Building and Environment 84 (2015) 89–104

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

An integrated energy–emergy approach to building form optimization: Use of EnergyPlus, emergy analysis and Taguchi-regression method

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form
17 September 2014
Accepted 13 October 2014
Available online 29 October 2014

Keywords:
Energy simulation
Emergy evaluation
Building form optimization
Taguchi-ANOVA method

ABSTRACT

This research presents a new methodology of environmental building design with an integrated energy–emergy (spelled with an “*m*”) approach to study building form optimization in the schematic phases. In architecture, selection of sustainability assessment methods critically affects design goals, favoring or restricting choices designers can make. A building subsumes matter and energy to support human lives, but current building performance indicators are still hard to equate technical sides and human dominant sides of various scales in a synthetic metric. Moreover, in order to achieve global sustainability in a building, as a part of the whole built environment, it is necessary to integrate energy and environmental impacts at the highest scope of analysis. Emergy analysis coupled with building energy simulation can be suggested as a holistic indicator for architectural design process. To test the proposed method, a pilot study with a mid-size office building evaluates the consequences of early design decisions such as basic geometry, aspect ratio, window-wall ratio, construction types, etc. The integrated energy–emergy approach to building form optimization consists of three modules namely, Building Energy Simulation (BES) module, Building EMergy Analysis (BEMA) module, and (iii) MetaModel Development (MMD) module. The BES module uses the EnergyPlus tool for whole building energy analysis, while the BEMA module employs analytical methods to estimate emergy quantities, and the MMD module employs the Taguchi method to develop a metamodel for faster and easier whole building emergy simulation. The metamodel developed using Taguchi-ANOVA method for building form optimization was validated with analytical test results to accelerate environmental design decision-making. This study demonstrates possibility of wider applications of emergy synthesis to building energy research and facilitates practical use of emergy simulation in the environmental design process.

1. Background

Nowadays the building production process is subjected to careful scrutiny based on growing environmental concerns. Architectural design processes towards “green” building, in which the domain of technology and aesthetics must be integrated, have also been advised by the assessment methods for environmental performance and potential impacts. From the point of view of architects whose desire is to achieve the optimal use of resources through a built form, definition and scope of environmental analysis strongly influence their design results and transform architectural style at the end (e.g. large solar panels on a rooftop). So it is required to ensure that system boundaries and metrics of the indicators are congruent to the full definition of building.

A building is a thermodynamic engine maintaining thermal balance constant for human dwelling, and it consumes global resources in the form of matter [1]. Most of the inputs are sourced beyond a site or local contexts in the way of production or delivery. For example, primary sources of operational energy are imported in whole or in part, and the building materials are manufactured with the elements extracted off-site. Besides, the quality of human labors and the states of social/cultural systems outside buildings are another concerns in the energetic exchanges. Those characteristics of building lead to identification of the sustainable buildings in terms of ecology, which says, a sustainable built form has the least impact on a natural cycle, and it belongs to larger environmental contexts including history and society [2,3]. Therefore, in an ecological sense, we must say that heat flows in a building

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http://dx.doi.org/10.1016/j.buildenv.2014.10.013

Nomenclature

SS_T	sum of squares
SS_A	sum of the squares of the S/N variation induced by parameter *A* around overall mean
SS'	pure sum of squares
SST	total sum of squares
MSS	mean sum of squares or variance
V_e	variance of error
θ	building orientation
AR	aspect ratio
W_{S1}	south-facing window-to-wall area ratio
W_{S2}	east-facing window-to-wall area ratio
W_{S3}	north-facing window-to-wall area ratio
W_{S4}	west-facing window-to-wall area ratio
M_1	insulation level measured in *U*-value for South and North walls
M_2	insulation level measured in *U*-value for East and West walls
ΔEm	emergy change amount
ΔEUI	change amount of energy use intensity
C.F.	correction factor
df	degree of freedom

ultimately relate to the thermal/resource balance of the largest environment system, namely, the earth. Monitoring the scope of mass/energy inflows to buildings is accordingly expected to be enlarged to the "maximum" extent to attain global sustainability [4,5].

Currently, there exist a number of elaborative environment assessment techniques such as embodied energy analysis, Life Cycle Assessment (LCA), or exergy analysis as well as the credited standards (e.g. Building Research Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Zero Energy Building (ZEB)) developed and applied in order to constrain resource consumption in increased energy efficiency. The green building standards (BREEAM, LEED) are comprehensive evaluation methods employing lists of indictors. The advanced efforts such as extended exergy analysis [6], LCA-ZEBs [7], renewable potential LCA [8], have attempted to acknowledge better different building typologies, materials, heat sources, and project boundaries, thereby encouraging building practitioners to adopt time and cost effective strategies.

Despite significance of the existing indicators at multiple scales from their physical aspects (e.g. geometry, construction types, interior conditioning, lighting, etc.) to social mechanisms, of human behavior systems, and at various perspectives (e.g. cost, source, emission, etc.) [9], they generally overlook to link the built environment effectively with loads of the larger geobiological systems, including solar, wind, other renewable and non-renewable resources, and ecosystem services [10,11]. Embodied energy calculates energy demands only from extraction of material, and it discounts the environmental loads in the material formation process in nature. Although some current LCA-based tools, both sector and process-based, have attempted to describe a building as a conscious thermodynamic engine over its useful life [12,13], they still brush aside the thermo-physical makeup of a building that illustrates energy networking of nature for raw material formation and human/social services. The thermo-physical composition also informs the ways in which people choose to utilize the building systems, with direct implications for the amount of operational energy that building occupants consume. Therefore, a holistic approach such as emergy that can analyze systems of different types and scales, and human communities, with a common indicator, is necessary to address the utmost sense of building sustainability and to provide synthetic information for facilitating energy benchmarking in the global energy flow context.

1.1. Introduction to the emergy analysis

Emergy, pioneered by H.T. Odum, refers to past available energy use to measure mass/energy flows in and out of an open ecosystem in thermodynamic accounts. By definition, it is the available solar energy or solar embodied energy used up, directly and indirectly, to make a service or product [14]. Emergy study set off with the question as to how to measure behavior of dynamic living systems. In the early 1900s, Alfred Lotka, a biophysicist, found that an ecosystem tended to increase total energetic power, rather than efficiency, to achieve population growth, biomass production, and self-organization. This process of obtaining maximum power could be generalized to describe the development of ecosystems. From that principle, H.T. Odum proposed use of emergy to quantify this process in which an energetic flow *i* is simply computed by

$$\boldsymbol{Em_i} = E_i \bullet Tr_i \tag{1a}$$

where *Em* denotes solar emergy of energetic flow, E_i is energy or mass input, and Tr_i is transformity that refers to specific emergy value of the input. Transformity means "emergy input per unit of available energy output" [14] and represents quality or value of energy. It is usually obtained from previous studies, emergy database, or rarely, derived from the global baseline so that it becomes a sort of property of energy and matter of a system component simultaneously.

Even though the maximum power conception is not yet fully demonstrated in the characterization of building systems, it reveals the causality for energetic shifts discovered in ecology and implies that terms of emergy can be directly applied to the analysis of building energy dynamics [4,10]. The reason for this is because a building, much like any creature, thrives through energy exchanges. Buildings behave theoretically like a thermodynamic engine that requires a great deal of energy concentration and transformation for its birth (construction), life (operation and maintenance), and in some cases, death (deconstruction). Consequently, emergy analysis provides building environment research with the following three major strengths based on the emergy theory's fundamental hypothesis that all energetic forms on the earth find their sources from solar, tidal, and deep heat.

- Emergy is the most effective synthetic tool for linking environmental science to the goal of building for sustainability.

Emergy identifies the earth with a gigantic open ecosystem and traces the origin of all energy generation to solar energy. So emergy evaluation integrates different metrics of resource use in a single measure of solar equivalent; solar emergy joule or *sej*. Among energy accounting related indices, few provides synthetic information in a single unit. Emergy can be an alternative to existing indicators used for switching and converting different metrics in the same way as primary energy use or CO_2 equivalent enabling the easier comparison of much broader environmental effects.

- Emergy combines natural process and human-dominated system.

A building is always situated within specific living contexts. Local climate, state of ambient settings, and social/cultural infrastructures are closely associated one another with a particular