse gas emissions is one of the most important strategies to mitigate climate change, climate change is not the only societal challenge. Other challenges such as food security, biodiversity, and disaster resilience are also important. While mitigating climate change and adapting to the impacts of a changing climate, there is a need to more holistically evaluate the effects of policies so that unintended consequences can be avoided. For example, building-scale energy retrofit strategies such as increasing building air-tightness can reduce energy consumption but may worsen indoor air quality by reducing the amount of fresh air entering the building (Dovjak, Slobodnik, & Krainer, 2020). Additionally, pursuing energy-efficient buildings may increase the use of insulation materials containing potentially toxic chemicals that can slowly permeate into indoor environments and increase human exposure (Poppendieck, Schlegel, Connor, & Blickley, 2017).

Preliminary efforts have been made to cover broader dimensions of sustainability and resilience. At the building scale, the sustainable human building ecosystem framework was built on the low carbon building and zero energy building frameworks (still focusing on energy) by emphasizing occupant behavior as an important component of building energy analysis (Talele et al., 2018). Healthy buildings broadened the green building assessment framework by adding health performance indicators (Allen et al., 2017). LCA was combined with life cycle cost analysis and social LCA to integrate economic and social dimensions of sustainability (Finkbeiner et al., 2010). At the urban scale, a circular economy was coupled with urban metabolism by integrating recovery of resources such as solid waste, wastewater, and food residuals (Cristiano et al., 2020).

3.3. Social systems are inadequately addressed

While many strategies to improve building and urban environments focus on technological innovations, limited consideration has been given to the social systems, which center on individuals living in a building or a city. Human behavior can play important roles in determining whether intervention or mitigation strategies can be effective. For example, window-opening is a commonly observed behavior impacting building energy consumption and indoor environmental quality (Fabi, Andersen, Corgnati, & Olesen, 2012), with window-opening behavior driven by physical environment conditions such as indoor and outdoor temperature (Fabi et al., 2012). The opening and closing of windows may, in turn, influence air exchange between indoor and outdoor environments. The feedback loop between human behavior and indoor environment parameters requires integration of social systems into assessment frameworks, particularly when examining human-intervention strategies.

In fact, many building- and urban-scale assessment frameworks mention the need to develop a human-centered approach, emphasizing social systems. For example, smart buildings equipped with smart HVAC systems can simultaneously satisfy energy saving and human comfort (Stopps et al., 2021), while urban resilience frameworks attempt to include human behavior and quality of life (Bozza et al., 2017). However, most existing approaches poorly integrate social systems or do not treat social dimensions as component systems. Instead, social indicators are usually included in a simple attempt to check the triple bottom line, but fall short when trying to achieve a more holistic assessment.

3.4. Building- and urban-scale assessments are poorly connected

While buildings are one of the most important components in a city, building- and urban-scale assessments typically evaluate building and urban environments separately. In fact, building and urban environments are connected in many ways and cross-scale impacts often involve feedback loops. For example, indoor emission of volatile chemicals contributes significantly to the formation of particulate matter in urban environments (McDonald et al., 2018), which may in turn infiltrate into buildings and consequently raise indoor exposure to particulate matter of outdoor origin. Many urban-scale frameworks use top-down approaches thus neglecting the individual characteristics of buildings. The lack of individually assessed buildings in urban-scale assessment frameworks may mean that spatially resolved impacts of buildings on urban environments cannot be included.

To make connections across building and urban scales, approaches are needed that connect across scales. To address this knowledge gap, some preliminary work has been done to expand the scope of LCA from single buildings to urban building stocks using a bottom-up approach. For example, Mastrucci, Marvuglia, Benetto, and Leopold (2020) proposed a spatio-temporal LCA framework to assess renovation scenarios of urban housing stocks by integrating (1) a geospatial building-by-building stock model based on geographical information systems, (2) an energy demand model, and (3) a product-based LCA model (Pomponi & D'Amico, 2020). Beyond the expansion of LCA framework, Al-Humaiqani and Al-Ghamdi (2022) pointed out the needs of incorporating resilience requirements into the built environment for promptly responding to climate change related disruptions. Caprotti and Romanowicz (2013) considered the design of individual buildings as one of the central components in the urban metabolism framework. However, further work is needed to evaluate the impacts of buildings on urban sustainability and, in turn, the influence of urban policies on building-scale assessments. For example, Apanaviciene, Vanagas, and Fokaides (2020) integrated smart building assessments into a smart city framework, emphasizing that the main challenge for the integration is to ensure that functionalities proposed in the smart domain of a city are applied in smart buildings and vice versa. Souza and Bueno (2022) proposed the concept of City Information Modeling (CIM) based on the integration of BIM, geographic information system, and an urban database.

4. More holistic approaches to assess sustainability and resilience across building and urban scales

4.1. Potential integration of existing approaches

As already emphasized, existing assessment frameworks typically have limited causal connections among constituent systems, cover limited dimensions of sustainability and resilience, do not include social systems, and rarely connect building-scale with urban-scale assessments. However, the drawbacks in some assessment approaches may be overcome in others and the integration of existing frameworks may be valuable as an achievable next step. For example, LCA can be coupled with rating systems to strengthen the analysis of structural and building envelope systems by including the embodied resource consumption (Alshamrani et al., 2014). While LCA requires extensive data, it can be integrated with BIM and used as a software platform to collect and manage data for LCA (Lu et al., 2021). The data storage and management capability of BIM can be strengthened by incorporating real-time physical parameters of building operations monitored by smart building techniques. Life cycle resource consumption captured via the coupling of LCA and BIM could be further enhanced by replacing static building operational impacts with dynamic connections using coupled multi-system models (Tieskens et al., 2021; Underhill et al., 2020).

4.2. More holistic approaches

Although it is increasingly recognized that the integration of multiple systems for a more holistic assessment is necessary, interdisciplinary integration is impeded by the complexity of the problem. Fortunately, much can be learned from several other closely-related fields of research including integrated assessment and modeling, social-ecological systems research, land systems science, and socio-environmental systems modeling, and we briefly introduce each of these emerging research domains below.

In contrast to traditional planning approaches employing a combination of professional expertise, scientific methods, and well-defined goals (Rotmans et al., 2000), integrated assessment and modeling is designed to synthesize diverse knowledge, data, methods, and perspectives in an overarching framework to address complex societal problems (Hamilton, ElSawah, Guillaume, Jakeman, & Pierce, 2015). Integrated assessment has been used to evaluate environmental science, technology, and policy problems including climate change (Robertson, 2020; Rose, 2014), human ecological impacts (Harfoot et al., 2014), the food-energy-water nexus (Kling, Arritt, Calhoun, & Keiser, 2017), and greenhouse gas emissions (Gambhir, Butnar, Li, Smith, & Strachan, 2019; Roh & Tae, 2017).

Social-ecological systems (SES) research is an emerging field that focuses on the interdependence between humans and nature (Schlüter, Müller, & Frank, 2019), with an emphasis on resilience and sustainability. SES models can serve many purposes including understanding system responses that emerge from complex interactions of subsystems, supporting participatory processes, which include the active involvement of experts, managers, stakeholders and policy makers in the modeling process, and analyzing the consequences of human behavior (Schlüter et al., 2019). Although the diversity of purpose, types, and applications of models offers great potential for social-ecological systems research, several challenges remain because modeling approaches originate in different disciplines, are based on different assumptions, focus on different levels of analysis, and use different analytical methods (Schlüter et al., 2019).

One of the modeling challenges is the multi-scale and multi-level nature of SES and models usually need to discriminate among scales (e.g., spatial and temporal), which may also be referred to as levels (e.g., jurisdictional (building, local, urban, regional, national) and institutional (rules, laws and constitutions)) (Cash et al., 2006; Gibson, Ostrom, & Ahn, 2000). The use of both system dynamics models (Elsawah et al., 2017) and agent-based models (An et al., 2021; Schulze, Muller, Groeneveld, & Grimm, 2017) is common when developing and implementing models of SES, and the use of agent-based models to simulate SES across scales is an active area of research (Lippe et al., 2019).

Land systems science (Meyfroidt et al., 2018; Rounsevell et al., 2012; Verburg et al., 2019), which might be thought of as an SES subdiscipline, focuses on monitoring and describing patterns of land-cover change and explaining the various drivers of change. Land system change, which can be monitored and modeled at increasingly fine spatial and temporal resolution, deepens the understanding of land-use displacements and the associated trade-offs (le Polain de Waroux et al., 2021), and is especially relevant at the urban scale.

Although closely related to social-ecological systems, socio-environmental systems (the two fields can be conveniently represented with the same acronym, SES) modeling integrates knowledge and perspectives into conceptual and computational tools that explicitly recognize how human decisions affect the environment (Elsawah et al., 2020). As with social-ecological systems, participatory processes support social learning and decision-making for achieving improved environmental and social outcomes (Elsawah et al., 2020). Several challenges associated with developing integrated SES models were recently identified, including bridging epistemologies across disciplines, multi-dimensional uncertainty assessment and management, scales and scaling issues, combining qualitative and quantitative methods and data, furthering the adoption and impacts of SES modeling on policy, capturing structural changes, representing human dimensions in SES, and leveraging new data types and sources (Elsawah et al., 2020).

With regard to the human dimensions of SES, social science is fortunately entering a golden age, marked by explosive growth in new data and analytic methods, interdisciplinary approaches, and a recognition that these ingredients are necessary to address our most challenging societal problems (Buyalskaya, Gallo, & Camerer, 2021). Indeed, the development of models that represent human behavior in social systems and decision-making within a policy context (Polhill et al., 2019; Schlüter et al., 2017; Malik et al., 2022; Schwarz et al., 2020) is a growing area of research with considerable potential for inclusion in building and urban systems.

4.3. A multi-scale, system-of-systems approach

As shown in Table 1, there are many societal challenges that need to be addressed at both building and urban scales. If the goal is to address each of the challenges separately, we must merge disciplines, methodologies, and technologies for every one of the challenges, and we must do this separately, which is likely an impossible task. Taking one of the societal challenges (i.e., adapt to climate change) as an example, interactions among at least 10 systems (e.g., land-use, agriculture, watershed, climate, energy, transportation, communication, economic, governance and other social systems) need to be considered. Furthermore, each of the 10 individual systems has many subsystems that not only create the internal dynamics specific to that system, but also interact with subsystems in the other systems. The presence (or absence) of an interaction would need to be characterized. If these interactions among the subsystems are studied two or three at a time, which is usually the case, we will need thousands of research projects to identify the interactions among the subsystems, and in the end, we will still not understand how the individual systems interact. To make matters worse, such an incremental approach entirely overlooks the fact that the societal challenges are interdependent (Wang, Guan, & Cai, 2019) because several of the relevant systems within a building or urban area are the same across many of the challenges.

While our review highlighted some early attempts to develop

Table 1
Examples in a family of societal challenges across building and urban scales

Stabilize carbon emissions
Provide access to clean water
Adapt to climate change
Improve infrastructure for an urbanized population
Feed a growing global population sustainably
Supply human needs for energy sustainably
Provide healthy living environments

integrated models at building (tens of meters) and urban (tens of kilometers) scales, those efforts typically focus on the integration of only two or three systems at either scale, generally omit social systems, and do not connect across building and urban scales. A more generic, systematic, and modular approach is needed. Fortunately, however, the family of societal challenges shown in Table 1 share the abstract common characteristics of broad scope, complex interdependencies, and multi-faceted causality, and also share several common systems, as shown in Fig. 2. Seizing on this conceptual opportunity, we are inspired by system-of-systems (SoS) approaches (Iwanaga et al., 2021; Little et al., 2019) where scientists and engineers work across disciplines to combine the structural, behavioral, and technological approaches needed to address large-scale societal challenges (Clark & Harley, 2020; Little, Hester, and Carey, 2016; Scoones et al., 2020).

A natural way to achieve this is to decompose building and urban environments into unique and common systems, with a preliminary listing of examples shown in Fig. 2. Then, building on rapidly accumulating knowledge in the fields of integrated assessment and SES modeling, we propose a multi-scale, system-of-systems framework (Iwanaga et al., 2021; Little et al., 2019) that could be used to integrate systems within buildings, to integrate systems within urban areas, and to connect some of the common systems across building and urban scales.

We would begin with the more conventional common systems, including energy, water and air, but connect them in a modular framework that can be extended to include other common systems later. As shown in Fig. 2, models could be coupled at the building and urban scale while the cross-scale integration of the common systems could be achieved by identifying aggregated versions of the common systems, which requires a taxonomy of building types. For example, we could identify a representative model for each common system in residential, commercial, and industrial buildings, respectively, and aggregate the building-scale model outputs to obtain urban-scale information. This is similar to the "urban cell" approach in which spatial coupling of buildings is achieved by aggregating neighborhood units including building stocks (Perera, Javanroodi, Wang, & Hong, 2021). Spatially-resolved building information at the urban scale could be handled using GIS (geographic information system) with the various types of buildings located spatially within the urban environment. Meanwhile, individual building-scale assessments could connect with common systems at the urban scale, including the influence of the urban environment on a specific building of interest, with building systems in this case that are not aggregated, but are specific to the building.

The implementation of a system-of-systems framework can take advantage of existing assessment frameworks in which causality among constituent systems is already represented, especially LCA, BIM and urban metabolism. As already mentioned, those frameworks also have the ability to store large sets of data within a software platform thus increasing the possibility of linking common systems across scales. Although we acknowledge the daunting nature of the task, we must simultaneously acknowledge the limitations of the current suite of assessment frameworks, and begin to implement a more systematic approach.

When developing a system of systems based on mathematical models, we need to distinguish between the modeling approach and the software framework (Little et al., 2019). The models themselves operate naturally at different temporal and spatial scales, and individual models have different mathematical foundations. Although the systems are coupled through information exchange, their models may have different inputs and outputs, which must be logically connected and scaled. In contrast, software frameworks (Lloyd et al., 2011) provide a reusable design, which guides software developers in partitioning functionality into software components, and specify how components communicate and manage the order of execution. Recent advances in model integration frameworks and interoperability standards have lowered the technical barriers to achieving model integration, and frameworks are largely programming language agnostic (Little et al., 2019). Furthermore, generic methods to design, implement and execute multi-scale simulations that encompass several component systems are available (Chopard, Borgdorff, & Hoekstra, 2014; Hoekstra, Chopard, & Coveney, 2014; Hoekstra, Portegies Zwart, & Coveney, 2019).

When simulating a system of systems, the computational cost of integrating many models directly can be prohibitive, especially at the urban scale, and when there is a need to run thousands of simulations to evaluate sensitivity and uncertainty and explore future scenarios. By creating simpler emulation or surrogate models (Little et al., 2019), the interdependent dynamics of many individual systems can be captured providing vital information about system-level drivers. Indeed, multi-fidelity methods (Peherstorfer, Willcox, & Gunzburger, 2018) are being developed that combine high-fidelity and low-fidelity model evaluations, where the low-fidelity evaluations arise from an explicit low-fidelity model (e.g., a simplified mechanistic approximation, a reduced-order model, or a data-fit surrogate) that approximates the same output quantity as the high-fidelity model. The premise is that the low-fidelity models are leveraged for computational speed while the high-fidelity model is kept in the loop to establish accuracy (Peherstorfer et al., 2018).

Finally, a decision-support system (Walling & Vaneeckhaute, 2020) is often used to facilitate participatory processes which enable the close involvement of experts, managers, stakeholders and policy makers in the modeling process. This may involve the engagement of the community through mutual social learning (Norström et al., 2020; Turnhout, Metze, Wyborn, Klenk, & Louder, 2020) and the co-production of knowledge, something that is especially important when developing and integrating models of social systems. The decision-support system may include participatory modeling, stakeholder engagement, adaptive management, and scenario analysis to characterize hypothetical future pathways (Little et al., 2019). In addition, problems involving multiple complex systems are generally characterized by deep uncertainty (Lempert, Groves, Popper, & Bankes, 2006) and many approaches to decision-making under deep uncertainty have been developed to enable quantitative analyses that support deliberation among multiple parties (Kwakkel & Haasnoot, 2019; Wilby & Dessai, 2010). These methods generally identify robust or low regret management strategies that perform well across a wide range of uncertain conditions.

4.4. An illustrative example

Here, we briefly illustrate the potential use of the system-of-systems framework across building and urban scales focusing on indoor and outdoor air pollution. Air pollution is responsible for about 8% of global deaths each year (Babatola, 2018). The release of volatile organic compounds (VOCs) is of great concern in air pollution because VOCs can react with oxidants in the atmosphere to form fine particulate matter ($PM_{2.5}$) and ozone, which have significant adverse health effects. Those VOCs emitted from indoor materials and products to outdoor environments can contribute to the production of outdoor $PM_{2.5}$ and ozone (McDonald et al., 2018) that may, in return, enter the indoor environment and consequently impact human health and comfort. The finding raises a critical need to study the complex interactions of pollutant transport between indoor and outdoor environments, and more generally, between building and urban environments, for reducing human exposure to air pollutants.

In this example, the source of VOCs is the use of various materials and products in buildings. Air is the medium transferring airborne pollutants (e.g., VOCs, $PM_{2.5}$, and ozone) between building and urban environments via building envelope systems and interacting with other systems within different types of buildings. At the building scale, building filtration system should be coupled in the example because filtration can remove $PM_{2.5}$ and the associated particle-phase organic compounds. Because the filtration system requires energy to operate, building energy system needs to be considered. At the urban scale, the formation of ozone in the atmospheric system is facilitated by the

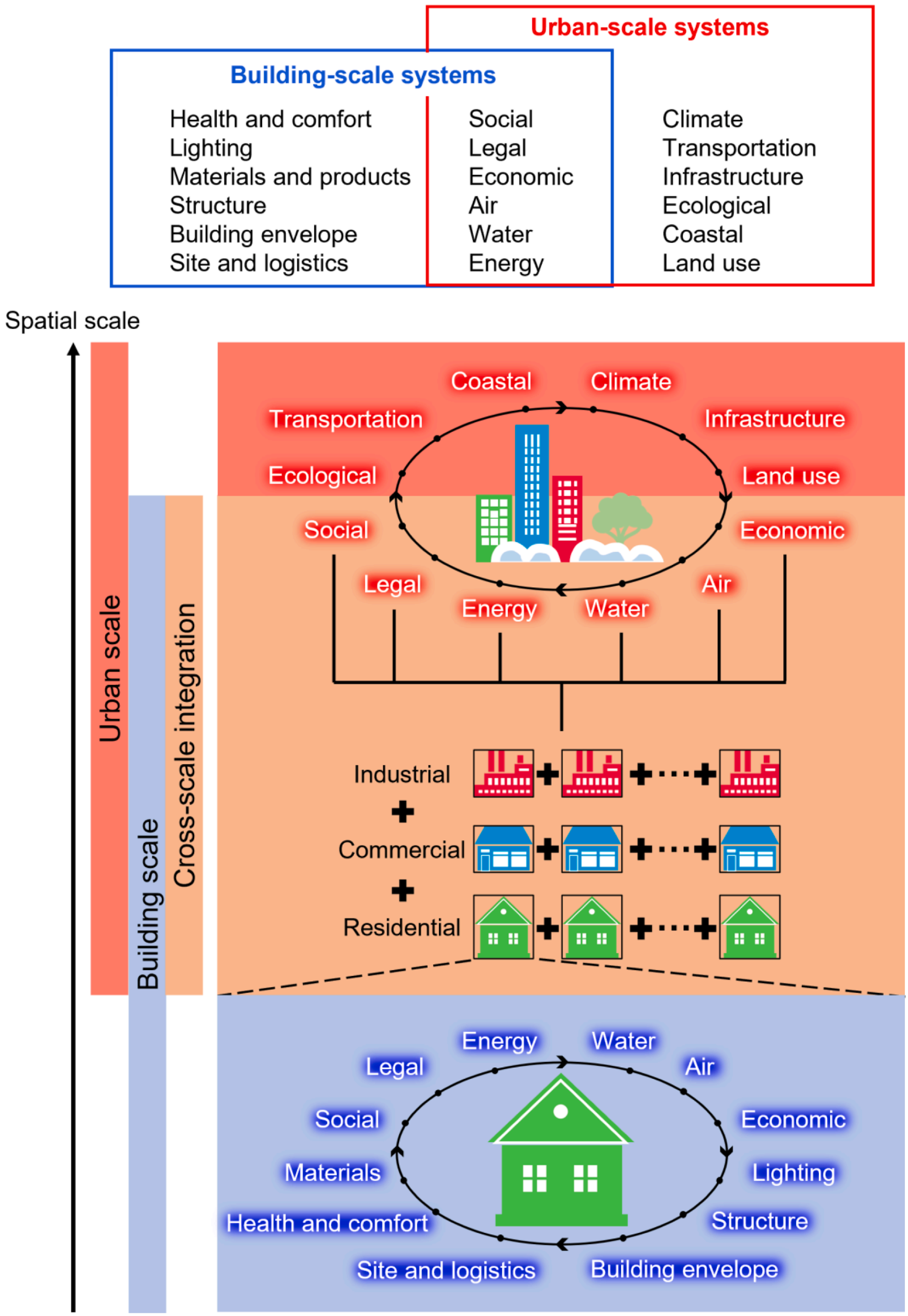

Fig. 2. A conceptual illustration of systems integration across building and urban scales with aggregated versions of the common systems connected based on a taxonomy of buildings (e.g., residential, commercial, and industrial buildings). Note that the specific systems included are for illustrative purposes only, and are not intended to cover all relevant systems across building and urban scales.

presence of nitrogen oxides (NOx), which are primarily emitted by vehicles in the transportation system. By establishing connections among inputs and outputs for the various systems, it should be possible to simultaneously increase human health and comfort, minimize building energy consumption, and improve urban air quality using the system-of-systems framework.

Since the problem mainly focuses on the transport of airborne pollutants, we could take advantage of existing indoor VOC emission models (Liu, Ye, & Little, 2013) to build the emission inventory in buildings. We could utilize atmospheric air quality models (Byun & Schere, 2006) to study the formation of ozone and $PM_{2.5}$ and the consequent impacts on climate and ecosystems. To represent social systems, we could consider the influence of human behavior since a significant portion of VOC emissions is related to the use of personal care products. The emission of VOCs from building and industrial sectors can be characterized based on the emission factors and purchase of industrial products from the economic system (McDonald et al., 2018). The initial system models would form the foundation of a system of systems for both the building and urban environment. Once an initial set of systems are being successfully coupled and simulated, we could consider other systems that are relevant to the socio-environmental problem. For example, vegetation in urban ecosystems may reduce ozone and $PM_{2.5}$ through deposition, while the change in atmospheric $PM_{2.5}$ may influence the penetration of solar radiation and the rate of chemical reactions in the urban atmosphere.

5. Conclusion

We briefly reviewed several assessment frameworks that integrate data and knowledge at building and urban scales, primarily based on the degree of causality among systems. We found that the connections among component systems and their subsystems in existing frameworks were poorly represented, particularly for rating frameworks that assign scores to pre-weighted indicators. The weighting of indicators is typically based on expert judgment and can be unreliable when used out of context. Although some pioneering efforts have been proposed to address the causal connections among systems at building and urban scales, they generally ignore temporal and spatial resolution and are constrained to a limited number of coupled systems or subsystems. Some frameworks have narrow definitions of sustainability, while many are redundant and focus heavily on topics related to climate change and green-house gas emissions, ignoring other important dimensions of sustainability. Additionally, although many assessment frameworks emphasize the need to include social systems, they are nevertheless poorly represented. Finally, while buildings are one of the most important and intimately connected components of a city, building- and urban-scale assessments typically evaluate buildings and urban environments separately.

To overcome these obstacles, we briefly introduced several closely-related areas of research including integrated assessment and modeling, social-ecological systems research, land systems science, socio-environmental systems modeling, modeling of human behavior, multi-scale modeling, and multi-fidelity modeling. Building on the rapidly accumulating knowledge in these emerging research domains, we proposed a more holistic, multi-scale, system-of-systems approach to systematically address complex societal challenges that span building and urban scales. We further provided an illustrative example to demonstrate the potential integration of systems across building and urban scales to simultaneously increase human health and comfort, minimize building energy consumption, and improve urban air quality.

Declaration of Competing Interest

The authors declare no potential conflict of interests.

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