INFORMATION IN ENVIRONMENTAL ARCHITECTURE

Ecological network analysis and new indices of building performance

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ABSTRACT

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Hwang Yi

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This dissertation suggests a new framework and indices of building performance evaluation based on an eco-systemic approach. The energy-efficient building construction and operation are important to achieve sustainability. Nevertheless, efficiency does not fully account for the building's complex environmental phenomena in which nature, art, and human living are inseparably involved. In particular, increasing efficiency cannot clearly associate the robustness and stability of the building's internal energetic organization (and trade-offs between energy efficiency and material use) with building form and occupant behavior. The purpose of this study is to argue that environmental information content is a substantial source to achieve building sustainability and to suggest that an emergy (spelled with an "m")-coupled information measure is the most comprehensive and holistic index of building performance.

Based on ecosystems theory, this dissertation defines building as a thermodynamic system that utilizes, transfers, and self-organizes the useful environmental resources—energy, material, and information—through networking processes. Definitions and formulas of information measures and ecological indicators from Shannon's information theory, Ulanowicz's ascendency principle, and Odum's maximum empower principle are discussed and adopted to develop a new methodology of integrating building information and emergy and a model of building emergy-flow networking. A hypothetical generic building system is modeled and tested to characterize the building's systematic behavior with the examination of information change. Results of the hypothetical tests show that the informational characteristics of building emergy-flow networking parallels the phenomenological evidences of ecosystems development and sustainability—increasing complexity, resilience, fitness, and useful energy (power).

To verify the consistency between ecosystem development and building sustainability, experiments were conducted with two case study buildings: a net-zero energy building (NZEB) and a non-NZEB. Emergy-integrated information analyses according to the suggested governing equations and system models were carried out. Results show that the non-NZEB tends to be more resilient and adaptable and to have more “generative” empower (or total system information), even though the NZEB is more efficient. This indicates that high-performance (high-efficient) buildings may end up greater nonrenewable inputs. On the other hand, the investigation of the information content of building envelope demonstrates that human activities can generate the largest amount of useful information content than any other building system components, and the responsive building form coupled with smart human behavior contribute the most to increasing resilience, power, and information. Findings demonstrate that buildings self-organize internally, like ecosystems, with the inputs and outputs of resources. This eventually suggests that increasing complexity, total information, and power be the final goal of building sustainability and environmental building design.

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CHAPTER 1

INTRODUCTION

Motivation and background

Sustainability has been studied and discussed over many scales in various disciplines. In architecture, nevertheless, it is still controversial to define what would lead to a sustainable building. As sustainability of contemporary buildings increasingly relies on energy-efficiency, we need more comprehensive ways to evaluate their environmental performance. However, several major problems are found in a range of environmental tactics as well as current performance evaluation metrics and methods, including that: (1) Building energy performance has been evaluated by modeling the building as if it is part of a mechanical product. All too often, due to the visually and physically solid enclosure, we regard it as an isolated object and discount inextricable direct or indirect connections to diverse contexts of social, economical, and environmental systems; (2) Energy use reduction is a very important technique of environmental design. Nevertheless, sustainability cannot be achieved solely by low energy use. It is necessary not only to consider what a building uses but also into what the building produces or contributes to the environment in a positive way. In this respect, the study of building sustainability requires a clear understanding of how building, its subsystems, and natural environment function collectively; (3) Environmental building design and management are concerned closely with a thermodynamic signature of mutual interactions among design elements (e.g., material use, infiltration, space size, lighting intensity, internal loads). Each building undergoes a singular situation within the mixed terrain of different thermodynamic contexts. Relative significance and function of a design element are thus contingent, and they end up with a dynamic behavioral pattern of environmental impacts. However, there is n clear performance index that can cover the whole range of complex thermodynamic phenomena. Synergies, trade-offs, and conflicts that trigger an intensive change of the pattern are little addressed through the current extensive/reductive approaches to performance evaluation.

Many scientific tools of performance evaluation and impact assessment (building energy simulation algorithms, Life Cycle Assessment (LCA), rating standards, etc.) have been developed primarily from the perspective that views the building as a physical object, and, consequently, discussions about building performance tend to address direct influences and immediate operating energy demands; they have given less attention to the important question of how a building interacts with complex socio-technological backgrounds and/or large-scale environmental systems, which is eventually crucial to decision-making processes about geometry, material selection, and spatial programming.

Specifically, in terms of methodology, existing agendas of the sustainable building solutions (for example, zero emission/energy use) are intrinsically based on the "principle of thermodynamic equivalence" which is the essence of the classical Newtonian paradigm (Ulanowicz, 1997) whose fundamental assumption is that time and energy can be homogeneous and articulated. It apparently helps to explore the transport of mass and energy explicitly at the micro levels, but any attempts to make a general macro interpretation of all thermodynamic phenomena, however, are subject to criticism due to the emergence of the contemporary science: statistical mechanics, quantum theory, and cybernetics. The common ideas of these theories assert that everything is interdependent to one another indeterminately at any level and that a (thermodynamic) system can never be identified without taking into account the presence of an observer or other systems/elements involved[1]. What we find from the system is, accordingly, just a snapshot of scores of probabilistic states of the system. Thus, it may be far-fetched to believe that an exact system performance (thermodynamic position) can be described.

Based on the recent awareness of a great deal of indeterminacy in building performance evaluation, a number of study have attempted to overcome uncertainty of metric systems and methods by incorporating new parameters and accurate data into a building model. Nevertheless, mechanics-based frameworks lack a clear account of how and why building communicates with the global environment, the openness of building elements to the universe, and/or the ambiguous causality that arises at any level of building performance analysis.

To address these concerns, it is desirable to focus on "relationships", "interactions", and the potential internal change that the complex building system undergoes. This idea is, in

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[1] Wiener (1948) says, "In Newton's dynamics, in its original form, we are connected with an individual system. However, in the vast majority of practical cases, we are far from that.", and also contends, "Property of every element is the result of transforming an element."

general, to acknowledge the empirical nature of building thermodynamics, i.e., dynamic balancing, that embodies multiple sequences of the various time-dependent events, but, more importantly, to underline the building's capability of self-alignment, responding to external/internal variations.

Aside from the conventional capacity-oriented performance measures that are centered on resource stock and quantity in consumption (e.g., energy use and material use), understanding the building as a responsive dynamic system allows for new indicators to describe relationships of energetic flows and intensive "system" dynamics (such as homeostasis, resistance, or robustness of energy flow patterns) as more significant performance evaluators.

The complexity of performance emphasizes interactive relations and reciprocal variations of the building's operational mechanism. It renders building sustainability with a new paradigm-shifting perspective; the energy-flow networking of the global environmental resources. At the end of the day, a system-based approach plays a key role to propose a new evaluation methodology of building performance.

1.1 New perspective of building sustainability

1.1.1. Emergence of a new paradigm

Despite the Rio declaration (1902), there is no general consensus on the notion of sustainability, and the definition of building sustainability is still debatable. Peacock (1999) categorizes the approaches to the sustainability into three concepts: (i) *business as usual*, (ii) *lifeboat*, and (iii) *mutual symbiosis*. The "business as usual" approach is very similar to the concept of "*technological sustainability*" defined by the environmental educator D.W. Orr (Van der Ryn and Cowan, 1996). It seeks to insist technical inventions are a panacea of all the environmental fear, and relies entirely on the foggy idea that either technological development or market solutions will resolve the demanding environmental pressure[2]. It is important to realize that it is too utopian to call for a fundamental innovation of sustainable building design.

The "lifeboat" is the most familiar, mainstream model that has also been used for the

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[2] The Brundtland Commission's statement ("Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).") is representative of an underlying direction of this idea.

sustainability campaign in the design community. The lifeboat is a metaphoric expression to describe our planet's limited carrying capacity of non-renewable resources. According to this idea, all human works are running down to be killed in the long run. There is no way that we avoid annihilation. The only action we can do is to restrict the rapid pace of resource depletion so as to delay the extinction as possible. It is horribly pessimistic. Proponents of this approach believe the rate at which a society operates must be restrained depending on the earthly supply given to us (Leadbitter, 2002; Meadow et al, 2003). As a result, of the crucial concern is overshooting of the building energy use, and, therefore, "efficiency" takes on the most important virtue while being employed to justify austerity of building design and occupants' behavior.

Fig. 1.1 Which building is more sustainable?: Each building could be sustainable in a different manner. The building on the left-hand side is likely to contribute to the health of natural environment, while the right-side building provides some nutrients to the sustenance of economic/industrial systems.

However, Peacock strongly denies the extremist attitudes, and urges us to stay on the ecological point of view —"peaceful coexistence" of man and nature through "symbiosis". The lifeboat metaphor theoretically originates in the dualistic tradition of modern science that separates living things from physical environment, which eventually provokes a negativism

— restraining the growth and development[3]. At ecosystem level, in contrast, all physical things as well as humans are not isolated individuals, but they are earthly biological components constituting the global ecosystem as a whole. Peacock likens the relationship between the earth and human civilization to heterotrophic organisms, and states the current environmental crisis due to the large amount of energy use and pollutant load is caused by parasitic association of the artificial and natural environment (Peacock, 1999). He emphasizes well-balanced mutualism between the host (the earth) and the parasite (civilization).

Notably, Peacock's bio-metaphorical definition is perfectly in parallel with Cabezas et al.'s perception that "the concept of (ecological) sustainability applies to integrated systems comprising humans and nature (Cabezas et al., 2005).", and manifested in an architect W. McDonough's argument that "buildings, systems, neighborhoods, and even whole cities can be entwined with surrounding ecosystems in ways that are mutually enriching (McDonough and Braungart, 2002)."

This mutualism perspective provides a principled basis for dissolving buildings and natural environment; i.e., patterns of the building system organization are directly associated with the natural and man-made environment, and the largest ecosystem, the earth. McDonough and Braungart (2002) assert that only a successful marriage of biological systems and technological systems ensure sustainability. Therefore, engagement of human activities through buildings is critical in deciding whether or not the flows of energy and materials are in a virtuous cycle. As long as the sun provides the most integral energy source, our ecosystem possesses the power of energy regeneration and redirection of information in the circle.

Energy determinism (survival with emergency food supply) of the lifeboat concept is rooted in the culture of modern civilization that has sharply distinguished nature from man. The terror of unpredictability and loss of control over the nature have made us face the limits to growth of the human world (McDonough and Braungart, 2002). However, it should be noted that our world is "one of abundance, not of limits (McDonough and Braungart, 2002)" under "continuous construction (Prigogine, 2003)", as long as we live on the earth. Which means the growth limit holds true only if it is meant to be an extension of the current ways and thoughts of human lives. Less nonrenewable energy consumption is important, but what

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[3] Boltzmann recognized physical systems, unlike natural environment, become increasingly disordered or deteriorated with time, and the effortless transformation to higher orderly states is "infinitely improbable" (Boltzmann, 1886).

is more crucial is the smart manner of utilizing the resources such as setting priority of fuel use (Campbell, 2004).

By incorporating the human attitude to cope with the environment in the definition of sustainability, the goal of sustainable growth can be switched from constraining the resource use to “perpetuating the cycling abundance of resources (Odum, 1971)”, because human intelligence and technological success are capable of acceleration of energy use intensity and effective arrangement of natural resources[4] (Peacock, 1999; Campbell, 2004).

Mutual symbiosis runs counter to the widespread lifeboat concept and may not be immediately intelligible. But it provides a helpful view of our built environment that sustainable buildings can be more productive, progressively ordered so that they enrich the biosphere. Sustainable development of building means design of the building ecosystem. So, a self-producing environment (Swenson, 1997) that compensates the cost of making it is imperative. It is not cowering over the terror of energy shrinkage, but generating useful power by well-disciplined activities with a clear purpose.

1.2 New approach to the evaluation of building performance

1.2.1 Criticism of mechanistic approaches and new questions

Kelly (2010) predicts that technology progresses into a certain direction on a macro scale, like biological evolution. For example, achievements of the machine age have driven our contemporary culture and the modern way of living to be shared, and for the inclination of universality has facilitated global exchanges of energy, material, and goods. As the energy capacity of the earth offsets a limit on the development of our civilization, increased concerns about energy issues (efficiency, scarcity, and the very importance!) became the most powerful and pressing constraints of building sustainability. And, to date, such concerns have led to the emergence of buildings equipped with highly efficient machines and with lower environmental impact.

A number of methods and techniques have been introduced and developed to facilitate the energy-efficient buildings. Proliferated for industry are nationwide certification standards (LEED, BREEAM, etc.) and accounting methods (e.g. LCA, Input-Output (I/O) analysis)

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[4] But our culture, too often, ruins highly organized nature for the seemingly more structured to human understanding such as gardens, lawns, or row crops (Odum, 1994).

based on various fields of knowledge. And more appealing terms such as net zero energy or net zero cost, have permeated into building design disciplines.

However, it is critical to point out that there are mixed signals from different definitions and measures of environmental buildings[5]. Although a few architects have questioned them, science of building assessment lacks an agreed metric or methodology that is fully available to all building types and timeframes. For example, building codes or rating systems such as ASHRAE 90.1 and Energy star, which are widely credited to US building industry, place significance on energy efficiency, but thereby, they underestimate energies embodied in building material use. LCA and I/O methods cover such drawback, but a target boundary the final impact arrives varies depending on applied fields.

On top of that, building analysts, mainly engineers, employ mechanistic techniques based on the conception that building components can be dissected to multiple elementary units of causalities (variation of glazing types and change thereof in energy use intensity). Afterwards, breakdowns for each element are generalized down to describe the overall behavior of a building. For such objects whose parts are combined in a straightforward fashion, mechanistic modeling is fairly powerful (Allen and Starr, 1982). However, this approach remains misleading of buildings in understanding interactive effects among the elements—sub-wholes as a matter of fact, on other lines of environmental stress, even though it may be a small bit, such as recycling rates, resource depletion, and so on.

Some of celebrated architects such as Frank Gehry or Peter Eisenman overtly express disagreement with present discourse of building sustainability, for designers are interested not in the results of energy-saving tactics, but in how individual treatments can be synthesized comprehensively to a formal gesture through design thinking. Unfortunately, no one clearly explains how the mechanistic tactics of low energy use became design conclusions, and often, codes of building sustainability end up creating a high-tech gizmo.

Living Building Challenge (LBC), a recently developed voluntary green building standard thatattempts to characterize a building as a biotic creature, may be an alternative to the criticism aforementioned, but it is only partially illustrative because it lacks comprehensive compliances to a “living building” and evaluation of the highest energy performance is subject to the Net-zero energy definition.

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[5] As a case in the United States, “State governments of Mississippi, Georgia and Alabama make efforts to ban federally adopted LEED certification system, claiming the USGBC’s closed-door approach and narrow-minded material interests have shut out stakeholders in various industries that could otherwise aid in the sustainable construction of environmentally-sensitive buildings (Cruz, 2013) .”

Therefore, we must look into building and performance, cutting across time and physical barriers of space with a cosmological perspective, which means exploration of environmentally reciprocal relationships between design elements within an extended context. From a geobiospherical view, a building is inherently the outcome of energetic exchanges of environmental resources to sustain a physical climate-modifying form of material organization (Fernández-Galiano, 2000). Seemingly, it is hard to tell how natural resources are transformed into a built form. However, in effect, a building functions to have different kinds of substances and energies consistently interconnected under a formal organization. In this sense, the building is a highly-complex pseudo living system.

In a narrow observation, building's environmental status generally looks as if it undergoes a steady variation; topological relationships of materials seem constant and thermostats work to turn on/off mechanical equipment within a certain range of temperature. In the macroscopic level considering multiple indirect influences, however, buildings dissolve human activities, social influence, and different cultural aspects. As a result, the building's environmental task of climate-modification faces a great deal of uncertainty, as broadened environmental conditions unpredictably change. Measuring building performance is all about a specific internal reception on which the building takes by reacting to a certain denotative (spatially/temporally-varying) situation, given the external conditions. Accordingly, we need a better understanding of "complexity" of building functions and environmental systems that cannot be unveiled solely by mechanistic thinking. Performance evaluation becomes thus a subject of modern complexity science that has primarily to do with controllability based on feedback between entities and organization of interactive communications. In this regard, it is noteworthy that Weaver (1948) characterizes the complexity of scientific problems with (i) unexpected behavior of human (ii) huge number of variables. This description characterizes the matter of building performance evaluation, revealing that problems with sustainable building design come under the label of complexity.

Then, with awareness of the complexity and living-systemic aspects of environmental building functioning, how could we measure performance? How should a building form look in order to be sustainable? A key point to finding answers is to see building's performance as a work of systematic phenomena in conjuction with the environment. Revisiting Weaver (1948)'s statements, he was convinced that a system as a whole has a certain "order" that is a specific property for a system status represented in averaged terms. If environmental buildings are the latest-evolved species benefitted from advanced technology, and, as Kelly insists, it is true a curve of high-technological system's development converges with a preordained ordering, like the Moore's law, in the same manner as biological evolution (Kelly, 2010), we would be able to track changes of an environmental "order" to identify propensity towards the final direction, as a measure of performance and sustainability. It may be accomplished by exploring parallelism between the structure and developmental sequences of living systems and those of buildings.

1.2.2. Need for a dynamic intensive system model in the evaluation of building performance

Current notion of building sustainability downplays systematic aspects of human-dominated environment, thereby revealing little about a general nature of building system's ecological behavior whose multi-interactive processing of energy and materials needs to be explicitly considered in design, construction, operation, and maintenance. To state the necessity of a new complementary evaluation framework, it is helpful to note that different methods of environmental assessmentcan be largely grouped into two categories; namely, "intensive or relative" and "extensive or absolute" (Kharrazi et al. 2013) that each of which needs a different approach, since "extensive properties depend upon the size of the system, but intensive variables are not affected by the size. (Ulanowicz, 1997)" Accounting for environmental building functioning with this categorization, input and output flows of resources through building systems are classified into an extensive domain, while energy transfers and reciprocal relations of material and services between system constituents become the focus of intensive evaluation.

All too often, the present discourse of building sustainability evaluation deduces general formation of evaluation based on the input-output model in the static settings of macro state variables. Environmental impact of a building has been determined by amounts of resource consumption, greenhouse gas emission, or efficiency of mechanical systems[6] that focus on the extensive realm, because not much is known about the complexity of the building system organization behind our observations, whereby it sets limits primarily to the external level of analysis—measurement of input-output relationships, leaving a building system a "black box." However, in fact, a building amalgamates various kinds of input-output components, and

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[6] LEED, ASHRAE 90.1

each of which interactively responds to internal/external changes. The articulation of the response is also neither aimless nor accidental. Even a single organizational behavior definitely heads towards goodness for its sustenance. So, as far as we do not understand the logic of system dynamics, the building environmental impact may simply be shifted or rebounded (Zhang et al, 2010). For this reason, evaluation of building sustainability is often a chicken-and-egg problem, and the nature of the building system suggests that building sustainability should be characterized with system level attributes. In this light, the dynamic energetic networking of building should focus on environmental resource-flow organization, which has been characterized in ecological studies with system descriptors: resilience, feedback, and stability.

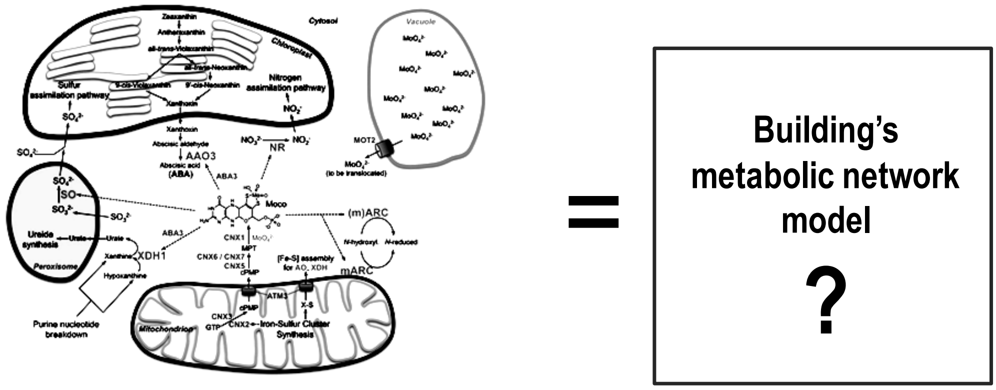

Fig. 1.2 Analogy of building to living organism's metabolism: If building is a living system, general biological principles can mark the final goal of building system development.

1.3 Building as an ecosystem: System networking of energy, matter, and information

"Ecosystems can exist in the dirt under your fingernail; and they exist in the rumen of a cow, and also on the regional, continental and planetary scale (Lovelock, 1979; Toussaint and Schneider, 1998).*"*

1.3.1 Building as a living system and thermodynamic analogy

William Cronon, in his 1991 book *Nature's Metropolis*, defines built environment as "second nature" atop the un-constructed natural world. Besides this, perception of building in association with natural creatures is not new to the architectural history. A building, in part or whole, has been likened to an animal or plant, and classical architectural styles have been described in mimicry of a human body. Semblance of a formal structure or a hierarchical assembly of parts found in living organisms was a target of architectural studies. Functional relationships of building components have also been characterized with those of the bodily parts performing specialized tasks[7]. And attempts to identify work of building functions with living organisms have agreed with an idea that "individual parts contribute to the effect or purpose of the whole (Steadman, 2008)." The principle of similitude was not only a central concept in the aesthetics of applied arts, but played a significant role in the production of architecture to reveal its wholeness and integrity.

Such biological comparison is desirable to some extent in that it provides a context in which we integrate variations of forms and functions of buildings with those of environmental systems. Steadman (2008) argues that an architectural style and formal characteristic resemble the growth of a plant as if they follow unconsciously certain rules of nature. Nevertheless, this identity remains half-baked until we seek teleological "metabolism" that enables to explain an evident similarity in internal structure, organizational characteristics, and behavioral phenomena in presence of external changes. Limiting the analogical narratives to the physical boundary of a building, without any details of emulation of living processes, may distract our understanding or end up with formal imitation, functional determinism, or just a rhetoric metaphor.Technically, buildings are not organic creature but man-made objects. However, a model based on an eco-systemic analogy helps to overcome some difficulties to identify metabolic homogeneity with axiomatic ruling principles of the external physical world—laws of thermodynamics.

From Carnot's elaboration, thermodynamic principles (energy conservation and energy degradation) in the 19th century had been affirmed as the universal laws that must be applicable to every phenomenon of the physical world[8], Ludwig von Bertalanffy, an Austrian biologist in the early 20th century, proposed the first modern systems theory, General Systems Theory (GST), that proved the physical laws applicable to the development model of living organisms with a systematic perspective. After him, a mathematician Norbert Wiener,

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[7] Galiano (2000) quotes F.L. Wright's saying, "Any house is a mechanical counterfeit of the human body. Electrical wiring for nervous system, plumbing for bowels, heating system and fireplaces for arteries and heart, and windows for eyes, nose, and lungs generally. The structure of the house, too, is a kind of cellular tissue stack full of bones (Galiano, 2000).", and also Corbusier's writing that "...the physiology of breathing with the ventilation of buildings; of the nervous system with the networks of electricity supply ... the circulation of the blood with the circulation of people or traffic (Steadman, 2008)."

[8] "The second law of thermodynamics indicates a general tendency in the evolution of physical world (Brillouin, 1961)."

in his book— *Cybernetics: or the Control and Communication in the Animal and the Machine*, enunciated the validity of the keen relationship between living systems and mechanical systems by saying “the modern automata[9] exist in the same sort of Bergsonian time[10] as the living organism (Wiener, 1948).”. This locates the living organisms and the man-made systems under the same thermodynamic laws.

The bottom line of a thermodynamic analogy between buildings and living systems is in the notion of an “open system” that implies a living organism and ecosystems are associated with the outside world at every level, in terms of energetic exchanges. Based on this idea, some of ecologists in the 1950s made efforts to characterize behavioral patterns of individual organisms by analyzing greater multi-scale engagement.[11] Eugene Odum (1959) thus named ecology series of this kind of study as ‘synecology’ against autecology whose research subject sets a limit on one or a few organisms. According to Hall and Fagen (1956), a system has three components: (i) object or component, (ii) attribute of object, and (iii) the relationship between the components[12]. Because the metabolism of living organism interacts with external forces and other ecological entities, investigation of external relationships is fundamental to give better visibility on the rules of ecological process.

However, in exploration of the analogical relationship between ecosystems and technological environment to which buildings are subject, we face a major barrier that we must explicate if ecosystem’s behavioral characteristics can be valid in the same manner to building systems. If several principles of systems ecology are consistent with building systems, buildings can be considered equivalent to ecosystem and thus performance can be evaluated with analysis methods from ecosystem theories. In this regard, systems ecologists found a number of common characteristics in ecosystem behaviors. Three major principles established from their findings are: (i) *Self-organization*, (ii) *Dissipative structure*[13], and (iii)

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[9] It could be understood as man-made machinery.

[10] Henri Bergson defines time as “duration” that must be distinguished from the time that is perceived in abstract space of homogeneous occurrences. Duration can never be thought of as being separated from space, and always invokes a series of heterogeneous moments. Underscoring the fact that it identifies non-recurring events of natural cycles, Galiano (2000) states that Bergsonian time marks a “process of creation”.

[11] The incipient appearance of the ecosystem concept dates back to 1914, much earlier before the ecosystem researchers employed the modern systems theory. Abolin, a Russian scholar, had used first the term *epigen* to correspond to the today’s ecosystem idea (Van Dyne, 1969).

[12] Schultz (1969) uses “elements” to refer to objects and “states” to attributes.

[13] It is the characteristic of an open system. The term, “dissipative system or structure”, is first clearly identified by I. Prigognine, as a simultaneous characteristic of the self-organization, in his book (1977), “Self-Organization in Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuations”.

Reductive system. (Odum and Odum, 1981; Jørgensen, 2000)

Self-organization is in fact the cardinal feature in the systematic understanding because it identifies the complexity of system that makes it difficult to apply conventional investigation based on the factor-result relationship. Wiener demonstrates that self-regulation is found in all kinds of systems during the development of feedback (or oscillation) loops. In ecology on the other hand, self-organization indicates that ecosystems distinctively transform for themselves properties of a network: attributes, number of components, and relationships, creating a particular form of the system hierarchy. It is an active process of adjustment, rearrangement, and creation of bodies of systems to adapt quickly to an environment for their survival, growth, and prosperity.

Every element of buildings, in fact, originates from nature. From the inference of the aforementioned principles, they are also ecosystems themselves. Not all may seem ecological, but in a macroscopic view, environmental behaviors of each building certainly resembles ecosystems, since essential characteristics of the building systems, self-assertiveness and cohesive tendency are also major properties of self-regulating open hierarchical structures (Koestler, 1967).

The long history of architecture shows many examples of self-organization. In terms of the fashion or style, from the primitive hut to modern skyscraper, buildings have been developed, not coincidently but decidedly, to “complex” systems by communicating with social and cultural contents as well as useful environmental resources. Several demonstrations show our built environment is structured hierarchically according to distribution of the energy quality (Huang et al., 2001; Odum, 2007; Abel, 2010; Braham and Yi, 2014). Abel (2013) traced fuel use patterns of US households and revealed a social hierarchy of buildings has followed the principles of the ecosystems self-organization. It is partly because, in a highly-developed built environment, all parts are increasingly dependent on one another (Kelly, 2010).

When one seeks to extend the building system boundary to a whole society, however, care needs to be taken. Even though Odum (1981) showed the feasibility of self-organizing structures for human environment, Fernández-Galiano (2013) points out “lack of self-limitation” in sociocultural systems, quoting Eric Jontsch’s argument that “socio-cultural systems obey the law of biological life only partially.”, and, for that reason, he is skeptical on the fact that built environment would spontaneously organize itself under a certain thermodynamic rule. But he shows no clear evidence; what he insists is the potential inconsistency between Prigognine's minimum entropy rule and human environment. However, he does not relate built environment to the law-like system-level maximum useful energy consumption, overlooking the fact that living systems always funnel energy into a large amount of dissipation towards growth and survival. Paradoxically, a highly-dense city reveals that the built environment responds to environmental crises by creating internal patterns of higher complexity. Environmental design is a conscious effort to make it in harmony with the environment, it is reasonable to assume environmental building systems will follow the biological laws. Zhang et al. (2006) also mentions built environment cannot be rigorously consistent with ecosystems due to the intervention of human activities, but apparently admits extrinsic variations change internal structures of a complex artificial networking into higher adaptability. Braham and Yi (2014) presents that a contemporary building is constructed to follow the self-organization principle and building components consist of an energetic hierarchy. Open thermodynamic systems develop dissipative subsystems for the sake of metabolic activities. Every living organism of an ecosystem has a dissipative structure. Each of individual absorbs outside energy and matter as input sources. Then they are transferred to other organisms or thrown away in part. This dissipation process controls the speed of metabolic rates. The same holds true for building systems. A building requires a certain amount of external energy and materials for operation and maintenance, but they are degraded and taken out of a building after use.

Energy demands for building systems operation also clearly demonstrate buildings develop reductive systems to aid human living as plants maintain homeostasis through photosynthesis. Photovoltaic equipments attached to environmental buildings provide an analogical example. Then what remains is to look to how the system network interacts and move toward growth and self-sustenance, according to the level of system complexity.

1.3.2 Building as thermodynamic organization

"*Architecture can be understood as a material organization that regulates and brings order to energy flow; and, simultaneously and inseparably, as an energetic organization that stabilizes and maintains material forms* (Fernández-Galiano, 2000)."

Fernández-Galiano's interpretation of a building replicates the ordinary characteristics of a dissipative thermodynamic system that imports useful energy and exports wasted energy to maintain a stable (living) state. As Wiener insists that all the elements underlying a system construction are held by “energy” and “its potential”, the essence of the systematic approach in the building-ecosystem analogy is to associate building systems with thermodynamic laws in which energy balance and the flow paths are determinant of all natural phenomena. Ecosystems obviously use an enormous amount of energy flows, and organize them in a certain order. In so far as mechanism of building systems is keenly tied to ecosystem metabolism, defining the medium of thermodynamic processes that interlink system components should be the core task to identify building systems.

In the tradition of biological study, the mechanism of a living system is identified with metabolized works of three cardinal quantities: (i) *energy*, (ii) *matter*, and (iii) *information*. (Jørgensen, 1992; Gatenby and Frieden, 2007). Jørgensen argues that those are driving constraints and inextricably connected inputs to which all systems behaviors are subject. Reception, storage, transmission, and utilization of the three elements dominantly contribute to settle a system into a particular state. Different fields of science use the terms in different contexts, though, to put it coherently in system study literature, energy is a capacity of activities whose two major categories are heat and work. Matter is generalized to refer to the physical substance of any material having mass whilst at rest. In living organisms, information is usually referred to as an inherited knowledge. Energy, matter, information are commonly inputted to create system objects and go through depreciation with temporal flows.

However, a question may arise; do flows of the elements through a system have dominance over each other? The answer is no. Matter and energy are equivalent as one can be converted to estimate the other. Matter can be seen as a statically concentrated carrier of energy, and thus, its quantification takes on a commeasurable metric of energy. What is noteworthy is the role and traits of information. Although, information is a formless quantity, it can be treated as a coequal thermodynamic property as energy and matter (Cabezas and Karunanithi, 2008) in that it plays a central role in mapping of a genetic expression with energy and matter. But the behavioral aspect of information is quite different among other elements. Matter and energy are conserved and some of useful content can be recycled for regeneration; the same statement does not hold for information. Instead, while available energy and matter could be limited in existence of a living system, information can be reproduced and transcended for the evolution of the system (Brown, 2005; Kelly, 2010). Since amplification of information is much easier than investment of energy and materials for reproduction (Tribus and McIrvine, 1970), a small quantity of information is capable of reorganizing fluxes of energy and matter and a specific transaction and arrangement of energy and matter are directed only by information (Gatenby and Frieden, 2007). For this reason, some researchers (Fath et al., 2003; Nielsen, 2000; Straskraba, 1995; Brooks and Wiley, 1986; Wicken, 1987) argue that an ecosystem is an "information system" as they take information as the most critical constraint of environmental systems development.

The use of thermodynamic explanation with energy, matter, and information is effective to drawing some useful principles of environmental building design. A building plan can contain all the information for a single building. During construction, great deals of material are transported to the site, and the building consumes energy for operation, responding to the embedded information. It is quite similar to the way a living organism grows. Therefore, the definition of a building as "a thermodynamic engine"[14] is explained with combination of the three constrations. A building as an open system absorbs, transfers, disposes energy, matter, and information in order to maintain itself away from thermodynamic equilibrium. Analyzing three elements separately will end up with incomplete knowledge to understanding building system's functioning as a whole. Meanwhile, along with Fernández-Galiano's assertion, the building form of environmental building is a physically revealed but "embodied" form of information to adjust the balance of energy and matter (Braham, 2015).

1.3.3 Form of (environmentally useful) information: Thermodynamic encoding of energy and matter

"From one cosmic perspective, information is the dominant force in our world. (Kelly, 2011)."

Information, which is a primary term in this dissertation, corresponds to non-physical, formless knowledge as in its everyday sense, but it should also be understood as a physical quantity that pertains to the arrangement of energy and matter in a system network. Limiting implications of information within a single definition may risk its applicability. Multiple applications of information-related terminology in various fields make it occasionally metaphoric and misleading in translation.

The modern system-based definition of 'information' was emerged from Wiener's *Cybernetics* in 1948. His enthusiasm for the human-machine analogy led to a mathematical

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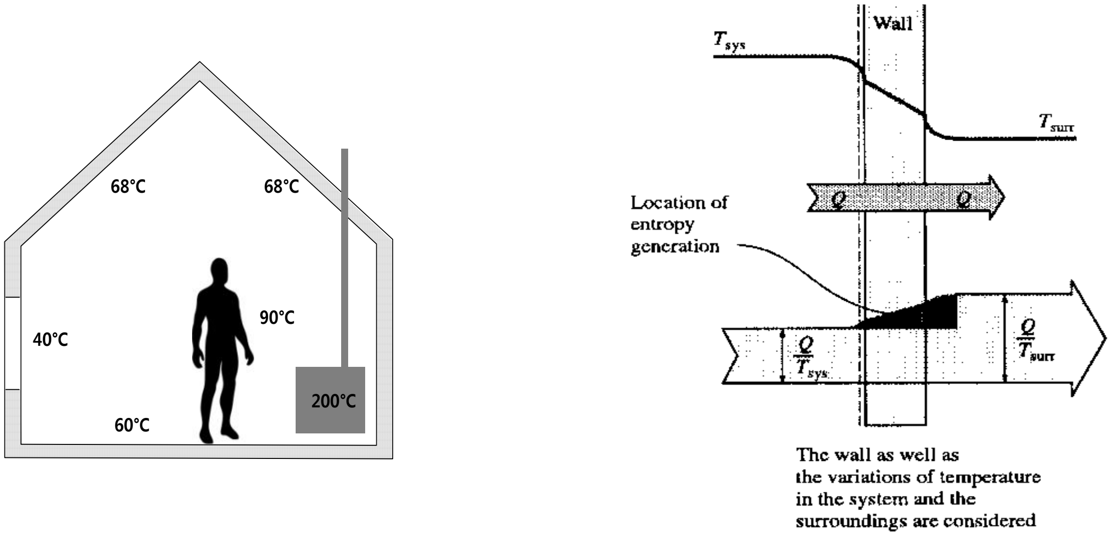
[14] cf. Wiener (1948) proclaims, "The living organism is above all a heat engine".

study of the signal delivery mechanism based on quantum physics and Gibbsian statistical mechanics. As a scientist, his concern was ultimately with the control of simultaneous interaction through the integration of system and signal from the outside. He defined information as “a message driving the internal mechanism into a specified direction (Wiener, 1948)”. Subsequently, three Russian cyberneticians, Aleksei Liapunov, Anatolii Kitov and Sergei Sobolev, expanded Wiener’s idea. They maintained that information is any sort of external data that is absorbed, processed, or produced within a system (Mindell et al., 2003). This stimulated the untapped potential of the term. Information was immediately transferred to different fields: data processing in computer, environmental change, genetic structure in biology, anthropogenic phenomena, human knowledge, etc.

In spite of the widespread multidisciplinary use, the definitions of information in the related disciplines (biology, communication, computer science) can be succinctly described with a double nature, i.e., (i) semantic information (useful meaning or instruction encoded in a system process as a form of a signal, bits, or data), and (ii) syntactic information (the sequence and structure of data). The semantic interpretation is based on the commonality underscoring qualitative aspects and, therefore, familiar to us, but the syntactic definition gives a clue that information could be used for indicating the magnitude and quantity of data and its structural configuration.

This dual nature of information can confuse the selection of technical measure of information. Randomness and unpredictability of data processing prevent the use of qualitative measures of communication. However, Hegel’s proposition reminds us that the nature of quantity is a return to a change in quality, and also “quality and quantity are united in measure (Hegel, 1816; 2010)”, the two categorizations of the information definition are not indifferent each other, they are two sides of the same coin.



(a) Distribution of conductive heat inside the building

(b) Generation of information (from Dincer and Cengel, 2001)

Fig. 1.3 What is the (environmental) building information?[15]

In architecture, an incipient source of information is the architect's (or client's) idea of design and planning. In turn, it is accumulated in form throughout the construction phases. So one may call a building *information memory*. However, the memory is decoded and encoded (spread, amplified, transformed, and mutated) by the various channels (e.g. occupants' lifestyles, adaptation to changing environment) throughout the building's life cycle.

Information in this dissertation is defined as the building's capacity for engagement, by tuning up its subcomponents such as human life, supportive social backgrounds, and physical elements. A first hypothesis is that such informational ability appears through the building's systematic networking. Therefore, building information could be anything that characterizes energetic flows across the components (e.g. operational energy, material, etc.). Note that a critical second hypothesis is that the process of information change is comprehensively embedded in the 'building form' which adjusts and controls the flow of the information content (Fig. 1.3).

On the other hand, from a cosmological view, Kelly (2011) finds that information holds

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[15] A building form can be understood as the key director of information generation. **(a)** A building "organizes" energy flows. Particles of imported heat (high-quality energy) are unevenly distributed through the entire building envelope and they create a certain form of heat "gradient" over the surfaces. **(b)** The building form regulates generation of an energetic order: The wall's control of heat exchange generates temperature difference and entropy that corresponds to information change of the building system. This example clearly demonstrates that building energy transport always integrates matter and information, and also that higher information indicates higher utilization of matter and energy

dominant power in shaping the technosphere. He explains, in the formation stage, i.e., Big bang universe, radioactive force was paramount, but afterwards, matter became the most prevailing with the creation of biosphere (Kelly, 2011). Since information imparts order and pattern to a system (Ulanowicz, 1997), information has been accumulated gradually throughout developmental stages of the environment, and now information governs all biotic/abiotic processes on Earth. Evidently, this argument is consistent with the idea that information has the highest quality of energy (Odum, 1988; Tribus and McIrvine, 1971).

Therefore, a building form as an information system is an "*exosystem*" (Fernández-Galiano, 2000), wherein continuous inflow of dematerialized force and energy maintains an (thermodynamic) order of a building system. Energy and matter can be easily measured and integrated as an energy account, since both are theoretically interchangeable substances. However, it is important to note that the building as a living system do not take in information directly, but information obtained from the incoming matter and energy is used up to agitates the system's internal structure of energy transformation processing. Information is thus created, destroyed, and augmented while in processing of energies and materials. Hence, it can be said that a small amount of energetic exchange may cause a building system to have a entirely different energy flow structure. (Aynes, 1976). At the moment, the building energy structure takes on a certain exosmotic order of complexity.

1.4 Brief introduction of terminology and principles of systems ecology and information theory

Emergy (spelled with an "m") is crucial to describing environmental phenomena and principles in this study. It is an accounting metric that measures embodiment of all types of useful environmental sources. Emergy enables to appraise energy quality and hierarchy of an environmental entity or process. Greater energy concentration generally leads to greater emergy and higher quality of output energy. Ecosystem's developmental tendency to maximize useful energy is explained with the maximum emergy power principle. On the other hand, based on information theory, an amount of uncertainty in probabilistic distribution of energy is related with a definition of building information content. Information is channeled through the building system, and the built form is a paramount agent in environmental building performance and impact. Odum's emergy power basically takes on an extensive perspective, while measuring information originated from an intensive analysis.

Not only that, information cannot be directly quantified, since, (i) by definition, it is observed only with system's internal structure change (network configuration); (ii) the capacity of a source of the human/building information is unknown. Nevertheless, by introducing information as a thermodynamic quantity, maximum power principle can account for why environmental buildings increase information, because involving human (genetic) information for building operation tends to increase power by developing a feedback loop. A number of other ecosystem/environmental indicators are discussed and compared in detail with thermodynamic principles in Chapter 2 and 3.

1.5 Objectives and hypotheses of dissertation

This dissertation addresses an intensive domain of performance evaluation and develops a new methodology for the holistic evaluation of building performance. To this end, models and methods incorporating flows of emergy (spelled with an "m") and information are established, so that building information content can be used to describe both qualitative and intensive aspects of sustainability in the processing of energy and material. This study identifies building thermodynamics with an interconnected dynamic networking of individual environmental flows. From an advocacy of the building-ecosystem analogy based on a thermodynamic understanding and awareness of the problems in current performance evaluation methods, this dissertation applies theorems of systems ecology, thermodynamic principles, and information theory, so as to clarify living-system-like building's environmental functioning at the system level and eventually to argue that an emergy-integrated information is a holistic index of building sustainability. Specifically, this study is primarily based on Shannon's mathematical definitions of information (Shannon, 1948), Ulanowicz's ecological interpretation of information theory (Ulanowicz, 1986; Ulanowicz, 1997), and H.T.Odum's principles of ecosystem behavior (Odum and Pinkerton, 1955; Odum, 1971; Odum, 1996).

Applications of network-based thermodynamic flow analysis to test cases seek to justify the building-ecosystem analogy, describe the characteristics of system development consistent with the general notion of building sustainability, and determine which kind of a building form and design is sustainable. Explanations of the methodology will be followed by suggestions for a new vision of sustainable architecture. Following hypotheses and ecological principles are explained and demonstrated with test buildings.

(1) Parallelism of ecosystems metabolism and building energy dynamics is substantiated, under thermodynamic principles, at all spatial and temporal levels. Individual phenomena we experience may be a highly contingent under random variations, but they can be explained with general principles of ecosystems growth and development (especially maximum power principle).

(2) Building and subsystems are subject to a certain energetic hierarchical structure which is likely to have a high degree of complexity and an optimized (intermediate) level of efficiency in the structural organization as ecosystems are. For this reason, both maximizing power and increasing information content become a common tendency of sustainable buildings and building forms (Fig. 1.4).

(3) A sustainable building form tends to self-organize functional interplays between internal and external coordinates of environmental resource flows. Since a resilient thermodynamic system gives feedback on its performance with greater potential of system learning and self-adjustment (Hasseler, 2014), it can be expected that highly resilient building would construct an energy transmission circuit to a high degree of potential human engagement and end up increasing information. In a system's state of high resilience, the building form becomes a game changer in the whole system functioning towards sustainability (Fig. 1.5). As a biophysical order is inherited through a certain "form" of DNA or a cell (not directly through genetic information), it is assumed that the building form is the final director over all building system behaviors and it seek to accumulate the genetic information while in responding to environmental conditions.

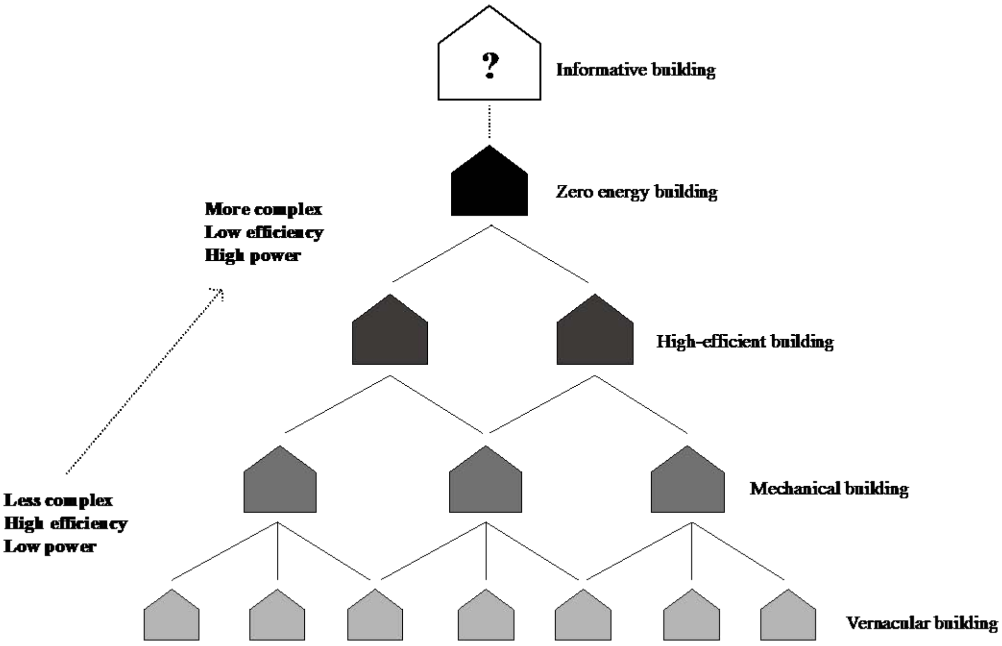

Fig. 1.4 Ecosystem-based hierarchical understanding of environmental building types[16]
(Sustainable building performance is not about increasing efficiency but power)

Major challenges regarding demonstration of the above hypotheses are:

- Identification of thermodynamic process in construction and operation of building systems.
- Building ecosystem modeling (definitions of the system boundary and components)
- A clear substantiation of how information indices can be incorporated into environmental building studies, provided that integrated indices can identify flow structures of building materials and energies.

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[16] This figure shows that historical developmental trends of environmental building types have been dependent on the system power, not efficiency. Vernacular buildings made of natural and local materials, without mechanical systems (e.g. a primitive hut), tend to carry less power, but their efficiency in terms of thermodynamic is very high, because there would be no significant difference between the inside and outside temperature and, thus, it is fully-reversible. As mechanical systems attached for thermal comfort, buildings become endo-irreversible, and efficiency decreases as the building undergoes more complex energy transformation processes. According to the ecosystems principles, such genealogical development of the environmental building type is quite natural, however, sustenance of the present hierarchy whose power sources rest mainly upon nonrenewable (e.g., fossil fuel, industrial goods) sources is highly contingent on the source availability, and must be vulnerable if the resources become scares. In this respect, zero energy building is just another developmental type following this way. However, information functions as a quasi-renewable source, because it is readily available, and its high quality help increase power as well. So, one may expect that future sustainable building would be more informative.

- Development of building performance indicator systems and computation algorithms that enable to integrate emergy units and the definition of information.
- Evaluation of building information content to characterize a thermodynamic status in a quantitative manner.

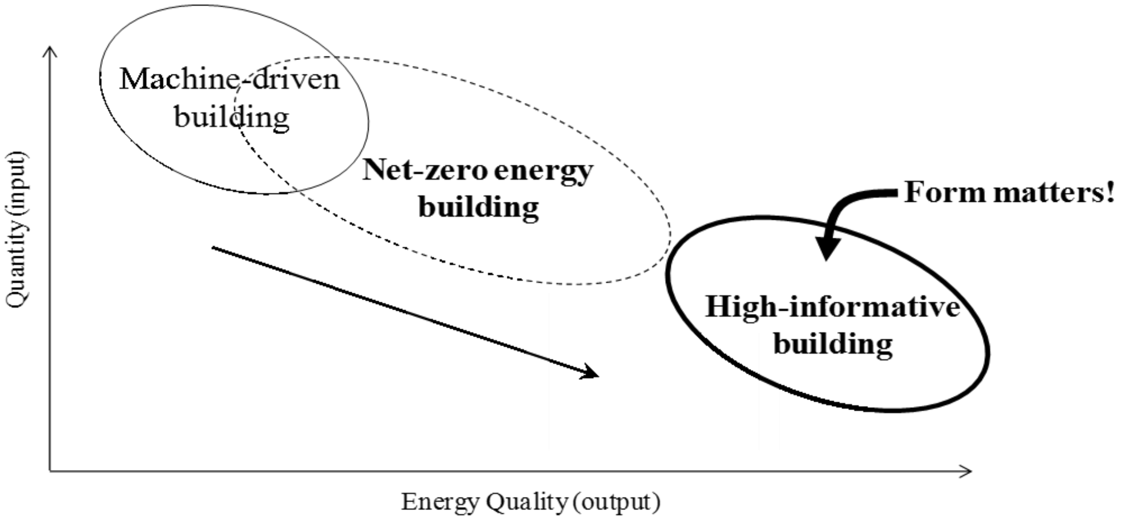

Fig. 1.5 Hypothetic quantity-quality diagram: Sustainable building shall be highly informative. Increased information content works to reduce the quantity of energy usage, while increasing the quality of the energy. An information-based understanding of building performance gives a scientific rationale for the tendency to increase information content of the future sustainable building, and also justify why we should explore information of the building form.

CHAPTER 2

A REVIEW OF BUILDING SUSTAINABILITY ASSESSMENT METHODS: METRICS AND APPLICATIONS OF SYSTEMATIC APPROACHES

2.1 Assessment of building sustainability

A goal of assessing building sustainability is to quantify the capability of a building to manage, conserve, and restore environmental sources, based on the measures that are bound to underlying ecological constraints. It is used to weigh a resource balance, to establish a direction and a rate of development or for benchmarking. Kharrazi et al. (2013) characterize the three categories of general constraints in environmental development: (i) resource availability, (ii) limits to inputs, and (iii) consumption efficiencies.

Specifically, if one sought to understand the nature of what is to be evaluated for buildings, there are challenges directed into twofold, i.e., “capacity” and “efficiency”. In effect, environmental resource availability and input limits of goods and services delineate a productive capacity of the social/natural environment. Efficiency depends on the rate of resource use, as well as various system-operation schemes of throughput management.

Capacity concerns donor-side aspects, addressing a consumer’s overall demands, whereas efficiency refers to the user-side ability to handle disposal processes. Each of which is mutually indispensable, and, in general, one cannot take absolute precedence over the other. For instance, if efficiency of consumption is a parameter which demonstrates the amount of resource used to provide heat, lower capacity (reduction of space heating demand) requires higher efficiency of machines, and lower efficiency demands a greater amount of carrying capacity of heating sources. Leslie White’s pithy formula that $E \times T \rightarrow C$[17] (White, 1949) also implicitly highlights that the degree of sustainability is reinforced by correlation of the two factors. For a more general definition, the expression could be rewritten as a cross product function of two vectors as below,

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[17] E denotes the amount of energy used, T is the quality or efficiency of the tools employed for harnessing the energy, and C is the degree of cultural development (White, 1949).

$$\mathbf{B} = \mathbf{C} \times \mathbf{I} \qquad (2.1)$$

where **B** denotes the degree of building sustainability, **C** is the capacity-related factors, and **I** is the efficiency-related variables. To be specific, the quantity of matter and energy are related to **C**, and **I** can be a flux density or a degree of concentration of matter and energy. Note that the final indicator **B** has both a magnitude and a direction whose interpretations and dimensions depend on the attributes of the inputs.

The symbiotic translation between two terms does not prevent trade-offs between them, and occasionally it is being misused, or interrelations are overlooked. "Net-zero", for example, means that 100% efficiency ensures an unlimited virtual capacity of nature or economy invested (Pless and Torcellini, 2010). But this enthralling assumption misshapes what a sustainable building is for. It does not explain different thresholds of throughputs, and not acknowledge that renewable resources are "forms of potentially unstable energy" which are not limitless (Odum, 2007; Srinivasan et al., 2012). In addition, energy or cost payback scenarios do not shed full light on future uncertainty since a building may not be working in the same way as it does at its birth (Fernández-Galiano, 2013). Net-zero definitions seem to rely on a short-term payback of any kind. Based on an understanding of the various strata of the relations between capacity and efficiency, an appropriate building sustainability quantification method will depend on two considerations: (i) the "medium" to be used for analysis and (ii) the "system definition" that is dictated by a scope of analysis (Zhang et al., 2010a). Both have much to do with the approach to understanding of buildings, including establishment of hypothetical models for sustainability evaluation. An appropriate quantitative measure of building sustainability can be derived from an investigation of the parameters characterizing a building as an ecosystem (energy, matter, and information) whose attributes vary according to variations of the two terms of sustainability: capacity and efficiency. Prior to a new suggestion, existing methods employed for environmental building studies are presented and critically reviewed in the next sections. Section 2.2.2 introduces methods of an intensive system measurement that is new to building sustainability, which provides essential concepts and techniques for this dissertation.

2.2 Methods of quantification and accounting measures

A building is bound to a set of natural/technological/social systems, which is demonstrated by (i) the number of variables to define the building system is extremely high, and (ii) the orientations and properties of numerous component connections are all different, and vary interactively. So, in order to examine sustainability, a large number of data sets representing the real system need to be gathered through a series of observations or experiments. Munda (2006) analyzes that sustainability assessment methods are developed by setting: (i) a purpose of evaluation, (ii) scale of analysis, and (iii) set of dimension, objectives, and criteria (Munda, 2006). Based on the above factors, the methodological approaches to characterize the complexity can be grouped into (i) reductionism and (ii) holism, according to the dimension of measurement, types of media, and the number of indicators to describe system performance (Fig. 2.1).

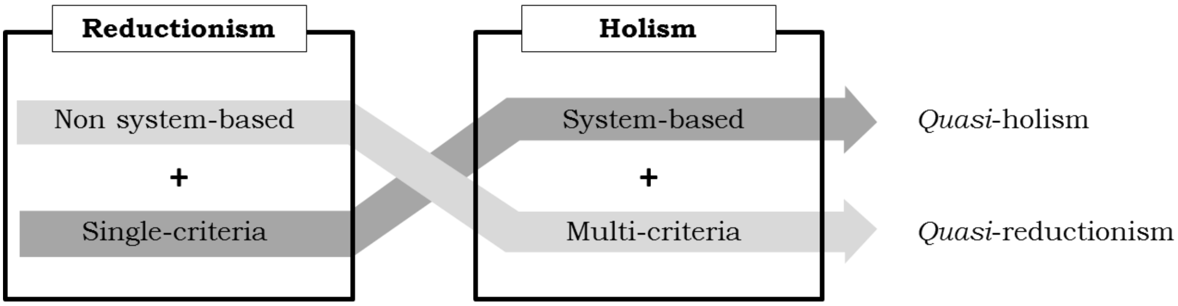

Fig. 2.1 Philosophy of sustainability assessment: Reductionism vs. holism

The perspectives to which each method holds can be subdivided largely into (i) extensive analysis (non system-based) and (ii) intensive analysis (system-based) (Fig. 2.1), depending on the level of resolution of the system structure, and the scale of analysis. One might be confused about the use of this classification because they are illustrated somewhat differently in the literature. Especially, several studies considered intensive analysis to be tantamount to holistic evaluation. For example, Jørgensen (1992) uses reductionism and holism in the same way as the distinction of the extensive and intensive analysis. Munda (2006) distinguishes reductionism only in terms of the number of criteria, while Reed et al. (2005) contrast reductionism against system-based approaches.

It seems apparently true that the resolution of the system structure under analysis renders a clearer definition for this distinction than the number of indicators. Notice, however, that selection of criteria is dependent on the structural detail. The extensive-intensive categorization sets the definition on the scope and the subject of accounting variables and data observation. At a molecular level, for instance, trajectory of movement, external work, volume of a molecule, and interaction between molecular particles, which depend on the size of a system, are the sources of external analysis. In contrast, intensive analysis deals with density, pressure, or internal temperature of the molecule, which identifies arrangement of the molecule structure. On the other hand, this reductionism-non-reductionism distinction concerns the way of conducting the observation and the final outcome of quantification. Reductionism is fundamentally based on a mechanistic point of view, taking for granted the common misconception that a total equals the sum of parts. As a result, reductionist methodologies do not consider an inner state of the system. Various complex phenomena during system processes fall into a set of causality of inputs and outputs, and monitoring system variations condense to a single or few key indicators (Reed et al., 2005). On the other hand, the holistic view emphasizes the local context of and internal change in the system. In the holistic framework, multiple techniques and tools can be implemented in different phases throughout the analysis, and it allows simultaneous use of various indicators (Bossel, 2001; Reed et al., 2005).

By suggesting subcategories within the division between reductionism and holism, various environmental accounting methods can be comprehensively reviewed in a more hierarchical manner. Below discussed are the developed indicators and tools.

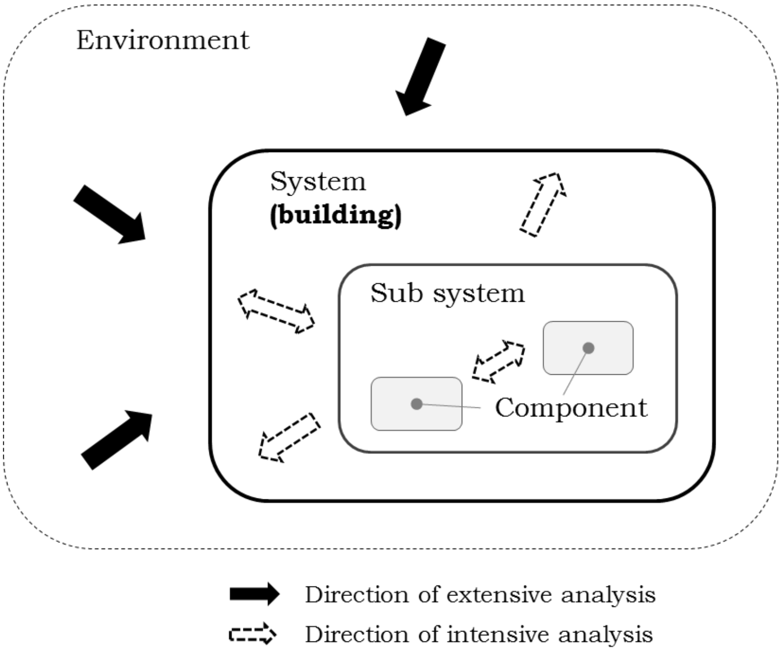

Fig. 2.2 Extensive analysis vs. intensive analysis

2.2.1 Extensive methods (Non-system-based approach)

2.2.1.1 Single-criteria measures (SCMs)

Reductionist descriptions for the building system represent a large number of variables with a single metric. In this claim, a sustainability index is obtained in such a way that the whole system is disassembled into parts mechanistically. This framework supposes that the property of the system simply consists in that of subcomponents, i.e., a total exactly equals to the sum of the parts and vice versa; thus a system can be identified by exploring a small subgroup of entities or even a single compartment.

The selected media for data reduction help to display a clear vision of a system state, and judicious use of the tools during the design processes can facilitate reasonable decision-making. However, this perspective may lack detailed specification of various local circumstances of the system.

(1) Energy analysis

American Society of Heating and Air-Conditioning Engineers (ASHRAE) standard 90.1 defines energy such as "the capacity for doing work, it takes a number of forms that may be transformed from one into another such as thermal (heat), mechanical (work), electrical, and chemical (ASHRAE, 2013)." Energy analysis (EA) measures the amount of energy that a system requires to produce a specified good or service (Brown and Herendeen, 1996).

Currently, energy accounting forms the basis of many building sustainability assessment methods including the credited standards (CIBSE, LEED, etc) and tools (EnergyPlus, IES-VE, eQuest, etc.). Theoretically, energy never disappears during all system processes, but only transforms into another forms. For example, one joule of heat is perfectly interchangeable with one joule of work, since it is based on the principle of "*thermal equivalency*" – the primary feature of the Newtonian paradigm – as the first law of thermodynamics (FLT), the law of conservation, supposes. It provides a very useful concept with which various forms of the system constituents can be evaluated on the same base. As Odum and Odum (1971) explain that energy is stored in the form of matter, materials and operational energies of buildings can be treated equivalently if they have the same joule of energy. As a result, energy illustrates a major limiting constraint for systematic phenomena (Kelly, 2011); i.e., energy measures are capable of providing a restriction on the gross energy usage that can be tracked though the partial amount.

However, the methods of assessing energy balance based on the conservation law do not bear any explanation on spontaneous processing of materials and products and their pathways. The energy equivalency, which perfectly meets the hegemony of mechanistic ideas that reductionism underlies, apparently downplays time and direction of the energy flows which are irreversible (Fernández-Galiano, 2000; Dincer and Cengel, 2001). Moran and Shapiro (2000) point out that the concept of energy flows is ill-suited to depict "significant aspects of energy source utilization".

(2) Exergy analysis

Exergy was first coined in 1950s to characterize thermodynamic potential of energy – availability of heat that can be transformed to work, but the concept was introduced long ago as "free energy" by W. Gibbs.

Exergy analysis (ExA) measures the system's maximum useful work, i.e., a rate of conversion of heat for effective use (work). While the concept of energy is that heat equals work, exergy does not. Even if energy is never destroyed during a process, the "usefulness" decreases according to thermal difference between the system and external conditions. System content of energy and matter are dissipated, degraded, and dispersed into the surrounding during any work process (Dincer and Cengel, 2001). Fernández-Galiano argues that exergy is the true author of all energetic phenomena (Fernández-Galiano, 2000). As Brown and Herendeen (1996) explain, EA does not quantify an emission or absorption from or to the environment, energy primarily accounts for the heat transfer within the system. In contrast, exergy accounts are descriptions of the conversion process of energy according to the interactive relationship between the system and the environment.

Thermodynamically, exergy is a measure of "distance from thermal equilibrium (Jørgensen and H. Mejer, 1979)." If a system is in the equilibrium with the surrounding, exergy is zero. Thermal equilibrium refers to the state of the system with no heat exchanges to the external environment, which means death of the system. Accordingly, quality and value of the system, in terms of the energetic utility, depend on the distance. The longer the distance becomes, the higher the quality of energetic (heat) content goes up.

Shukuya (1994) introduced ExA to building study, and exergy has been widely utilized to measure the thermodynamic efficiency of building's heating, ventilation, and air-conditioning systems (HVAC) or overall performance of building systems. Szargut et al (1988) proposed an extension of exergy analysis called cumulative exergy consumption (CExC) analysis. This method implements the total efficiency of energy carriers of natural resources.

Exergy is based on the second law of thermodynamics (SLT), and it is closely related to the concept of "*entropy*". Unlike energy, entropy is not on casual perception. Entropy (S) is defined by change in heat content (Q) of a system divided by the system temperature (T), such that

$$\Delta S = \Delta Q / T \geq 0 \qquad (2.2)$$

Eq. (2.2) is called the Clausius equality. Entropy always increases and entropy change (ΔS) is irreversible. ΔS becomes zero in the rare case of the reversible system.

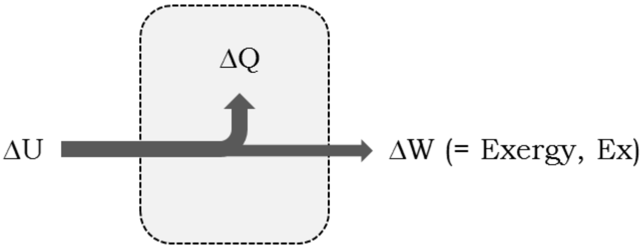

Fig. 2.3 Thermodynamic relationship of input energy (U), exergy (W) and internal heat (Q)

The correlation between exergy and entropy is identified with a simple example (Fig. 2.3). Given the external input energy (ΔU) to a system, by FLT, $\Delta U = \Delta Q + \Delta W$, where ΔQ is a finite increment of the internal heat content, and ΔW indicates the part of the input energy that participates into doing actual work. Introducing the energy conservation, Eq. (2.2) becomes,

$$T\Delta S = \Delta U - \Delta W \qquad (2.3)$$

The amount of the useful work done is equivalent to exergy (Ex) of the system. Assuming no external energy is entered (spontaneous process), i.e., $\Delta U = 0$, finally we obtain,

$$\Delta Ex = -T\,\Delta S \qquad \leq 0 \qquad (2.4)$$

Eq. (2.4) demonstrates that exergy varies inversely to entropy, and the fact that exergy increment is always less than or equal to zero reveals energy is always degraded accompanying the entropy increase in the natural process ($\Delta U = 0$) unless the positive amount of energy from the surrounding flows into the system.

Entropy (S) is the central concept for understanding the system status. It is a state function or a state variable at the same time, since it refers to accumulation of internal heat whose concentration leads to an ordered state of the system structure (Odum and Odum, 1971). Boltzman explained it as the number of possible quantum states, and formulated it as a function of probabilistic distribution of the energetic states. Entropy change can be used as a measure of intensive analysis. Due to the strong correlation between entropy and exergy as shown in Eq. (2.4), exergy might also be able to be categorized as an intensive measure. (Its implication is discussed with the statistical formulation in detail in Section 2.2.2 and Section 2.3).

Dincer and Cengel (2001) state that energy and matter in the universe can be rated with level of usefulness, Jørgensen (1992) argues “exergy illustrates pathways to create organization that move away from the thermodynamic equilibrium,” which leads to his ecological law of thermodynamic; we can characterize complexity and hierarchy of system from exergy levels. Entropy and exergy as thermodynamic measures will be discussed further in association with information theory and Odum’s order and disorder model through Section 2.3 and Chapter 3.

(3) Embodied energy analysis (Input-Output analysis)

Embodied energy analysis (EEA) is also called Input-Output energy analysis. The objective of EEA is quite often energy cost-based economic planning and decision-making (Bullard et al, 1978; Burnakarn, 1998). Correspondingly, the target is to estimate the total energy consumption of manufacturing goods and services.

One of the key concepts to understand EEA is “net energy” (Bullard et al, 1978; Brown and Herendeen, 1996), since it aggregates various types of energy processing during the production of a unit of good and service into an energy input-output framework.

While EA measures consumption of energy sources at a specified time frame. EEA extends the time and scope on a energy flow chain to account for indirect energy and material inputs. However, care should be taken in the setting of the EEA boundary and conversion of indirect energy sources since the separation of energy from matter is improbable. Identification of the union of matter with energy with an appropriate conversion ratio is not easy.

(4) Emergy analysis

Emergy (spelled with an "m") was developed by H.T. Odum in the early 1970s, to estimate solar embodied energy invested for producing goods and services. Emergy is "the available energy of one kind required to be used up previously, directly and indirectly, to generate the inputs for an energy transformation (Odum, 1996; Brown et al., 2004) ". Emergy is rooted in the concept of embodied exergy. It can be understood as an utmost extension of embodied energy, since it accumulates all kinds of direct/indirect energy flows stretched from the natural formation of materials. Specifically, similar to embodied energy, emergy is (i) process-based, and includes (ii) economic value and (iii) indirect effects of energy flow. Inspired by ExA, emergy is also concerned with quality of energy, and implicitly sums up all contributions of useful energy (exergy) inputs[18] (Bastianoni et al., 2007) (EEA also acknowledges different quality of energy sources, but it follows the energy conservation law in computation).

Emergy-based energy flow accounting, called emergy synthesis, and more formally emergy analysis (EmA), traces the flows of the thermodynamic quantum (emergy) within an analysis boundary. EmA underscores bookkeeping of all energy flows, and records the trajectories in its quantity.

Emergy emphasizes the donor-side perspective rather than receiver based. i.e., similar to EA, Exergy, and EEA, emergy aggregates upstream (inflow) impacts. While other extensive

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[18] In emergy theory, H.T. Odum distinguishes available energy and useful energy in definition. *Available energy* is defined as "potential energy capable of doing work and being degraded in the process" (Odum, 1996; 1998), which is known as a synoym of *exergy*, and *useful energy* is an 'actually' used portion of the available energy for increasing system production. However, in many literatures, occasionally, the definitions are mixed. Available (potential) energy is generally appeared to imply both (Odum, 2007). Mellino et al.(2014) states that available energy can be identical to useful energy only when the reference state of environment is the standard laboratory condition for pressure and temperature.

measures set an upper limit of processes so as to fit the goal of evaluation, emergy locates it at the extreme capacity of global resources such as solar insolation, tidal flow, and deep earth heat that are eventually normalized in a single energy source—the sun. As a result, the measure of emergy aggregates all type of energy into the equivalent solar energy, namely, solar emjoule (sej).

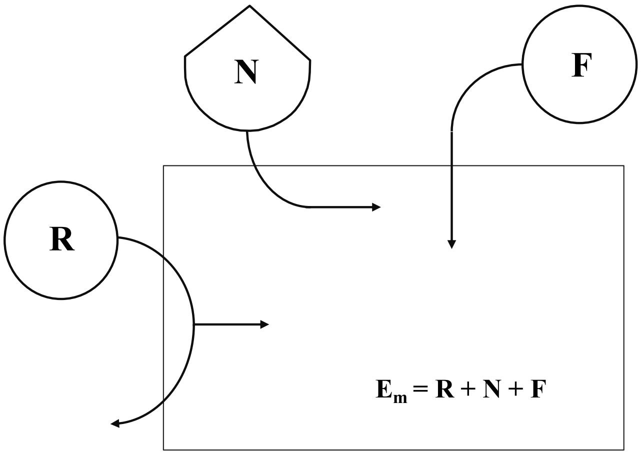

Fig. 2.4 Three major inputs in the emergy analysis (Redrawn from Morandi et al., 2013).
Abbreviations: $\mathbf{E_m}$, Emergy; **F**, purchased emergy sources; **R**, renewable sources; **N**, non-renewable sources.

Unlike exergy-based analytical methods, EmA makes a clear distinction among energy sources (renewable, nonrenewable, and imported) (Kharrazi et al., 2014), and proposes sustainability indices such as environmental loading ratio (ELR; ELR = F+N/R) and emergy yield ratio (EYR; EYR = emergy of products (Y)/F). Also from the ratio of ELR and EYR, EmA suggests a emergy sustainability index (ESI or SI), i.e., ESI = EYR/ELR (Brown and Ulgiati, 1997).

Mathematically, due to the use of the common denominator (solar energy), every matter and energy has a specific emergy value, i.e., emergy intensity termed transformity (some literature uses unit emergy value (UEV; sej/unit quantity) to include the case of material inputs (Brown and Cohen, 2008)). Transformity is substantial to understand emergy. Transformity describes the quality of energy (a degree of energy concentration) and reveals the hierarchy of energy transformation, as Odum presented a series of cases from a small food chain to a large social structure for the demonstration of hierarchical system development (Odum, 1971; Odum and Odum, 1981; Odum, 1996; Tilley 2004). In a hierarchical chain, a system component with larger transformity (e.g. human information) takes one or more levels higher, governs larger supporting subsystems, and also has longer turnover time than one with lower transformity. In this sense, it is possible to suppose that an item/process with greater tansformity has greater responsibility of environmental development, because greater investment of emergy is more likely.

Use of the emergy concept in the observation of systematic phenomena explains the ordering energy hierarchies, and inextricably reveals the following principles as to the fundamentals of ecosystem theory.

The ecological notion of self-organizing system is based on the hypotheses that all systems (e.g. living, human, cosmological, etc) develop specific forms of hierarchies ‘spontaneously’, and through trial and error, in such a way that all components constrain one another in selection of alternatives (Odum, 1996). It concerns shift of the system status that is driven by communication between system organization and external conditions. Odum (1988) demonstrates that given more available energy flows into a system, a network of the system structure evolves from simple linear to complex autocatalytic paths.

Maximum empower principle

Maximum empower principle (MePP) can be referred to as a principle of energy transformation in system designs. Power is specifically defined as “rate of useful transformation of the available energy for each available energy source” (Odum, 1988) and represented with emergy per unit time. It suggests that all self-organizing systems evolve to utilize maximum available energy (emergy), and a system with higher empower thus prevails in competition with others.

This theorem begins with the Lotka’s law of maximum power in biological systems (Lotka, 1925). Odum (1988) points it out that it lacks (i) definition of human work and (ii) quantitative evaluation of different energy types, and, in turn, he proposed to use emergy instead of energy, contending “it is incorrect to use energy as a measure of work where more than one type of energy is concerned (Odum, 1988).” The maximum empower principle can be understood as an energy-quality sensitive maximum power principle. Boltzmann (1905) defines system development is “a struggle for free energy” (Jørgensen, 1992), and Jørgensen (1992) states an ecosystem with a higher level of exergy prevails.

The MePP clearly explains why and how a system develops, and Odum and Hall (1995) states that the empower principle and the hierarchical transformation rule are the fourth and fifth law of thermodynamics.

Odum (2007) contends that human affairs are also regulated by the energetic laws, MPP applies for explanation of civilization development. Let's say a farmer plans to draw water from a well for irrigation. In the primitive stage, simply using a bucket, he or she would irrigate the soil efficiently with less energy invested in a short amount of time. But with a pumping machine installed, more volume of water (more available energy) can be supplied. Notice that maximum empower—a system's full usable power is achieved when all system components develop feedback loops to amplify input sources. In this case, additional drainage pipelines will return gray water to the ground to be reused later as an underground water source. It will culminate in far more increased emergy flow per unit time.

H.T. Odum further demonstrated that 50% of input energy must be drained to sink, i.e., the intermediate efficiency, so as to reach the maximum power state (Odum, 2007). To be specific, in Fig. 2.5, a maximum output occurs at a trade-off point between speed and efficiency (Jørgensen et al., 2007). Let E_p denote potential energy of a heat reservoir, E_u be actual energy used to do work, and *dt* elapsed time to have the work done. Then, efficiency is given by E_u/E_p, and power (W) is E_u /dt. At the point 1 on the left diagram, $E_u = E_p$, so, the efficiency becomes 100%, however, since dt → ∞, and W → 0. At the point 2, conversely, the work is done very fast. But no useful work is delivered ($E_u = 0$), hence, W = 0 as well. In the reality, the torque (power)-speed (*rpm*; i.e., rate) curve of a car engine shows the power is maximized at around 3000 ~ 4000*rpm* that is half of the maximum speed. The speed is inversely proportional to gas consumption (i.e., efficiency).

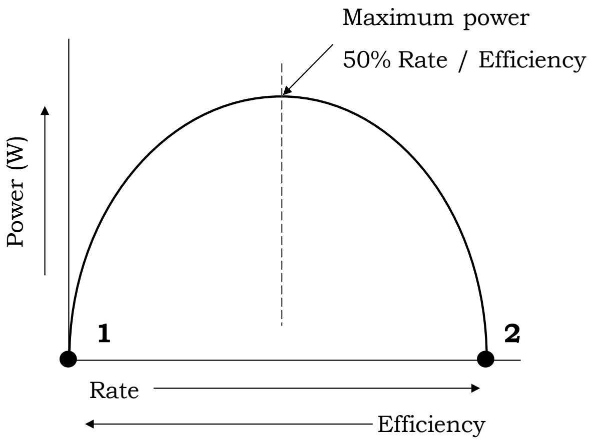

Fig. 2.5 Maximum power and efficiency

On the other hand, the MePP is mutually indispensible to the concept of self-organization, because the goal of self-organization is to facilitate maximized useful energy throughput.

In large built environment systems, particularly quasi-living systems such as cities or states, direct destinations and turnover time of feed-back loops of a network may not be observed in the reality. However, the self-organization towards maximum emergy flows identifies the invisible reinforcement (Odum, 1988; Lee et al., 2013). Previous studies successfully find spatio-temporal hierarchies of energy flows in cities, landscape, and regional systems (Odum et al., 1995; Huang, et al. 2001; Abel, 2010; Lee et al, 2013). As for building systems also, Braham (2012) mentions "buildings are tools in a vast evolutionary process of self-organization", and Braham and Yi (2014) substantiate that building production is a "formal cause[19]" of an energetic order of building components.

EmA, in fact, has been criticized from other environmental study disciplines mainly due to the uncertainty in the calculation of the global emergy baseline— annual total emergy input from the global sources to support the whole geobiosphere— and the specific emergy values. Ayres (1998) and Cleveland et al. (2000) doubt credibility of emergy models due to inaccuracy of emergy parameter values. To be specific, any particular EmA is measured relative to the emergy baseline, but the datum is quite uncertain. Odum (1996) gives 9.44 x 10^{24} *sej*/yr under the assumption that every source is independent, yet no one perfectly ensures that the three sources are not mutually dependent (Hau and Bakshi, 2004; Ulgiati et al., 2005)[20].

Moreover, if one were to strictly follow the emergy theorems, specific emergy values should be obtained case-by-case because even similar sorts of materials may not go through an identical process (Hau and Bakshi, 2004). It is, however, impossible to synthesize every different processing for every case of analysis and, consequently, EmA applies the same transformity for similar sorts of energy sources and matter. In spite of recent achievements for the baseline (Brown and Ulgiati, 2010), transformity data refinement (Brown and Buranakarn, 2003; Bastianoni et al., 2009), and uncertainty analysis (Campbell, 2003; Ingwersen, 2010; Hudson and Tilley, 2013), the questionable generalization on the baseline,

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[19] Ulanowicz, R.E., Ecology, the Ascendent Perspective, Columbia University Press, NewYork, NY, 1997.

[20] Intervention of the three sources (sun, tide, and geothermal heat) are considered in the maximum empower principle.

insufficient data collection, and lack of quality assurance are still major barriers to deter its wider application into various fields.

Nevertheless, building emergy analysis (BEmA) is a valuable tool for building sustainability assessment, because (i) Emergy provides a 'holistic' indicator (from the receiver-side perspective), particularly bridging a site-specific local system and global energy resource flows and depletion, and (ii) Emergy evaluates all natural (renewable) sources as limited source. Meillaud and his team (2005) first attempted to measure building emergy use with a small building case. Pulselli et al. (2007) comprehensively analyzed whole building emergy consumption for manufacturing and operation. Srinivasan et al. (2012) pioneered new definition of zero energy building based on the maximum energy feedback concept. BEmA methods are constantly being evolved. Recent studies include a new methodology for emergy simulation (Yi et al., 2014), comparison of emergy and life cycle assessment (LCA) methods (Srinivasan et al., 2014), development LCA-based building emergy indicators (Reza et al., 2014), and a case study for an off-grid house (Rothrock, 2014).

Meanwhile, emergy reveals clear limits on the investigation of internal system states. Odum (1988) argues that different system behavior depends on different operating mechanisms, but he argues that the prediction of system performance is enough with including combinations and availabilities of external sources. The strength of systematic power, however, can fluctuate with time while in the development towards maximizing empower. He suggests pulsing as a general pattern observed during a self-organizing process (Brown et al, 2004). It is difficult to precisely expect and evaluate of the magnitude of power oscillation, and the I/O-based measure remains a limitation of EmA, because it may aggregate the multivariate aspects of system complexity. On top of this context, current BEmA methodologies do not fully elucidate the following questions for more comprehensive environmental building research.

(A) Lack of a full spectrum of illustration on receivers' response and ability.

(A)-1 The same quality of material (the same UEV) can exist in various kinds of building forms and energy processing. Suppose two building of the same energetic quality with the same amount of emergy have different forms. The form affects the building energy use pattern in a different manner. Then, it remains questionable to answer how we evaluate the sustainability of building?

(A)-2 Lack of a threshold for drawing a system structure, and no focus on the strength of individual flow paths. For example, in an energy diagram, BEmA is descriptive of links between compartments. However, aggregation of multiple paths shows little or no difference in results. Provided a specific external environment change occurs, a code, like genes, to regulate a threshold and a preferred pattern of separate flow variation certainly exist in an embedded form of a receiver, but the emergy measure itself cannot detect it explicitly.

(B) Does it ‘really’ deal with energy quality?

Emergy is based on the concept of available energy, but does not directly calculate the actual maximum work depending on the surrounding temperature in which the energy flows are generated. In many cases of BEmA applications, e.g., consuming fuels for building operation, emergy is obtained by multiplication of given transformity and raw energy inflows, not exergy. Therefore, one may say BEmA does not accurately reflect thermodynamic irreversibility and energy loss during an energy transformation process (Zhou et al., 1996). This may also lead to domino-type uncertainty in all emergy-based decision-making.

2.2.1.2 Summary and comparison of single-criteria measures (SCMs)

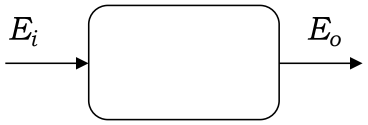
This section recaps the definition of SCMs and clarifies the difference and limit of each SCM by direct comparison. Technically, exergy is not a state variable, but it could be, since it is dependent on the system state change due to external conditions (Jørgensen, 1992; Zhou et al., 1996). So, if energy is “bookkeeper”, exergy is a “director” (Jørgensen, 1992).

Energy based analyses such as EA and ExA may discount the play of renewable energy and energy in small quantity (e.g., sunlight and human service). However, they are not free, and a service involving human body is a work of low quantity but high quality. Different quality of energy is acknowledged in ExA, but it only considers a narrow range of energy transformation (Odum, 1996).

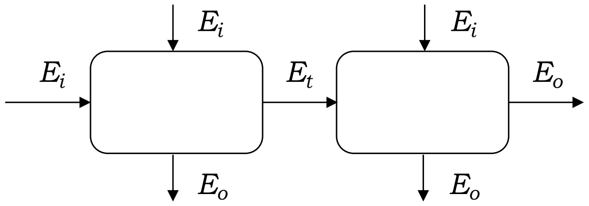
Table 2.1 Comparison of SCMs

Method	Target	limit capacity	Transfer dir.	Efficiency
EA	net change	●	x	E_o/E_i
ExA	net negentropy net 'useful' energy (internal potential)	●	●	Ex_o/Ex_i
EEA	net energy	●	x	$\Sigma E_o/\Sigma E_i$
EmA	energy 'flow', accumulation of net 'available' energy	●	●	EYR

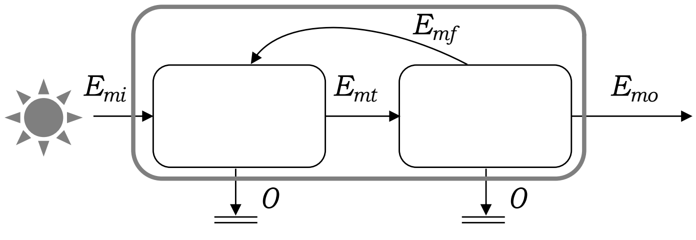
SCMs except for EmA neglect environment-supporting services that cannot be estimated in a common single unit (Zhang et al., 2010a). EmA overcomes such a problem, and highlight indirect impacts. Nonetheless, the point is, they all tend to assume buildings as static systems, i.e., the systems are degraded through linear-static processes.



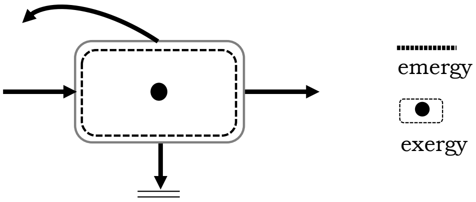
(a) Energy analysis (EA): $E_i = E_o$



(b) Embodied energy analysis (EEA): $E_i + E_t = E_o$



(c) Emergy analysis (EmA): $E_{mi} = E_{mt} = E_{mf} + E_{mo}$



(d) EmA vs ExA

Fig. 2.6 Comparison of extensive analytic methods (E: energy, E_m: emergy, i: input, o: output, t: transfer, f: feedback)

- EA and EEA focuses on the interchangeability of heat and work, and does not account for the energy quality.
- EmA primarily deals with ‘flow’ of energy as the Odum’s empower principle defines empower as the rate of emergy delivery, but exergy concerns with the energy ‘fluxes’ of internal states of a component in the presence of the external energy exchange.
- It is at the first transmission process (E_{mi}) that the rate of emergy inflow (empower) is measured to identify the maximum power principle (MPP). In the case of multiple first energy exchanges, each emergy output of which must be evaluated (Cai et al, 2004), because MPP takes all the energy directly supplied from the source into account (occasionally, but not too often, in a complex system, it is hard to identify every input point, thus, a total of dissipated energy is measured instead (Odum, 1996)).

2.2.1.3 Multi-criteria measures (MCMs)

MCMs employ a comprehensive set of indicators to illustrate system behavior. Reductionism is an effective way to map complex phenomena around a system-specific domain into a universally applicable causality which contributes to the analysts’ decision-making. But the problem is that the level of sophistication is limited due to its inherent top-down framework, and decisions based on a single objective as to selecting alternative processes may be misleading (Reed et al., 2005; Allen and Starr, 1982). In order to overcome the shortcoming, MCMs highlight to describe the diverse aspects of a system. Multi-criteria methodologies promote use of various individual indicators and interdisciplinary combination of the SCMs.

Life cycle Assessement (LCA) and hybrid indicators

In fact, LCA belongs to an intersectional area of SCMs and MCMs, depending on the evaluator's selection of energy delivery media and indices, since LCA focuses on scoping "phase"-based processes (generally, cradle-to-grave—i.e., production, use, and disposal), not development of a specified metric or an index. That is, life cycle of a building can be investigated with various terms such as physical energy units, monetary and cost units, or social effects based on the I/O analysis (Bekker, 1982).

LCA standards prescribe four steps for analysis, namely, goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. LCA targets an evaluation of full range of environmental impact during an industrial process, and it highlights both upstream and downstream impact (Raugei et al., 2014). The upstream impact is primarily assessed by life cycle energy analysis (LCEA) (Fay, 2000) that aims to accounts for all energy inputs invested at every stage, aggregating them using a single energy unit (Joule or Watt), whereas LCIA employs carbon dioxide (CO_2) equivalent to estimate all downstream waste (e.g., green house gas emission, water-borne pollutants, etc.). The two different directions are complementary to each other.

Even though the need of LCA is strongly underpinned by the stage-based chain of resource circulation, it is fundamentally based on the I-O analytical framework. So, industrial manufacturers can estimate consequence of decision-making, and LCA reports are used to improve environmental performance of the process such as reducing input sources, emission of pollutants and waste (Buranakarn, 1998).

Indication of each reductionist measure is inherently restricted to a system boundary and its unit bounds up with the sort of quantum of the processing flows (Fig. 2.6). Therefore, many studies attempt to synthesize and integrate SCMs with LCA, orchestrating the advantages of each SCM to fit specific objectives of evaluation. The multi-disciplinary compositions are developed to new MCMs frameworks and hybrid measures. Examples are emergy-based LCA (Ingwersen, 2011; Raugei et al., 2014; Reza et al., 2014) such as ECO-LCA (Zhang et al., 2010b), exergetic LCA (Cornelissen and Hirs, 1997) or LCA-based exergy based on the cumulative exergy consumption (CExC) (Liu et al., 2010), and Life cycle energy analysis (LCEA) (Cabeza et al., 2014).

Hau and Bakshi (2004) attempted to expand exergy analysis to include ecological processes. Ukidwe and Bakshi (2005) propose thermodynamic input-output (TIO) analysis as an extension of the traditional CExC approach so as to integrate ecological and human sectors with industrial processes. They used monetary flows and global exergy inputs as well as the EmA indices to deal with the comprehensive aspect of the economic-ecological-social (EES) system.

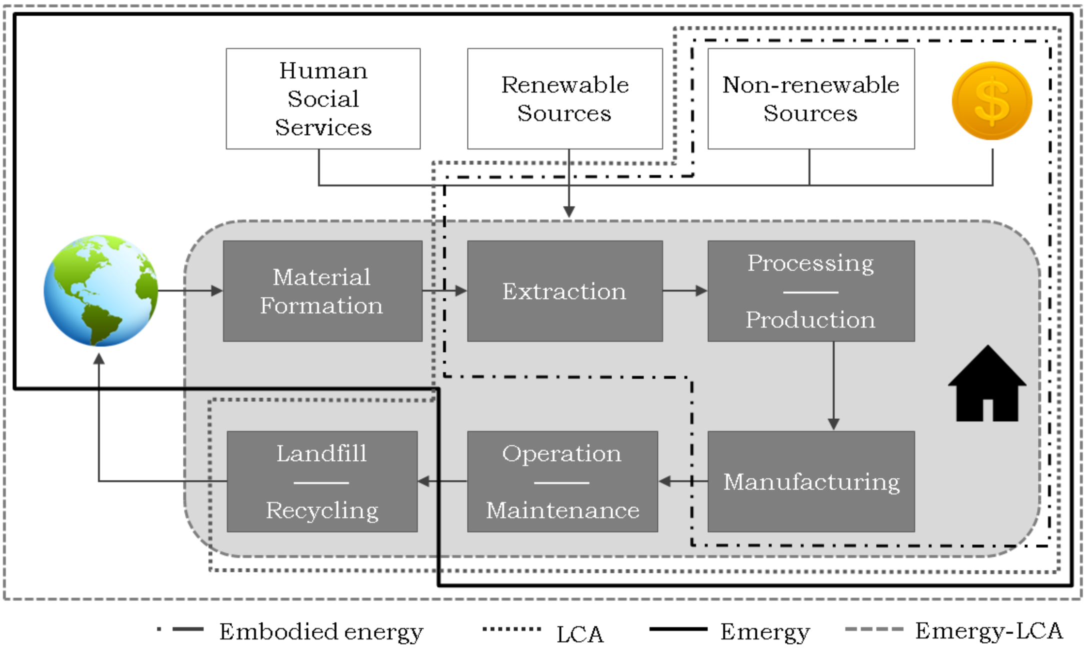


Fig. 2.7 The whole extensive process of the building system and the scopes of the reductionist methods based on the traditional concept of each SCM (EEA and LCA could include a renewable input but cannot evaluate the value as a limited environmental source.)

2.2.2 Intensive methods: System-based complexity measures

The methods and tools presented in Section 2.2.1 decode Eq. (2.1) in terms of the full reductionist and the quasi-reductionist perspectives. They employ aggregated indicators to measure depletion of material and energy resources, and evaluate the system efficiency based on the input-output framework. As an occasion arises, a building is sectioned off into the individual subset of elements such as structure materials, HVAC systems, glazing, interior furniture, and so forth. Then, a summation of the energy carriers accounts for the whole building system performance.

However, despite the wealth of knowledge from the reductionist tools on the overall building system performance, they do not provide much useful insight into the internal organization of and interactions between the individual elements, or the mutual relations between each phase of the building life cycle. Jørgensen (1992) points out that (i) “a direct overview of the many processes that work simultaneously is not possible, (ii) the interaction of all processes and components are contingent, and (iii) the conditions determined by the external factors keep changing.” Specifically, the building extensive measures primarily consider quantity of throughput of the energetic structure. The concept of exergy and emergy informs the qualitative aspects of energy equivalency and illustrates the hierarchical context of building energy use (direction of the flows from high quality to low quantity), but it does not render a clear vision as to how the system constituents are integrated to adjust capacity and efficiency. i.e., reductionist methodologies underestimate organizational complexity of the building systems internal structure, which is implicit, or even invisible, but clearly influential to the ability of energy intake and processing (Eq. (1)).

A building is more than a mechanical assembly. It is analogous to an organic body that cannot be fully described without investigation on the internal metabolism. As Grumbine (1994) finds that monitoring ecosystems metabolism should focus on (i) ecological boundaries, (ii) degree of integrity, (iii) local context, (iv) inter-agency cooperation, and (v) organizational change (Czech and Krausman, 1997), building analysis needs to explore new indicators to identify those factors.

Based on these backgrounds, methods and indicators for intensive analysis are from the system-based approach. Intensive measures concern the degree of system organization, opposing the reductionist claims. It is based on the modern systems theory, and aims at taking closer look at internal variations among systems, subsystems, and components. Intensive analysis has not yet been introduced to environmental building research, yet adaptation of information theory is not new in the literature. It has been studied earlier in the field of system ecology (synecology), and emerging in other disciplines such as urbanism, city planning, regional policy studies, environmental management, and economics.

The following subsections introduce the theoretical backgrounds and discuss applications to the ecosystem and other disciplines.

2.2.2.1 Information theory and Shannon index

Thermodynamic entropy and Boltzmann equation

Methodological development of the system-based complexity analysis that is currently used for a broad spectrum of interests is indebted to the rise of modern physics based on probability theories (especially, statistical mechanics and quantum theory). At first glance, physics seems to have little to do with other fields directly, but the revolutionary idea that a system state perceptible at human scale can be explained by the system's microscopic network is derived from physicists' persistent endeavor that opposes to the idea that heat is indestructible regardless of the system content.

The first attempt to quantify the inner state of a system was made by a group of theoretical physicists in the mid1800s. In explaining behaviors of mechanical systems in terms of the thermodynamic laws, what they noticed was that knowledge of the general thermodynamic properties (e.g. energy, pressure, temperature) of the system was not fully insightful to and not necessarily consistent with that of atomic-level attributes (e.g. molecular kinetics, chemical composition of a particle). This discrepancy had been noted earlier by D. Bernoulli and S. Carnot who had recognized that energy was a motion of granular particles, and vibration of the molecular structure generated heat (Brillouin, 1961).

It was clarified that the observation of macroscale properties that was explained by the Newtonian mechanics involved with a great deal of uncertainty in terms of the microstates of the system, and which served as an incentive that the classical mechanics was integrated with probability theorems.

In the course of the transitional moments, Ludwig von Boltzmann (1886) is the most responsible for describing the second law of thermodynamics, which applies to every state of the universe as a whole, in probabilistic accounts. Boltzmann thought the thermodynamic property of entropy could be approximated by the statistical measure of number of possible molecular or atomic states.

To be specific, if energy is the outcome of molecular vibration as supposed, there need a small part of total molecules to be active in a high-entropy system (i.e. a macrostate in large amount of unavailable energy). Accordingly, one may observe variety of discrete combinations of the individual particle to participate the given energetic state. In other words, a large number of micro thermodynamic states can be chosen under a macrostate.

For an equilibrium system, entropy (S) or Boltzmann entropy is defined as a logarithm of probable microstates, Ω;

$$S = k_b log\, \Omega \qquad (2.5)$$

where k_b is Boltzmann constant (1.38×10^{-23} J/K), and Ω denotes the number of cases of microstates corresponding to the macroscopic state of the system. Then, S is the entropy of a system thermodynamic state at a macro scale.

Compared to the Clausius's formulation(Eq. (2.2)), the above formula establishes an innovative way of measuring thermodynamic entropy. Eq. (2.5) can be rewritten in the classical form as,

$$S = -k_b log \frac{1}{\Omega} = -k_b \log P \tag{2.6}$$

Now, we obtain a clearer picture of the relationship between probability of macro states (*P*) and the macroscopic attribute of a system process (*S*). Based on this idea, entropy corresponds to a degree of variability or freedom of choice in a deterministic observation that can be finally compiled to balance of the internal complexity. For instance, if every system particle (quantum) is presumed to be available for heat generation, choice of the particle combination must be unique. Therefore, probability (P) to represent this state becomes 1, bring on minimum entropy (S=0), which is actually unprobable in the reality.

Meanwhile, it should be noted that this statistical entropy theorem was induced by Boltzmann's experimentation with ideal gas, and is premised on the independence of each particle. If particles interact one another, system states could be unpredictable from the combination of individual particles, because even a single particular combination can have a wide range of energetic states (Jørgensen, 1992).

Shannon information (Shannon index)

Harry Nyquist (1924) first demonstrated that a large source of communication inputs can be defined as the logarithm of the possible sequences of input signs. After him, Shannon (1948) developed the concept of information or information entropy to calculate the capacity of signal transmission in telegraph communication. The simplest system of delivering telegraphic messages consists of an information source producing messages, a receiver as a terminal, and a channel as the medium used to transmit signals (Shannon, 1948). This theory basically intends to identify how many bits are required for the signal delivery to a destination. Note that it has nothing to do with what the contents stand for. For example, when one sends a symbolic message such as ABA|ABA on 2-bit basis, he or she must set the limit of the capacity to not less than 64 bits (2^6) for proper operation in noiseless environment. If the first two characters (AB) were fixed, the capacity is reduced to 16 bits (2^4). Those results can be expressed in logarithm such that $6 = \log_2 64$ and $4 = \log_2 16$. One may easily notice that the form of expression is quite similar to that of the Boltzmann equation. If we let p_i denote the frequency of a target signal measured on the i-th of n channels, the information entropy (H) 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. This leads to Shannon's major theorems. Let's say we have several compartments (transmitter) within a simple flow graph, and then information entropy or Shannon index is given by:

$$H = k\left(p_1 log\frac{1}{p_1} + p_2 log\frac{1}{p_2} + \cdots + p_n log\frac{1}{p_n}\right) = -k\sum_{i=1}^{n} p_i log\,(p_i) \qquad (2.7)$$

where k is a positive constant that amounts to unit selection (it is usually set to be 1), n is the number of total channels. Negative sign means information is inversely proportional to the number of possible signal occurrence.

The general expression of Eq. (2.7) for continuous variables is[21]

$$H = -k\int p\,(x) \log p(x) dx \qquad (2.8)$$

For Shannon index, common bases are 2 and e, or sometimes 10, and the selection of the bases does not critically affect the information value. When 2 is used for the logarithm, the unit of information is *bit* (binary digits). When 10 is used, then it is termed *dit* (decimal digits; Shannon, 1948) or *hartley*. For the natural logarithm, the unit information is called *nit* (natural unit) or *nat*.

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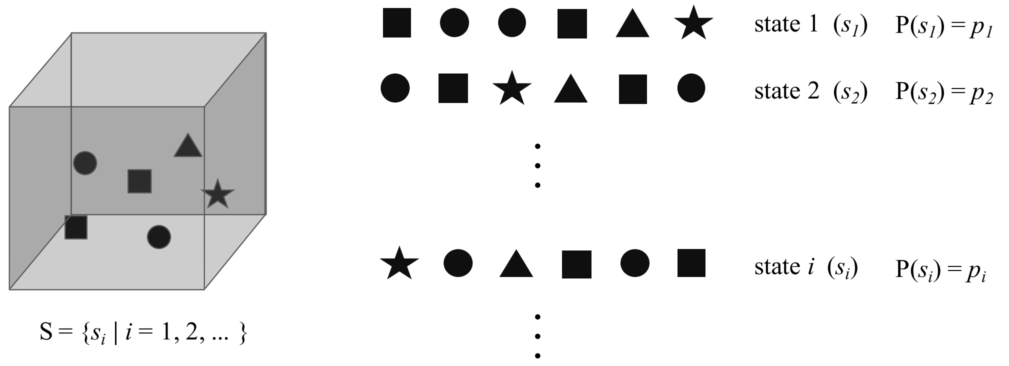
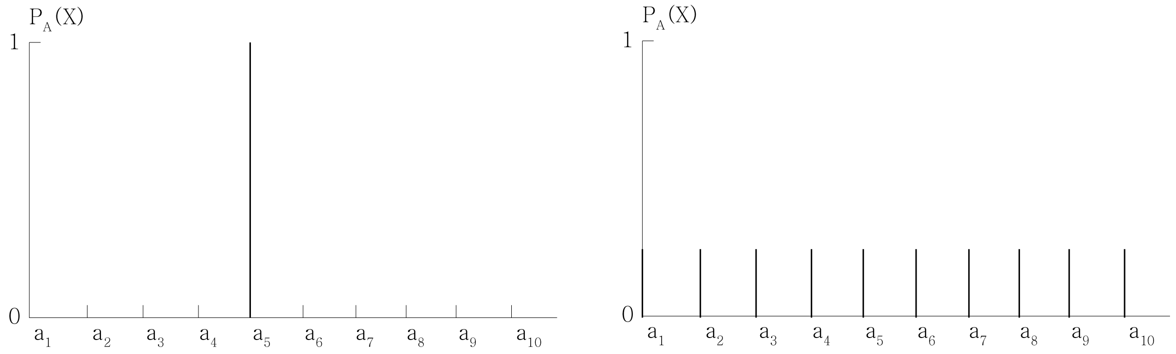
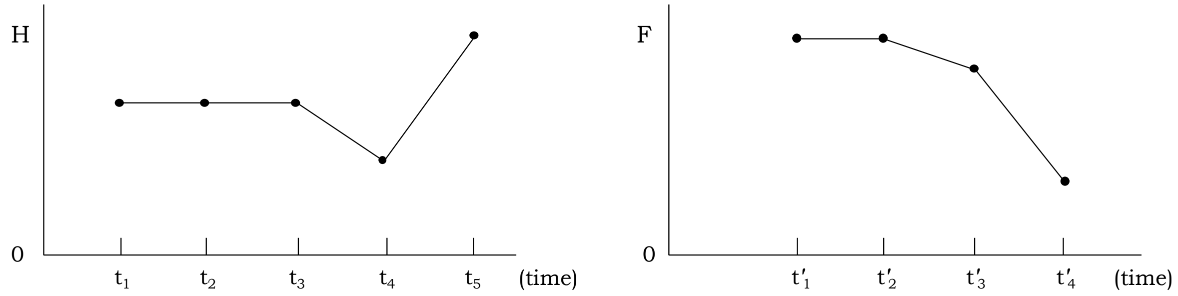
[21] However, the continuous form cannot be directrly derived from passing the discrete expression (Eq (2.7)) to the limit. (see Appedices)



(a) Concept of information entropy



(b) Shannon information becomes zero (left), and reaches the maximum (right)



(c) Hypothetical profile of Fisher information variation given Shannon information (left) for a time-series dataset

Fig. 2.8 Concept of Shannon information and Fisher information

2.2.2.2 Kullback–Leibler information

Kullback-Leibler information (KL-divergence; D_{KL}) is also called relative entropy or information gain. It evaluates the extra 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 a degree of uncertainty in the approximation of P given a prior distribution Q. The following equation computes the KL divergence:

$$D_{KL}(p||q) = \sum_i p(x)\, log \frac{p(x)}{q(x)} = H(P, Q) - \ H(P) \qquad (2.9)$$

2.2.2.3 Fisher information: A local index of system behavior

MacArthur (1955) introduced information theory to ecology. Replacing p_i of Eq. (2.7) with a fraction of species number in an ecological web, he used Shannon information as a stability indicator of a trophic structure.

Shannon information successfully aggregates a degree of 'equitability' and 'variety' of a given data set into one index (Odum, 1969). However, the matter is, it does not depend on the sequence of the data collection (e.g. in Fig 2.7 (a), the order of the individual distributions has nothing to do with the final value. Switching a_5 and a_6, to make $P(a_5) = 0$ and $P(a_6) = 1$, ends up with none of information content as one expected), because the Shannon index finds its purpose in representation of 'average' indeterminacy (degree of freedom) of a unit medium of a system in a certain state. It follows that it cannot account for the variation of ordering of system components (Fath et al, 2003; Eason and Cabezas, 2012). If attribute and order of compartments are constant, it will always give the same information regardless of the ordering. In the case of which we could ensure that any variables do not counteract one another, emphsizing the averaged aspect of a particular system observation (for this reason, Brian D. Fath and his team (Fath et al., 2003) assert to call Shannon index a "global" property of a system), in a way, is advantageous especially in terms of its capability of measuring information changes that are not affected by adjustment of data arrangement.

However, real ecosystems tend to move away from equilibrium during developmental stages. In the course of the movement, external purturbations agitate, either radically or moderately, an organization of the system so that it is occasionally driven into an unexpected extraordinary state. Such transition is occurring through time— a universal independent variable, and, therefore, Shannon information that is a static measure does not help studies whose focus is on the unusual paradigm shifts of a system.

For that matter, in an effort to monitor sequential variations of system components in a dynamic manner, an alternative indicator[22], Fisher information, is employed to detect the re-ordering of an internal organization without change of probability values.

Fisher-information

Fisher information (named after the statistician Ronald Fisher) is defined as the variance of the expected values of observed distributions. Mathematically, from Eq. (2.7), if the parameter θ is non-random, Fisher-information is formulated as,

$$F(X|\theta) = \int_X \frac{1}{p(x|\theta)} [\frac{\partial}{\partial \theta} p(x|\theta)]^2 \, dx \qquad (2.9)$$

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

If the probability of the prototypical trial *X*, $p(x)$, varies with a certain regularity organized by the parameter of interest θ. This is not a function of a particular observation, but implies a continuous description of dynamic system behaviors.

Suppose one seeks to track of regime (state) changes with the strength quantified. In this case, the system variable *x* that characterizes system states can be imposed over a time-based system trajectory. Let the trajectory be a vector *S*. Subdividing the path into several segments so that each includes major transformation of microstate changes, we represent *S* as a set of segment vectors i.e., $S = \{ s_1, s_2, \ldots, s_i, \ldots \}$. Now, the system variables (x_i) can be grouped to occupy a state of a certain time period (s_i), and, then, the independent system variable of Fisher information is substituted with the state variable *s*. This process turns the original form (Eq. (2.9)) into a new formula as below,

$$F(s) = \int_S [\frac{d}{ds} p(s)]^2 \frac{ds}{p(s)} \qquad (2.10)$$

which substituting $p(x)$ with $p(s)$ yields the likelihood that one observes the system being

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[22] Another information indicator is Gini-simpson information, $G = 1 - \sum_{i=1}^{n} (p_i)^2$,which is unpopular, and has not yet been introduced to environmental study. Similar to Shannon index, it also sets limit on detection of global system change.

in a particular state s. Notice that Eq. (2.10) uses the derivative term *dp(s)/ds*, which means Fisher information is proportional to the rate of distribution change. If the system stays longer within a particular state, Fisher information goes up for that period of time. Therefore, it follows that Fisher information is a measure of '*invariability*' of local system states (Karunanithi et al., 2008). Meanwhile, for practical applications, it is necessary to transform Eq. (2.10) into an expression for discrete variables because most natural phenomena are discretely perceived.

It is important to distinguish what Shannon and Fisher information mean to measure respectively in terms of the theoretical implication as well as practical purpose. Suppose the shape of the density function $p(s)$ is flat, then the overall system state is extremely unstable. Accordingly, information required to identify individual states is huge, and the Shannon index should be the maximum. However, what about Fisher information? *dp(s)/ds* approaches zero, and, therefore, nothing is given to Fisher information. What do these results imply?

As discussed earlier, system organizations keep changing, whether it is on a small or large scale, and the order and pattern of the change always occurs on a time basis. At this point, Shannon information attempts to describe the status quo from the macroscopic viewpoint, just as statistical entropy (Eq. (2.5)) defines the energy systems. Accordingly, Shannon information is effective to examining how distant the observed state of the system is away from equilibrium (maximum entropy). Fisher information concerns the history of the state variation within the observed range of time. Shannon index could be time-sensitive by tracing a sequence of numerical quantities distributed on a time axis, but Fisher information basically always requires time-series data.

Shannon and Fisher information are not opposed to each other, but illuminate different sides of the same event for different questions. Shannon index tends to be associated with the concept of homogeneity, diversity, or capacity, whereas Fisher information is used as an indicator of regime change (Fath et al., 2003), of the system moving away from usual fluctuation, and it quantifies the degree of vulnerability and the homeostasis of the organization.

2.3 Information entropy, thermodynamics, and applications to environmental studies

Boltzmann linked the entropy of mechanical systems with stochastic configuration of the internal states (Section 1.2.3 and 2.2.2.1), entropy is the central concept in the development of statistical mechanics and it also has been understood as an iconic name of the network complexity measure.

As soon as Shannon generalized entropy under the context of communication (Shannon, 1948; Tribus and McIrvine, 1971), non-physicists became aware of its universal applicability. Simultaneously, inspired by thermodynamic laws, the measure of entropy and energy degradation spread widely to characterize various processes of multiscale systems (e.g. geographical, social, economical, and biological systems) far beyond the investigation of mechanical systems. Using thermodynamic accounts, we are capable of explicating the energetic states of a system that are indeed segmented according to our interest from nature; thus it does not seem strange that different areas of study have implemented it to identify systematic problems of their own fields.

However, the bottom line is that entropy is meant to be a thermodynamic term that is consistent with the classic mechanics (In this dissertation, *entropy* only refers to thermodynamic entropy of Clausius and Boltzmann. Use of *information entropy* is restricted to refer to the indices derived from the Shannon index or Fisher information for the clarity of terminology use). Accordingly, we need to draw a sharp line between the metaphorical adaptation and applications from the genuine definition of entropy to avoid intellectual confusion, since it is too often employed indiscreetly, and occasionally abused to some extent in various contexts and research fields of different culture. Even if the law of entropy must be self-evident in all disciplines, expanding the use of the term outside the scientific terrain without delving into the thermodynamic postulates and empirical evidences risk lending itself to misinterpretations. The relationship between information entropy and entropy is still open to debate. Nevertheless, as Jørgensen(1992) asserts, information entropy and thermodynamic entropy are seemingly analoguous but not the same, it is certain that information entropy is not exactly the same as that of thermodynamics for chemical reaction, microscopic free-energy change, molecular binding, etc[23]. Therefore, critical scrutiny should be given to ambiguous and misleading distinction about (1) information (entropy) and (thermodynamic) entropy, and (2) entropy and disorder. It is because the concept of entropy and its theorem are

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[23] Warning about the popularity of information theory beyond communication problems, Shannon highlights that "the hard core of information theory is, essentially, a branch of mathematics, a strictly deductive system (Shannon, 1956)." His apprehension is also shared by Chapman (1970)'s statement that "without a temperature constant entropy in information theory defines a property of an equation and not the inevitable state of a closed thermodynamic system (Ayeni, 1976)."

adapted in different fields with different models for which they are designed. The following sections clarify the definitions that can invoke constructive discourse of building sustainability. To this end, along with a review on previous studies, applications of information and entropy are examined for the development of the methodology in this dissertation.

2.3.1 Information entropy and thermodynamics

The technical definition of information based on entropy has been organized since the anthropocentric interaction of a system mechanism began to draw the modern system theorists' attention. Based on the fact that every system process is connected to the outside world[24], information can be conceptualized as "a measurable but invisible body corresponding to the outside context" that is transferred through system processing to maintain a desired mechanism (whether or not it is deterministic or self-governing). In this sense, Wiener(1948) enunciated information becames "time-dependent" and shapes a "vital structure." In the way that the information content flows along substantial network paths, its behavior is similar to quantum of energy and matter (Fig. 2.8). However, recalling that the external intelligence provided for the system adjusts the distribution of energy and matter, it is appropriate to regard information as a more generic concept than other two elements. And at this point, information tends to be analoguous to thermodynamic entropy in such a way that both are the index of probability assignment of matter and energy. Meanwhile, as explained in Section 1.2.3, information has double nature in interpretation: (i) any form of knowledge delivered to a system (e.g. human language, signal, numeric data, genetic code, etc.) and (ii) a measure of network complexity based on mathematical reductivism. However, this differentiation may not be contradictory or dissimilar in the context of system evaluation, because the system analysts aimed at integrating mechanical systems with human intelligence by quantification of information content. Wiener was aware of this problem, and he embraced the different implications in a single definition of information[25], (i) "the knowledge of all positions and momentum at any moment" and (ii) "the number of decisions to be made for system processing (Wiener, 1948)" for the semantic definition. His idea is supported by the

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[24] Note that measure of thermodynamic entropy is applied to the analysis of both isolated and non-isolated systems, but information is always premise the system being under study is open.

[25] http://www.informationphilosopher.com/solutions/scientists/brillouin

Ulanowicz’s statement that information is “anything that constraints the system elements so as to change their probability assignments (Ulanowicz, 1997).” Either way, this framing identifies information as an extension of thermodynamic entropy in similar situations (Wiener, 1948). However, campaigns of information theory associated with entropy cannot be undoubtedly justified because Boltzmann entropy is a measure of atomic organization of ‘energy’ which is directly germane to the classical thermodynamic laws. On the other hand, information entropy that incorporates any kinds of media in its formulation may not strictly follow the law of entropy. Thus, in this light, Jaynes (1957) mentions that thermodynamic entropy is a subset of information entropy (Fig. 2.9).

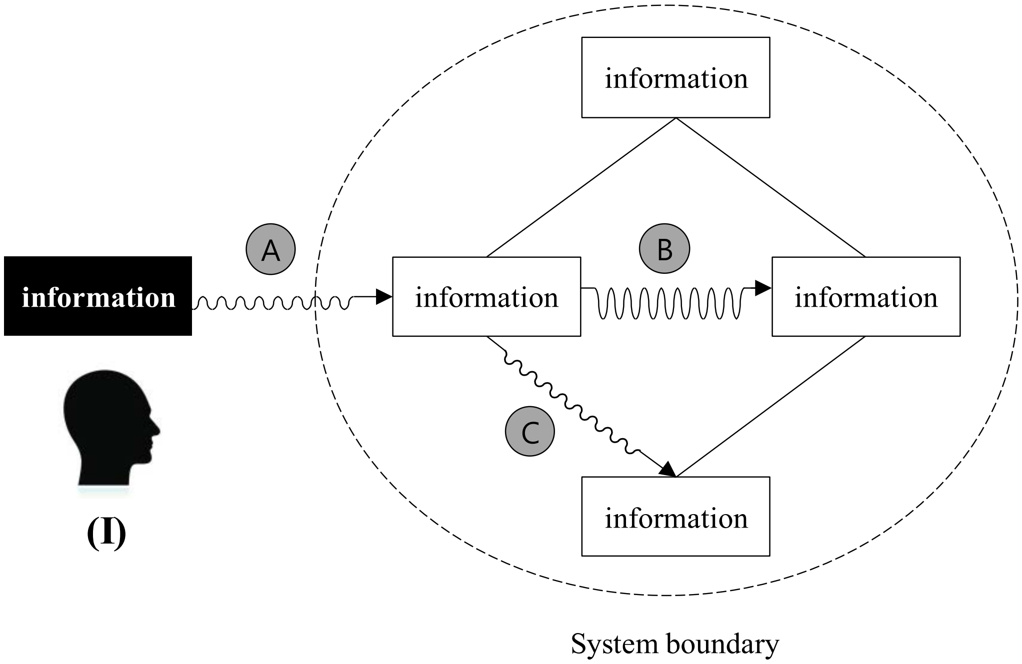
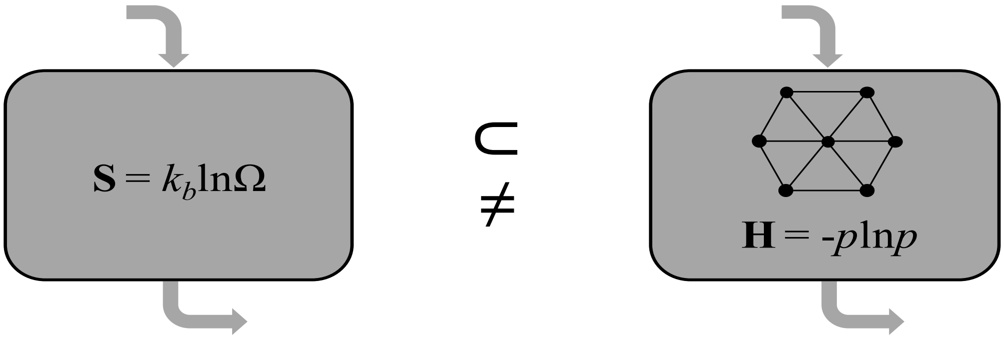


Fig. 2.9 Transformation of the semantic level of information (knowledge) into the syntactic structure: External information (***I***) is transmitted into the system’s internal network whose subcomponents, likewise, consists of energy, matter, and information. The external information is delivered through some of the network channels in a direct manner (B,C). While in transfer, information does not spread homogenously. The information content can be augmented (B) or even faded. As a result, it induces (1) internal resonance of the system structure (2) a set of network instances. Any of which could be an object of analyst’s measurement, namely, evaluation of semantic information content dissolved in the structure of the system network.



(a) system's thermodynamic state (b) system's network state

Fig. 2.10 Intent and limit of the analogy in quantification: Information entropy (H) could be understood as a generalization of the notion of thermodynamic entropy (S). However, during this remarkable moment of analogical transition, the measure of information entropy is away from the direct link with thermodynamic principles.

Wiener's first categorization deals with the methodology of quantifying information. It implies that any external signal acts as a stimulus to affect change in the system's internal organization to some degree. For example, let's say a driver is going to accelerate a car. He or she would step on the gas pedal, and the pressure applied to the pedal switches on the spark, and the driving power generated from the engine is transmitted through the gearbox and shafts to the wheels. Elements of the vehicle driving system operate selectively, which changes the configuration of the organization of active components. The driver does not touch any of internal elements other than the accelerator, and does not know any details of the principle of motion. However, the whole system has been manipulated at will by introduction of the information the driver possesses. Therefore, this case can be generalized to suggest that variations of system networking are a surrogate of human knowledge (information) that the system obtains.

The second categorization is more directly related to measurement techniques. However, as Batty (1974) points out, there are two different theoretical roots that confuse the choice of information measurement. One originates in Shannon's theory (1948) and another derives from the idea of Wiener (1948) and Brillouin (1961). It is a common ground that both understand information as the number of observer's decisions (particularly, that of binary choice) regarding system manipulation, but the derivation process and implication are quite different. First, as seen in Eq. (2.6) and (2.7), the main fuel that connects entropy to information theory is the similarity of the formulaic expression. Shannon's equation describes nothing more than a degree of the unpredictability of data. Nevertheless, he insisted on calling information entropy, and definitely suggested the index of uncertainty as a measure of information. However, note again that the focus of the Shannon index is different from entropy in physics. Misinterpretation primarly lies in the translation of entropy (S) to the carrying capacity of signal (H). It could be employed to measure entropic phenomena, but has no direct implications for thermodynamic actions (Fig. 2.9). In other words, information entropy is a mathematical expression that was developed to describe non-thermodynamic content. As a result, information entropy has no absolute reference value. (it be indexed to *H* maximized, but it is not invariable.) However, thermodynamic entropy is always estimated from the reference state (S_0) of absolute zero ($T = 0K$), where entropy becomes zero ($S_0=0$).[26] Therefore, empirical justification is required when information entropy is applied to represent the states of a system, even though any system in the universe must be under the law of entropy.

In this context, Thims (2012) argues that Shannon-based thermodynamic "campaign" —information entropy— has nothing to do with entropy, and that information entropy does not correlate rigorously to thermodynamic issues, thereby conclusively suggesting to call Shannon index (H) "*bitropy*" (Thims, 2012). Jørgensen (1992) insists it must be flawed if *H* is interpreted as the actual information we have. He states that *H* is an amount of information that needs to be acquired to fully identify the microstates of a system.[27] Meanwhile, the calibration of information proposed by Wiener and Brillouin is more related to the interpretation of biological communication processes in the context of a mechanical automation, i.e., estimation of man's knowledge supplied to activate the system operation (one can notice that this is the method of quantification directly motivated by the Wiener's first categorization of the information definition). To this end, Brillouin (1949), who first infused Wiener's cybernetics into physics, attempted to generalize the principle of irreversibility and entropy increase to the process of (human) 'thought'. He assumed, in a system process, a change of entropy corresponds to that of information (e.g. observer's input of light beam to investigate a dark object changes its quantum structure, i.e., chage of entropy(*S*)), and finally argued that it is "negentropy", the negative of entropy, which is

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[26] So, in fact, **Eq. (2.5)** implies the expansion including the reference state such that $\boldsymbol{S} = S - S_0 = S - 0 = k_b log\, \Omega - k_b log\, 1$

[27] A study argues that inclusion of time is the critical difference between entropy and information entropy (https://sites.google.com/site/markovchainuniverse/understanding-information-and-thermodynamics/information-entropy-vs-thermodynamic-entropy. Accessed September 18, 2014)

translated to the ability to produce work, which represents information. For this formulation, information (I) can be written as,

$$I_B = NE = S_1 - S_2 = -\Delta S \qquad (2.11)$$

where *NE* denotes negentropy, S_2 is entropy of the observed state, S_1 is entropy of the reference state, and ΔS is total entropy change. In the Brillouin's theorem, there are two points that claim our attention. First, he expanded entropy to the notion of the "value" of other phenomena, and, no matter what the content is, the value is determined relative to the surrounding conditions, as heat of the same quantity has different entropy according to the ambient temperature. Second, unlike Shannon information, Brillouin information (Eq. (2.11)) presumes entropy of a certain state (S_2) degenerates from a reference state entropy (S_1). In this case, the reference state is not necessarily absolute zero. S_1 can be an initial entropy before observation. Because of the two features, Brillouin's negentropy theorem is far more consistent with the physical and thermodynamic principles than the Shannon index. He addresses the fact that every observation consumes information with coupling of a man and observations in a physical experiment. If a man observes a stem that transits from state 1 to state 2, the observer must invest knowledge to identify a system state into the system. The knowledge is an energetic work of the brain in useful work. Therefore, information supplied by the observer to read the observed system is negentropy, in other word, negentropy must be inputted to extract useful data (information) from a system under study. As a complex system require a large amount of information, information becomes a complexity measure[28].

This progressive idea influenced researchers of other fields (Marchand, 1970; Landauer, 1991; Jørgensen, 1992), particularly a group of ecologists who dealt with information in terms of accumulation of genetic data. To integrate the Brillouin's idea with the Shannon index, they set a reference as an equally probable state which is analogous to thermodynamic equilibrium. Then, observed information entropy is counted from the reference, which gives a new definition of information using Shannon index. This is given by

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[28] For example, think of a paper with full of a single letter 'A' and a newspaper article. Suppose a man would read them. Which one requires less time to read? (not understanding) Absolutely, the former. This indicates that the work with complicated words, which actually tends to deliver much more information contents to the reader, needs far more knowledge to read—higher level of information.

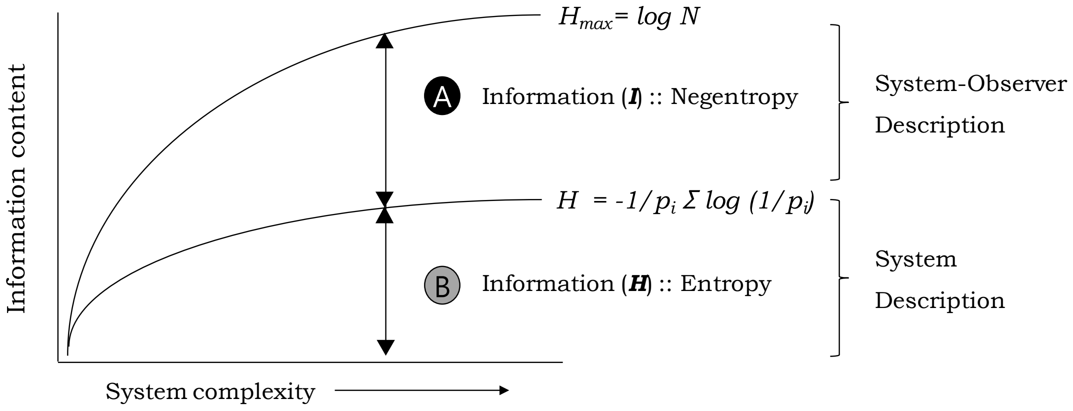
$$I = H_{max} - H \tag{2.12}$$

where **I** is (obtained) information, H_{max} is maximum Shannon index, and H is observed Shannon index. H_{max} is always greater than H. This equation indicates that an entropy increase (increase of Shannon index, H) results in a loss of information (**I**).

In this equation, the formulaic similarity strongly implies that an observer's information gain corresponds to relative entropy (KL-divergence). Thus, **I** is a potential measure of information gain which becomes a possession of the observer immediately after observation. In other words, it can be understood in a way that **I** (and $\boldsymbol{I_B}$) is the knowledge of how much the observed system is structured, namely, degree of organization. In contrast, Shannon information (**H**) can be referred to as the description of unstructured parts (Fig. 2.10).

Compared to Eq. (2.11), Eq. (2.12) is still flawed because of the equivalence of the Shannon index (H) and thermodynamic microstates (S).[29] Nevertheless, many studies following Brillouin's approach name information as **I**, and adopt **H** as system entropy. The reversed relation is used to characterize the relationship of information and entropy (Marchand, 1972; Jørgensen, 1992; Balocco and Grazzini, 2006).

Note that **H** and **F** are descriptions of the system itself. Information quantifies various aspects of complexity. Moreover, in the semantic sense that man's knowledge is related to something that we know, it is more natural to call the information measure estimated from Eq. (2.12) information. **H** and **F** are more appropriate to describe the system's unstructured instance.



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[29] Layzer (1976), Books et al. (1989), and Jørgensen (1992) state that H corresponds to entropy of the ecosystem.

Fig. 2.11 Definition of information and two types of information content

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

2.3.2 Entropy, order, and disorder

The popular conception that “entropy is a measure of disorder” may be correct in special cases of physics or chemistry, but must not be generally accepted for all cases (Leff, 2012; Martyushev, 2013). It may be due to no single definition as to what is ordered and how much strongly it is ordered. Depending on the subject of interest, order can refer to spatial regularity, systematic arrangement of a structure, a specified orientation of the arrangement, or a high density of substances, frequency in occurrence of an event with time. Distinction between order and disorder may also depend on whether a system is opened or closed. Previous research provides two interesting examples to break commonality of order and disorder, particularly with respect to spatial order and order of self-organization.

First, if disorder means rupture, falling apart of spatial structure, all rusting process should accompany an increase of entropy. But Leff (2012) shows that oxidization of metal decreases entropy (4Fe + 3O2 → 2Fe3O3; $\Delta S = -0.5$kJ/K) while increasing the surrounding entropy to 5.7kJ/K.

Second, according to the common sense based on theory of evolution, organisms such as plants and animals are a more ordered system, a result of the self-organizing mechanisms and low entropy than inanimate bodies. However, Martyushev (2013) shows that entropy of an animate body can be both higher and lower than inorganic substances (S_{wood} = 2.8kJ/K, S_{silica} = 0.7kJ/K, S_{air} = 6.8kJ/K).

In principle, as Clausius’s formula (Eq. (2)) indicates, entropy is essentially related with the energetic status of a system. Most, yet not all, stable energy systems have ordered spatial structures and orientations to preserve stored energy against frictional forces, but those observed phenomena are merely byproducts of atomic reactions and exchanges of the energy quanta within a certain timeframe during a system lifecycle. More correctly, Leff (2012) defines entropy as a “distribution of energy over system’s volume” and “spreading over accessible microstates” (Leff, 2012). He correspondingly argues that entropy is a measure of uncertainty of energy states. This is consistent with Boltzmann's idea and Odum's statement that defines disorder as spatial dispersal of "energy" (Odum, 1971).

However, if an observed system is not isolated (i.e. allowing heat exchange with the external environment), and regulated by an innate genetic mechanism, the uncertainty of an ordering process may or may not go through a local decrease at a certain moment depending on the mechanism. Therefore, a trend of entropy 'change', rather than entropy value itself, must be examined throughout the system development. It should be noted, at this moment, that entropy change does not depend on quantity of energy potential but does on the amount of heat transfer. Energy influx itself may not be conducive to maintenance of a low entropy level, for the arrangement of quanta can cause a chaotic state due to introduction of new quanta (similar to turbulence generation when two flows converge). i.e., in order to decrease entropy, energy quantum must be concentrated.

In a nutshell, we may continue to use entropy for environmental study not as a measure of disorder, only as a measure of '*energetic disorder*'. Meanwhile, if one seeks to identify the global disorder of a system, the whole ordering cycle must be explored with measurement of entropy change. Then, the object of the measurement should pertain to the *distribution of energy quantum positions*.

CHAPTER 3

THERMODYNAMIC METABOLISM OF BUILDING SYSTEM AND NETWORK ANALYSIS

Glossary

- **H** (bits): Shannon index; a degree of uncertainty in the distribution of resources; the diversity of resource flows per individual; the complexity of network flow pattern; the proxy of the potential power of energy network organization.
- **AMI** (bits): Average mutual information per individual; a portion of efficient resource transfer; a degree of order in the network organization.
- **L** (bits): A degree of redundancy (or disorder) per individual; a degree of freedom in the selection of flow pathways; system resilience (L = H – AMI); the proxy of system's self-organizing potential.
- **C**: System capacity (Ulanowicz, 1986); C = H·T (system size).
- **A**: System ascendency (Ulanowicz, 1986); A = AMI·T (system size).
- ϕ: System overhead (Ulanowicz, 1986); $\phi = C - A$.
- **F**: Fitness (Ulanowicz, 1986); a degree of adaptability; the logarithm of the ratio of AMI (A) to H (C).
- **R**: Robustness (Ulanowicz, 1986); R = F·T (system size).

This chapter addresses a system-level perspective and tools of environmental performance evaluation that are new to building sustainability. Ecosystems principles are hypothesized to work at the building system level for material selection and organization of a specific formal pattern. For the specification of buildings systematic behavior in the next chapter, a generic model of the transport of environmental resources is presented at the system level with an application of the fundamental principles of the ecological development, before it is considered for the indication of sustainability. Section 3.1 introduces a system-networking concept of sustainability with thermodynamic accounts, in an effort to reveal a new dimension of building sustainability. Section 3.2 presents a schematic building network model and thermodynamic ecosystems principles that are applicable to the new definition of building sustainability. Section 3.3 introduces mathematical definitions of information-based ecosystem indices. Pilot experiments are conducted to identify applicability of ecosystems principles to building with establishment of a generic building system model. Findings from the tests provide a rational for the use of information as a new building performance indicator.

3.1 "A world of two metabolism" and global sustainability

McDonough and Braungart (2002) recognize that our planet is sustained largely by two kinds of energy source cycles; namely, the cycle of (i) technical and (ii) biological nutrients. The technical nutrients are the inflows of matter and operational energy that support our *technosphere* — man-made technology-driven environment to which built environment belongs, and the biological nutrients feed natural environment. Each of which consists of own metabolic flows of physical substances, but the conclusion is that those two are not indifferent. The technical nutrients of our civilization are in fact entirely obtained from nature.

McDonough and Braungart assert that cradle-to-cradle (C2C) recycling of technical (abiotic) products helps promote ecologically efficient environment, and eventually enhances the state of global sustainability. As mentioned in Section 1.3.1, the C2C idea is congruent with Peacock's mutual symbiosis concept, but more useful in a way that suggests a clearer configuration of the ecosystem design. C2C points out that the earth is a self-contained ecosystem through recycling of biological substances, but men's poor understanding of the cycling has worsen the negative environmental pressure.

A general life cycle of an industrial product from the prevailing life-boat model can be schematized as in Fig. 3.1 (a) and (b). In this extensive energy transport process without recycling, environmental resources are simply thrown away as waste in the long run. To prevent the depletion, one may recycle, reclaim, or reuse the resources in part or whole in the middle of the process, and then believe that the recycling is closer to sustainability.

However, C2C identifies the blind spot of this process. As a manufactured product is recycled, the quality of usability decreases, and accumulated emission of pollutant aggravates environmental health of our planet. As far as the recycling loop is opened, it is eventually depreciated, and, during the cycling, our environment becomes increasingly degraded (Fig. 3.1 (b)). McDonough names this vicious circle "downcycling".

Therefore, to maximize the full advantage of recycling, the recycling loop must be closed with the tight connection of the biological and technical metabolism.[30] At a glance, the closing is not feasible, because any transport process of an industrial material always comes with an entropy increase, and, technically, a return to the same state is impossible. Nevertheless, notice that solar energy is plentiful enough to transform effluxes of hazardous disposal to useful natural sources. Ideally, at the end-of-life stages of the material, it can be disassembled into biological and technological nutrient. The biological constituent can be decomposed and become provision for plants and animals. Technical waste can supply high-quality raw materials of other industrial products. This metabolic coupling characterizes a virtuous cycle (*upcycling*) of an environmental system that leads to sustenance of high-quality, and the goal of sustainability is to maximize the nutrient flows[31] (McDonough and Braungart, 2002).

This new paradigm of sustainability based on a positive symbiosis has been mentioned earlier by E.P. Odum, who said, “Mutualism seems to replace parasitism as ecosystems evolve towards maturity (Odum, 1983)”. So, that nutrient flows of the building are influxes of useful energy in terms of thermodynamics is in parallel with the ecologist’s recognition. Therefore, a tendency of increasing nutrients through a closed-loop recycling could be consistent with the maximum power principle of autocatalytic ecosystem development which will be discussed in Section 3.3.

However, our built environment is neither perfectly open nor fully closed-loop. It is being settled in the middle of them. So, an integrated model of being mutually closed for biological and industrial cycle renders a clear description of how environmental building design actually develops (Fig. 3.1. (c)).

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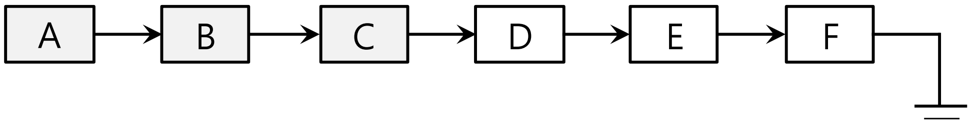
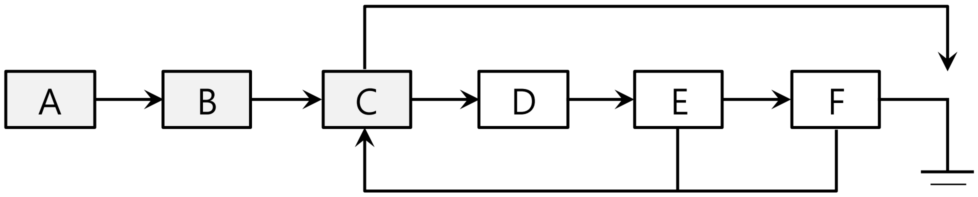
[30] The definitions of the terms to describe the recycling processes vary from one author to another. The Global Development Research Center (GDRC), McDonough and Braungart (2002), and Yuan et al. (2011) use “closed”-loop recycling to refer to potential transformation of a particular mass of material into a different type of product, whereas the same characteristic of a system is termed “open”-loop recycling by US Environmental Protection Agency (EPA) and Lacarrière et al. (2015). This difference comes from which the former authors focus on overall shape of a recycling chain, but the latter focus more on the size of a potential production domain on which the material is recycled.

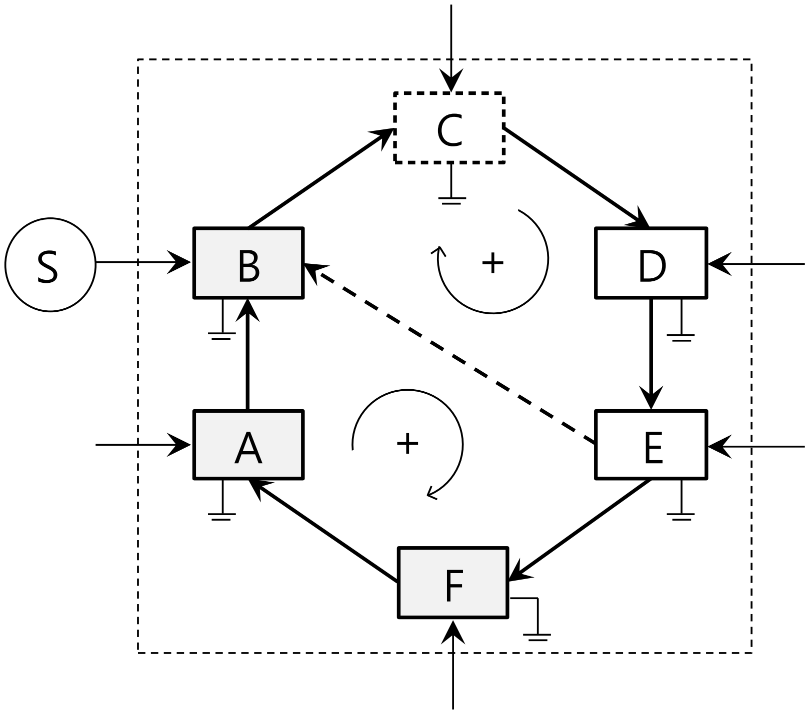
[31] Bekker (1982) provides an illustration of upcycling in a nationwide system. According to his estimation, buildings in Netherlands dispose one million tons of wood annually to demolition. If two thirds of this waste were properly treated (collection, separation, and chipping), it could amount to be a source of all kilns of the whole brick and tile industry and also suffice to heat 125,000 dwellings. The different pattern of house conditioning and material production would create new jobs and increase household income, while saving around 300 million cubic meters per annum of natural gas.



(a) Parasitism (life-boat model): no recycling



(b) Parasitism (life-boat model): open-loop recycling



(c) Mutualism: closed-loop recycling

Fig. 3.1 Conceptual representation of sustainability models (A: material formation, B: social/industrial source, C: manufacturing/production, D: use/operation, E: waste disposal, F: decomposition and generation); B-C-D-E : technical metabolism, F-A-B : biological metabolism, S: source energy (solar, tidal, and geothermal heat)): Energy/material stock is easy to observe but changes at a slow pace. Flows are relatively harder to quantify but more effective to characterize system dynamics and sustainability due to its suddenness of variation and higher sensitivity to the environmental change.

3.2 Global thermodynamic principles of the analysis of an ecological system network

The second law of thermodynamics (law of entropy; SLT) is a universal principle applied to the entire processes of life and death, and predicts the termination of all living and non-living systems in the universe, thermodynamic equilibrium. If energy in a system is depleted and becomes wasteful (low quality energy; e.g., heat), the system will perish, and, conversely, if it gains useful energy (high-quality energy), it survives. However, it does not directly clarify the logic of ecosystems driving them to keep persisting against the death. In other words, even though SLT is ubiquitously true, it does not clarify why a highly-ordered system is naturally selected, survives in competition, and eventually well-fitted to the environment.

When SLT is applied to living organisms with respect to their sustenance, it presents a dilemma—what Jørgensen (1992) calls the *environmental paradox*. According to the SLT, any system has to maintain a lower entropy state during its life cycle to avoid thermodynamic equilibrium (heat death). However, every attempt to do so requires more energy inputs and information (negentropy), and, thereby, shapes a lengthy chain of energy exchange. In this process, SLT is indicative of more energy loss (waste of heat), and greater generation of entropy budget (Jørgensen, 1992). In other words, maintenance of the low entropy always brings on a higher entropy state.

This contradiction has been first noticed by Lotka (1922) in his study of ecosystems. He found that the "course of events in a physical system" did not strictly follow SLT, and mentioned "freedom of choice" in the course —system processing of energy transformation— is the main method of resisting to the equilibrium (Lotka, 1922). At the large system scale— the universe, there is no doubt about SLT, because the universe is assumed to be an isolated system. But, as Lotka (1922) suggested, systems continuously moving towards a non-equilibrium state are not subject to the thermodynamic statement within the scope of the specific system level. The same holds for buildings. The following addresses a thermodynamic account of how building systems construct complexity in the account of thermodynamics. Measures based on similar but somewhat different hypothesis for system development must be integrated.

3.2.1 Order and disorder model and a metabolic understanding of building environmental functioning

The underlying process of all natural phenomena is the transition from order to disorder. They sound like casual words, but an energy-based perspective adds a thermodynamic rigor to both macro- and micro-scale observations. A system's energetic order requires (i) ability to maintain potential energy (low-entropy) and (ii) thermal concentration (spatial intensity that is differentiated from the dispersed entities of surroundings) (Odum and Odum, 1976).

A probabilistic definition can bridge the micro- and macro-scale processes, the order appears in a predictable state of molecular motions of a system, which is in fact a low-entropy state in terms of the Boltzmann's understanding, whereas disorder means a gain in uncertainty to describe a specific state of the system. That is, the justification for the use of information to identify order and disorder. The quantitative aspect of the system **order** can be referred to as the dual meaning of information which interchangeably connected: (i) amount of an observer's information (negentropy) about how much energy is associated at any instance with each mode of system quanta's energy possession (Dincer and Cengel, 2001), and (ii) low system's information entropy as a complexity measure indicating predictability (restraint of the "freedom of choice") of the quantum positions in the system's internal network.

A clear relationship between order and information is revealed throughout the order-and-disorder transformation. As SLTexplains, orderliness of energy particles of a substance spontaneously turns into disorderliness with time (dissipation), and, vibration and motion of the particles in the way of the process generate useful energy as well as increase the freedom of choice and complexity of energy structure. So, more energy inputs enhance the complexity, which leads to higher information entropy.

In the growth and the evolution of biosystems and organisms, however, they generate a new order and maintain it from disorder through a hierarchical energy structure and metabolic functions. At the system level, the process of generating order pertains to a matter of "reproduction" by extracting or exchanging essential values of the available energy (useful energy) from low-entropy sources. A building is a highly-ordered system in terms of thermodynamics. It extracts energy from relatively disordered raw materials, and restructures them in a specific pattern. In an effort to reconcile physical laws and the process of life, such striking feature of the living systems, *order-from-disorder*, was proclaimed by Schrödinger

(1944), as a central dogma of system organizations in both animate and non-animate processes. He said, “An organization is maintained by extracting order from environment (Schrödinger, 1944; Jørgensen et al, 2007)”, as an extended statement of SLT. What should be noted is that system complexity is directed to shape a hierarchy of energy flows. The inherent order of living systems is designed by a thermodynamic mechanism (Ulanowicz and Hannon, 1987). Through its life cycle, the construction of a building is to weave “energy” into a specified pattern. In this manner, all subsystems and component are affected by a higher level of order. In this understanding, a generic building system diagram based on the Odum’s order-and-disorder model provides a basis for identifying general dynamics of the energy transformation work (Fig. 3.2).

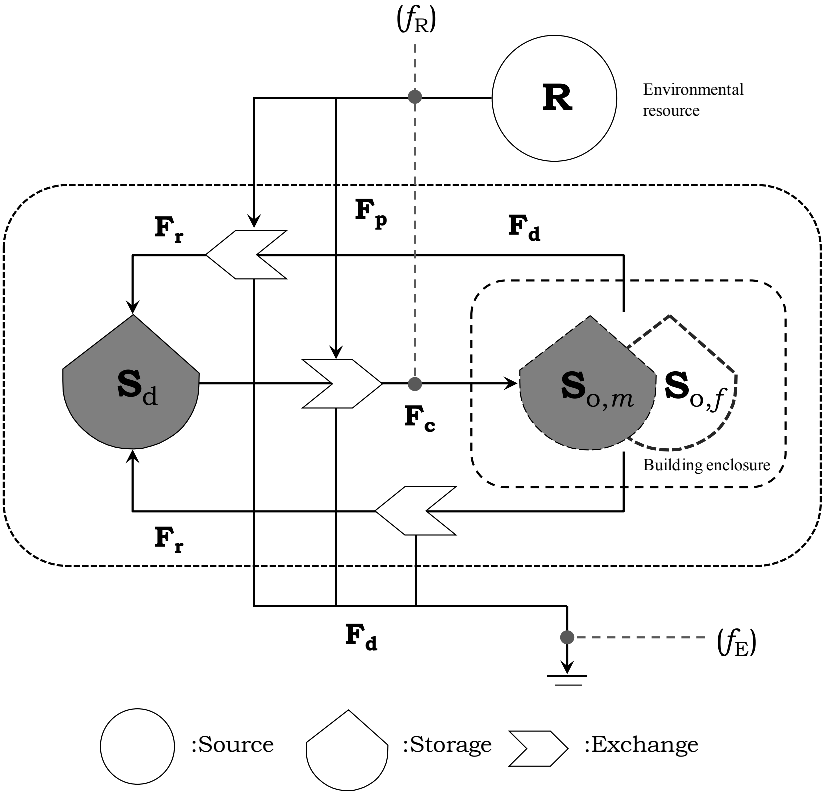


Fig. 3.2 Schematic system network model of building energy-matter metabolism: This model is based on the Odum’s order-disorder theory. (forcing functions: f_R, f_E) Each flow is denoted by R: potential energy resource, S_d: storage of disorder, S_o: storage of order ($S_{o,m}$: one of materials ,$S_{o,f}$: one of building form). F_c is an “input” of the ‘place-based building system, but, in terms of the whole building system, it is an “output” available for future use. *Production* (F_p): According to above definitions, all input sources of an ecosystem (e.g., fossil fuel, sunlight, raw materials, etc.) are in states of order and low-entropy (the solar energy is a huge low-entropy source due to the tight intensity of energy photon), and the ecosystem funnel the potential energy into their own mechanism. *Consumption* (F_c): occupant’s activities for energy acquisition and utilization for human living. *Regeneration* (F_r): transition from order to disorder is natural, but living systems purposely feed

backward flows for intensive upstream flow (F_c), by recycling material/energy, refurbishment, and employing human knowledge and/or intelligent devices. *Deconstruction* (**F_d**): emission, disposal, landfill.

3.2.2 Global principles of self-organization: Maximum entropy production (MaxEP) and maximum power principle (MPP)

Just as the spontaneous emergence of an orderly pattern during a living systems' developmental stages provoked a controversy over the SLT, it inspired many ecologists and physicists to explore more immediate theoretical foundations to explain the thermodynamic systems behavioral programs (such as homeostasis against perturbation) and the selective logic of system evolution. Most of the arguments for potential principles have been based on the survival of living systems. Without nourishment, no systems exist. Meanwhile, as Odum (1976) states "*everything is energy*," any form of nutritional substance on the earth is a form of energy. So, the acquisition of nutrientsis the acquisition of useful energy, which is an essential prerequisite for the viability of all physical and biological systems. In effect, the energy acquisition needs extraction work. And, according to SLT, the work indispensably involves an entropy increase as it discounts the potential energy of a source. Hence, it is reasonable to postulate that production of entropy is a dominant indicator of all biological metabolisms.

Laws of entropy production

In mechanics, Prigognine established the theorem of minimum entropy production (MinEP) in 1945. The MinEP principle argues that a stationery or near equilibrium system has a tendency to maintain the lowest entropy production rate (Prigognine, 1945)[32]. Prigognine's identification is notable because it presents a general mathematical derivation consistent with SLT, as it proves an orderly stable state must produce lower entropy. However, MinEP is a local theorem which is effective only with a strict linear condition and a state of very slow, purely diffusive transfer (Nicolis and Prigogine, 1977; Martyushev, 2013). It does

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[32] *If the stationary state of the process is stable, then the unreproducible fluctuations involve local transient decreases of entropy. The reproducible response of the system is then to increase the entropy back to its maximum by irreversible processes: the fluctuation cannot be reproduced with a significant level of probability. Fluctuations about stable stationary states are extremely small except near critical points (Kondepudi and Prigogine 1998, page 323).*"

not justify the transient increase of entropy of non-equilibrium, nonlinear systems which are far more general in animate systems. So, in a generalization of the narrow rationale, Jaynes (1957) and Ziegler (1963) recognized the concept of maximum entropy production (MaxEP), and Swenson (1988) articulated it as a cardinal thermodynamic principle. Later on, Schneider (1994) adopted it for the formulation of ecosystem models and functions. If an open system has a sufficient degree of freedom for system organization (e.g., molecular structure), it evolves towards a steady state with a more complex configuration that produces maximum entropy.

The MaxEP principle has two significant implications for system analysis. First, it breaks the common notion that entropy is an indicator of disorder. Proponents of the MaxEP principle have demonstrated that a system developing towards orderliness is an accelerator of entropy increase (Schneider and Kay, 1994; Toussaint and Schneider, 1998; Meysman and Bruers, 2010). Second, it is syntagmatically applicable to organizing behavior of biological and non-biological (physical) systems.

Most importantly, the theorems of entropy production (MaxEP, MinEP) feature in common they concern the "*rate*" of entropy increase. SLT introduces the notion of *time* to characterize the irreversibility of thermodynamic work as well, but does not explicitly employ it for energy discounting processes (Odum and Pinkerton, 1955; Ulanowicz and Hannon, 1987). The cornerstone of entropy production theorems is to incorporate the temporal scale (*a magnitude of duration* of the energy discounting) as a key indicator of the degree of system complexity (Ulanowicz and Hannon, 1987; Schneider and Kay, 1994).

System optimization principle: Maximum power and maximum empower

Earlier than propagation of the entropy production principles in mechanics, an ecologist Lotka (1922) argued that living organisms tend to maximize the rate of resource utilization for their growth (succession in ecological terminology) and biological systems with higher temporal density of energy output ("output" here means available energy stored within the system's body, it does not necessarily exit it.) are more likely to succeed in the struggle for existence. Inspired by the Lotka's tentative theorem, Odum formulated maximum power principle (MPP) extending it to all types of ecosystems, arguing that "living and also man-made processes (including human civilizations) do not operate at the highest efficiencies that might be expected of them (Odum and Pinkerton, 1955)".

The key concept of the MPP is that it associates the maximum power state with “optimal” efficiency, which is always less than maximum efficiency. Physical and biological systems sacrifice efficiency of energy transport for obtaining more quantity of useful energy and vice versa (reciprocity of power and efficiency) (Odum and Pinkerton, 1955) (see Appendix D). It is important to note that the effect of optimization does not necessarily appear over every component of the systems. Since the principle deals with system-level attributes, not individual compartment, the system efficiency is not maximized under a normal external condition, even if a single compartment attains 100% efficiency.

Odum refined the MPP to a principle incorporating the accumulated inputs of all upstream direct/indirect energy budgets, *emergy*, and finally proposed the maximum empower principle (MePP) (Odum, 1996). In a way, MePP is an extension of the MPP that sets temporal intake of “all available energy” as a cardinal index of biological development (Cai et al., 2004; Ulgiati et al., 2007; Li et al., 2013). Conflation of the energy quality and quantity helps elucidate the hierarchical transformation of energy, extending it to the most primitive inputs (sunlight, mineral, rainwater, etc.) (Hall, 2004). MaxEP, MPP, and MePP are compatible with one another (Appendix D.1) in that they deal in common with the change of total “free” energy inside the system. An entropy increase involves exergy change (Eq. (2.4)), and MPP is a quantitative postulate of the trade-off between the entropy change rate and system efficiency.

Importantly, those principles expound the final cause of development— a system’s spontaneous resistance to modification of the external environment and acquisition of more useful energy. At a glance, the notion of maximum power sounds scientifically controversial, because conservation of diminishing sources is a demanding pressure. The struggle for the least stressful condition and maximized harnessing of available energy can be seen as a greedy act. However, such narcissistic behavior of a single organism is not self-centered but a self-reinforcement to benefit a whole ecosystem through feedback, since sustenance of geobiosphere is profitable for the organism itself in the long run. Therefore, the maximum power production is the ultimate goal of sustainability of all physical, non-physical systems in the earth. As Odum speculated (Odum and Pinkerton, 1955), sustainability of our civilization and building environment must be subject to attainment of maximum power, not the blind commitment to reaching maximum efficiency. Odum proposed the MePP as a comprehensive indicator of system development as it has been used to illustrate various types of system mechanisms, and, following Lotka's suggestion, he even proclaimed MePP as the fourth principle of thermodynamics. However, despite its paradigm-shifting support to the mutualism-based sustainability, there are several criticisms: (i) it does not predict any threshold of power at the maximum stage, (ii) although the principle has been noticed by observational investigations, the laboratorial monitoring still lacks sufficient number of empirical demonstration, and (iii) it is not unconditionally true. Since it premises a dynamic state with plentiful food supply to ensure full degree of material choice of the system organization, a system under insufficient supply of the resources could pursue maximum efficiency rather than intermediate efficiency. Although, applicability of MePP for buildings will be explained in this study, many researchers have challenged the first and second concern through case studies (Cai et al., 2006; Li et al, 2013), and noticed the increase of useful energy influx through complex changes of community structure and chemical constituents. Previous studies found the maximum value of system power depends on the attributes of energy pathways, and external forces.

The third criticism is especially noteworthy. If an abundance of resources is not the case of a system, maximum power may not be effective. A cactus enhances its overall power for effective absorption of water, limit of choice of material on a barren land may bias against MePP. And in a barren regions, ecosystems grow quickly to use up immediate resources.

Our focus on global sustainability must be based on the MePP. When it comes to building sustainability, which has to deal with global development of human society, this is a local deviation, or temporarily appears due to the recognition of resource shortage. For example, as shown in the recent explosive production of shale gas in US, if we innovate conventional ways of energy exploitation, operative resources for our society are not insufficient as far as solar energy is transmitted to the earth.

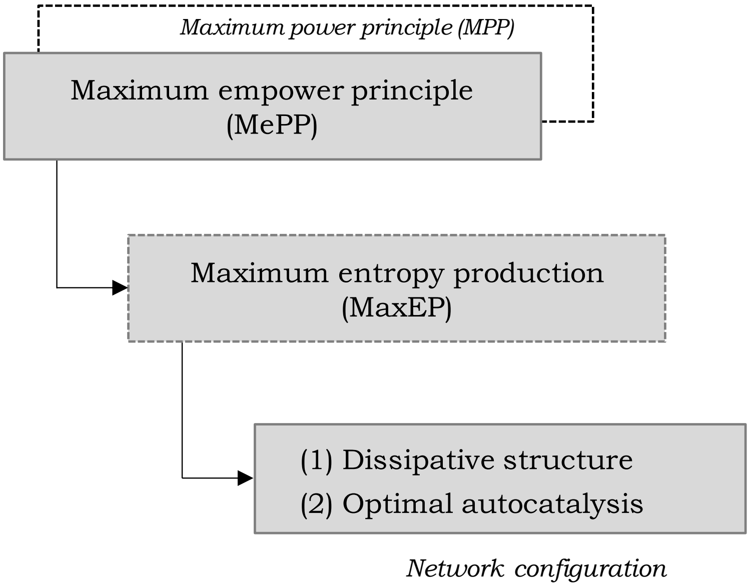

Fig. 3.3 Compatibility of global ecosystem development principles: Increased available energy intake towards development does not only affect quantity of the energy flow but also leads to notable characteristic of system properties and configuration of pathways through self-organization such as: (i) higher diversity, (ii) development of feedback loop (iii) pulsing between producers and consumers, (iv) relatively higher efficiency after growth (a state of minimum entropy production) (v) hierarchical structure of energy transaction based on the energy quality (Jørgensen, 1992; Toussaint and Schneider, 1998; Cai et al., 2004). For network analysis, the most critical aspects of self-organizing complexity are (i) *autocatalytic* organization through increased cycling activities and (ii) generation of diverse pathways for maximizing total *dissipation*. Diversity of system components, pulsing, and the appearance of hierarchical trophic levels are results of the construction of complex structure.

3.2.2.1. Development of dissipative structure

In the process of utilization of environmental sources, an open, far-from equilibrium system tends to dump wasted energy as a form of heat (Prigogine, 1980). If the system produces more energy, it needs to be able to degrade the energy more quickly with an expanded structure. That is, the goal of dissipative structure is to abet entropy production. Effective complex and elaborated network structure of exergy drainage must emerge in system growth and development, which lead to maximum power.

3.2.2.2. Autocatalytic network and maximum complexity

The complexity of self-organization often depends on “indirect” connectednesses between compartments (a causality of input-output is found between nonadjacent nodes). However, such indirectness is not unconditionally conducible to sustainability, because disoriented complexity can bring on a biased development that makes fragile an ecosystem in the end (Ulanowicz, 1997). In that sense, the mutual sustainability needs the system to develop *autocatalytic* network (Ulanowicz, 1997). Autocatalysis means that an outcome of energetic reactions becomes a catalyst for first reactants (inputs).

Like dissipation (exergy destruction), autocatalysis is compatible with MePP in that storage of the power is maximized only when system components of different scales are collectively, interdependently connected on a balanced circulation of input-output of the sources (matter, energy, and information). Autocatalysis is also an identification of the system’s ability to recycle; i.e., use wasted energy and matter to feed itself back so that they amplify generation of the sources, which is a fundamental activity of enhancing network quality towards mutual symbiosis. Hence, a maximum power state at which none of absorbed energy leaks attains full autocatalytic connection— energy is stored, conserved, and managed to be circulated throughout the whole ecosystem.

The increased amount of internal material flows caused by autocatalysis corresponds to longer cycling lengths and a decrease of turnover time of the cycling (Schneider and Jay, 1994). The greater number of the circulation the more complex system organization, which leads to an increased amount of power. Ecosystems develop control functions of power progressively through the cyclical pathways (Patten, 1992; Odum, 1996). In this sense, the indirect effects of the autocatalytic network have been called “*amplification*”, “*synergism*” (Fath and Pattern, 1999), or environmental “*order*” due to its ability to maintain the potential energy (Ulanowicz, 1997). Hence, by applying the degree of autocatalysis as the fundamental criterion to evaluate the system states, we can assess power intensity and the degree of sustainability (Fig. 3.4).

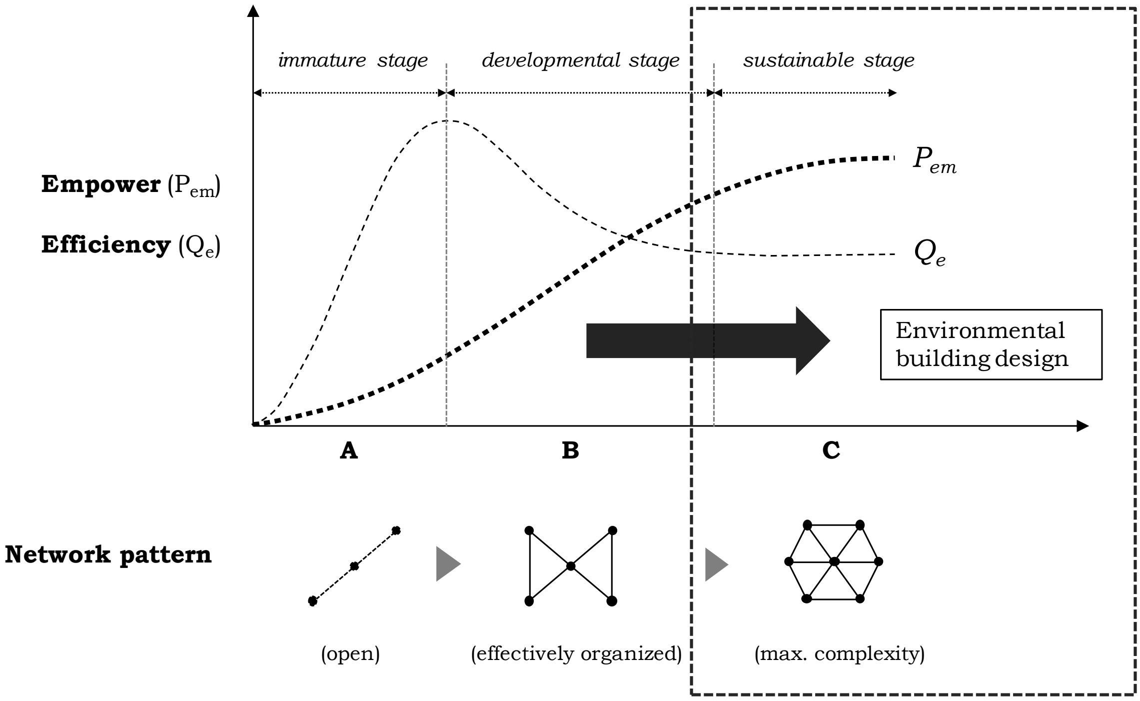

Fig. 3.4 MePP, self-organization, and degree of global system development (under steady-state condition): MaxEP, MPP, and MePP are essentially extended statements of SLT, and the specific structural organization of resource flows (dissipation and autocatalysis) is a network-version surrogate of the principles.

3.3 Power and Resilience: System-level indices of sustainability

As discussed in Section 3.2, indication of building sustainability is associated with combination of extensive and intensive changes (Eq. (3.3)). Non-equilibrium systems undergo fluctuations of extensive input quantity; e.g., the variable rate of throughput of energy, matter, and information. Such fluctuations belong to a function of external constraint (*f*) and complexity of internal organization, which are subject to temporal intensity of the external variations. However, further elaboration is required to clarify the formula with the following questions: how do local ecosystems control the balance of external and internal functions? Which contributes more to the systems to maintain developmental activities over time?

In 1886, Boltzmann asserted, even though he found little immediate evidence, that living system's general struggle for their survival was not for acquisition of raw materials (because the global ecosystem was not yet at the equilibrium, and relatively plentiful are air, soil, or water) and energy, but for “entropy”—utilization of the energy and matter (Boltzmann, 1886; Schneider and Kay, 1994b). This argument means the quantity of external resources function (***f***) is not the most limiting factor of ecosystem development (Jørgensen, 1992), but the system’s “response” to the external stress and managerial ability is critical. Therefore, we have to notice that the function (***g***) of intensive parameters is the key to achieve building sustainability, because it connotes the time and context of our civilization in which the boundary conditions of the building system is situated, and explains the supportive backgrounds of the social and cultural forces (e.g., climate, technology, and social content). In the scarcity of the external sources or external perturbations, the organizational state controls how to gain access to the environmental sources, and acts as a brake that manages inflows when the external quantity enters the building system. Eventually, the strength of the internal composition becomes the power to resist the unfavorable conditions.

From this perspective, the organizational aspect of system network properties for survival should be the imperative of sustainability evaluation. So, the evaluation of the mutualism-based building sustainability is refined to the level of exploring the characteristics of the network itself, such as total throughput, degree of cycling, turnover rate, and direction of interactions that are widely used in ecosystem analysis to identify the system’s capacity to retain function, structure, and feedback. To identify such properties, systems ecology sets the tone for the research of “*stability*.” Ecosystem stability is a highly complex definition (May, 1973), and its evaluation is not possible without a rigorous consideration of the methods of quantitative measurement as well as study of reaction mechanisms. Many researchers have proposed multiple biological concepts and definitions to describe associative system properties such as *adaptability*, *buffer capacity*, *resistance*, or *elasticity* (Jørgensen et al., 2007). However, direct use of those constructs may be too general for a cursory analysis, or too speculative to understand the complexity of the systems energy exchange based on the networking of entities.

Nevertheless, among those measures, resilience is of particular importance, because it refers to the system’s ability to self-organize (Meadow, 2008). The ecosystem’s ability to evolve and sustain itself is in parallel with that of adaptation by restructuring a resource flow circuit. Resilience is, in effect, a multi-disciplinary concept widely adopted in different domains, from economics through social science and computer engineering, to characterize a system’s capacity for flexible self-recovery against untoward external conditions and unexpectedly varying circumstances (Smith and Stirling, 2008; Stokols et al., 2013).

Resilience as an environmental measure was first discussed in the ecological arena by Holling (1973). He defined resilience as the "persistence of ecosystems and their ability to absorb change and disturbance and maintain the same relationship between state variables (Holling, 1973)." Resilience does not only highlight the homeostatic aspect but also the evolutionary capability such that a circuit of energy within the system forms a dynamic closure (Ho and Ulanowicz, 2005). Depending on situation, a structure of closed connection can be opened to yield energy flows to those that require energy for the system growth.

Based on these statements, this study finds resilience as a definitive index of systematic ecosystem sustainability, in addition to the system power. While the power is primarily concerned with resource availability and the development of the hierarchy of forward transmission, resilience, and stability, underline the network balance between self-prosperity (*robustness*) and flexibility (*adaptation*) through the development of feedback loops in presence of perturbation. E.P. Odum argues that mutualism evolves to produce resilient systems (Odum, 1983). Fath et al. (2003) define, "ecosystem resilience is a measure of the ability of an ecosystem to maintain function in the presence of disturbance and change[33]" In this sense, we conclude that resilience is the most appropriate term to characterize mutual networking of a building system, because it is the most inclusive ecological concept of describing the stability of the organization, which can also be extended to refer to "resistance" and "*buffer capacity* (Jørgensen, 1992)" (Jørgensen et al., 2007). It is similar to elasticity (Orians, 1975) but more inclusive (Jørgensen, 1992).

3.3.1 Locality of building sustainability and information

Sustainability based on mutual metabolism complies with the principles of biological and non-equilibrium thermodynamic system development, such as maximum (em)power and maximum entropy production, because the mutual connection of ecosystem functions is the best way of augmenting useful energy inflows and dissipation by autocatalytic feedback. Autocatalysis is an efficient way of self-proliferation and multiplication of a biological entity, because the synergetic cooperation between components continuously spread over the whole system with the least number of pathways. R.E. Ulanowicz argues that autocatalysis accelerates a system's centripetal tendency to bring more energy and information into the

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[33] However, Jørgensen (1992) is reluctant to use the concept resilience as a quantitative term, because a system theoretically resilient, but technically never return to an original state before perturbation.

system circuit (Ulanowicz, 1997). In this mechanism, the conventional relation of source, producer, storage, and consumer is incessantly reconstructed with the variation of compartmental connectivity and storage power (Fig. 3.1. (c)). Even though the law of maximum (em)power is valid at every scale (Odum and Pinkerton, 1955) and fine-tunes ecosystems like the "invisible hand" (Li et al., 2013), examination of mutualism using short-term emergy fluxes may lead to a biased interpretation and not provide a practical sustainability assessment of *local* ecosystems (such as building and built environment). This concern is largely due to the following reasons: (1) theoretically, emergy power can be estimated by identifying initial inlets of energies or the total amount of energy degraded, yet the measurement involves a great deal of uncertainty, particularly for complex systems *dynamically* moving away from thermodynamic equilibrium, (2) the behavior of local systems can be quite different from that of the global system. Scarcity of local sources may cause the development strategy of the local system to prefer conservative activities by reducing entropy production, and, hence, the maximum power law may not apply at this case, since the principle presumes abundance of useful resources. (3) Due to the limit of the system analysis window, it is very hard to estimate the contribution of local systems activities to global evolution towards maximum power. Even if that is possible, the generality would diminish the resolution of the result, and (4) As Jørgensen (1992) argues, ecosystems never return to the same state. Even though behavior of a local state is clearly analyzed and predicted, the general local system order does not deterministically match with the attributes of the global complexity due to the randomness of the organizing pattern of the geobiosphere functions. Thus, mutualism based on autocatalytic mechanisms and the degree of useful power must be a global model of sustainability, but, they may not be appropriate to be a direct indicator of local system states. As for built environment, like any other local living systems, stable cycling of subsystem populations and a durable supply of biological/technological sources around a local area has a powerful impact on the sustainability. Therefore, we have to focus more on the system's instant *potential* that draws its spontaneous move contributing to a continuous global increase of the system power in accordance with other local systems as well as the global system. In this sense, a degree of resilience can be seen as an inclusive measure to reflect the qualitative/quantitative aspects of the system's self-sustenance, controllability, and protection.

For building design, a hidden side of the attempt to characterize every facet of self-organization (e.g. hierarchy and degree of energy accumulation) in a fixed position can be seen as an extension of the mechanical idea, because the hierarchy between system elements and the intensity of energy exchange are not explicit, but ever-changing. In this light, the resilience-based view of sustainability embodies a profound transition in the examination of sustainability in two regards: (1) it requires us to shift our attention from a deterministic judgment about building performance of a static state into a *probabilistic* description of the building's dynamic behavioral *tendency* heading to evolutionary design, (2) The quantity of energy and mass is still influential, but the main target of performance evaluation should be their flowing direction and distribution throughout the building ecosystem's metabolic network. Now, we have to answer some questions that may arise at this point, such as: what makes the flux of energy and mass change? And what do we have to measure to monitor the degree of resilience? As shown in the Schneider and Kay (1994a)'s Bénard cell experiment (Section 3.2), variations of external conditions eventually affect the entropy production rate (system behavior). This clearly demonstrates that "something" stored in the system becomes a dominant player in rearrangement of the internal motions of energy and mass; that is, *information*. As Odum (2007) illustrates, living systems try to utilize more energy to maintain non-equilibrium state at an optimal operating point(s), but it is only accomplished by "continuous application of information (Gatenby and Frieden, 2007)." Information is transmitted through and stored in a *network configuration* of an ecosystem, and it maps the energy and mass over the organization by controlling the activation of useful nodes and links during the developmental stages and crisis (Janssen et al., 2006), thereby changing (1) the level of connectivity between system components, (2) network centrality, and (3) the strength of power storage. So, that information is the most critical factor to indicate the system's resilience, and it is a macroscopic system-level property. This finding also lets us define a building as a channel of information (e.g., adding a new material to the building envelope would change the internal heat distribution due to the information encoded in the material), and informs that the environmental performance of the building can be monitored by information change.

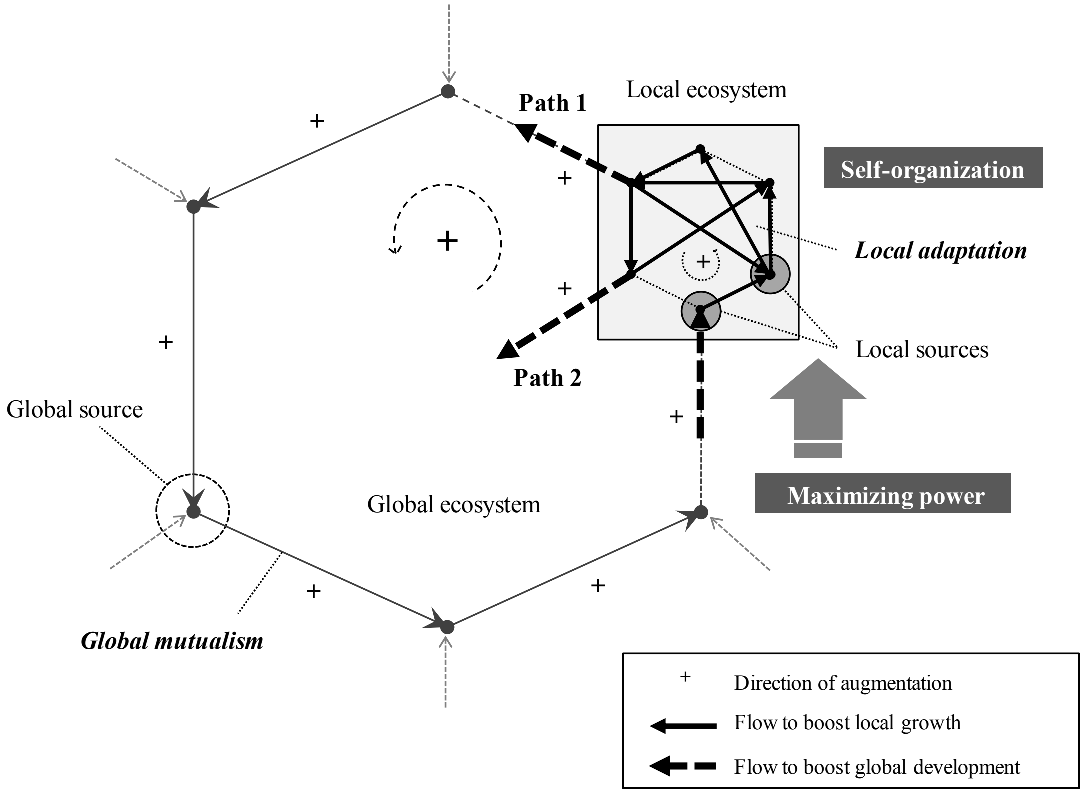


Fig. 3.5 Concept of system resilience and duality of systems sustainability: Path 1 and 2 indirectly amplify the local sources for the local ecosystem to obtain more potential energy by augmenting remote global sources. Internal autocatalytic network directly strengthens the local sources. Resilience refers to assurance of the local system's spontaneous interplay of the indirect and direct effect, thereby ability of existence under unpredictable global conditions.

Nevertheless, the task of quantifying resilience with information is challenging. First, even though information is recognized as a physical quantity, it can be noticed only by a variance of its carrier's state variables and relationship with other substances. The following section discusses the quantification methods of resilience. Second, a large stack of information leads to a highly-developed system (Odum, 1981), but the simple complexity due to incoming information does not guarantee a "resilient" hierarchy of the system components. As discussed in Chapter 2, information of the energy network is measured with stochastic distribution of quantum, which are generally assumed to have no interaction to one another, but they are not in fact completely independent (Wiener, 1948). Koestler (1967) mentioned "self-assertiveness" of energy particles of biological systems (called "*holons*") (Allen and Starr, 1982). This means that energy fluxes of ecosystems are not arbitry, but the particles of the flows integrate particular functions of a larger whole. Koestler asserts that the development of a hierarchical organization based on the energy particles' dual tendency is the inherent hallmark of all living systems (Koestler, 1967). That is, we have to understand that resilience is an emergent property from self-cohesiveness. It is consistent with embedded information that is subject to external perturbations. The "independence" and "dependence" of the system organization must be considered simultaneously in the evaluation of resilience (Fig. 3.5).

3.3.2 Evaluation of information content: Quantification of power, organization, and complexity

A few quantitative evaluation methods of the flow topology of an ecosystem network have been proposed. They stem from a similar intuitive understanding—a cycling of a medium on pathways, but each measure has a different mathematical background. Bernard Patten (1985) analyzed a distribution of total throughput over the structured pathways of the ecosystem with a Leontief's matrix function for economical input-output analysis. Although this study does not explore his theory, Ulanowicz's ecosystem analysis shares its fundamental understanding, partly derived from the Patten's, and it focuses more on the uncertainty of a single quantum by reinterpreting Shannon's information theorems in average mutual information (Ulanowicz, 1986).

3.3.2.1 Evaluation of reciprocal connectivity (developmental organization): Average Mutual Information

The definition and mathematical formulation of average mutual information (AMI) were introduced by Gallager (1968) within the communication theory discipline. Rutledge et al. (1976) applied it to systems ecology to characterize the stochastic nature of ecosystem succession. Based on the hypothesis that the ecosystem organizations mature towards autocatalytic networks for succession (Ulanowicz, 1980), Hirata and Ulanowicz (1984) proposed an AMI-based index in order to assess the developmental pattern of an ecosystem structure.

Then, why and how is AMI chosen as a system maturity index? Because the concept and the target of measurement are consistent with the major ecosystem principles such as (i) the maximum power principle (Lotka, 1922; Odum, 1963) and (ii) the exergy-storage hypothesis outlined by Jørgensen (1992), which both state system evolution increases system throughput by developing various routes of energetic sources particularly including “feedback” loops. Intuitively, we are aware that the more inter-compartmental flows are diffused, the complexity of the total organization increases. Uncertainty of the flow distribution accordingly will rise. However, in terms of where a flow originates, uncertainty (capacity of information) may or may not be increased depending on the diffusivity of the network configuration.

Suppose that a simple binary network is composed of two elements namely *i* and *j* (Fig. 3.6). The inflow to *j* (f_1) from *i* yields a constraint of the flow capacity. However, as *j* develops a positive feedback path (f_2), the flow out of *j* may influence $f_1$conversely. That is, jointly, both *i* and *j* are a “source” and a “reservoir” at the same time. One may need to assess such an interactive effect. As for a system network, information is the stochastic index of the network structure that is indeterminate but apparently away from an arbitrary configuration. Therefore, mutual information evaluates the “reciprocal restrictions of the compartments” that make the network organized in a certain manner. “Mutual” here refers to “an indirect relationship” between a pair of compartments due to feedback paths or unclear source of the inflow for each element. Therefore, the mutual information is a suitable measure to identify a constraint from an implicit interaction occurred in the self-organizing ecosystem progression.

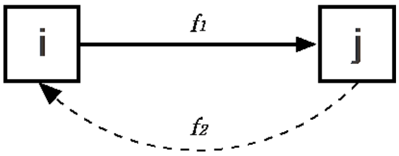


Fig. 3.6 Representation of the AMI concept

For mathematical discussion, the mutual information can be defined as the measurement of residual uncertainty due to “unknown (unobserved)” events given probabilistic events of flow distributions (Latham II and Scully, 2002). Then, AMI is a weighted sum of the uncertainty for each unit flow. This reminds of Bayes Theorem that deals with *posteriori* and *priori* distribution.

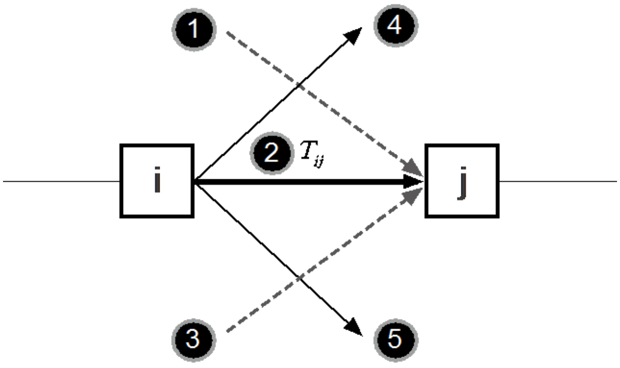


Fig. 3.7 Formulation of AMI: (1) external import to *j*, (2) internal transfer from *i* to *j* (T_{ij}), (3) internal transfer to *j*, (4) flows out of *i* to other comportments, (5) export and dissipation.

AMI is represented with the logarithm of the probabilistic ratio of a posteriori to a priori event (Appendix A) which means subdivision of uncertainty in a known source (a priori) from total uncertainty (a posteriori). Extended from Fig. 3.6, Fig. 3.7 displays all possible flows between the pair. Let uncertainty of this unit pair be U_{ij}, by the Shanon information, U_{ij} is obtained by,

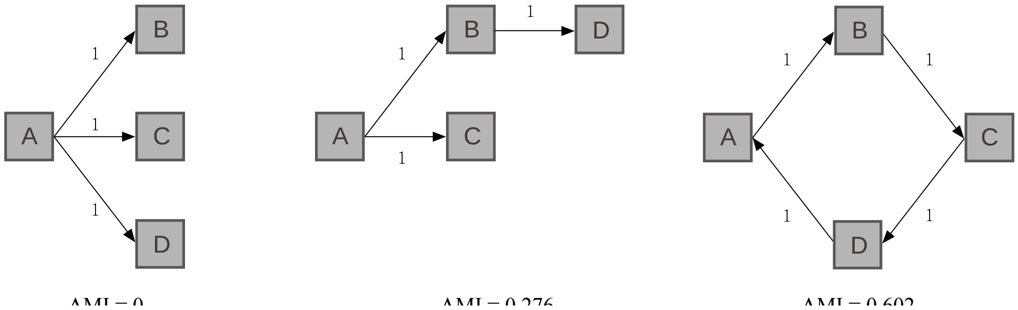
$$U_{ij} = -k \ log \frac{T_j}{T} - \left(-k \ log \frac{T_{ij}}{T_i}\right) = k \ log \frac{T_{ij}T}{T_iT_j} \tag{3.7}$$

where *T* is total system throughput, T_i is the total flows leaving from *i* (②+④+⑤), T_j is total inflow to *j* (①+②+③), and T_{ij} is transfer from *i* to *j*. Setting the the coefficient *k* of the scalar constant equal to 1, the weighted sum of unit uncertainty becomes AMI as follows,

$$\text{AMI} = \sum_{i=1}^{m} \sum_{j=1}^{n} U_{ij} = \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{T_{ij}}{T} log \frac{T_{ij}T}{T_iT_j} \tag{3.8}$$

where *m* is total number of outflow paths of *i*, and *n* is total number of inflow paths of *j*.

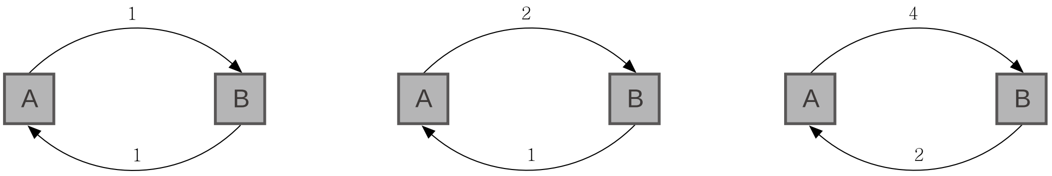
Fig. 3.8, 3.9, and 3.10 show AMIs calculated for three sample networks. Fig. 3.8 demonstrates that AMI is a measure of system organization. In Fig. 3.8 (a), T_i equals to T, and T_{ij} also equals to T_j, thus AMI becomes zero which means no flow from unknown sources (all flows to B, C, and D come from A). In the perfect autocatalytic loop (Fig. 3.8 (c)), AMI reaches the maximum.



(a) AMI = 0 bits (b) AMI = 0.918 bits (c) AMI = 2 bits

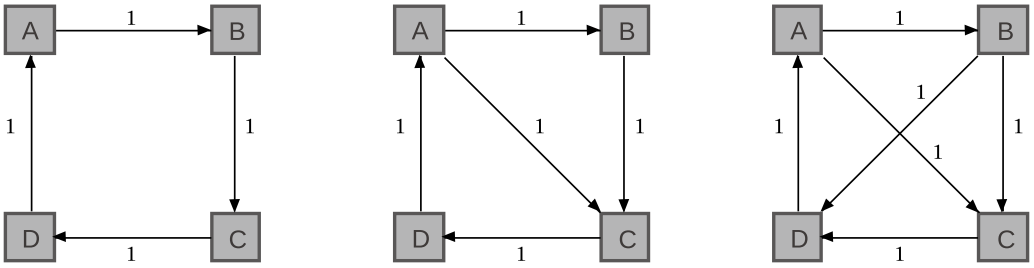
Fig. 3.8 AMI is the measure of a network

Fig. 3.9 demonstrates AMI is not only the measure of the profile of network construction. A target of AMI measurement is the unit of flows, i.e., a quantum of the flows, because average mutual uncertainty is dependent on the relative flow quantity to which a quantum belongs to. That is, AMI is the "quantum-based" description of a network configuration.



(a) AMI = 1 bit (b) AMI = 0.918 bits (c) AMI = 0.918 bits

Fig. 3.9 AMI is the quantum-based measure, a probabilistic distribution of quantum



(a) AMI = 2 bits (b) AMI = 1.522 bits (c) AMI = 1.252 bits

Fig. 3.10 AMI is not the measure of the intricacy of a configuration. Pruning of redundant paths increases AMI.

As depicted in Fig. 3.10, AMI is maximized when a quantity of medium is evenly distributed on each path branching into a perfectly cyclic direction. However, the maximum level of AMI, which becomes the same as the total information of the system network, can never be achieved for local ecosystems because the ecosystems always encompass open ends such as sources and sinks.

AMI is, therefore, compromised by being reduced into a certain level. Work of adjustment is the work of self-organization. The balance and the level of complication at which AMI is compromised are the targets we have to evaluate for a sustainability index.

3.3.2.2 Probabilistic indicators of local system behavior

(A) Asendency and Overhead

Resilient ecosystems basically seek to run under an optimal system operation with an alignment of network balance between metaphysical efficiency of internal development and system redundancy against extraneous perturbations (Ulanowicz, 1997).

In an operational process, efficiency is maximized if and only if the ecosystem medium (energy or mass) is circulated through each participating component via an autocatalytic loop. The information of autocatalysis results in an effective self-enhancing mutualism that prunes pathways of untoward (less efficient) directions. In this regard, AMI is a perfect indicator of such patterning, because it is also maximized if the quantities are evenly distributed over pathways of a circulating alignment. From this finding, Ulanowicz defines "*ascendency* (*A*)" as a measure of system development using AMI (Eq. (3.8)) multiplied by total system throughput (*T*) such that:

$$A = T \cdot \mathrm{AMI} = T \sum_{i=0}^{m+2} \sum_{j=0}^{n+2} \frac{T_{ij}}{T} log \frac{T_{ij}T}{T_i T_j} = \sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}T}{T_i T_j} \qquad (3.9)$$

(0: external input (import), m+1 and n+1: system output to external environment (export), m+2 and n+2: depreciation)

Ascendency becomes an indicator of "structure-enhancing configurations (Ulanowicz, 2009)", and the capability of system repair for self-development. However, full autocatalysis is a result of mechanical construction and highly improbable in reality, because it easily fails (brittle) in the case of unpredictable events (noise), which occurs quite frequently in the real world in which local systems are immersed. Accordingly, to maintain system integrity (order), local ecosystems prepare for the emergencies by embracing internal disorder, which Ulanowicz (1980) calls "*overhead* (ϕ) ." The concept of overhead is critical to the quantitative definition of resilience in that it stands for the system's flexibility and potential of future evolution (Ulanowicz et al., 2009). Overhead is calculated by subtracting ascendency from total system *capacity* (*C*). The capacity is calculated by multiplying system throughput (*T*) and overall uncertainty of particle distribution (Shanon information, Eq. (2.7)). During the system's development, it is hypothesized that capacity gradually increases. Capacity is given by:

$$C = T \cdot H = -T \sum_{i=0}^{m+2} \sum_{j=0}^{n+2} \frac{T_{ij}}{T} log \frac{T_{ij}}{T} = -\sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}}{T} \tag{3.10}$$

And, then, overhead is computed as:

$$\phi = C - A = -\sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}}{T} - \sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}T}{T_i T_j} = -\sum_{i=0}^{m+2} \sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}^2}{T_i T_j} \tag{3.11}$$

where C $\geq \phi \geq 0$ and C $\geq A \geq 0$.

System resilience (L) is defined,

$$L = \frac{\phi}{T} = H - AMI \tag{3.12}$$

(B) Fitness of system evolution and consistency of resilience indicators with maximum power principle

The resilience indicators (A, ϕ, and C), were integrated by Ulanowicz (1997) to suggest new indices of ecosystem resilience, namely, "*fitness* (*F*)" and "*robustness* (*R*)." Fitness is the ratio of ascendancy and capacity multiplied by the logarithm of the ratio, and robustness is a sum of the fitness for each particle such that:

$$F = -\frac{A}{C} log \frac{A}{C} = \frac{\sum_{i=0}^{m+2}\sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}T}{T_i T_j}}{\sum_{i=0}^{m+2}\sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}}{T}} \log \frac{\sum_{i=0}^{m+2}\sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}T}{T_i T_j}}{\sum_{i=0}^{m+2}\sum_{j=0}^{n+2} T_{ij}\, log \frac{T_{ij}}{T}} \tag{3.13}$$

$$R = T \cdot F \tag{3.14}$$

This formulation seems straightforward, though; metaphysical interpretation implies that *F* is the average uncertainty of an energy quantum towards ecosystem's order— i.e., a normalized factor of effective accumulation of useful energy and the local system's potential to self-organize for evolution. Robustness (R) is an adjusted value of fitness augmented by the magnitude of total network flow. Both have essentially the same nature, representing a system's adaptability to changes in the external world, and an observer may choose one of them as a design criterion. Robustness is suitable for evaluation of different kinds of systems because it reveals the scale of the system being assessed. However, if one seeks to identify inherent resilient attributes of system activities or fraction of resiliently active fluxes in throughput, fitness would make greater sense, since it measures "developmental" adaptability by normalizing the degree of sustainability regardless of the system size and the amount of throughput (attributes of the system growth). A system with a fixed value of fitness may improve overall resilience by absorbing energy flows, thereby increasing robustness.

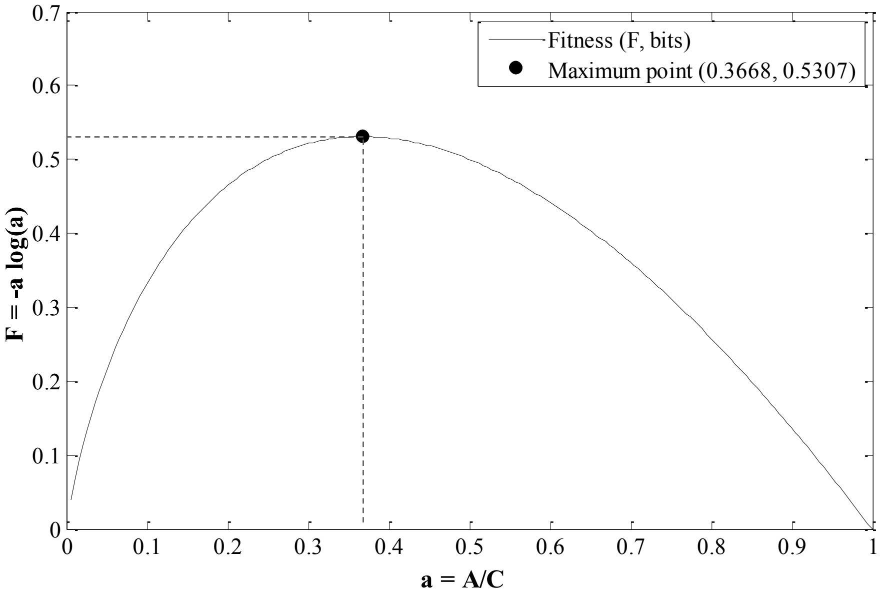
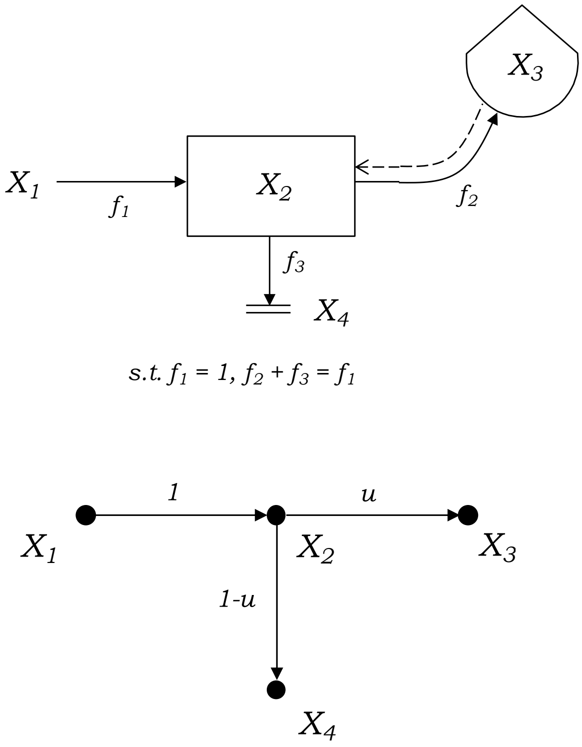


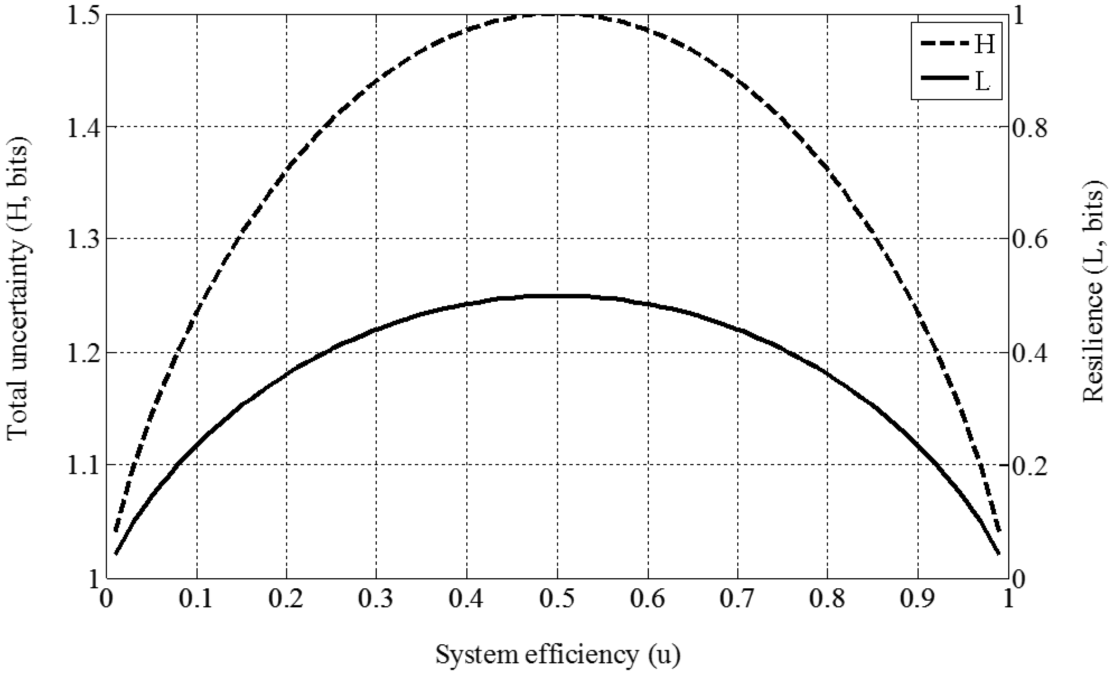
Fig. 3.11 Curve of system fitness and its maximum value: This graph shows an optimal ascendency or a capacity can be proposed for maximizing the potential of system evolution. For the maximization of a fitness value, an intermediate system component becomes a critical player.



(a) System representation: system diagram (upper) and digraph (below)

Efficiency, *u* (%)	AMI	A	C (H)	L	F
0	1	2	2 (1)	0	0
10	1	2	2.47(1.24)	0.24	0.25
20	1	2	2.72(1.36)	0.36	0.33
30	1	2	2.88(1.44)	0.44	0.37
50	1	2	**3.00(1.50)**	**0.50**	**0.39**
70	1	2	2.88(1.44)	0.44	0.37
80	1	2	2.72(1.36)	0.36	0.33
90	1	2	2.47(1.24)	0.24	0.25
100	1	2	2(1)	0	0

Note: (1) A: Ascendency, C: Capacity, F: Fitness (-(A/C) log (A/C)), where T is a system throughput), (2) When f_2 = 0.9 and f_3 = 0.1, then the system efficiency equals 10% (2) In this case, fitness is the same as robustness (R). (3) Measures are all for the internal organization (i.e., no external import and export).



(b) Test result of system attributes (resilience and total uncertainty)

Fig. 3.12 Test of the measure of resilience (and robustness): Results show the degree of resilience is consistent with the maximum (em)power principle in steady state development.

(C) Reconciling stock and flow-focused measurements

H.T. Odum's descriptive term for a sustainable ecosystem construction, "self-rewarding loop (Odum 1971)", recalls the Ulanowicz's "autocatalytic" reaction. Most of Ulanowicz's arguments about the resilience of a network configuration is similar to Odum's energy principles of compromise efficiency and maximum (em)power, and the postulates on resilience could also be understood as embracing Odum's principle. Although he does not make a direct correlation to the Odum's statements on maximum power,[34] theoretical consistency can be found by a simple experiment, shown in Fig. 3.12. Suppose a thermodynamic system is in a steady state development. Then, the system's energy transformation processes are aggregated into a single compartment (X_2) so that it simplifies this theoretical test. This system has three energy pathways: inflow (f_1), outflow (f_2), and degradation (f_3). Let X_1, X_3, and X_4 denote a source, a storage (or a consumer), and a sink respectively. The system operation can be depicted as a digraph (Fig. 3.12 (a)), and the system efficiency is computed by f_2/f_1, denoted as u. Since the system is steadily working, f_1 shall equal $f_2 + f_3$.

To parameterize each of the flows with the efficiency, let the input be a unit flux. Then, f_2 and f_3 are denoted as u and $1–u$ and total throughput becomes 2. Now, we can calculate the informational indicators (A, C, ϕ, and F) in various magnitude of efficiency by altering the values of f_2 and f_3:

$$\text{AMI} = \frac{1}{2}\log_2 2 + \frac{u}{2}\log_2 2 + \frac{1-u}{2}\log_2 2 = 1$$

$$\text{H} = -\left(\frac{1}{2}\log_2\frac{1}{2} + \frac{u}{2}\log_2\frac{u}{2} + \frac{1-u}{2}\log_2\frac{1-u}{2}\right) = 1 - \frac{u}{2}\log_2 u - \frac{1-u}{2}\log_2(1-u)$$

where $0 \leq u \leq 1$.

The results are presented in Fig. 3.12 (b). Interestingly, it shows that fitness (F) is maximized when the efficiency reaches a mediated level (50%), while A/C becomes

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[34] Ulanowicz emphasizes that ascendency synthesizes E.P. Odum's 24 attributes of ecosystem development (Odum, 1969), and then he puts it, "Optimal ascendency translates into maximal work, when the medium of interest is energy (Ulanowicz, 1986)." Although Ulanowicz disagrees with H.T. Odum's maximum power at 50% efficiency (Ulanowicz, 1980), by extending his arguments, when the medium changes to emergy, optimal ascendency represents maximal empower. However, a problem involves our understanding of optimal ascendency. In a benign condition (also in a steady state), system ascendency reaches its full (maximum) potential at optimality so that the ascendency theorem perfectly works with maximum (em)power principle. Nevertheless, such maximal tendency should be compromised in an external disturbance or severe environment, then, consistency of the two principles becomes undermined. An increase of ascendency is influenced by compartmentalization (i.e., specialization and internalization) as well as attributes of the flow configuration (i.e., concentration and cycling). For these reasons, as Ulanowicz (1980) suggests, behavior of the ascendency's optimality is not yet clearly revealed, and it shall be an interest of further study. Ulanowicz (1986) finally states, "*It is inappropriate to compare competing descriptions for the purpose of deciding unequivocal acceptance or rejection. Just as a phenomenological statement cannot be completely verified, neither can it be entirely falsified*." This dissertation takes only theoretical utility of ascendency and the emergy metrics to discuss a holistic system configuration under steady-state system development.

minimized. Since the directions of pathways and total throughput are fixed ($f_1 + f_2 + f_3 = 2$), AMI and ascendency are constant. But one can notice that the system capacity (C) is variable, and also maximized at 50% efficiency.

The fixed value of AMI and ascendency implies a network constraint that the size (throughput) and the number of effective pathways of the system organization are constant. In this condition, the only way of system development is to increase flow diversity (uncertainty of information content). The diversity of quantum flows is ensured with an assumption of growth in steady state without any external perturbation, which is a fundamental premise of the maximum power principle.

Even if the system size growth is limited, an increase of capacity means a gain of uncertainty in the identification of the system configuration. That is, the system networking becomes highly sensitive to the position and intensity of a single particle of a flow pathway. If the “usefulness” and “quality” highlighted in the description of the maximum (em)power principle can be interpreted as equivalent to “significance” of a single energy particle’s contribution to the overall energy transaction, then this case suggests that the concept of resilience based on the network examination and the maximum (em)power based on the input-output analysis are, inevitably, two sides of the same coin.

(D) Understanding the relationships between the informational performance measures and system efficiency

This is an advanced extension of Ulanowicz’s experiment (Appendix F) for the purpose of an enriched understanding of hypothesized relationships between information-based measures of system performance. To generalize the results of Appendix F, consider the following multi-compartment system with one-way flow of a medium (energy or mass), so that the topology represents the general case of an open-loop biological system (Fig. 3.13).

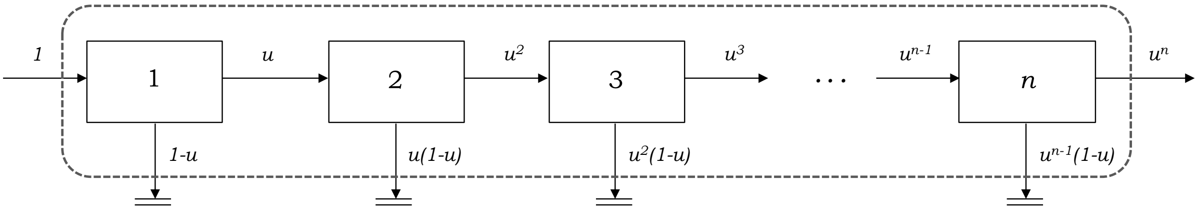


Fig. 3.13 General structure of a one-way flow system with *n* compartments

This complex model consists of *n* system compartments. No export, import, and backward flows are considered for the system work to mimic the chain network of a trophic system in a simple scheme. We set the efficiency of each unit compartment (trophic efficiency) equal, and denote it as *u* so an output of a single compartment is the multiplication of *u* and an input to the compartment. Limiting our discussion to the steady-state flux, i.e., gain and loss at each node are the same, if 1 is an initial input to the system, the total flow transaction eventually gives a useful medium of u^n from the *n*-th compartment. Hence, the efficiency of the entire system is measured u^n. A unique parameter of the flow topology is the efficiency value. Total system throughput (TST, T_n) is the sum of all individual values on pathways such that:

$$\mathrm{T}_n = 2 + u + u^2 + \cdots + u^{n-1}$$

And system complexity, AMI, and resilience are computed by:

$$\mathrm{H}_n = log(\mathrm{T}_n) - ((u^2)' + (u^3)' + \cdots + (u^n)' + u^n)\frac{1}{\mathrm{T}_n} log(u) - (1 - u^n)\frac{1}{\mathrm{T}_n} log\,(1 - u)$$

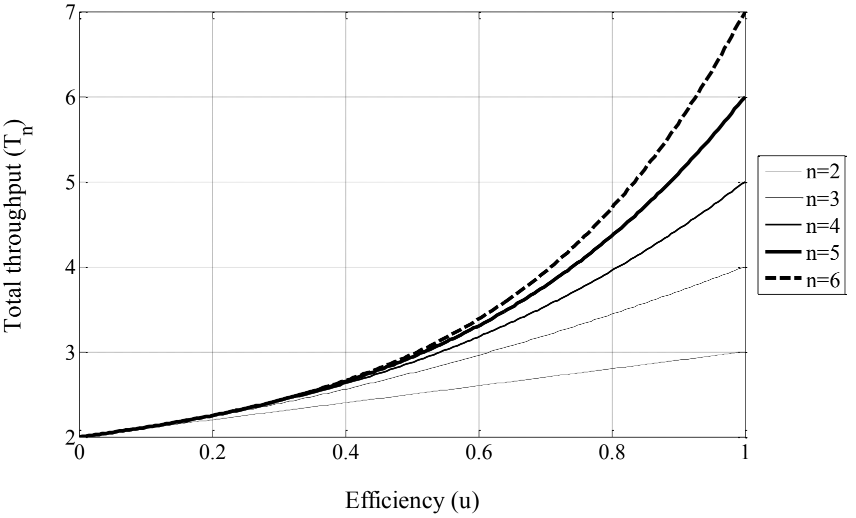
$$\mathrm{AMI}_n = log(\mathrm{T}_n) - (1 - u^n)\frac{1}{\mathrm{T}_n} log(\mathrm{T}_n - 1) - (u^2 + 2u^3 + 3u^4 + \cdots$$
$$+ (n-1)u^n\,)\frac{1}{\mathrm{T}_n} log(u)$$

$$\mathrm{L}_n = \frac{(1 - u^n)}{\mathrm{T}_n} lo\,g\frac{T_n - 1}{1 - u} - \frac{2log(u)}{T_n}\left(u + u^2 + u^3 + \cdots + u^{n-1} + \frac{2 - n}{2}u^n\right)$$

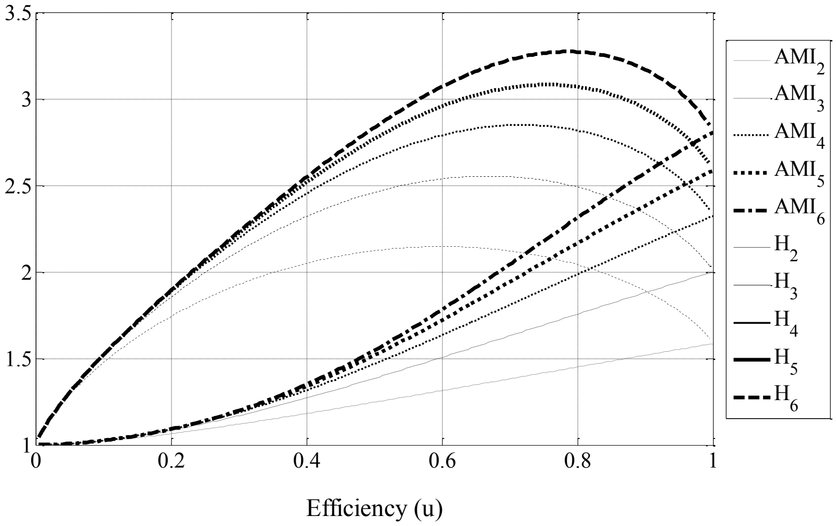
System ascendency and capacity are calculated as,

$$\mathrm{A}_n = \mathrm{T}_n\, log(\mathrm{T}_n) - (1 - u^n)\, log(\mathrm{T}_n - 1) - (u^2 + 2u^3 + 3u^4 + \cdots + (n-1)u^n\,)log\,(u)$$
$$\mathrm{C}_n = \mathrm{T}_n\, log(\mathrm{T}_n) - \ ((u^2)' + (u^3)' + \cdots + (u^n)' + u^n)\, log(u) - (1 - u^n)log\,(1 - u)$$

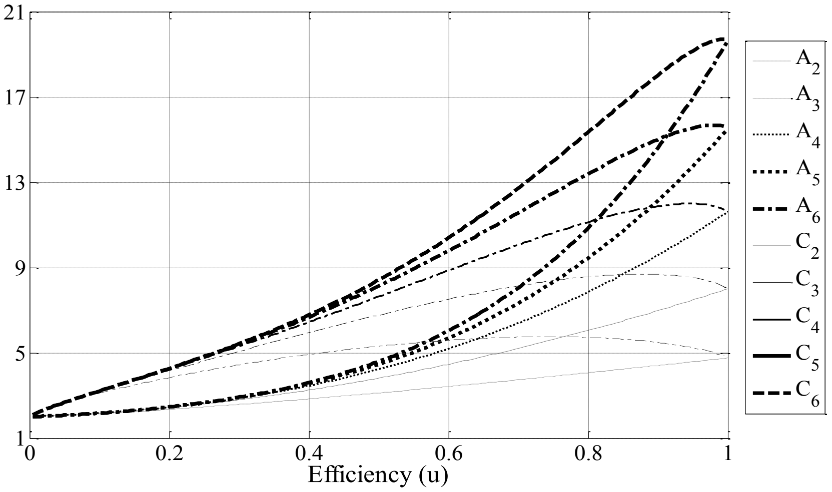
Fig. 3.14 exhibits variations of the system-level attributes and information indices according to variations in the number of compartments and the efficiency of each compartment within the test flow chain. In Fig. 3.14 (a)~(c), we observe that TST, AMI, acendency (A), and capacity (C) increase proportionally to the number of compartment and the efficiency, while complexity (H) peaks at an intermediate efficiency level and decreases. It is noticeable that TST exponentially increases after a certain level of efficiency, and this trend becomes intensified as the system adds compartments. Also, ascendency variation shows a similar trajectory. This result reveals that a system grows with an increase in individual compartmental efficiency, and augmentation of the scale of flow quantity has a strong leverage to that of ascendency.



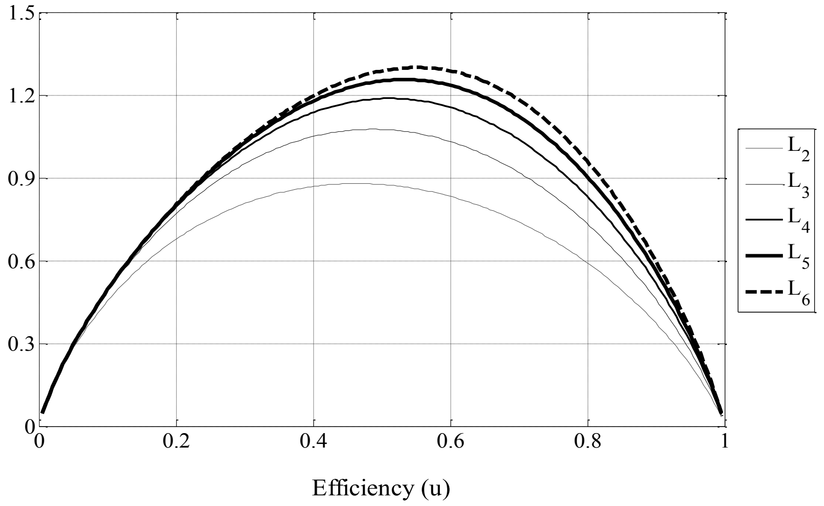
(a) Compartment efficiency and system throughput



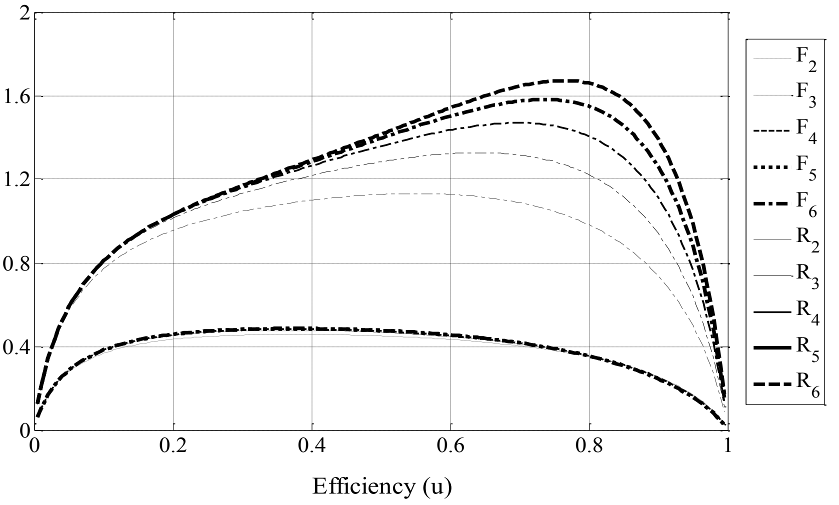
(b) Compartment efficiency and average mutual information (AMI) and complexity (H)



(c) Compartment efficiency, ascendency (A), and capacity (C)



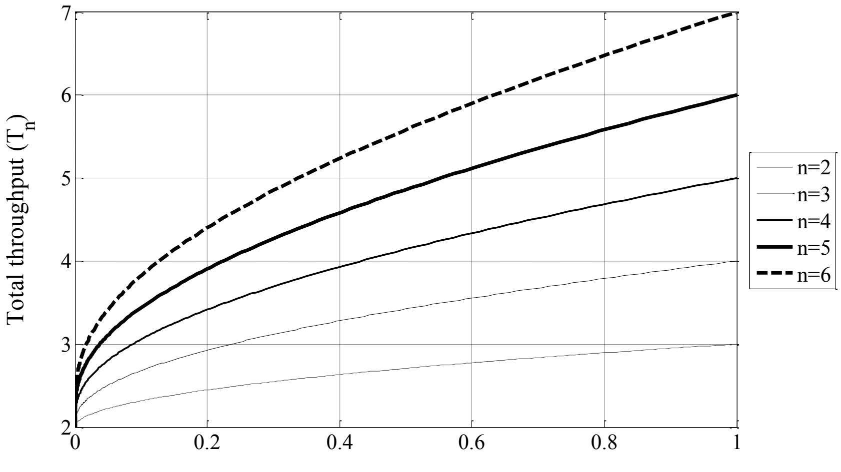
(d) Compartment efficiency and Resilience (L)



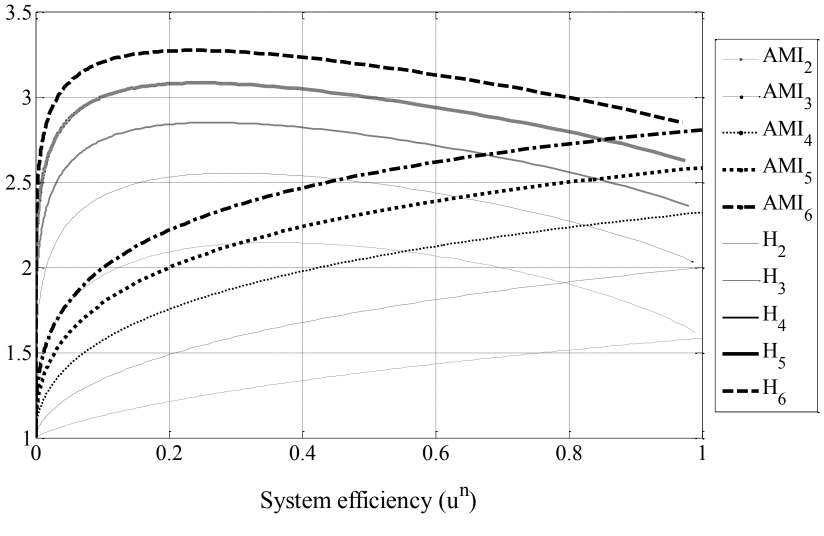
(e) Compartment efficiency, fitness (F), and robustness (R)

Fig. 3.14 Compartment efficiency (u) and information indices

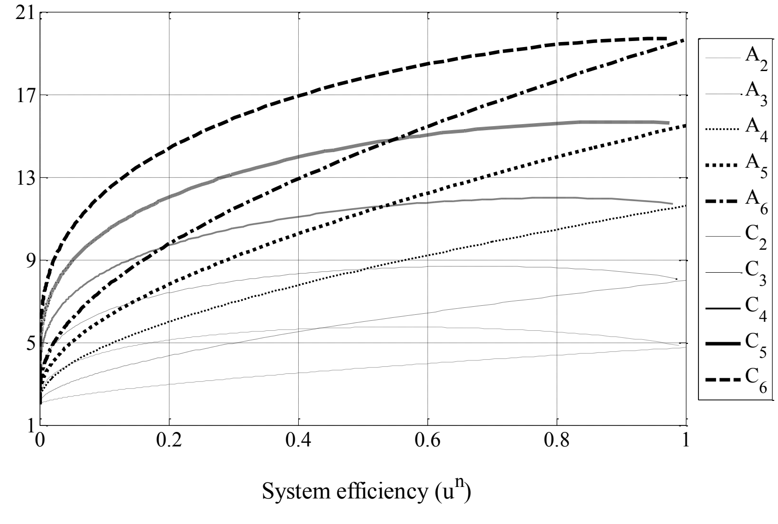
It is important to notice that AMI increases in parallel with the efficiency, because it substantiates that AMI is a surrogate of network-based efficiency. By definition (Shanon, 1948; Ulanowicz, 1986), AMI refers to a system's retaining ability of quantum on the pathways. Since greater compartmental efficiency ensures that more initial inputs stay all the way through the flow structure, we identify that a longer chain of a resource flow with high efficiency augments AMI. These phenomena are consistent with our conventional (mechanistic) understanding that increased efficiency followed by energy conservation assures system growth (greater TST) and development (greater AMI), as if it underpins that system sustainability gain advantage solely from thermodynamic minima (reduction of energy loss and greater efficiency). However, the profile of system complexity (H) and ecosystem indices pertaining mainly to system stability (resilience, fitness, and robustness) tell us that the system is likely to be unstable if the efficiency increases excessively (Fig. 3.14 (d) and (e)). Complexity profiles in Fig. (b) roughly follow the findings from the experiment with the single compartment model. Complexity (a proxy of system power) is maximized at about 50~80% efficiency, even though peak points of efficiency move up as the system expands.



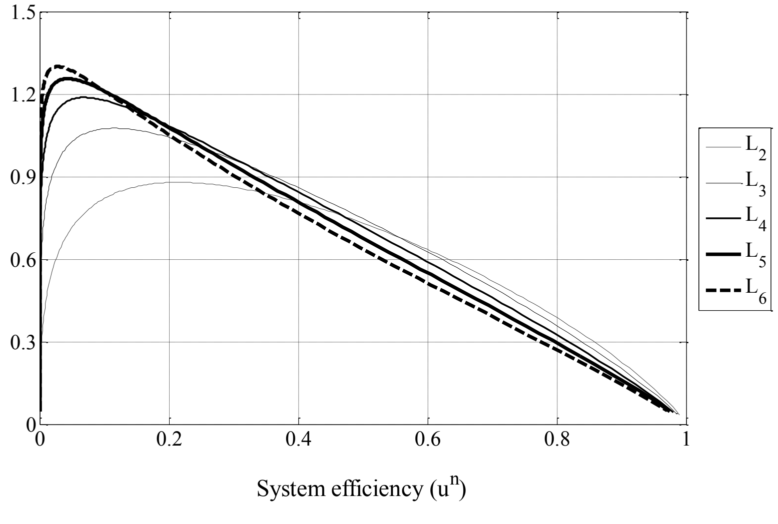
(a) Whole system efficiency and system throughput



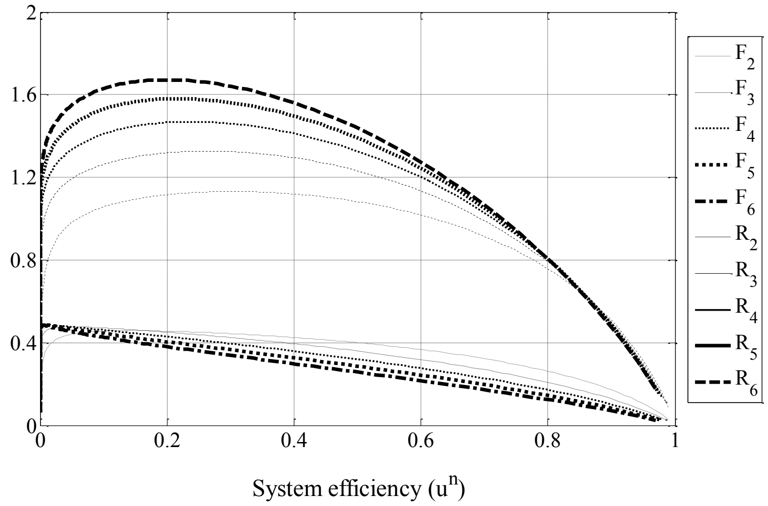
(b) Whole system efficiency and average mutual information (AMI) and complexity (H)



(c) Whole system efficiency, Ascendency (A) and Capacity (C)



(d) Whole system efficiency and Resilience (L)



(e) Whole system efficiency and fitness

Fig. 3.15 System efficiency, AMI, fitness, and robustness (bits)

In Fig. 3.14, Resilience (L) profiles look similar to complexity (H), but maximal values appear within a narrow and lower range of efficiency. Fitness (F) is maximized relatively earlier at around 20~30% efficiency, when the system is under development (lower AMI and H). It proves that an environmental system is likely to be more flexible (adaptable) before it is fully organized (structuralized in flow network configuration). It is interesting to observe that system robustness increases along with the increase of capacity and sharply drops after a peak point.

These findings clearly show that augmentation of compartmental efficiency is not always conducive to the intensive system-level properties such as system's power accumulation, potential of reorganization, adaptability to environmental change, and resistance to perturbation (strong forcing function from the external sources). In order to identify that an external observation of efficiency aquires with the above findings, indices are coordinated with the whole system efficiency (u^n) (Fig. 3.15).

Interestingly, the increasing tendencies of TST and AMI at high efficiency slow down. System complexity (H) increases with growth of the system. However, comparing to Fig. 3.14, H is maximized around a far lower level of efficiency (about 10~30%), and the efficiency of maximum uncertainty moves down as compartments are added (system growth). This finding makes sense along with the fact that ecosystems trophic level efficiency is often around 10% or less. The system grows with increased number of compartments and fluxes, but slowdowns of the AMI and capacity increase show that increased efficiency sets a certain limit on the system development. Similar to the complexity trajectory, resilience, fitness, and robustness are also maximized at low efficiency and this trend tends to be intensified as the system flow network is more complicated (Fig. 3.15 (d) and (e)).

From the whole system perspective, thus, system descriptions of internal states can be very different, because the whole system efficiency does not parallel compartmental efficiency. Accordingly, it turns out that

AMI is network efficiency but it should be distinguished from the efficiency of a unit process. Lowering system efficiency for greater AMI looks incompatible with the general notion of sustainability.

Nevertheless, as shown in Fig. 3.16, system efficiency and AMI have an inverse correlation, since total efficiency of coupled compartments is, according to the SLT, always less than that of a unit transfer. Looking back into Fig. 3.15 (b), it is clarified why a developing system sacrifices efficiency. The six-compartment model is far less efficient than the two-compartment model, but, in general, natural adaptation will prefer the six-compartment system because it has greater potential of carrying power (higher uncertainty in source selection, H). That is, this test implies that *system development goes through a trade-off between efficiency and complexity.* Higher complexity means less efficiency. However, the degrees of the complexity are not limitless, yet they are clearly bounded, as less efficiency (or too much AMI) results in lesser power (Fig. 3.14). At this point, it recalls the Ulanowicz's statement that maximum AMI is not desirable for self-organizing ecological communities and, so, an ecosystem in a steady state would find an optimal level of system efficiency and AMI to increase fitness, resilience, and power.

To summarize the terms of information indices, the ratio of AMI and H (AMI/H) refers to developmental (organizational) efficiency of system flow networking, while system complexity is a proxy of the potential developmental power. Resilience and fitness are significant attributes for examining developmental adaptability. However, increasing tendencies of H and L do not necessarily coincide (Fig. 3.17). A complex system network tends to have greater H and L, but they are maximized at different developmental levels. Therefore, we can suppose that an environmental system maximizes resilience when increasing power is not available with current resource availability. The system status can move back and forth between maximum power and maximum resilience, by switching priority depending on an external thermodynamic constraint. Nevertheless, it is clear that a general tendency towards sustainability is to increase both.

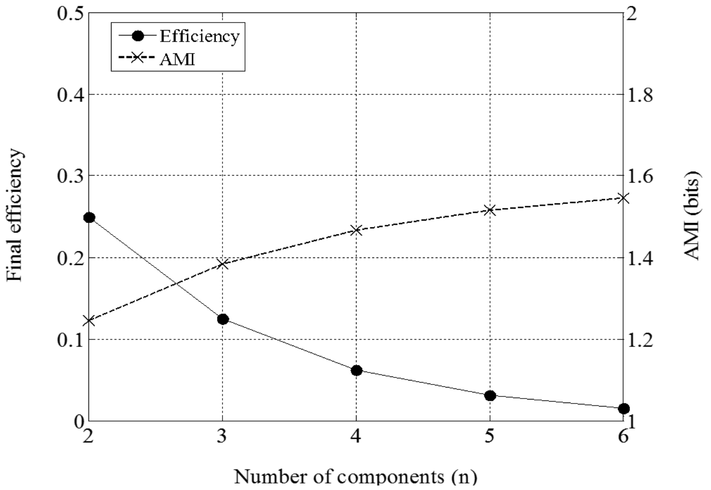
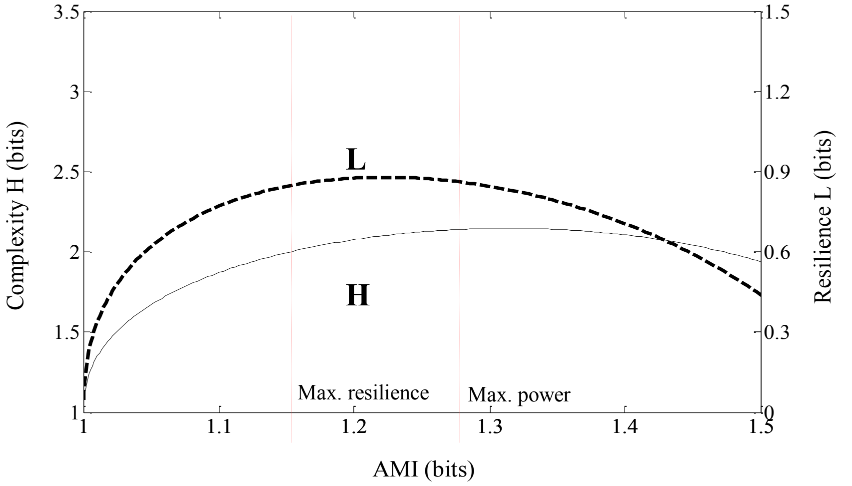
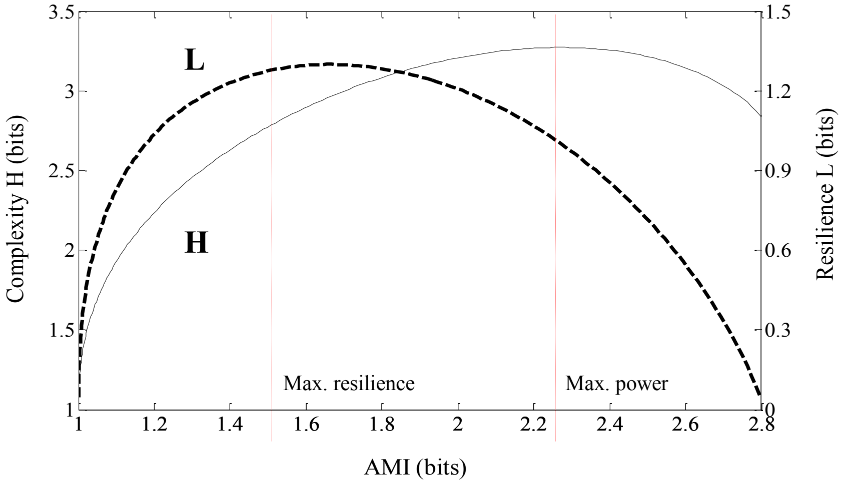


Fig. 3.16 Final system efficiency and AMI



(a) Two-compartment model



(b) Six-compartment model

Fig. 3.17 Variation of complexity (H, total system uncertainty) and fitness

3.3.3 Application of an ecological understanding to building systems

3.3.3.1 Pros and cons of the eco-centric approach

This dissertation attempts to demonstrate that the ecosystem principles (maximum power, increasing fitness and resilience, and optimal efficiency) are applicable at a building scale and to different types of building systems. However, even though the thermodynamic principles obtain generality in many disciplines, and also provide a great deal of advantages in the description of causality of system events, conceptual utility of ecological principles and appropriate interpretation of mathematical measures have been demonstrated primarily by empirical evidences of natural environment. Some hypotheses for thermodynamic understanding are also structured with "phenomenological" terms. For these reasons, they do not always aling with outright acceptance. Paul Stoy (2010) criticizes that, to some extent, "all ecosystem theories are: (i) overly abstract, (ii) oversimplified, (iii) not universally applicable, or (iv) too difficult to test." In effect, the Odum's maximum (em)power principle does not articulate a full insight for development in harsh environment and a dynamic setting (i.e., scarcity of resources and disturbance) (Odum and Pinkerton 1955; Stoy 2010; Ulanowicz 1980). Ulanowicz's ascendency principle also draws a limit due to (i) lesser number of rigorous empirical tests and (ii) selection of flow metrics[35] (Odum 1996). Admittedly, both theories rely on a network construction, which suffers from lots of uncertainty arisen mainly from (i) difficulty in estimating unknown medium values (parameter uncertainty) and (ii) modeling (there may exist some network pathways unknown to an observer.) (Ulanowicz 1986; Stoy 2010).

However, in spite of some disputes in the biological community and problems of data approximation and system modeling, a comprehensive biological view of sustainability provides an effective theorems and tools to newly and correctly apprehend building form and function. Even though the emergy and ascendency theorems are primarily developed for living systems, those conceptual principles can be applied to building study, since growth and development are general phenomena in all environmental disciplines, regardless of temporal intervals or physical scales (Odum and Pinkerton, 1955; Ulanowicz, 1986). Even if the treatment of growth and development as independent variables remains problematic, it is significant to notice that Eq. (3.9) ~ Eq. (3.12) couple external factors (T) and the internal

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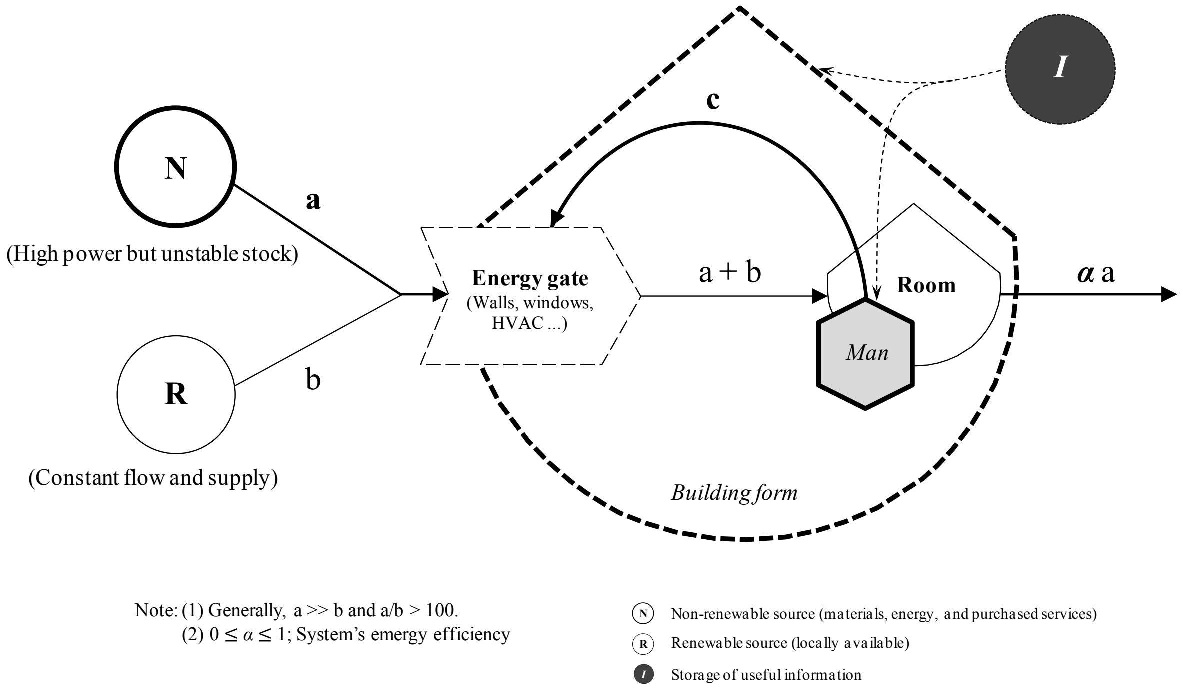
[35] Howard Odum mentions, "It is better to use emergy rather than energy (Odum, 1996)."

factors (H, AMI), which agrees with our hypothesized equation for quantifying holistic building sustainability (Eq. 2.1). Depending on the type of a flow quantum (e.g., energy or mass) for the throughput parameter (T) and identification of information gain (H, AMI), we find Eq. (3.3) also strongly parallels it. This formulaic parallelism encourages the practical utility of informational indicators for the building sustainability assessment. Adaptation requires some technical treatment followed by theoretical articulation.

3.3.3.2 Pilot test: Hypothetical experiment on the generic building network model

Information-based ecosystem indices do not include the whole building's information content. They account for "thermodynamically useful" content of whole building information, so they identify system-level building performance and sustainability. It is by incorporating an emergy unit into the information indices, that building performance and sustainability can be characterized at the global-system level.

To verity applicability of ecosystem indices and system interpretations to building thermodynamics, the following generic building system was designed to emulate the metabolism of a living system as simply as possible (Fig. 3.18).



Note: (1) Generally, a >> b and a/b > 100.
(2) $0 \le \alpha \le 1$; System's emergy efficiency

Ⓝ Non-renewable source (materials, energy, and purchased services)
Ⓡ Renewable source (locally available)
● Storage of useful information

Fig. 3.18 Generic model of the building metabolic system: Information is a substantial environmental resource that is plentiful and readily available (thus, it functions as a surrogate of renewable source). However, the size and capacity of its storage are unknown, and cannot be measured directly. Information is measured only by observing changes in the configuration of flow networking.

System design and parameters

This network model was designed to have primary building components only, and was drawn with Odum's emergy diagram symbols. Flow quantity over each path indicates the emergy value of each flow. Most physical elements that are in charge of building energy transactions (e.g., building façade, mechanical equipment, windows, doors) were lumped into a single component named energy gate. It was assumed that the building has three categories of environmental sources: renewable (R) and nonrenewable (N) that include both energy and matter and information (I). However, despite its importance, building information is accumulated from a storage whose capacity and location is unknown. So, this model monitors pattern changes of the emergy flow networking to detect its effects. This is because (1) information content is only measured by observing the change in system organization; (2) the two external sources (R and N) have distinctively different characteristics (stock-constrained and flow-constrained); and (3) this test aims in part to demonstrate that information-based performance indication is not incompatible with the common notion of building sustainability (e.g., reduction of nonrenewable energy use). Emergy gained from the resource reservoir through the energy gate is transmitted to interior space (room and man), and computed as $a+b$ according to the emergy accounting rule. Behavioral interactions (opening windows, lighting control, etc.) that control the energy gate and any feedback from interior space to other building components were represented as a backward flow (c). The building system yields a useful product, but it can be varying depending on the (emergy) efficiency of the space. As for the system, total system throughput (TST, T) is a function of four parameters and computed by adding up all flow quantities such that:

$$\mathbf{T}(\mathrm{a}, \mathrm{b}, \mathrm{c}, \alpha) = (2 + \alpha)\mathrm{a} + 2\mathrm{b} + \mathrm{c}$$

And H, AMI, and resilience are calculated respectively as follows:

$$\mathbf{H}(\mathrm{a},\mathrm{b},\mathrm{c},\alpha) = log\mathrm{T} - \frac{1}{\mathrm{T}}\{\mathrm{a}log\mathrm{a} + \mathrm{b}log\mathrm{b} + \mathrm{c}log\mathrm{c} + (\mathrm{a}+\mathrm{b})\log(\mathrm{a}+\mathrm{b}) + \alpha\mathrm{a}log\alpha\mathrm{a}\}$$

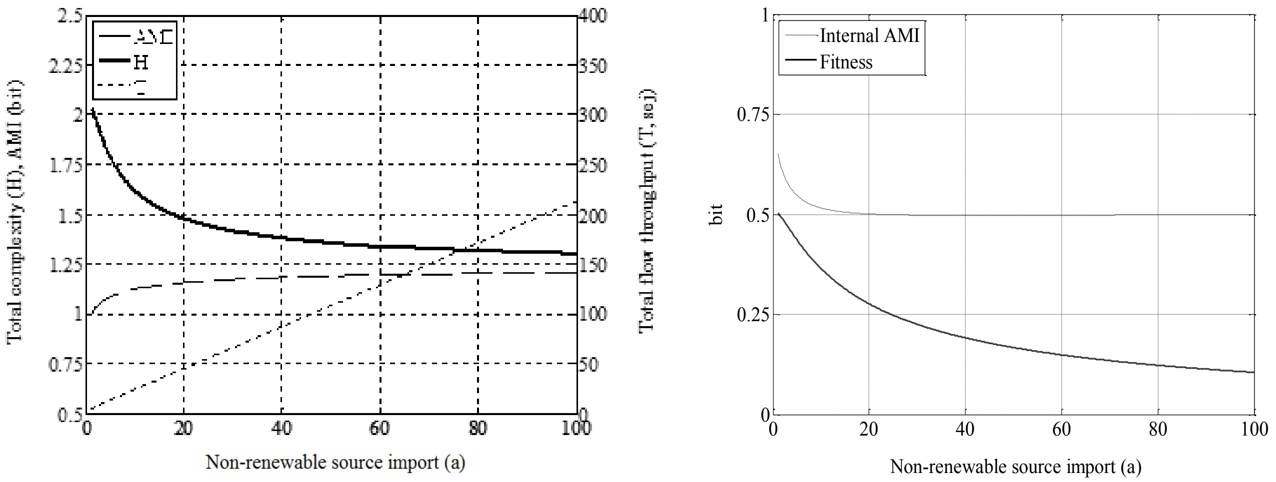
$$\begin{aligned}\mathbf{AMI}(\mathrm{a},\mathrm{b},\mathrm{c},\alpha) = log\mathrm{T} - \frac{1}{\mathrm{T}}\{&(\mathrm{a}+\mathrm{b}+\mathrm{c})\,log(\mathrm{a}+\mathrm{b}+\mathrm{c}) + (\mathrm{c}+\alpha\mathrm{a})\,log(\mathrm{c}+\alpha\mathrm{a}) \\ &+ (\mathrm{a}+\mathrm{b})\,log(\mathrm{a}+\mathrm{b}) \\ &-\mathrm{c}log\mathrm{c}\}\end{aligned}$$

$$\begin{aligned}\mathbf{L}(\mathrm{a},\mathrm{b},\mathrm{c},\alpha) = \frac{1}{\mathrm{T}}\{&(\mathrm{a}+\mathrm{b}+\mathrm{c})\,log(\mathrm{a}+\mathrm{b}+\mathrm{c}) + (\mathrm{c}+\alpha\mathrm{a})\,log(\mathrm{c}+\alpha\mathrm{a}) - \mathrm{a}log\mathrm{a} - \mathrm{b}log\mathrm{b} \\ &- 2\mathrm{c}log\mathrm{c} - \alpha\mathrm{a}log\alpha\mathrm{a}\}\end{aligned}$$

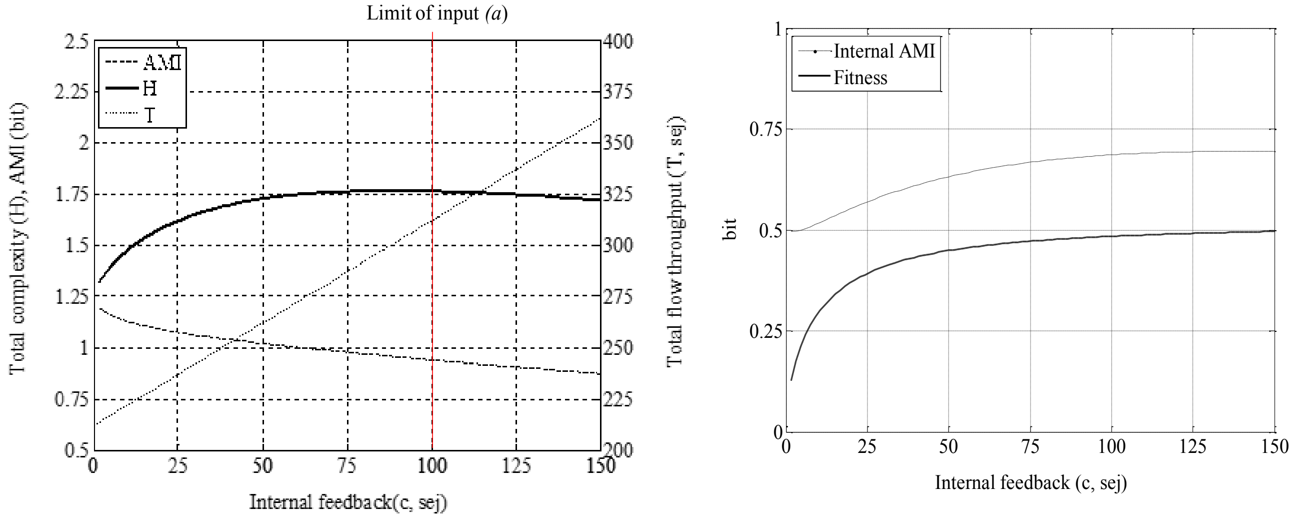
System ascendency and capacity are calculated by multiplying AMI and H by the system scale (T).

Test results

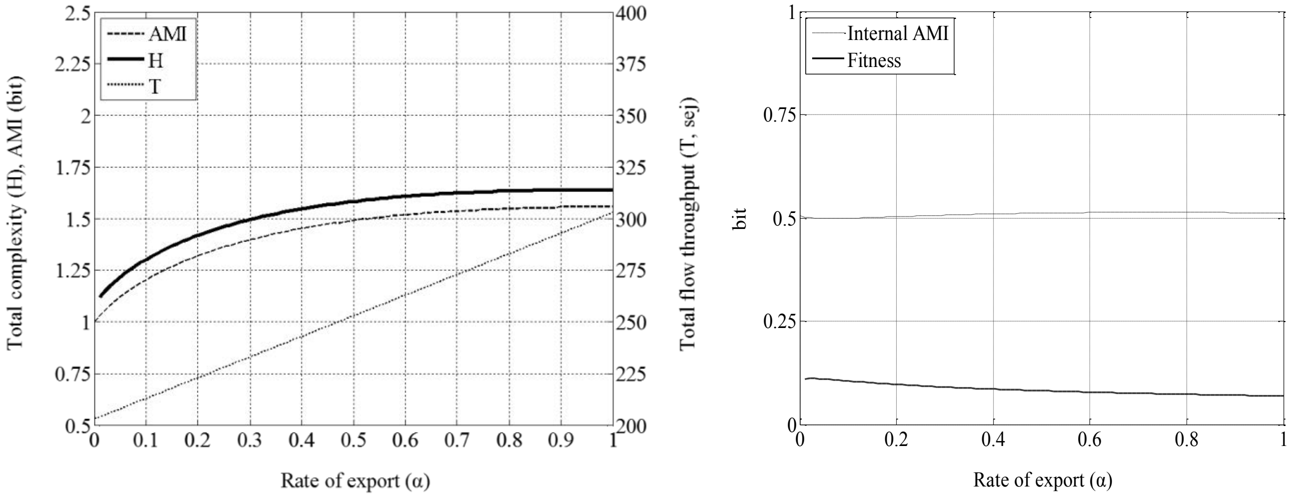
In order to identify the influence of each parameter and their contribution to building sustainability, tests were conducted with variations of individual parameters (Fig. 3.19 and 3.20). First, to confirm the consistency of information-based examination and the general notion of building sustainability, information profiles were observed by changing the nonrenewable source import (a) with other parameters fixed (Fig. 3.19 (a)). Results show that reducing nonrenewable source use triggers an increase of complexity (H), i.e., system power, while adjusting AMI to a lower level. Another sign of sustainability is an increase of fitness. We can observe that both complexity and fitness sharply increase as the system self-organizes to significantly reduce nonrenewable emergy flows. Similar trends are found with activation of feedback flows (c). In Fig. 3.19 (b), feedback increments cause the system to have greater power (H) as well as greater fitness with low AMI. This means that an engagement of the feedback loop in system networking (e.g., human activities for building energy control) contributes to achieving sustainability. That said, it is noteworthy to see that the system may collapse if the feedback is excessive beyond input quantity. Fig. 3.19 (c) shows that increased emergy efficiency (α) is conducive to gain greater power (H). However, as opposed to the previous tests, it helps to augment system organization (AMI), whereas it decreases adaptability (fitness). It tells us that appropriate partitioning of export and feedback would be significant in determination of a degree of sustainability.



(a) a=[1,100], b=1, α=0.1, c=1

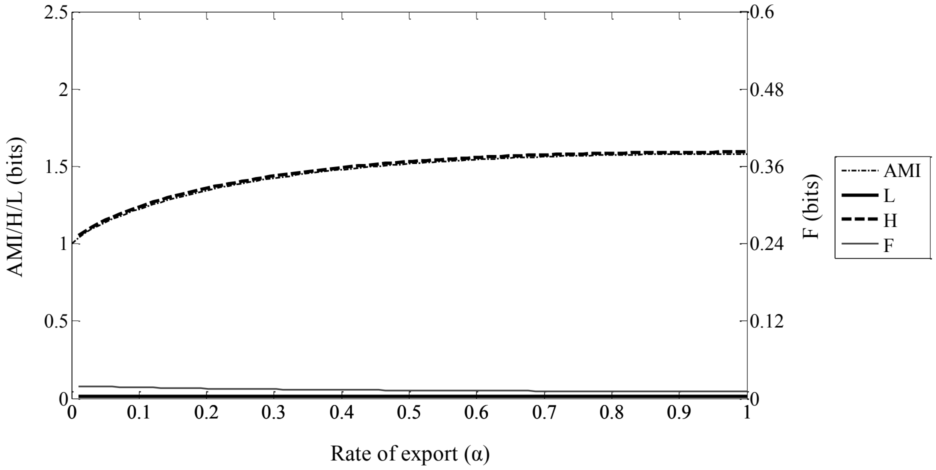


(b) a=100, b=1, α=0.1, c= [0, 150]

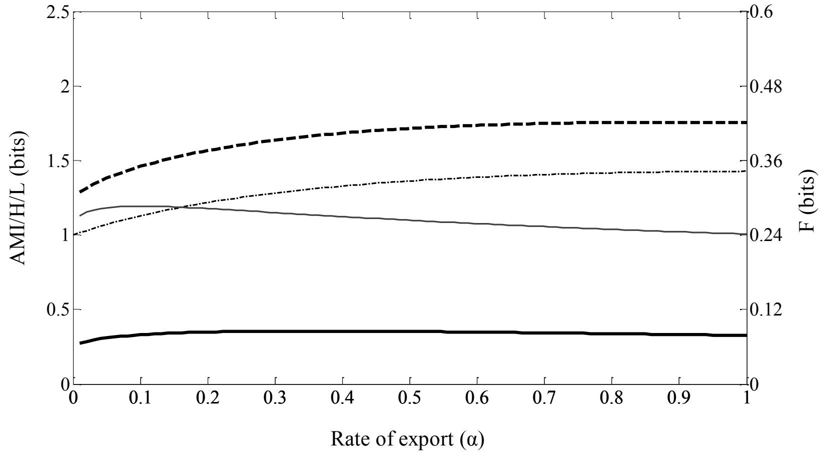


(c) a=100, b=1, α=[0,1], c= 1

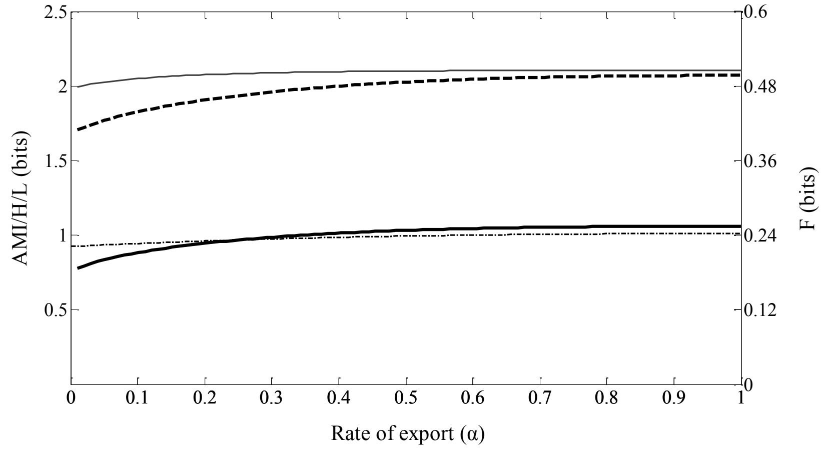
Fig. 3.19 Results of the pilot test



(a) a = 1000, c= 1, b=1



(b) a = 200, c= 20, b=1



(c) a = c= 20, b=1

Fig. 3.20 Results of the pilot test: Export rate and information change

Findings from Fig. 3.19 demonstrate that reduction of nonrenewable source use, increment of internal recycling or feedback, and greater export rate contributes to maximizing system power and sustainability. It is consistent with the ecosystem-based argument of sustainability that "a self-organizing mechanism that eliminates any one pathway from being more limiting than others is contributable to the maximum processing of the available energy (Odum, 1995; Hall, 2004)", because, by definition, greater complexity (H) refers to greater uncertainty in source selection and flow distribution.

MePP coherently works for examining performance and sustainability of natural systems, for they do not use nonrenewable sources for development in general. Application of the principle to built environment, however, seems to be incompatible. In other words, in terms of ecosystem development, it is contradictory to define a building of reduced fuel use as a sustainable system, because it is likely to carry low power. However, as hypothesized, by incorporating information as a significant environmental source of the building, MePP clearly accounts for this paradox. Even if we do not perfectly clarify the origin and capacity of building information sources for now, it is a high-quality (large transformity), almost limitless, and quasi-renewable source (Odum, 1988). Building energy reduction due to an environment-conscious control, accordingly, justifies a far greater emergy inflow and greater empower involving information. By the same token, it can be assumed that even though the building system undergo a TST decrease (without presence of information), system complexity (H) can increase as an indication of system development and sustainability, because, in effect, reduction of flow quantity from the renewable and nonrenewable source is not possible without an increase of information. Then, it eventually turns out that the building ends up having an increased TST and capacity (N+R+I). The presence of information in the processing of energy reduction can be proved by activation of the feedback loop (particularly an increase of resilience that highlights potential human intervention in flow networking).

Fig. 3.20 demonstrates this assumption. Having the renewable source flow constant as a unit quantity (b=1), we identify that an increase of the feedback flow (c) to 20 with decreased nonrenewable flows (a; from 1000 to 20) eventually leads to a higher state of system resilience at the expense of efficiency (AMI). In terms of network configuration, resilience shows that securing redundant flow pathways (making the system more complex) is desirable to increase power (from information) rather than creating an efficient (autocatalytic) connection. Since resilience and adaptable stability concern the accumulation of information content, utilizing an information source could be a very effective type of development, especially when environmental conditions are so stressful that amount and sorts of resources are limited to choose.