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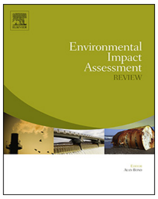

A biophysical approach to the performance diagnosis of human–building energy interaction: Information (*bits*) modeling, algorithm, and indicators of energy flow complexity

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ABSTRACT

This article addresses the utmost upstream impacts of human–building energy interaction by proposing a network-based model, algorithms, and indicators. Hypothesizing that human behavior is a key factor for the symbiotic development of building and the geobiosphere system, the author seeks emergy (spelled with an "*m*")-information integrated measures to indicate dynamic system-level performance of the interaction with building energy flow topology. To validate the hypothesis and methods, four representative building cases were tested on the building form (envelope) of (i) a building with no occupant intervention (baseline), (ii) a building controlled by responsive human behavior (bioclimatic adaptation), (iii) a building with reinforced insulation and behavior-dominated control (passive design), and (iv) a net-zero energy building (NZEB). The results demonstrate that adaptive human behavior in building operation increases the information content and complexity of energy-flow networking, improving performance and sustainability. Findings also reveal that increasing information, complexity, and power (energy availability over time) parallel the general energetic features of developing biophysical systems (greater feedback, internalization, and recycling of materials and energies). It becames clear that active behavioral response is a dominant agent of sustainable environments even on a far broader system scale.

1. Introduction

Buildings support human dwelling, and from an ecological point of view, both are equally part of the global biophysical environment. Despite the evidence that living and non-living worlds are synthesized to constitute larger environment systems (Fernández-Galiano, 2000; Peacock, 1999; Sampson, 2007), the mainstream missions of building sustainability—maximizing efficiency and minimizing energy use—overemphasize narrow mechanical aspects of building performance (Yi et al., 2017); inherent problems found in the current energy performance evaluation methods and measures include: (1) Performance is generally evaluated by modeling buildings as mass-produced energy machines, based on the conservation of energy; complex social, economic, and natural systems networked with building energies are underplayed in the energy models; (2) production of different kinds of building energies and their positive contribution to the complexity of the global biophysical system (geobiosphere) are not clearly explained by the categorical performance goal–maximizing energy efficiency (Cole, 2015); and (3) they are less concerned with the impacts of biophysically systemic interactions (e.g., synergies, trade-offs, and conflicts) among the components of building energy models (material, infiltration, space, lighting, internal loads, and occupant behavior, etc.). No clear index, thereby, exists to indicate the thermodynamic complexity of systematic phenomena between physical and non-physical building components.

Increasing agreements on the problems (Fernández-Galiano, 2000; Peacock, 1999), specifically regarding the collective functioning of buildings, their subsystems/components, and nature, are leading to a metabolic understanding of building performance (Yi et al., 2017). Recent studies address interactive/behavioral aspects of building environments (Hong et al., 2016; Ioannidis et al., 2016), and efforts are made to evaluate building performance using biological terms (e.g., homeostasis and resilience) (Gamage and Hyde, 2012). Along with this shift, this study seeks a more profound methodological transition through the lens of network analysis, systems ecology, information theory, and thermodynamics. Systems scientists, including (Schrödinger, 1945) and (Odum, 1971; Odum, 1996), state that, based on the law of entropy, all the environmental phenomena end up with maximum energy dispersal; "energy flows and matter cycles (Odum, 1971; McDonough and Braungart, 2002)" can also be applied to

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understanding the performance of human-dominated physical systems, such as buildings.

To identify building performance with metabolic terms, this study proposes an energy-flow network model (integrating material, form, and occupant behavior), algorithms, and indicators (Section 3). In this model, a building is characterized as a "living" system (in that both living and non-living things, during their lifecyles, go through the same physical process–energy dispersal (Sampson, 2007)), which is part of larger biophysical environments. This approach associates the final cause and impact of building-scale energy use and performance with the global energy-flux phenomena. Technical methods to quantify metabolic performance are borrowed from theorems of (Ulanowicz, 1986; Ulanowicz, 1997), (Odum, 1971; Odum, 1996), and (Shannon, 1948). Emergy (utmost embodied content of useful energies) and information (information content of building energy networking) employed to comparative analyses of two building types (Appendix)—an ordinary building and a net-zero energy building (NZEB)—help identify the thermodynamic complexity and dynamics of building's energy organization. Introducing four test cases ((i) a test building with full mechanical air conditioning and fixed thermostat settings (baseline), (ii) a test building with human–building interactive control, (iii) a test building with behavior centric building management and enriched insulation (following the Passive House standard), and (iv) an NZEB), different environmental building scenarios over various time frames (hours, months, and years) are evaluated to indicate environmental performance of building form, energy feedback, and human-building energy interaction in information units. This approach, at the end of the day, aims to suggest that information content of energy flow topology identifies both qualitative and intensive aspects of building performance, and emergy-integrated information offers a holistic index of building sustainability.

2. A biophysical paradigm of building performance evaluation and information

2.1. Systemic understanding of building energy

A building is an environmental system by itself, where it interactively shelters interiors, spaces, and humans by channeling a variety of heat, matter, and information (Fernández-Galiano, 2000). Thermodynamically, building components distribute and assemble different resources in complex ways, mediating climate conditions consistently through its physical (formal) setting, which is activated by building occupants. In other words, a building organizes energies and materials for climatic modification through its physical settings like a living system and also uses a neural-like information from occupants as a third environmental source. These features allow us to characterize building performance with the hypotheses and principles of environmental phenomena addressed mostly in systems ecology. Based on the second law of thermodynamics, ecologists, quantum physicists, and others have long claimed the holistic principle that living things maintain order and life to harness more energy, which increases entropy (Schrödinger, 1945; Brillouin, 1961), and the final cause of this is to maximize power (energy availability per time) rather than efficiency (Lotka, 1922; Odum and Pinkerton, 1955); they also understand that non-living objects amalgamate various kinds of energies to increase power in response to internal and external changes.

This elucidation about the common nature of the living and nonliving world seems to contradict current efficiency-oriented approaches to building sustainability, because they tell us that power may sacrifice efficiency for better performance. The point is, however, that this argument is made in the context of systems analysis. Some specific parts of a building, such as mechanical equipment, can or should be more efficient than others, but the building on a whole (being a system) ends up accumulating greater power with intermediate efficiency. This suggests that building performance be evaluated at a macroscopic level, and overall environmental responses from a building are neither aimless nor accidental but a result of structuralized behavior to pursue goodness (i.e., power) for its sustenance. In this understanding, building sustainability is characterized with system-level attributes. Any change in the attributes then becomes a paramount descriptor of sustainability.

Input–output (or black box) building models are usually scantily concerned with such systemic aspects when evaluating performance; all too often, building performance is indicated by aggregated extensive measures, such as end-energy use, material quantity, or efficiency of a mechanical system, which is not representative of temporal/spatial variations. Little is known about the complex dynamic organization of building elements, energies, and materials as well as how they inform performance and sustainability on a global environmental scale. To find a solution for this issue, H.T. Odum's theorems on ecosystems are referred. He states that every environmental entity is hierarchically structured internally and externally in an energetic order (Odum, 1971). Although this idea is essentially reductionistic, it accounts for intensive aspects of system performance by configuring compartmental energy dynamics with flow networking. Characterizing flow quantities with an embodied solar energy unit—emergy—enables us to appraise the quality and topological patterns of energy flow organization for system development. Use of emergy as an integral unit of a flow quantum in building thermodynamics, accordingly, has some distinct advantages: (1) Integrated accounting for different kinds of energies (from human economy, environmental services, nature, etc.) in a unified measure; (2) greater sensitivity than energy in the indication of system performance than non-system-based metrics; and (3) capability to associate local system behavior directly with the global environment (Yi et al., 2017; Odum, 1996).

2.2. Building as a form of information

Information is a scientific term used to describe causality of decision making. Despite its double nature of semantic and syntactic description, according to Wiener's *Cybernetics* (Wiener, 1948), information is defined as a system's capacity to fine-tune system components for normal operation. With this understanding, information content is measured in a degree of uncertainty in the probabilistic distribution of any type of system resources (Shannon, 1948). In this context, the flux of environmental resources through a building implies that a building forms an information system as well. Building information could be anything that characterizes system dynamics across components. From a thermodynamic perspective, information features non-physical properties but channeled through a building's formal setups, controlling energy–matter organization. This understanding is consistent with the ecologists' clarification on system-level attributes in which energy, matter, and information are three fundamental elements of a living system's thermodynamic transformation (Jørgensen, 1992). Importantly, although these three elements are deemed interchangeable in physics, information governs the other two by encoding them in its own format. In any system, environmental information processing is embedded implicitly in its physical setting so that it adjusts and controls the circulation of thermodynamic content. This strongly suggests that building performance, as the working of an environmental system, be measured in information, making the physical structure of energy–material flow a major target of our observation.

2.3. Human-building interaction on a system scale

Information is dominant to ensure stability and resilience of physical system operation, as it helps to configure a robust feedback loop quickly (Meadows and Wright, 2008). By the same token, in the course of the climate modification of a building as a shelter, human engagement (as the most informative building component) can strengthen the climatic adaptation of a building by allocating environmental resources effectively within a reactive energy flow topology. However, since