Highlights of Sustainability

Review

Beyond Energy Efficiency in Building Sustainability: A Review of Emergy and Information for Systemically Characterizing Building Performance

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Abstract Sustainable buildings tend to maximize power and information rather than efficiency. The multidimensional concepts and tools provided by systems ecology and thermodynamics aid the understanding of building performance and sustainability as part of the global and complex thermodynamic phenomena in living systems—energy is not concentrated, but it flows, increasing the flow rate of useful energy. From such an extended macroscopic perspective, this paper addresses holistic eco-systemic criteria of building performance evaluation, focusing on e*m*ergy (spelled with an "*m*") and information—the two critical indices of extensive and intensive analysis. Emergy aggregates the utmost and upstream energetic impacts, whereas information evaluates the structural pattern of the energy-flow distribution. These indices are theoretically correlated under the principles of ecological energy transformation and are often practically compatible. To clarify the definitions and appropriate scientific contexts of the new indices for environmental building studies, we review information theory, ecological theorems, and a few pioneering studies. Emergy and information have a great potential for advanced environmental building analysis, but building-scale implementation of emergy, information, and system principles remains a scientific challenge. The findings call for further research into the improvement of building-specific emergy/information data and reliable evidence of the analogy between building and open living systems.

Keywords building performance; emergy; information; building sustainability; energy efficiency; maximum power

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1. Introduction

1.1. Ecology of Building Performance and Sustainability

In most building studies and practices, saving energy and increasing efficiency form the foundational goals of designing, analyzing, and constructing sustainable buildings [1–3]. Even in well-established procedures—regulation codes, rating standards (LEED, CIBSE, etc.), and accounting methods or tools (EnergyPlus, IES-VE, eQuest, etc.)—to support environmental sustainability, performance evaluation relies overwhelmingly on the quantity of energy. In turn, the degree of sustainability is primarily represented by aggregated terms of end-energy use (Joules, Watts, or Btu) or the ratio of energy saving to input energy. Consequently, technical building methods to achieve high performance, such as energy conservation measures (ECMs), are often implemented to manage energy efficiency instrumentally (e.g., turning off lights, reduction of plug loads), which may obscure a broader understanding of the complex and multiscale behavior of the building environment.

In terms of building performance indication, such narrowed energy-oriented observations on the operational balance and efficiency are rooted in the first law of thermodynamics (FLT) and its limited use within the small physical boundaries of a building. Under this principle, buildings are assumed to be stand-alone consumers of mass-produced energy and material, even though building processes rarely occur in isolation [4]. This conventional mechanistic paradigm is radically demonstrated through the manifestation and practice mission of high-performance buildings: maximizing efficiency, minimizing energy loss, and net-zero energy building (NZEB).

However, this perception may be misleading for understanding building sustainability and can conceal bigger questions. For example, NZEB's attainment of maximum energy efficiency is undertaken only at the expense of additional material, labor, and cost input [5,6]. The NZEB definition also provokes the controversial assumption that renewable energies, which are not "free" in fact and potentially unstable, are permanently renewed and limitless [5,7]. Moreover, if an NZEB produces as much energy as it consumes, the NZEB disregards input energy types and usage thresholds. There is ambiguity surrounding the inclusion of unsettled future events for buildings and occupants in the short-term energy/cost payback planning [8,9]. These challenges make us suspicious of the "net-zero" or energy efficiency, as the predominant building performance and sustainability metrics.

Building energy is affected with an ensemble of human activities, large-dimensional social services, economy, and nature, all of which are parts of the global environmental system [10–12]. Complex external and living agents may therefore influence building energy, and building performance and sustainability must be explained in terms of higher-level phenomena. Nevertheless, in current building practice, involving large-scale constituents is a rather delicate task because it calls for a different understanding of building sustainability, including the ecological rationale behind building sustainability and the extension of the energy principles to symbiotic building work and their ecological reasoning. For substantiating this new approach, we have to consider that living things and designed environments share an identical energetic nature, in that "energy disperses and material flows" [4], as described in the principles of thermodynamics. As Braham [9,13] states, environmental building sustainability and performance are coherently and universally indicated with phenomenological accounts based on the causality of empirical systemic events in the bio-spherical context of building energies.

1.2. Scientific Philosophy of Performance Evaluation

A building performs based on a set of natural, technological, and social systems, and there are numerous parameters that define the building system performance because the orientation and properties of component connections differ greatly. To characterize sustainability, a large set of data representing the real system should be gathered through a series of observations or experiments. Munda [14] analyzed the development of sustainability assessment methods by setting: (i) the purpose of evaluation, (ii) scale of analysis, and (iii) set of dimensions, objectives, and criteria. Given the above factors, to describe system performance, the methodological approaches that characterize complex factors can be grouped into (i) reductionism and (ii) holism [15,16], according to the dimension of measurement, types of media, and the number of indicators. Contrarily, according to the scope of assessment, performance evaluation methods are broadly divided into (i) extensive analysis (non-system-based) and (ii) intensive analysis (system-based) (Figure 1).

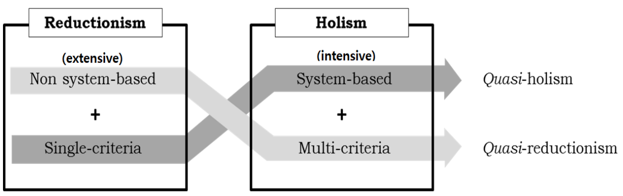


Figure 1. Philosophy of sustainability assessment: reductionism vs. holism.

Corresponding to the view of reductionism, the extensive approach considers resource depletion, focusing on overall energy efficiency based on an input–output system description. However, because a building is not a mechanical assembly, it is insufficient to provide insights into the internal organization of and interactions among individual building elements as well as the temporal reciprocity of the building life cycle phases.

Systemic (intensive) analysis addresses simultaneous energy processes, contingent energy work, and the conditions of energy operation. This approach is rarely applied in environmental building studies, as it is based on modern systems theory [17], which is foreign to the dominant reductionist ideals. Systemic analysis considers the systemic organization and flow configuration of energy and material, focusing on the reciprocity of subsystem components. Accordingly, defining a system boundary and structure is crucial; consequently, the selection of criteria is dependent on the structural detail and analysis resolution. The difference between extensive and intensive analyses is emphasized when setting the scope of variables and data observation.

Similarly, the reductionism-vs.-non-reductionism distinction is associated with differences in the resolution of investigation and the number of criteria. Reductionism explains complex systemic processes by mechanical causality of inputs and outputs, and the diagnosis of systemic variations is condensed to a single or few indicators [16]. This disregards the internal dynamics of a target system and the consequential performative impacts. A holistic view emphasizes local contexts and component-driven changes in system performance. This forms a multi-criteria framework, possibly combining cross-disciplinary techniques and tools to characterize the different phases of analysis, allowing the integrated implementation of diverse indicators [18–20].

1.3. Systemic Descriptor of Building Performance: Emergy and Information

Odum [21] states that building design and management are short-term components of the biosphere (largest ecosystem) evolution. Additionally, Schneider and Kay [22] declare that every environment must be understood as a whole system. They strongly support the need to understand the (eco)systemic properties of building performance. Although environmental decisions are not the sole drivers of the design and construction of buildings, they are a formal arrangement of the flow of material, energy, and information—three cardinal elements of the universal environmental system [13,23]. Thus, it can be concluded that a building spontaneously organizes a complex thermodynamic structure to interactively channel those elements, similar to other environmental systems. This structure may be implicit or indirectly observable in physical construction, but it explicitly requires the ability to intake and process all energy exchange [6].

From this perspective, the goal of building sustainability is to increase the capability of the whole environment to systematically manage, conserve, and restore global resources, which are largely bound to the following constraints: (i) resource availability, (ii) limits to inputs, and (iii) the consumption rate of the geobiosphere [24,25]. To this end, we should incorporate the attributes of the indirect work of the large-scale environment into direct building performance indicators. Accordingly, the environmental capacity and efficiency [26]—the two primary attributes of system performance—must be addressed at the macroscopic level for building analysis. However, the aggregated indicators of efficiency in the predominant reductionist (or even holistic) approaches tend to lack a comprehensive diagnosis of sustainable building processes.

To address the limitations inherent in the mechanistic terms of building efficiency, this study seeks to deliver critical thoughts and methods of complex and holistic environmental building assessment, which has not received substantial attention in building studies. Focusing on the "systemic process" of building energy exchange associated to the performance indication, cardinal principles and indices must be studied from the interpretation of ecosystems growth and development—particularly, the e*m*ergy (spelled with an "*m*"), information, and underlying principles. Specifically, emergy represents all upstream energy/material deposits and globally characterizes the extensive system capacity involving the donor-side resource availability and production limit of goods and services. Additionally, information is defined as the dematerialized codification of energy [27]. Moreover, the global system efficiency, an intensive aspect of resource utilization, can be identified by informational indices, to quantify the user-side ability to affect material processes, energy flow, and the schemes of throughput management.

Specifically, this study reviews and discusses thermodynamic definitions, metrics, and system theories of emergy and information and investigates their potential building applications and overall utility in the context of the built environment. The remainder of the article in divided into the following sections. Sections 2 and 3 briefly review the scientific context of the definitions and metric units of energy, emergy, and information through a comparative study, and Section 4 addresses the ecological principles of emergy and information use. In Section 5, we investigate the current research orientation and application of systemic indicators to evaluate buildings and built environments. Section 6 presents the critical challenges posed by current emergy and information indices. Finally, emergy and information are comparatively discussed to characterize the building sustainability as the long-term and directional magnitude of ecological development.

2. Indices of Energy and Information

2.1. Indices of Energy Stock (Concentration)

2.1.1. Energy and Entropy

Energy often accounts for the capacity for doing work, and form of energy varies according to its sources, carriers, and storages [28]. Energy analysis (EA) measures an amount of energy imported and consumed to produce target services [29]. According to the FLT about energy constancy, it never disappears but only transforms. In building studies, for example, if energy stored in materials is the same quantity as heating or cooling energy, they are considered equivalently [30]. Formal interchangeability is a primary feature of energy accounting and shapes the basis to evaluate the performances of various buildings and systems.

However, as Moran and Shapiro [31] point out, direct energy stock evaluation under FLT cannot clarify the environmental impact of energy flow and transformation. For instance, material cycling, heat dissipation, and degradation of the energy stock are not identified in the EA metric system. In particular, the idea of energy equivalency (heat equals work and energy is not destroyed) is ill-suited to elucidate irreversibility and directional effect of energy flow [27,32].

To avoid the pitfall of energy conservation, we refer to the SLT and the free/available energy in which takes only useful part of energy, i.e., heat convertible to work. Unlike energy, free energy focuses on the accumulated measurement of the "distance from thermal equilibrium (no heat exchange with the external environment)" [33]. This approach also pertains to the concept of "entropy" that allows for hierarchical energy structuring that characterizes thermodynamic energy flow complexity [15]. By introducing the Clausius inequality, the amount of useful work done becomes related to system entropy. For example, if no external energy enters a system, change in free energy is inversely proportional to the entropy in the system. Entropy better explains natural phenomena of energy degradation and dispersion found in every energy transformation process [32]. Understanding that energy is harnessed for sustainable living, free energy and entropy are central to identifying energy performance and the interaction between systems and environments [27,29].

2.1.2. Embodied Energy and Emergy

Embodied energy (EE) is called the input–output energy. The estimation of "net energy" [34] is a key concept in understanding EE. For system evaluations of complex industrial manufacturing and services, it is necessary to aggregate various types of work and energy processing during the production of a unit of goods and services into an energy input–output framework [35]. While energy often measure on-site consumption of resources within a small observation window, EE tends to extend the analysis scope to a greater energy "flow" chain, including indirect energy and material inputs. To evaluate performance using EE, it is critical to establish analysis objectives and boundaries and to convert indirect energy sources in a unified manner, as energy and matter are rarely separable in complicated system configurations. EE analysis (EEA) incorporates different qualities of environmental resources, but generally follows the energy conservation law.

By combining entropy and EE flow and extending them to the utmost spatial and temporal boundary, a holistic concept of energy—emergy—can be defined, referring to "the available energy of one kind required to be used up previously, directly and indirectly, to generate the inputs for an energy transformation" [36,37]. It is articulated as an upstream extension of "embodied exergy" because it accumulates all types of direct/indirect energy flows starting from the natural formation of energy and matter. By doing so, emergy enables the evaluation of different environmental production and services similar to solar embodied energy input. Similar to EE, emergy is also (i) process-based, includes (ii) economic value, and considers (iii) indirect effects of energy flow. Unlike energy, emergy is pertains to energy quality and transformation, and implicitly summarizes all the contributions of exergy inputs [38]. Emergy-based energy flow accounting—also known as emergy synthesis (EmS) or emergy analysis (EmA)—describes a unit of emergy as a thermodynamic quantum and traces its flow within a system boundary, recording all quantitative energy trajectories (Figure 2).

Unlike exergy-based indices, emergy categorizes energy types according to the source of generation: renewable (R), nonrenewable (N), and imported/purchased (F) [39]. The distinction between these categories forms the basis of emergy sustainability indicators: the environmental loading ratio (ELR; ELR = F + N/R) and emergy yield ratio (EYR; EYR = emergy of products

(Y)/F). In addition, from the ratio of ELR to EYR, EmA suggests an emergy sustainability index (ESI or SI), that is, ESI = EYR/ELR [40] (Figure 2).

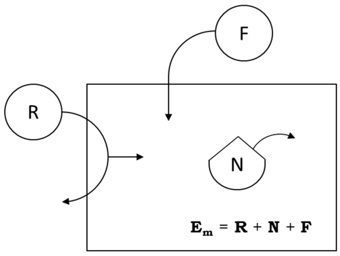


Figure 2. Three major input sources in a basic emergy analysis diagram (Em, Total system emergy; F, purchased emergy; R, renewable; and N, nonrenewable) [41].

2.2. Information: Indices of Energy Flow Distribution

According to the SLT, the nature of energy use considers directional degradation (the irreversible energy flow from high to low quality). A building must be evaluated by understanding the internal energy flow structure. Exergy and emergy form the qualitative aspects of energy equivalency, illustrating the hierarchy of different energy use, but they are inappropriate for directly measuring the complex characteristics of energy flow distribution.

Information can be introduced to complement concentration-based definitions. Information, originally describing a mathematical measure of signal transfer in telecommunication networks, refers to a reduction in decision-making uncertainty. In an environmental context, it is a generic unit of ecosystem equivalent to embodied energy and matter [42,43]. To evaluate systems using informational indices, an analogical recognition of the energy processing of ecosystems as well as methodological inferences (from thermodynamic entropy and information theory) are required. Methodological inferences are based on the assumption that energy-channeling systems are structured with an indeterminate (stochastic), rather than arbitrary, order. The following subsections briefly review the major information indices and mathematical formulations.

2.2.1. Shannon Information

Harry Nyquist [44] first demonstrated that a large dataset of communication input can be computed using the logarithm of the possible sequences of signals. To identify the transmission capacity in telegraph communication, Shannon [45] developed the concept of information. Unlike the semantic definition of information, Shannon's definition measures an amount of "uncertainty" that is required for secure signal delivery. If p_i denotes the frequency of a target signal measured on the i-th of n channels, the information of the channel system and the probability (p_i) are related such that $p^H = p_1 p_2 \dots p_n$, assuming that each channel is independent. For several compartments (transmitter), the information entropy or Shannon index (H) is obtained by

$$H = k\left(p_1 log\frac{1}{p_1} + \ p_2 log\frac{1}{p_2} + \cdots + \ p_n log\frac{1}{p_n}\ \right) = -k\sum_{i=1}^{n} p_i log(p_i) \quad (1)$$

where k is a positive constant depending on the unit selection and n is the total number of components. A negative sign indicates that the information is inversely proportional to the probability of a target signal. This expression is similar to that of the Boltzmann equation in statistical mechanics. The logarithm bases were 2, e, or 10. This formula can indicate thermodynamic entropy if k is Boltzmann's constant, and the natural logarithm base is used. The theoretic entropy built with the information theory employs $k = 1$ with a binary base, so the information unit is a "bit". The choice of the base does not critically affect the interpretation of information values.

2.2.2. Kullback–Leibler Information

The Kullback–Leibler information (KL-divergence or D_{KL}) is also called relative entropy or information gain. It evaluates the additional information required to estimate a true probability distribution P (e.g., true values or observed data) with a hypothetical distribution Q (e.g., theoretical probability function). KL divergence is closely related to Bayesian inference because it represents the degree of uncertainty in the approximation of P, given a prior distribution Q. The following equation computes the KL divergence:

$$D_{KL}(p||q) = \sum_{i} p(x)\, log \frac{p(x)}{q(x)} = H(P,Q) - \; H(P) \tag{2}$$

2.2.3. Fisher Information

Fisher information is defined as the variance in the expected values of the observed distributions. Mathematically, if the state parameter (θ) is non-random, we cannot follow the Shannon information approach. Instead, derived from Equation (1), the Fisher information is formulated as

$$F(X|\theta) = \int_{X} \frac{1}{p(x|\theta)} [\frac{\partial}{\partial\theta} p(x|\theta)]^2 dx \tag{3}$$

where θ denotes a random parameter of the random variable x and $X = \{x_1, x_2, \dots, x_i, \dots\}$.

Note that this is not a function of a particular observation, but implies a continuous description of dynamic system-level behavior. Suppose that one seeks to track the enumeration of the system state change with a quantified strength. Substituting the independent variable x with a state variable s, the Fisher information can be rewritten as

$$F(s) = \int_{S} [\frac{d}{ds} p(s)]^2 \frac{ds}{p(s)} \tag{4}$$

where $s \in$ S and $S = \{s_1, s_2, \dots, s_i, \dots\}$, and $p(s)$ is the likelihood that one observes the system to be in a particular state. The derivative term $dp(s)/ds$ indicates that the Fisher information is proportional to the rate of distribution change within the system.

2.2.4. Average Mutual Information

In ecosystem studies, Shannon information is generally used to quantify the diversity of a media distribution [46], or the complexity of a channeling pattern. However, it does not describe the dependent media exchange between the system components. Thus, the average mutual information (AMI) was introduced to measure system interconnection. Suppose that we have a binary system network, as shown in Figure 3a. AMI is mathematically expressed as a weighted sum of the probabilistic uncertainty of a compartmental flow [45,47], such that

$$\text{AMI} = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{T_{ij}}{T} log \frac{T_{ij}T}{T_i T_j} \tag{5}$$

where T is the total system throughput, T_i is the total flow leaving from i (②+④+⑤), T_j is the total inflow to j (①+②+③), and T_{ij} is the transfer from i to j. Note that AMI refers to the degree of component association and is maximized at feedback networking, or the so-called autocatalytic networking, when both i and j become sources and receivers.

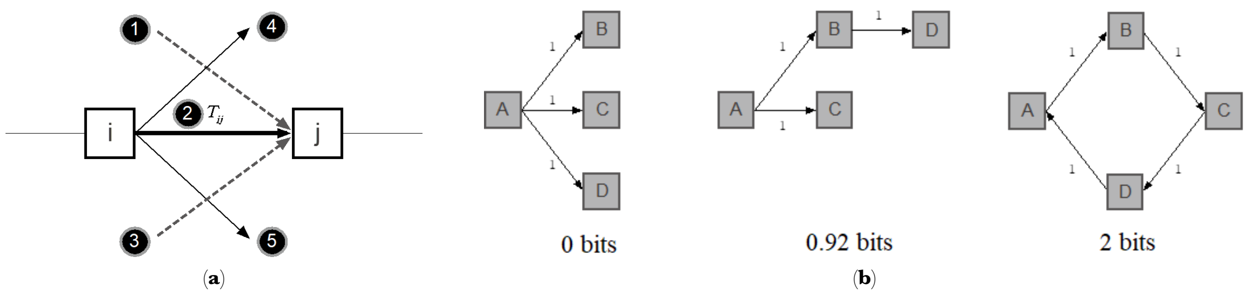


Figure 3. (**a**) Formulation of AMI: (1) external import to j, (2) internal transfer from i to j (T_{ij}), (3) internal transfer to j, (4) flows out of i to other comportments, (5) export and dissipation; and (**b**) AMI calculation examples: AMI tends to be maximized where the medium is evenly distributed over the circulating flow alignment.

2.2.5. Ecological Measures of Information

According to biologists, information indices can be compiled to evaluate system-level events and structural behavior. Particularly, Hirata and Ulanowicz [48] proposed information-based system attributes such as ascendency (A), capacity (C), resilience (L), fitness (F), and robustness

(R). A is introduced to measure the system development by multiplying AMI and the total system throughput (T), as follows:

$$A = T \cdot \text{AMI} = \sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij} \, log \frac{T_{ij} T}{T_i T_j} \tag{6}$$

where $i, j = 0$ denote the external input (import), and $m + 1$ and $n + 1$ are the system outputs to the external environment (export). $m + 2$ and $n + 2$ denote depreciation.

As efficiency corresponds to the degree of particle (energy or material) circulation in a flow-based understanding, we may say that AMI indicates system efficiency. Therefore, the degree of autocatalysis or self-enhancing mechanism, A, refers to the networking of effective transport links [49]. In contrast, the overall system developmental status can be identified using the system capacity, C, which is expressed as

$$C = T \cdot H = - \sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij} \, log \frac{T_{ij}}{T} \tag{7}$$

C is related to the homogeneity of the spread of a system's individual granular particles and the overall flow complexity. These indicators are based on a phenomenological understanding that the uncertainty of resource distribution increases with the development of systems. An increase in A or efficiency indicates that the system becomes structurally rigid (or ordered). The degree of internal disorder or freedom is represented as the system overhead (ϕ) and computed by subtracting A from C, that is, $\phi = C - A$ ($C \geq \phi \geq 0$ and $C \geq A \geq 0$). ϕ is the residual uncertainty and represents the potential of the system's future evolution [50]. This interpretation leads to a quantitative definition of L as follows:

$$L = \phi / T = H - AMI \tag{8}$$

Resilience evaluates system-level preparedness or flexibility against external perturbations. This understanding is developed to propose new indices of system resilience: F and R. F is the logarithm of the ratio of A to C, and R is the fitness augmented through T [51]. They are computed as

$$F = -\frac{A}{C} log \frac{A}{C} \text{ and } R = T \cdot F \tag{9}$$

As shown for F, a compromise between the system's order (A) and disorder (ϕ) is critical for constructing an effective and adaptive energy transport structure and its sustainability. If A/C exceeds a certain threshold (0.37, [49]), the system is too structured and brittle. F is the peak at the balance point, as shown in Figure 4. Fitness can be an index of system sustainability [39] as it indicates system adaptivity for future events. Improved fitness also indicates that the potential of the energy flow increases.

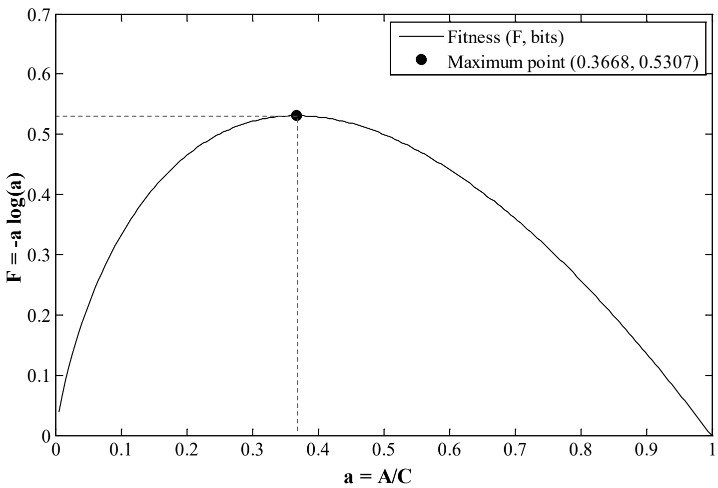


Figure 4. Fitness curve (redrawn from [52]).

3. Comparison of Emergy and Informational Indices

3.1. Energy and Emergy

The stock-based indices, including emergy, highlight donor-side aspects rather than receiver aspects, so they aggregate upstream (inflow) impacts on the building. However, most extensive stock measures generally set limited accounting boundaries. For example, the indirect work of renewable and small quantities of energy is discounted by energy and exergy in performance evaluations. The qualitative difference of energy is considered in exergy analysis [15,53], but in energy transformation, it covers only a narrow domain [36]. Additionally, energy assessment excludes various indirect environmental support services [24]. Emergy significantly enlarges the scope of building energy work to the global capacity of environmental sources, for example tidal flow and deep earth heat, which are eventually represented in a single source term—the solar energy. Different types of energies are aggregated by a unit of emergy into a unified solar energy equivalent—solar emjoule (sej) [54]. To summarize, the difference between energy and emergy are as follows (Table 1; Figure 5):

- EA and EEA focus on the interchangeability of heat and work and do not account for the energy quality.
- EmA primarily deals with the flow of energy as Odum's empower principle defines empower as the rate of emergy delivery, but exergy is concerned with a component's internal states energy "fluxes" in the presence of external energy exchange.
- During the first transmission process (E_{mi}), the rate of emergy inflow (empower) was measured to identify the maximum power principle (MPP). In the case of multiple first energy exchanges, each emergy output must be evaluated [55], because the MPP considers all the energy directly supplied from the source (occasionally, it is difficult to identify every input point in a complex system; thus, a total of dissipated energy is measured instead) [36].

Table 1. Comparison of stock-based indices and efficiency measures.

Index	Quantification	Transfer Direction	Capacity Limit	Efficiency
Energy	Net change	×	●	E_o/E_i
Exergy	Net negentropy Net useful energy	●	●	Ex_o/Ex_i
EE	Net energy	×	●	$\Sigma E_o/\Sigma E_i$
EmA	Energy "flow" or the accumulation of net "available" energy	●	●	*EYR*

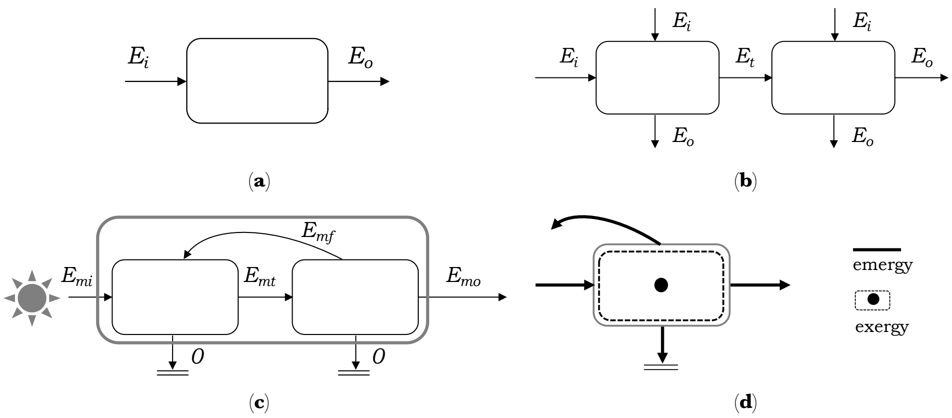


Figure 5. Comparison of extensive analytic methods (*E*: energy, *Em*: emergy, *i*: input, *o*: output, *t*: transfer, and *f*: feedback): (**a**) *EA*: *Ei* = *Eo*; (**b**) *EEA*: *Ei* + *Et* = *Eo*; (**c**) *EmA*: *Emi* = *Emt* = *Emf* + *Emo*; and (**d**) *EmA* vs Exergy.

Emergy's uniqueness lies in the universal measurability of energy and material phenomena of all environmental systems in thermodynamic terms and the description of a macroscopic system order based on energy transfer chains. In emergy accounting and analysis, using the common denominator (solar energy) includes every component carrying specific emergy intensity values, the unit emergy value (UEV; sej/unit quantity) or solar transformity (sej/J). The UEV is critical for understanding the energy quality change during the transformation process. Odum noted that UEV is naturally found, regardless of scale, and a small food chain, building, and social structure develops hierarchical energy systems [30,36,56].

3.2. Information Indices and Entropy

In comparison to the energy analysis, a novelty of emergy and information is found in their search for addressing the "flow" and transformational "linkage" of assorted materials and energies. Information probabilistically measures the structural pattern of flow networking, while emergy expresses the accumulated effect of complex energy exchange and deterministic quantities resulting from the flow configuration.

Rutledge et al. [46] first applied the Shannon index to characterize the diversity of biological succession. Since then, it has been used to explain ecosystem phenomena in thermodynamic terms [51], particularly, a trophic structure's topological composition of nutritional equitability and biodiversity [21]. However, dynamic environmental ordering of an individual pattern remains unclear through the Shannon index [57,58], because it codifies "averaged" and static indeterminacy of a system-content unit in an observed state, regardless of the data sampling sequence or flow pathway direction. The effectiveness of the Shannon index depends on whether flow individuals are perturbed by an external rearranging force. However, due to the normalizing aspect of the Shannon index, Fath et al. [57] describe it as a "global" system property. In case of a continuous phase transition in system evaluation, Fisher information is alternatively employed to monitor sequential (re)organization of flow patterns. Moreover, Fisher information changes over time; thus, it can be a measure of "invariability" of local system states [59].

Thus, emphasizing the theoretical and practical distinction between Shannon and Fisher information is crucial. If the flow density function $p(s)$ is constant, $dp(s)/ds$ is zero, and the Fisher information is minimized, implying that there would be no local variation. In this case, the Shannon index value would be the greatest, implying that the overall system states are extremely unstable. The Shannon index measures the system's movement from the thermodynamic equilibrium (maximum entropy state), whereas Fisher information is used to trace the history of state variation over time. Therefore, the Shannon index is related to the ecological concept of homogeneity, diversity, or capacity, whereas Fisher information indicates stochastic flow regime change or the degree of vulnerability/fluctuation.

4. System-level Thermodynamic Principles

4.1. Maximum Power Principle (MPP)

In biology and ecology, the MPP refers to theorems of energy transformation in system designs, defining all natural phenomena as maximizing power and optimizing efficiency. Schrödinger found that system prevalence is "a struggle for free energy" [15,60]. Similarly, MPP finds that survival in competition and energy transformation structures is hierarchically self-organized to participate in this struggle. Thus, all environmental entities tend to "systemically" increase power at an intermediate level of efficiency. In the MPP, system power refers to a "rate of the useful transformation of available energy sources" [43], often represented as energy per unit time. This theorem originates from Lotka's finding of maximum power tendency in living organisms [61]. To these findings, Odum [36] added evaluation methods, including (i) human work and nature and (ii) different energy types, finally establishing the maximum empower principle (MePP), which is a complementary extension of the MPP. It was developed to account for the qualitative aspects of the energy population in terms of emergy [56].

Maximizing the empower excludes indiscreet energy exploitation. Rather, the MePP confirms that high-performing systems carry fine-tuned feedback loops of emergy flow to amplify the system power by circulating input sources. This leads to a trade-off between the energy capacity and efficiency. As shown in Figure 6, Odum demonstrated that the maximum-power state is ideally achieved at approximately 50% efficiency [7]. If the efficiency is close to 0% or 100%, the power becomes zero, and indicates that the system is highly vulnerable.

The ability of a system to survive in nature implies its potential for sustainability. If the MePP accounts for nonliving but nonequilibrium systems (i.e., civilization/sociocultural development, human affairs), as Odum [7,36] insists, it can be inferred that the MePP also manifests in the built environment. Performatives can then be indicated through the characteristics of prevailing natural systems, such as the development of energy hierarchies and flow feedback. Evaluating these criteria in a building boundary, different ecological developmental stages of building sustainability can be defined. The systemic developmental types of buildings are categorized into four regimes, as shown in Figure 7. In more developed and sustainable phases, the input energy must be reduced while increasing the processing quality (transformity) for maximizing power. In the final phase of development, the MePP indicates that the energy transfer mechanism is finely organized and the efficiency reaches 50%.

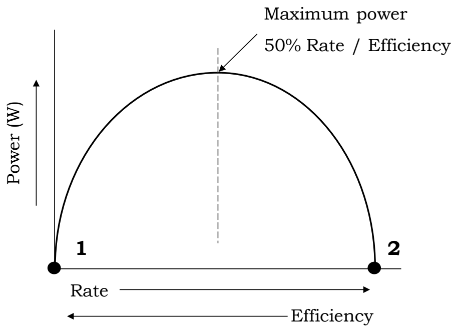


Figure 6. The maximum power at 50% efficiency.

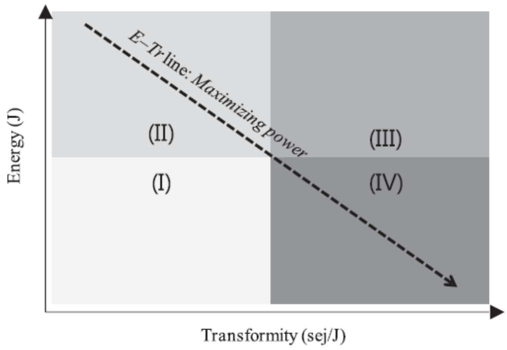


Figure 7. System developmental stages: (I) Premature, (II) Embryonic, (III) Growth, and (IV) Development [6].

4.2. Informational Ecosystem Principles

Using information entropy, information principles in ecology attempt to articulate the cause of a system's natural choice—among many random possibilities—of specific energetic arrangements. The fundamental hypothesis is that for performing work, ecosystems develop structural fluxing pathways to harness optimum input exergy. To discover a certain energetic order of developmental phenomena of ecosystems and the emergence of an evolutionary structure, information measures focus on the topological characteristics of energy/material flow, whereas the MPP advocates "power" as an integral indicator.

Originally studied by Jayne [62,63], the principle of maximum entropy (MaxEnt) or entropy production is the basis of ecological information principles, such as the maximum entropy theory of ecology (METE) [64], or maximum information entropy (MIE). In MIE, the system tendency to increase the thermodynamic entropy rate is compared with the complex form of macroscale flow networking, clearly observable in natural ecosystems [22].

Information and entropy are often collectively defined, or even interchangeably used, in a broad spectrum of environmental scientific contexts [27,42]. This is because they share the same hypothesis originating from SLT, that maintaining thermodynamically far-from-equilibrium states explains the vitality of all active physical systems. Thus, at a macroscopic level of system observation, information inferred from statistical mechanics becomes relevant to describe the uncertainty of a thermodynamic system state and stochastic energy assignment.

Nevertheless, universal agreement of MaxEnt remains a controversial topic among ecologists [65]. Moreover, to avoid misconceptions, there should be a clear distinction between the informational notion of entropy and thermodynamic entropy [66]. In thermodynamics, information is defined as the negative entropy (negentropy), explicitly carrying entropic attributes of physical reaction (molecular kinetics, chemical composition of a particle, etc.) [67]. In information theory that uses the mathematical (theoretical) entropy without thermodynamic rigor, information typically measures the reduction in uncertainty to characterize a system state [68–70]. System-level interpretation of information is primarily derived from the information theory, and it is often termed potential or syntactic (structural) information [71].

The probabilistic alignment of energy quantum and matter and the topological resonance of a system is captured by the syntactic information content in a model of a biotic flow web [72].

Since MacArthur [68] applied the Shannon index to measure the ecological diversity of species, MIE has been verifiably explaining the self-coordination of living systems for the deployment of environmental sources in nature. Among many studies, Ulanowicz's [51] interpretation of information indicators is noteworthy because he establishes the information-based principle of ecosystem development and sustainability—maximum complexity and optimal autocatalysis. Autocatalysis describes the hierarchical construction of an energy-circulating pattern to augment effective flow pathways corresponding to conversion "efficiency" through the network. Oriented proliferation of input sources through an autocatalytic network is conducive to accelerating delivery efficiency and improving organizational quality. However, autocatalytic connections exceeding a certain level of efficiency do not ensure the maximum entropy or power state. This is because the networking of only a few dominant paths leads to inflexibility and unreliability for importing unexplored resources. Thus, for sustainable ecosystems, the flow complexity needs to be increased at an intermediate level of autocatalysis, such as by balancing power and efficiency.

This understanding concurs with Odum's [43] statement that if more available energy flows into a system, the network of the system structure evolves from simple linear to complex autocatalytic paths. As revealed in the simplest thermodynamic flow network (Figure 8), information entropy is maximized at 50% efficiency similar to power described by Odum. From this demonstration, we suggest that building sustainability depends not on maximizing efficiency but maximizing overall (emergy) power and complexity (informational uncertainty) of emergy-flow networks. Thus, high-performance buildings eventually evolve into high-information buildings (Figures 8 and 9).

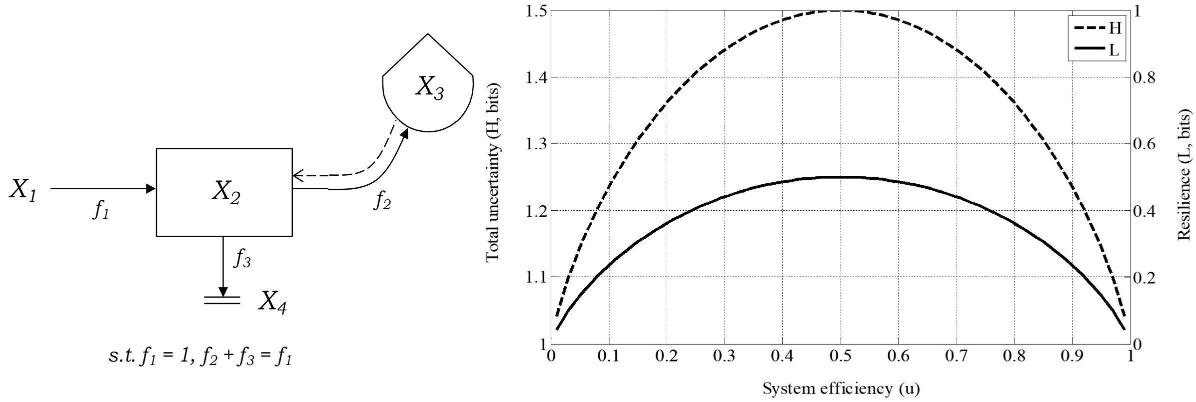
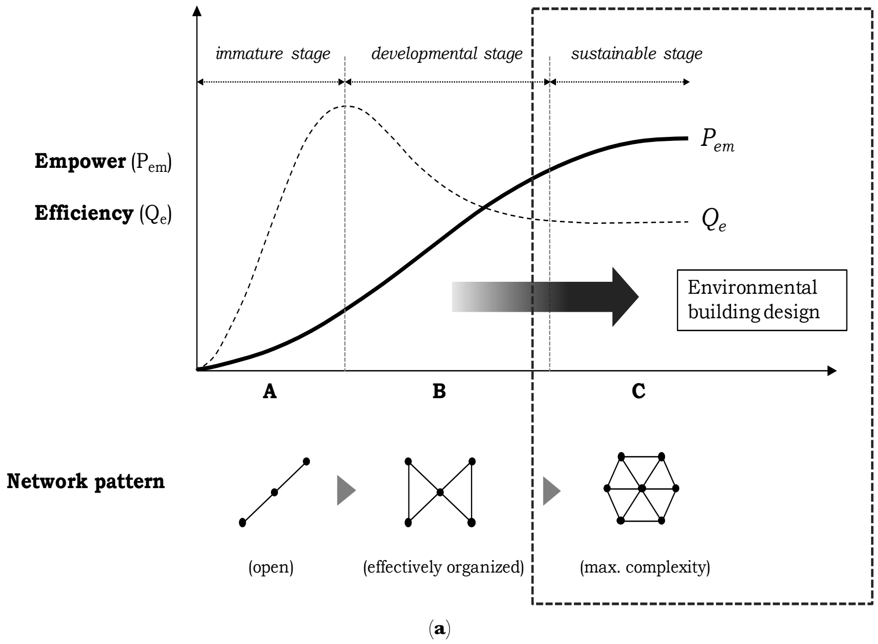
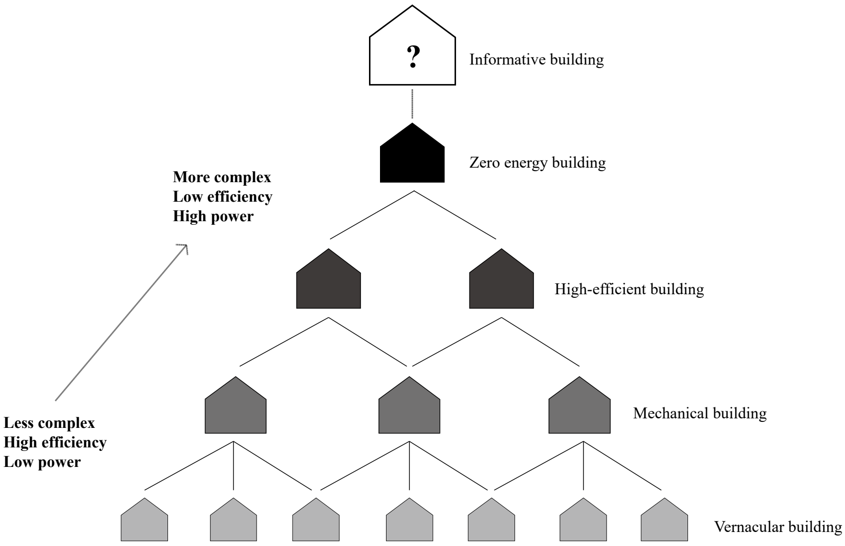


Figure 8. Comparison of MPP and information.



(**a**)

Figure 9. Ecological understanding of building sustainability: (**a**) parallelism between MPP and Informational principle (**b**) trophic representation of sustainable building development.



(**b**)

Figure 9. (*Continued*)

5. Research Orientation and Applications in Built Environment

Emergy, information, and system principles remain to be explored outside of systems ecology and biology, as it is difficult to access the underlying knowledge owing to insufficient non-biological precedents, algebraic uncertainty, and remaining scholarly controversy about their universal extension. The following sections discuss scholarly efforts to implement them as a methodology for comprehensively evaluating the built environment.

5.1. Emergy Approach to Building Application

The ecological notion of self-organizing systems is based on the hypothesis that all systems, including building and built environments, develop specific spontaneous forms of energy hierarchies through vital communication between the system and external agents. Braham [73] states that "buildings are tools in a vast evolutionary process of self-organization". Moreover, Braham and Yi [74] substantiate that building production is a "formal cause" of an energetic order of building components. This definition not only extends the theoretical understanding, but also indicates the practical sustainability. Figure 10 (sourced from [6] and [74]) displays the results of a building emergy analysis through a comparative analysis of non-NZEB and NZEB. The dynamic trends of nonrenewable emergy during a building's lifetime (50 years) show that the NZEB's sustainability is achieved by increased resource use (empower), rather than the reduction of energy and material.

Amaral et al. [75] reviewed the emergy theory and practice in terms of energy sustainability, and Chen et al. [76] and He et al. [77] performed an extensive bibliographic study to provide an overview of the current trends in emergy research. The simplicity of the computing techniques led to the dissemination of emergy to built-environmental areas and its combination with other evaluation frameworks, such as the life-cycle assessment (LCA) [78,79], or ecological footprint (EF) [80,81].

In architecture and building, the works of Fernández-Galiano [27] and Braham [73] are progressive attempts to position studies on building form, material, and performance at an intersection of SLT, ecology, and systems. In the study of building science, Brown and Buranakarn [82], Meillaud et al. [83], and Pulselli et al. [84] noted the early introduction of EmS for environmental building sustainability. Brown and Buranakarn pioneered the emergy values of building materials, suggesting their UEVs. Based on these achievements, Meillaud et al. [83] and Pullselli et al. [84] contributed to estimating the total input emergy for the entire building manufacturing and construction. The most recent building emergy studies focus on extending the EmS for analyzing different building types/components [6,78,85–93]. Meanwhile, methodological advancements [78,80,94–96] and the suggestion of new indicators [5,78] have also been explored. In particular, Srinivasan et al. [5] proposed a new building performance indicator based on the balance of renewable and non-renewable energy. Additionally, several researchers have studied optimal building design using emergy simulation [94], comparison of building EmS and LCA [79], and development of LCA-based building emergy indicators [78].

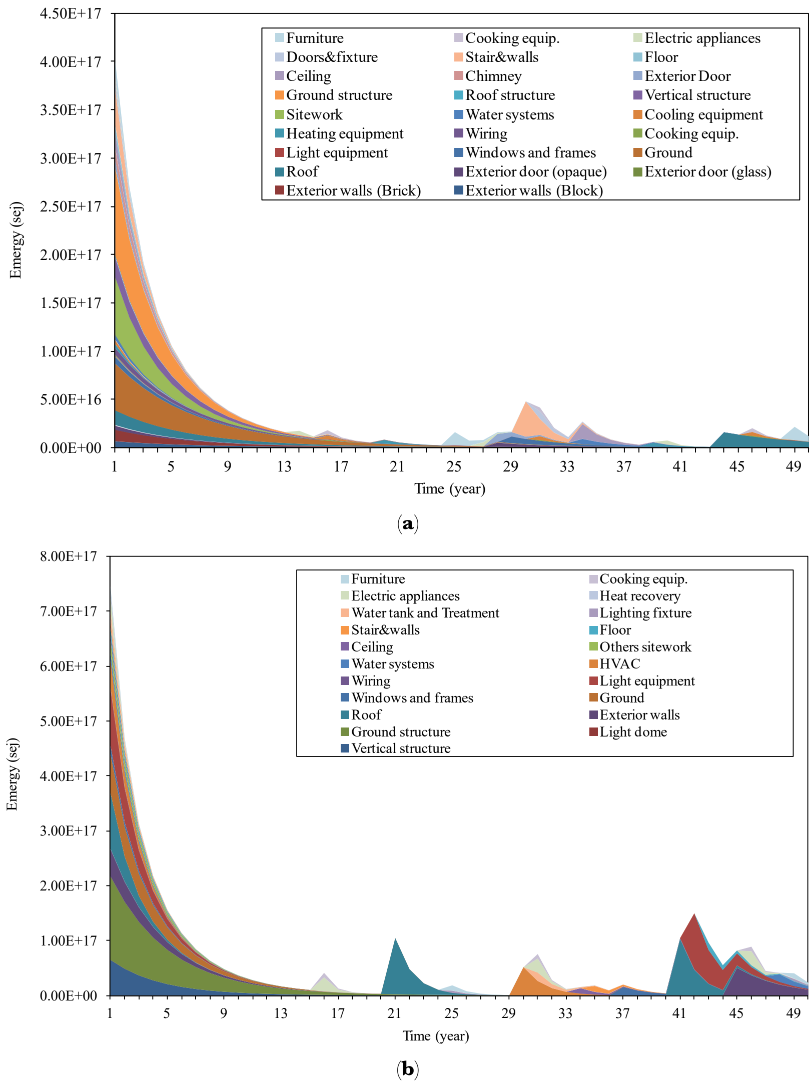


Figure 10. Nonrenewable emergy-intensity input during building life cycle. (**a**) Non-NZEB, (**b**) NZEB.

Prior to the expansion of building emergy studies, system ecologists attempted to demonstrate hierarchical spatio-temporal energy distribution on the urban or regional scales [97,98]. This is because (i) the macroscopic characteristics of emergy indices may be relatively more consistent with large built environments and (ii) according to the city or regional evaluation analyzing the natural performance of elements, EmS is more advantageous than other methods. According to the MPP, ecosystem components with greater UEV (e.g., human information) have a higher position supporting subsystems with a longer turnover time. Built-environmental investment of items or processes with large transformity has a greater responsibility for sustainability. Based on this understanding, Huang et al. [99] and Lee et al. [100] analyzed the systemic characteristics of energy flow in an urban landscape. Lei et al. [101], Lee et al. [102], and Huang et al. [103] further attempted to evaluate the large-scale emergy contents of an entire city/city block and supported the metabolic understanding of urban development. Urban studies using emergy have recently extended to specific topics of urban system configuration, such as the influence of public services on the pattern of residential population [104] or municipal wastewater treatment [81] (Table 2).

Table 2. Major studies of building emergy application (2003–2021).

Category	**System**	**Target Process**	**Method**	**Performance Indicator**	**Ref.**
Building material	Construction material	Manufacturing [85] Recycling [82,92]	EmS	Total emergy [82,85,92] Embuilding/money [85] Emergy ratio (%) [92]	[82,85,92]
Building component	Green wall/Envelope	Manufacturing & Operation [86,90,91] Life cycle [87]	EmS EA	Total emergy [86,87,90,94] Emergy cost [87] Emergy payback time [86]	[86,87,90,94]
Whole building	Education/Office	Manufacturing [80] Manufacturing & Operation [5,83]	EmS	Total emergy [83] Spatial emergy intensity, Emergy eco-efficiency [80] Renewable emergy [5]	[5,80,83]
	Single-family house	Manufacturing & Operation [6,89]	EmS EA	Total emergy, Emergy intensity, ESI [6,89]	[6,89]
	Multi-unit housing	Manufacturing [84]	EmS LCA	Total emergy [84] Emergy eco-efficiency, ELR, ESI [78]	[78,84]
	Net-zero energy building	Manufacturing & Operation	EmS EA	Total emergy Transformity, Empower, ESI	[6]
	Healthcare building	Manufacturing & Operation	EmS	Total emergy, Emergy intensity	[93]
Multiple buildings	Urban landscape	Operation [99,100]	EmS	Transformity [99,100]	[99,100]
	Urban buildings	Manufacturing & Operation	EmS EA	Spatial emergy intensity	[102]

The advantageous position of emergy in the observation of systematic building phenomena explains the ordering of energy hierarchies and inextricably reveals the fundamental system principles. However, the system self-organization and energy transformation phenomena for attaining maximum empower are often unnoticeably reinforced [43,100], and the turnover time or development of feedback loops of energy networking may not be directly observed in the physical setting of buildings or cities. Therefore, in many building studies, emergy is considered as a quasi-holistic quantity, and is simply obtained by the summation of itemized emergy use. In addition, for ecologists, a building is often construed as an emergy storage, simply taking linear-static energy input. The effect of productive output and energy dissipation of buildings on building sustainability are not considered in the ecological notion. To address this issue, Yi et al. [6] suggested a generalized building emergy diagram (Figure 11). Derived from the basic emergy system model (Figure 2), this model configures essential system components, flow work, and production related

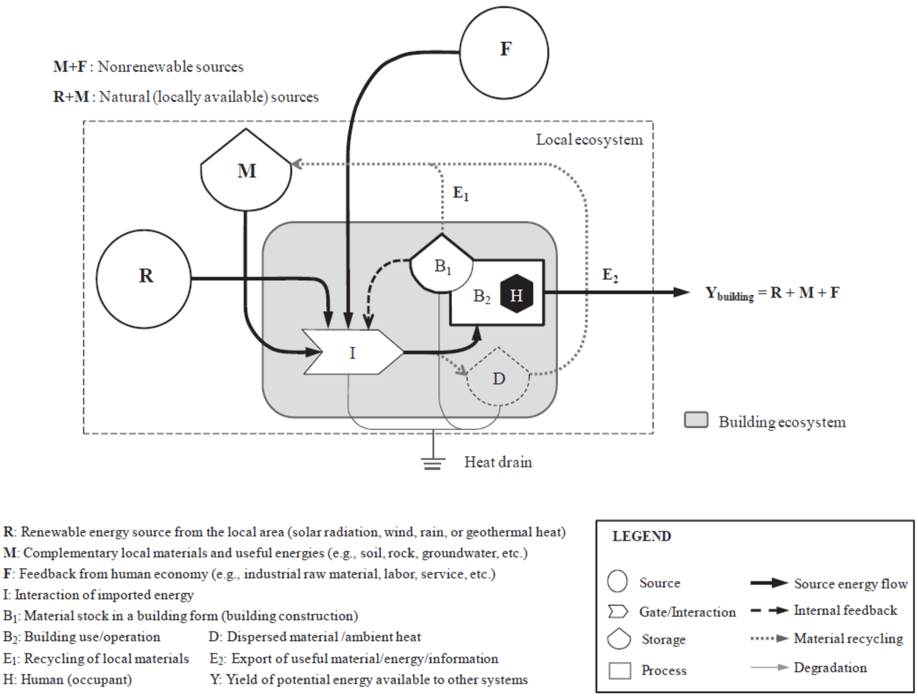


Figure 11. Building emergy system model [6].

to the emergy indicators. Building analysis using emergy diagramming is a valuable tool for building sustainability assessment. This is because (i) emergy is a holistic energy measure (from the receiver's perspective) that connects a local building system and global energy resources, and (ii) emergy can be used to evaluate all types of natural (renewable) sources. As shown in the building emergy diagrams in Figure 12, buildings are part of larger systems, and determining the analysis boundary emphasizes our focus on the impact of building performance.

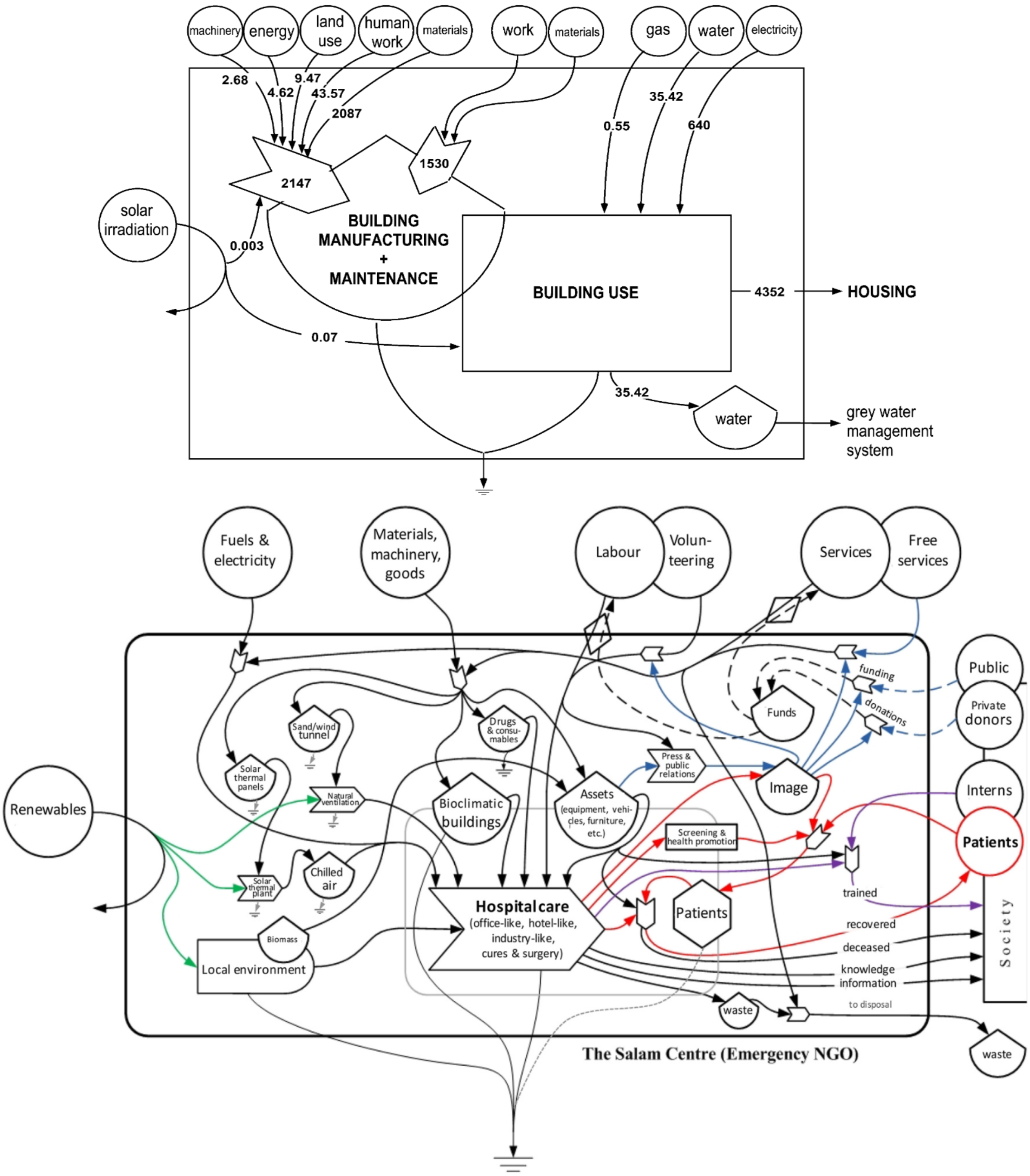


Figure 12. Building emergy diagrams: [84] (top), [93] (bottom).

5.2. Application of Informational Measures in Built Environments

5.2.1. Dissemination of Information

Schrödinger, Shannon, and Wiener's statement that "all organisms are heat engines" [105] inspired biologists and ecologists. Henry Quastler first attempted to quantify genetic content using information [106]. Ecologists explained information measures indicating the diversity of species [68] and the prosperity of living communities [69]. To achieve a unified comprehension of complex sociocultural and human-dominant phenomena as natural self-organization, indices of information entropy and methods of ecological network modeling have emerged across diverse areas including geography [70], language [107,108], sociology and economics [39,59,109], and city planning and regional policy [110–112] (Table 3). Moreover, for disciplinary purposes, information theory, thermodynamics, and entropic principles have been contextualized to extract knowledge and make decisions. Such a cross-disciplinary merger of informational measures on the artificial-environmental domains is not always successful because it leads to confusing and problematic conceptions of thermodynamic entropy and information [113,114]. Furthermore, based merely on mathematical similarity, the mixed use of terminology and indices manifests an unclear interpretation of the general thermodynamic and ecological principles [115].

Table 3. Summary of analysis methods, system designs, and hypotheses in major information-based socio/built-environmental studies.

Area	Study	Index	System Model	Indicator	Criteria
Geography	[70]	*Shannon*	N/A	Diversity	N/A
Urban Regional Planning	[110]	*Shannon*	8-subsystems with 4-metabolic interactions	α: Growth, β: Steady state	$y = -x^3$, $y = x^{1/\beta}$ (x: ΔS_{in}, y: ΔS_{out})
	[109]	*Shannon*	2-subsystems (Actions and Factors/Actors)	Redundancy	Repercussion eff.
	[58]	*Fisher*	6-subsystems (demographic, energy, food production, etc.)	High Fisher information	N/A
	[116]	*Shannon*	N/A	Diversity	N/A
Economics	[25]	*Mutual*	6-subsystems (e.g., water, oil, iron and steel, global commodity, etc.)	Ascendancy Robustness	Ascendency
Sociology	[109]	*Fisher*	a single system with parameters from global political database	High Fisher information	N/A
Building	[117,118]	*AMI, A,C,F*	3-sub systems Multiple components	Fitness	Complexity Autocatalysis

5.2.2. Information Application in the Built Environment

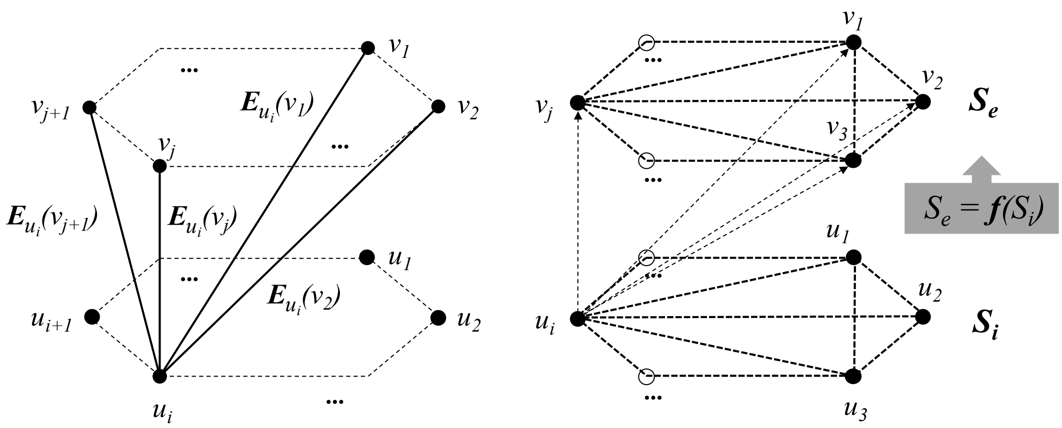
As a new dimension of built-environmental study, the emergence of cybernetics [105] supporting metabolic parallelism between organisms and inanimate systems encourages the insightful application of informational methods to relatively more complex human-dominated phenomena such as urban settlements, social activities, and economic trade of goods and services.

Since Berry [119] and Wilson [120] pioneered the informational concepts of entropy to model population density and spatial distribution of urban transport systems, urbanism and geographical investigations of macroscale operations of the artificial environment have become major domains of information application. Researchers note that the human living space is a complex, indeterminate ecosystem. To suggest the most feasible form of urban patterns based on the MIE, they adopt syntactic information as a diagnostic measure of civic infrastructure, transport of services, and distribution of human dwellings [120–123]. Ayeni [123] attempted to characterize the functional components and subsystems of a city environment, envisioning a structural city network model with matrix-based joint information measures. Moreover, according to early demographic studies [124,125], information content is a sustainability indicator of societies and human behavior [25,126,127]. However, these early attempts were criticized due to their lack of scientific rigor. As Marchand [124] admitted, finding an appropriate equivalent thermodynamic energy is highly complex in ecological modeling of human systems, in that it calls for (i) assuring the independence of observed system variables and (ii) unification of various units and scales, which is very challenging. In this regard, entropy was occasionally used as a conceptual vocabulary for thermodynamic camouflage, and thermodynamics or quantum theory may have embellished the assumption that the random motion of human interactions corresponds to that of molecules.

Nevertheless, information has recently advanced to becoming more than a complexity analysis tool [128,129]. Using Fisher information, Karunanithi et al. [109] attempted to trace the dynamic transition of political systems and measured the strength of the social organization of individual countries. Gudmundsson and Mohajeri [70] used Shannon information to indicate an urbanization pattern with several geographical traits, such as diversity of the alleyway orientation or street size.

To evaluate the sustainability of urban energy retrofitting strategies, Balocco and Grazzini [110] employed mixed informational measures such as entropy, joint entropy, and conditional entropy. The urban energy process was modeled by layering three subsystems and assigning communicative network characteristics: "actions (sender)", "actors (receiver 1)", and "factors (receiver 2)". These characteristics refer to energy-saving technologies on a building scale (solar collector, thermal insulation, renewable energy use, etc.), human engagements (occupants, building management, etc.), and environmental conditions (energy availability and climate), respectively. This study assumed that greater information entropy (uncertainty) in the presence of factor/actor variations indicates the success of an action, and lower redundancy defines sustainability. Balocco and Grazzini's work involves observers (actors) in urban planning models, but their system model is not flow- but matrix-based. Insufficient identification of flows and system-level interconnections prevents generalization.

In this regard, Zhang et al. [111,130] suggested an important example of informational urban system modeling and hybrid sustainability indicators (Figure 13). Holistic urban ecosystem functioning is defined by entropic flow exchange inside and outside the system ($\Delta S_{total} = \Delta S_{in} + \Delta S_{out}$), and information is used to measure urban developmental states ("production-feasibility curve") combined with non-informational indication of "developmental degree (degree of urban growth)" and "harmony degree (degree of stability)". This framework not only develops Ayeni's early urban network model, but also presents an open self-regulating model specifically profiling the metabolic elements of urban transactions (production, consumption, regeneration, dissipation, etc.).



(**a**) (**b**)

Figure 13. Conceptual illustration of system modeling in two studies: (**a**) [111], (**b**) [130]. The two studies are common as the balance of in and outflux is a key function of the system model. A set of vectors provide a mathematical description of the system such that $S = [U, V]$, $U = [u_i | i = 1,2, \dots, m]$, and $V = [v_j | j = 1,2, \dots, n]$, where S is a vector set to represent a system, and $\boldsymbol{U}$ and V denote input/output subsystems of which u_i and v_j are components. The components are independent variables distributed in a phase-space. For the input subsystem U, the total number of microstates, TU, is calculated as $TU = \prod_{i=1}^{m} u_i$, where m is the number of components. The probability that the same state occurs is given by $\boldsymbol{P}(T_U \cap T_U) = 1/T_U^2$, and if m is large enough, $\boldsymbol{P}$ converges to zero such that $\lim_{m \to \infty} \boldsymbol{P} = 0$.

Additionally, Fath et al. [57] and Eason and Cabezas [58] made a significant contribution to the related literature. In previous research, using the Shannon index, system modeling and performance indication were limited to static system variations. After Cabezas et al. [57,131] investigated Fisher information for human-dominated systems and Eason and Cabezas attempted to characterize the dynamically changing sustainability of a local city (San Luis Basin, US) using Fisher information. They presented a system model with six types of subsystems by parameterizing major regional sustainability factors, such as population, built-up area, food production rate, and CO_2 emissions. Fisher information was calculated using time windows, and the trajectory of temporal information change was indicated using the environmental performance of the city. Rather than developing a system model limited to a specific case, Kharrazi et al. [25] considered generalizing the use of Ulanowicz's ecosystem modeling [48,52] beyond ecology. They extended their information measures (A, R, and F) to understand the phenomena of global energy/material (oil, iron, water, etc.) trades.

From these urban-scale evidences, we find that informational approaches can be extended to the study of building performance and sustainability. To this end, Yi et al. [132] suggested a generic systemic building model of flow networking by integrating an emergy-based understanding of building energy exchange (Figure 14). In their study, renewable and nonrenewable imports were set as independent external resource agents, and the mechanical building systems and construction components were defined as an energy gate wherein energy concentration was controlled by building occupants and space use. Information—as an environmental element—is implicitly created by human work in the building process or included in resident behavior.

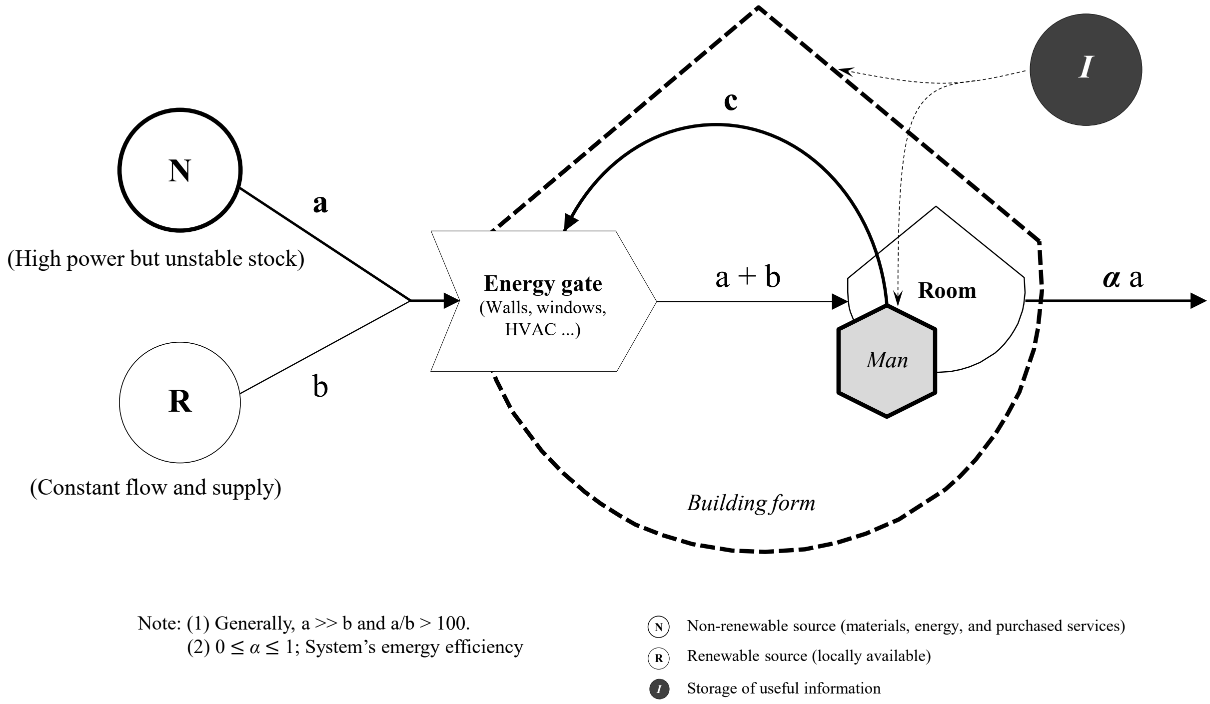
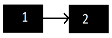


Figure 14. Integration of emergy and information in building application [132].

To establish a proper informational indication of building performance, the building scheme of compartmental networking can be characterized by applying Ulanowicz's ecological indices. Figure 15 shows information measurement on a system of two compartments that represent a simple generic thermodynamic ecosystem. The results illustrate that, if the system becomes more complex (), system capacity (C) and overall developmental balance (A/C) tend to be maximized at an intermediate level of component efficiency (μ). Since it is known as a natural phenomenon that living systems configure complex flow distribution to maximize (em)power for sustainable development, this firmly indicates a linkage of systemic behavior between empower and information under the ecological principles about maximum energy dissipation. We can evaluate systemic performance and sustainability by extending this finding to building ecosystems. In particular, Yi [118] and Yi et al. [132] presented an entire building network model that defines system nodes and flows (Figure 16; Table 4). The performance behavior was dynamically identified using emergy as a flow quantum.

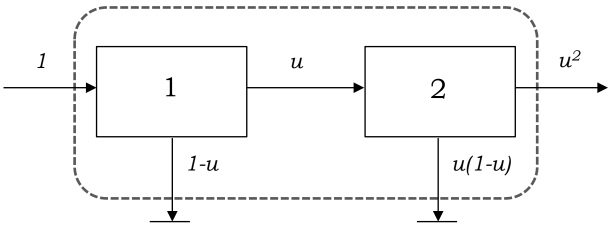


Figure 15. Relationship between efficiency and system indicators (Extended from the Ulanowicz's exemplar experiment [133]).

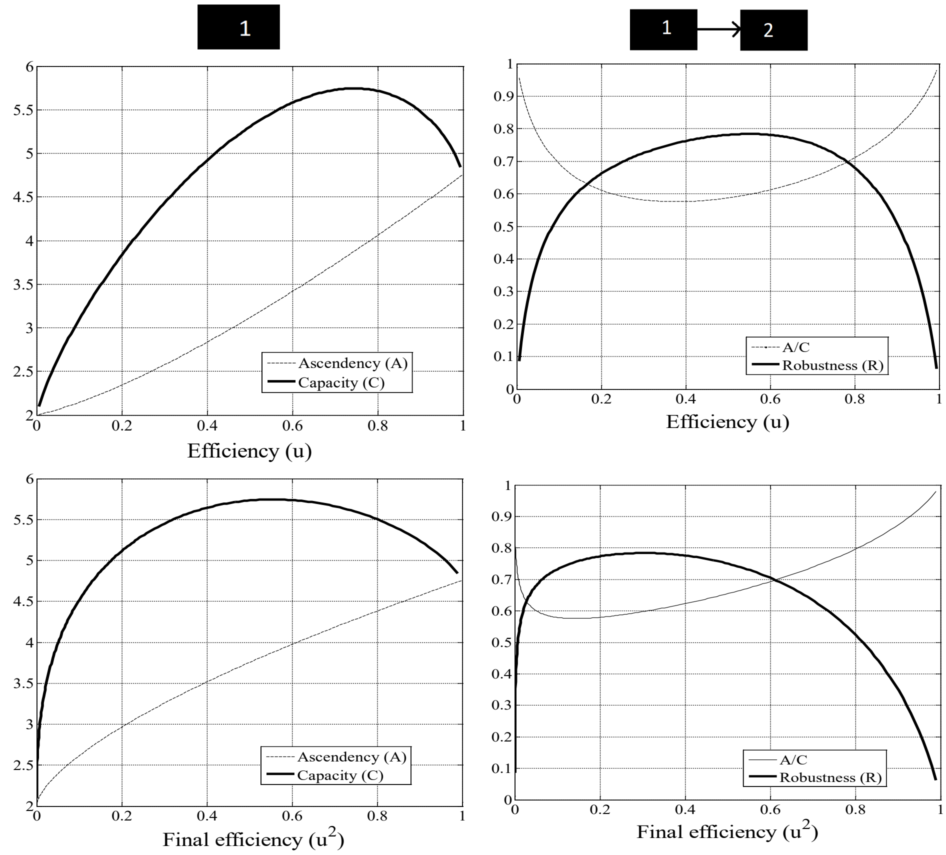
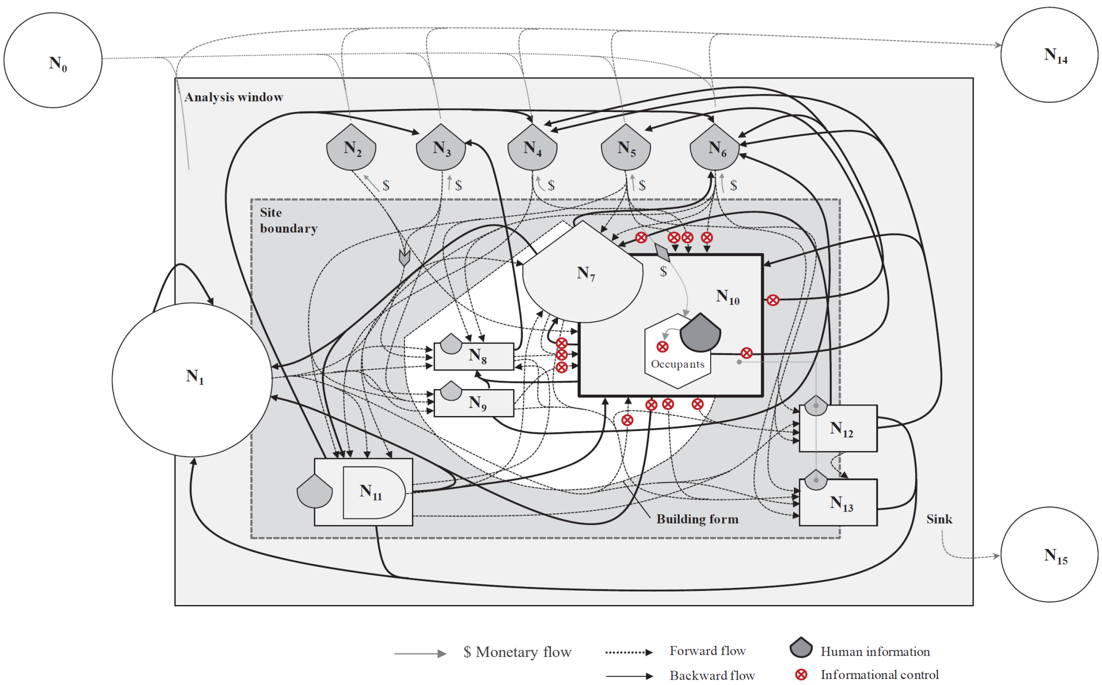


Figure 15. (*Continued*)



N_0: Import N_1: Renewable sources N_2: Gas N_3: Electricity
N_4: Water N_5: Service N_6: Raw material N_7: Building structure
N_8: Building systems N_9: Electrical use N_{10}: Domestic energy use N_{11}: Land use
N_{12}: Waste disposal N_{13}: Site emission N_{14}: Export N_{15}: Waste heat

Figure 16. Network building system model: Emergy diagram, Network representation, and information contents [118].

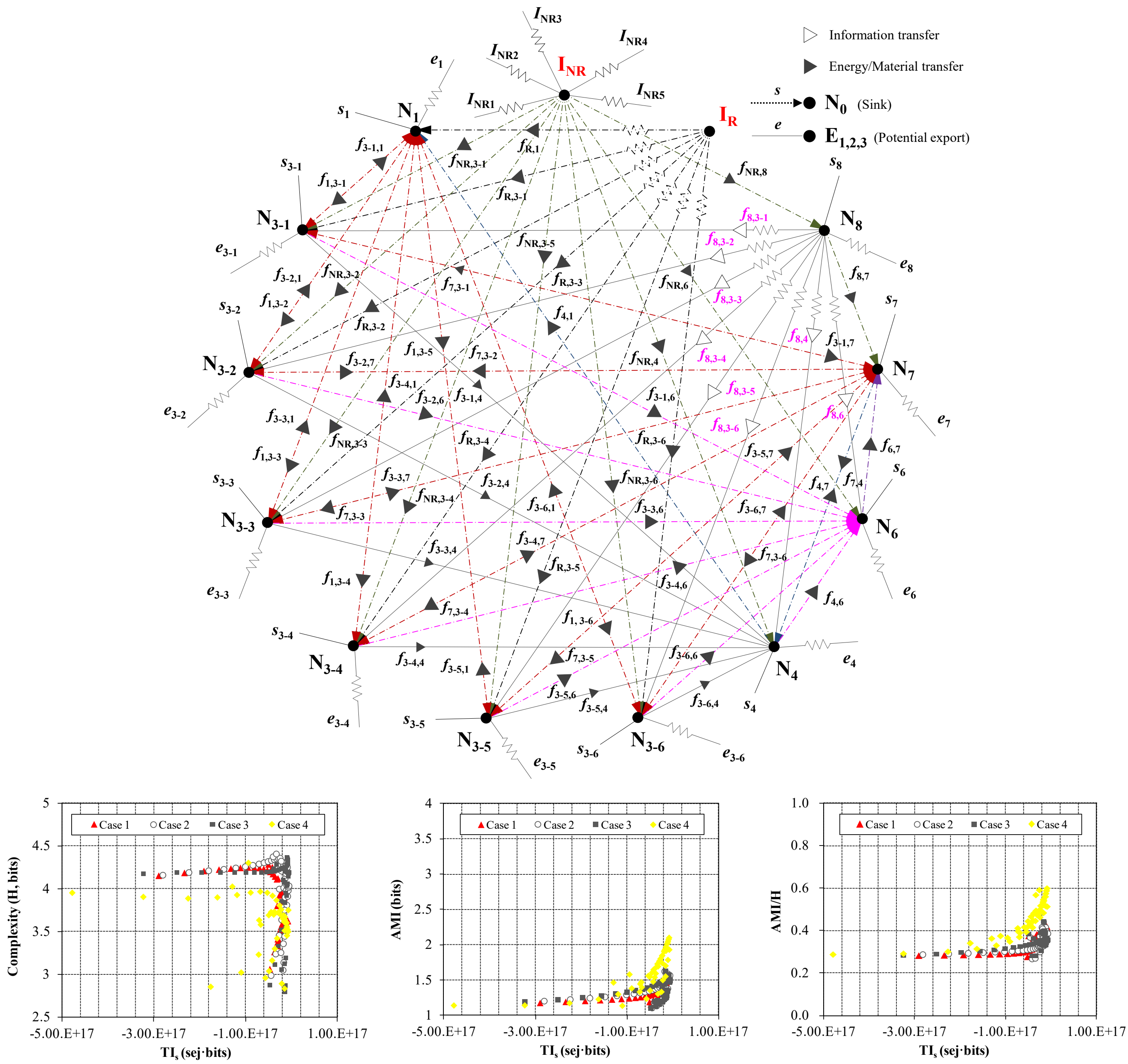


Figure 16. (*Continued*)

Table 4. Summary of building network flows [117,118].

Flow	Description	Flow	Description
		Forward flows	
$f_{R,1}$	Solar radiation onto a building site	$f_{5,8}$	Energy gain from hot water shower/food
$f_{R,2}$	Renewable source inputs to landscape	$f_{5,E3}$	Recycling of clothing, appliances, or furniture
$f_{R,3}$	Solar/wind energy onto a building envelope	$f_{6,7}$	Internal heat gain from lighting devices
$f_{R,4}$	Renewable inputs to mechanical equipment	$f_{7,3}$	Heat transfer to an envelope (conduction/ventilation)
$f_{2,4}$	Energy transfer from landscape to HVAC system	$f_{7,4}$	Heat pump source flow in winter
$f_{3,1}$	Heat loss to ambient environment	$f_{8,2}$	Human labor for landscape maintenance
$f_{3,4}$	Energy generated within the envelope and structure	$f_{8,5}$	Human labor (indoor)
$f_{3,6}$	Natural light/sunlight penetrating an envelope to a lighting device (e.g., light shelf/duct)	$f_{8,7}$	Internal heat gain from human bodies

Table 4. (*Continued*)

$f_{3,7}$	Heat conduction from walls/direct radiation through windows and perforations/heat recovery	$f_{8,E3}$	Upcycling export of useful energy (e.g., material export for recycling, work activities, etc.)
$f_{4,1}$	Heat discharge from cooling systems	$f_{NR,2}$	Material, water, goods, and services for landscape
$f_{4,2}$	Grey/rain water reuse for landscape irrigation	$f_{NR,3}$	Raw material, goods, and services for building manufacturing and maintenance
$f_{4,5}$	Hot water /utility for cooking and home appliances	$f_{NR,4}$	Gas, electricity, water, material, goods, and services for mechanical system manufacturing and operation
$f_{4,6}$	Electricity for lighting fixtures and luminaires	$f_{NR,5}$	Raw material, goods, and services for interior space construction, appliances, and furniture. (food supplies, financial income, etc.)
$f_{4,7}$	Energy use for space heating	$f_{NR,6}$	Purchase of luminaires or other lighting devices
$f_{4,E3}$	Export of electricity to grid	$f_{NR,8}$	Purchase of clothes, food, and accessories
$f_{5,7}$	Internal heat gain from electric/gas equipment		
	Potential regeneration flows		
$f_{4,R}$	Heat transfer from HVAC system to ground (e.g., GSHP)	$f_{5,4}$	Restoration of grey water/heat pump source in summer
	ETC		
$s_{1\sim8}$	Heat sink/depreciation of material and information	$a_{1\sim8}$	Potential export of solid waste or water
$b_{1\sim8}$	Potential export of discharging gas	$f_{2\sim6,E}$	Export of material, useful energy, and information

6. Challenges and Discussion

6.1. Limitation of Emergy

Emergy has been criticized in other environmental study disciplines, primarily because of the uncertainty in calculating the global emergy baseline [134]—annual total emergy input from global sources to support the entire geobiosphere, and testability of specific emergy values. Ayres [135] and Cleveland et al. [136] doubt the credibility of emergy measurers due to the uncertainty of parameter values and the model scenario. All emergy indices are derived from the baseline empower of the geobiosphere [36], but only the pending variability (9.44E+24 sej/yr [36] to 1.2E+25 sej/yr [134,137]). EmS also assumes that every input source is independent; thus, modeling and computation (the "track-sum" method) are simplified. However, the mutual independency of resources remains unclear [138,139].

To apply the EmS theorems, as Odum [43] admits, UEVs should be obtained on a case-by-case basis, as all energy work undergoes specific transformation processes under different thermodynamic conditions [138]. However, in EmS practice, it is nearly impossible to consider every exclusive process. Consequently, similar cases are applied by finding specific emergy values from previous studies. This EmS procedure leads to uncertainty.

More importantly, because of the inherent "external (or input/output (I/O)-oriented)" and donor-side perspective [140], emergy lacks the insight to investigate a full spectrum of the internal performance (e.g., energy interaction among components) or emission [141]. For maximizing power, empower tends to exhibit large unsteady fluctuations, but Odum [36,43] argues that system performance is predictable only by identifying external source availability. As emergy construes the temporal pulsing of power as a general occurrence during self-organization [37], it is difficult to evaluate the dynamic impact of power oscillation events. The multivariate performative aspects of system complexity (diverse structural patterns of energy, material, and information flow) are limited to an aggregated emergy indicator. To compensate for this drawback, the integration of emergy and information can be an effective holistic strategy. Christensen [142], Yi [118], and Yi et al. [132] suggested emergy as an informational-network medium for ecological and building systems analysis.

Recently, emergy research communities have grown across various disciplines. Achievements regarding the baseline setting [137], refinement of UEVs [82,143], and uncertainty identification [95,144–146] contribute to advancing emergy science. Nonetheless, the questionable general discourse of the baseline, insufficient data collection, and the lack of quality assurance hinder its wider application, except for a few areas pertaining to natural products.

Nevertheless, the current BEmA approaches are constrained by critical challenges. First, building emergy disregards the impact of building "form" which can affect the building energy use pattern in various ways and results in the transformation of building energy quality. Second, the available energy concept may not directly calculate the actual maximum work depending on the surrounding conditions wherein the energy flows are generated. In many cases of BEmA applications—for example, consuming fuels for building operation—emergy is obtained by multiplying the given transformity and raw energy inflows, not exergy. Therefore, the BEmA results may not account for the thermodynamic irreversibility and energy loss during energy transformation [53]. This leads to a domino-type uncertainty in indicating the emergy of building sustainability.

6.2. Duality of Information: Mixed Definitions

The ambiguity of the definition is a challenge in using information for building analysis. In the literature on thermodynamics/biology/ecology/systems science, information has a double nature, which often distorts appropriate scientific understanding: (i) any form of knowledge delivered to a system (e.g., human language, signal, numeric data, genetic code, etc.) and (ii) a probabilistic index of systemic network complexity [42]. A common feature in these fields is that information is drawn to measure the engagement of some external agents influencing system operation and decision-making. However, even if the law of entropy is self-evident in all areas, significant misperception may occur, especially when extending the physical entropy (S) to information content, originally described as a carrying capacity of a signal (H) in communication. Information terminology must be emphasized if system-level principles are claimed to be beyond physics.

The Boltzmann's entropy expression fueled Shannon's algorithmic development of mathematical/statistical information and Weiner's effort to interconnect physical system behavior with intellectual controllability [105]. Ulanowicz's statement that information is "anything that constrains the system elements so as to change their probability assignments" [51] also seems to support the interchangeability and universality of thermodynamic entropy concepts.

However, overgeneralization of the thermodynamic analogy in the built-environmental system design may aggravate terminological confusion [147,148]. Jørgensen [15] insisted that if H is interpreted as semantic information, it must be flawed. Moreover, Thims [149] asserted that information theory is a thermodynamic "campaign", and suggested that the Shannon information must be termed as "bitropy". To avoid the abuse of entropic analogy, the thermodynamic entropy is restricted within the scientific terrain of classical mechanics, as a measure of the atomic organization of heat. Moreover, the information entropy, as a complexity index, is only a mathematical quantity of probabilistic and unstructured distribution [72] (Figure 17).

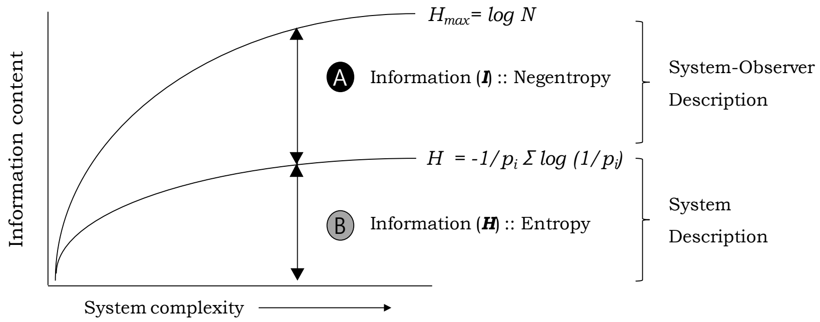


Figure 17. Definition of information and two types of information content: (**A**) degree of organization (order) and (**B**) degree of disorganization (uncertainty, disorder, unpredictability) (Given a system, if N number of microstates are equally probable, in the most uncertain situation, the probability of each state (p_i) becomes 1/N. Then, the information entropy is maximized such that $H_{max} = -\sum_{i=1}^{n} \frac{1}{N} log \frac{1}{N} = \ log\, N$.

In addition, Brillouin's statement of information [67], "negentropy (NE)" [60,150]—the amount of entropy change (typically degeneration) between an observed and reference state—inspired other researchers [15,110,124,151], and they construed the loss of information entropy as the information obtained by the system. In this framework, the physical reference state of thermal equilibrium is compared to an equally probable state (H_{max}) of data, and the information gain is the relative information entropy (KL-divergence). Information entropy that incorporates any kind of media in its formulation may not strictly follow the law of entropy in a system boundary. Therefore, thermodynamic entropy could be understood as a subset of information entropy [62,152] (Figure 18).

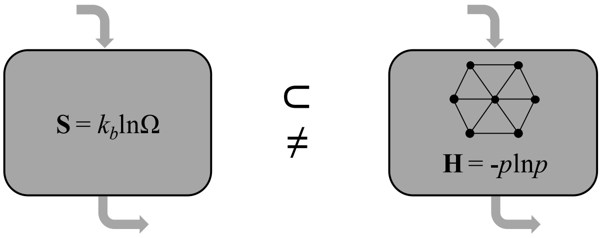


Figure 18. Distinction of thermodynamic entropy (S) and information entropy (H).

6.3. Difficulty in System Modeling and Performance Benchmarking

The benefits of ecological inference cannot be generalized unless the basic postulates of system ecology and the fundamentals of thermodynamic mechanisms are properly substantiated at a building scale.

As the exergy definition requires a reference environment for analysis [152], thermodynamic entropy is driven from the reference state at zero degree (0 *K*). However, information entropy does not carry such an absolute reference to compare system performance [72], because information entropy is derived from the mathematical expression that describes non-thermodynamic content. This may lead to an elusive indication of the metabolic balance of building information, leaving many questions on the hypothesis of ecological development and hierarchical energy order in built-environmental contexts. This worsens insufficient discourses and lack of a universal agreement on the informational metric system in building.

Since the evaluation of emergy and information highly depends on the design of system configuration, lack of reference thresholds about maximum power or information can be a significant issue for environmental decision-making based on a system model. Particularly in building studies, there is little discussion on the establishment of such a standardized building emergy diagramming or energy-flow modeling method. Ecological building system entities (compartments), system structure, the number of required nodes and paths, analysis boundary, and model resolution should be clearly defined before comparing the ecological performance and sustainability of different case studies. The standard system design should also consider scale unification as various units of socio-economic energy are engaged in a building lifecycle. Non-unified scales of data risk bridging indices, principles, and applications.

In addition, it is difficult to validate system-level principles with immediate deduction. At a building scale, entropy production and energy dissipation through energy flow are long-term events rather than instantaneous accidents in physics [153]. Accordingly, MaxEnt and MIE are necessarily convinced by setting a proper time step for data collection and analysis of a building model. However, in real building operations, energy flows among system components are far more difficult to observe than the overall energy concentrations.

7. Conclusions

From an ecological perspective, human beings, nature, and building are all integral and inseparable components of the global living system—the geobiosphere. In terms of thermodynamics of the whole extensive environment, they mutually produce and consume energy, material, and information for their shared goal of survival and development. Providing that building is part of such a self-organizing thermodynamic system, building performance must be addressed at the highest dimension of sustainability as well as through the flow network of environmental resources. However, current building performance metrics, such as the quantity of utility use or the ratio of energy efficiency measured within a limited site boundary, do not sufficiently indicate the holistic impact of building energy work.

In this paper, we reviewed ecological metrics of e*m*ergy (spelled with an "*m*") and information for building applications, by revisiting system principles of energy and performance indices derived from ecosystems theories. Our findings suggest that both emergy and (syntactic) information (entropy) extend the building energy accounting, streaming of material stock, and occupant activities to the greatest scale. Emergy of building identifies all upstream impacts of useful energy in aggregated terms, including natural formation of materials, human labor, and economic services, and information, as a network complexity measure, intensively characterizes dynamic organization of the building energy transport. More importantly, we found that ecosystem principles built on the concept of entropic energy availability regard energy efficiency merely as a means of sustainability. In the metabolic processes of all living agencies in the environment, energy efficiency and related indices (fitness, AMI) are controlled at an intermediate level, while power and total system information (complexity) increase to the maximum. This idea is a key to understand building as an open thermodynamic living system and to explain its performance by actively employing the metrics of emergy and information. Recent studies of building performance analysis under the maximum (em)power/entropy principle demonstrate that the energy reduction in so-called high-performance buildings, such as NZEBs, leads to an increase of the rate of energy disspation, energy quality, and the complexity of energy distribution, which are all indicated as the final cause of sustainability in systems ecology.

To advance the dominant efficiency-oriented views on building sustainability, this review investigated a volume of building emergy and information studies originated from the ecological understanding. However, despite scientific rationales for the use of the thermodynamic principles and technical indices in the study of building sustainability, limited field data and few evident cases are huge obstacles in the full accounting of building performance at the global system level. On the other hand, technical terms and methodological discourses across disciplines still remain mixed and unclear on various scopes and scales. In this respect, other major challenges include demonstration of the ecosystem hypothesis, standardization of a generic building system model, and establishment of plenty unified information references for performance benchmarking and sustainability assessment accordingly. For wider acceptance and robust application of the suggested emergy methods and informational indices in the study of building energy, phenomenological ecosystem theorems should also be proven scientifically at the building level in a complete manner with the context of ecological energetics properly adapted to the building environment.

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Author Contributions

H.Y.: Funding acquisition; Conceptualization; Methodology; Formal analysis; Writing—original draft. A.M.: Investigation; Writing—review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

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