Leveraging Emergence for Enhanced Planning and Decision-Making in the Built Environment: Application in Resilience and Sustainability Planning

ABSTRACT

The built environment consists of various, diverse, and independent systems distributed across different organizational levels, such as team, project, regional, state, and national, creating a structured hierarchy. Interactions within and between these hierarchical levels, involving human participants, physical resources, and policies, are crucial for the functionality and efficiency of these systems. However, these interactions—physical, spatial, logical, and cyber in nature—can lead to unexpected 'emergent' properties or behaviors not anticipated in the original design of the systems.

Emergence, a concept well-recognized in systems engineering, has not been fully integrated into research and practice related to the built environment. Scientific attempts to study processes in the built environment often adopt a reductionist perspective, treating the outcome of the built environment as the sum of its individual elements, thus simplifying and neglecting the complexity arising from continuous interactions among components. This simplification can overlook emergent behaviors that significantly influence planning and management across various areas, including construction productivity, safety, infrastructure planning, and operations, either positively or negatively. Considering the magnitude and nature of impact of any resultant emergent behavior on the holistic outcome of operations and processes in the built environment, it is crucial to acknowledge and account for emergence during planning and decision-making. This necessity becomes especially vital within the framework of resilience and sustainability planning, where achieving ambitious goals demands a holistic approach that transcends isolated entity planning.

To date, research exploring emergence within engineering contexts has been limited. Even among the limited engineering studies that recognize the potential impact of emergent behavior and its significance, formalized analysis approaches are lacking. Moreover, none of these studies have endeavored to regulate the interactions underlying emergent behavior in pursuit of more favorable outcomes. As such, the potential of incorporating the concept of emergence in built environment planning and decision-making, particularly within the realms of sustainability and resilience, remains largely untapped. This research seeks to fill this gap by developing a formalized

framework for effective modeling, analysis, and control of emergent behavior. It begins with establishing a taxonomy of emergent behaviors, classifying them into four distinct types based on (a) nature of underlying interactions, (b) level of complexity, and (c) boundaries of information available. This taxonomy is then used as a foundation for a three-dimensional framework – (i) classification, (ii) operationalization, and (iii) implementation – for the systematic modeling and analysis of the different types of emergence within construction and infrastructure engineering and management applications. This study demonstrates the efficacy of the developed framework in augmenting and guiding system- and operational level planning and decision-making within the contexts of infrastructure resilience and construction sustainability planning through two case studies.

The first case study examines the disparities in the resilience of municipal solid waste management systems (MSWMSs) during the COVID-19 pandemic stemming from their complex socio-technical interactions. Specifically, empirical investigation of the operation of MSWMSs during the course of the pandemic was conducted in order to investigate the variance in their adopted adaptation pathways as a function of their systems characteristic, particularly in terms of composition, topology, and control. Subsequently, these variances were used to explain the emerged resilience performance of MSWMSs, particularly with regards to (i) the resourcefulness of each system in establishing and implementing response measures and (ii) its rapidity in recovering and adapting to increasingly complex and dynamic conditions. Findings from this case study serve as a foundation for enhancing the resilience of MSWMSs to future pandemics and other disturbances.

The second case study investigates the improvements or reductions in the productivity of heavy equipment during demolition debris sorting operations stemming from their spatial interactions. Specifically, lab-based scaled models of demolition operations utilizing small-scale excavators were employed to monitor the variables impacting the underlying spatial interactions, particularly (i) the proximity between excavators and (ii) the orientation of excavators during operations. Statistical models were subsequently established to explain the resulting impact on the collective productivity based on these variables. The insights gained from this case study provide a basis for optimizing excavator allocation and spatial arrangement during material separation operations to maximize the recovery of recyclable demolition waste.