Habitat patterns and their environmental implications

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1 ABSTRACT

This paper deals with the evaluation of the environmental implication of the built environment. Specifically, it argues in favor of evaluative strategies that transcend single-criteria object-focused thinking.

Keywords: Habitat, environment, life-cycle, evaluation

2 INTRODUCTION

Traditional approaches for the evaluation of the performance of the built environment have been limited in two respects:

- The analysis domain has been often limited to building components or – at most – whole buildings. Contextual and regional issues have been often neglected. While the constitutive elements of a building can be evaluated in terms of economic and environmental criteria, a meaningful environmental evaluation of building products must go beyond the production phase. Building products must be transported to a construction site and be put together, resulting in various environmental effects. Moreover, the nature and quality of these products has an enduring effect on the operation and decommissioning phase of the whole building life-cycle (energy use, maintenance, renovation and overhaul, etc.). Yet even the whole building level is not the appropriate "balance domain" for life-cycle analysis as applied to building activities. In order to evaluate the environmental impact of a building design, the region and context in which a building is sited cannot be ignored. This is true in the simple case of estimating operational energy use, where the micro-climatic context of the building and, to some extent, the building's orientation are important. It is also true in estimating environmental impact, where the impacts from material selection, construction methods, operation, and decommissioning will depend on the proposed building location. For example, the energy used by one person to commute by automobile can equal or even exceed one person's share of the annual energy used to provide heating, cooling, lighting, and electrical power to the building where he/she works.
- Building evaluation criteria have been typically limited to first cost and energy use. Early approaches toward the evaluation of the environmental performance of buildings concentrated on energy consumption. Subsequently, additional factors such as the embodied energy (of the products involved) and CO_2 emissions were considered. Recently a consensus has recently emerged that more comprehensive criteria must be considered, if a meaningful evaluation of the environmental performance of alternative solutions (for building components, whole buildings, and regional planning issues) is to be performed. Specifically, life-cycle assessment (LCA) has emerged as a comprehensive approach toward environmental evaluation of products and processes in general and built environment in particular. LCA is defined as a four step process (Fava et al. 1992, 1991) consisting of goal definition and scoping, which defines the objectives of the study and determines the analysis boundary; inventory analysis; impact analysis; and improvement analysis, which is an evaluation of the environmental loads identified in the previous stages in order to determine modifications to the product or process that will reduce environmental impact. Life cycle inventory is a summation of the environmentally relevant aspects of the system under study. Life cycle impact analysis evaluates the effects of the constituents of the life cycle inventory. The methods developed have used a number of different strategies. The most straightforward and simple methods use factors such as energy use or pollutant emissions as indicators of environmental performance. Other methods use categorization and weighting strategies. These gauge the effects of the emissions and use a weighting or effect formulation to normalize, compare, and group emissions so that a single indicator value or multiple values can be calculated. While LCA-based environmental impact assessment methods have improved considerably, limitations remain. Generally speaking, current environmental impact assessment tools for buildings do not fulfill the strict definition of a simulation as a model of the processes in a system that enables one to gain transparent information and understanding about its functionality and behavior. Toward this end, a simulation of environmental impact must be more than an application of an accounting method.

The present contribution first quotes an illustrative case to demonstrate the importance of contextual factors in the environmental performance of buildings (section 3). Subsequently, a computational perspective is presented to support comprehensive simulation-based evaluation of the environmental performance of the built environment (section 4).

3 AN ILLUSTRATIVE EXAMPLE

3.1 Motivation and background

We argued that a comprehensive evaluation of the environmental implications of building construction and operation cannot be carried out as long as the analysis domain is limited to individual buildings. Rather, the region and context in which buildings are to be located must be considered. To illustrate this point, we compared in a previous study (Mahdavi et al. 1998) two distinct patterns of settlement in view of their environmental implications. The first pattern involved a suburban residential component, with offices, retail, and entertainment located in downtown as well as in suburban malls and office parks. The dominant mode of transportation was in this case private and individual. The second pattern involved a mix-use compact urban setting with a predominantly public mode of transportation. This comparison seems to be particularly relevant, as it is estimated that by the first quarter of this century, two-thirds of the world's population will live in an urban environment. Historically, urbanization has afforded residents opportunities for economic advancement and an improved quality of life, which continues to drive urban migration today. As compared to wide-spread suburban settlement patterns, denser urban formations make alternative means of transportation (such as mass transportation, bicycling, and walking) and energy production (such as cogeneration) viable, and generally, attached urban buildings have lower operational energy use. Additionally, providing an equivalent level of service infrastructure for an urban environment in a developed country is comparably less energy and resource intensive.

To capture environmental impact for the present comparison, we considered land use, as well as energy consumption and loads to water and air resources due to construction and operation of buildings and infrastructures. The comparison was performed using an original computational modeling tool named ECOLOGUE (Mahdavi and Ries 1998, Ries and Mahdavi 2001a). ECOLOGUE estimates environmental impact of buildings over their life cycle. The life cycle of buildings is defined as acquisition of materials, construction and operation of the building, and eventual decommissioning. The approach toward environmental impact analysis applied for this specific case study stems from the Eco-balance methodology (Etterlin et al. 1992, Müller-Wenk 1978). This methodology relies on two different strategies for quantifying environmental impact, namely "Critical Load Method" and "Eco-balance with Eco-points".

In eco-balance methodology, the first step is to define the "balance domain". The balance domain represents the region (or portion of the life-cycle) to be included in the evaluation which defines the parameters relevant for the analysis. The data which is relevant for the evaluation is called the "basis data". Generally, an eco-balance requires data pertaining to virgin and secondary material consumption, emissions of pollutants to the air and water, energy and water consumption, solid waste, and residuals. The values in the previous categories are grouped into energy consumption (in $MJ.kg^{-1}$ of material) as well as loads to water, air, and land (in $m^3.kg^{-1}$ of material). Energy consumption and solid waste volume (loads to land) are represented in their "natural units". Loads to the air and the water are handled differently. These values aggregate various emissions which have different levels of toxicity, so a simple volumetric unit would not describe the individual pollutants properly. The loads to the air and water are converted from units which represent pollutant volume, into a unit that expresses the volume of air or water which would be contaminated to its legal threshold limit by the pollutant. This value is called the "critical volume". The legal threshold limit represents a value reviewed and agreed upon through public processes.

The present case study is organized into six scenarios in which three family types (a family of four with young children, a retired couple, and a single person) in two alternative settlement patterns (suburban and urban) are considered. The environmental impacts for the two alternatives are measured in terms of production and operation of housing and transportation, which is derived according to the eco-balance method in terms of loads to air, loads to water, and energy use, and an additional land use indicator.

3.2 Assumptions

3.2.1 The Demographic Model

We assumed that the population consists of three equally sized social units. The first unit is a family of four, i.e., parents and two children (F4). We assume that there are two wage earners in the family, and that both commute to their respective workplaces. We also include other travel trips for shopping and errands, for daycare, and for recreation and entertainment. The second unit, the retired couple (R2), consists of two persons who no longer work. Travel trips for shopping and errands, and recreation and entertainment are included. The third unit, a single person (S1), commutes to a local workplace, and has additional travel trips for shopping and errands, as well as recreation and entertainment (for more details on the assumptions underlying this case study see Mahdavi et al. 1998).

3.2.2 Habitat Models

We assume that the social units described above may reside in an urban context (URB) or in a suburban setting (SUB). A summary of the scenarios is shown in Table 1. The suburban family scenario (F4-SUB) assumes conditions typical for a suburban family in the United States. The living quarters is a 170 m^2 detached wood frame house (DH-170) with a concrete foundation. The housing for the suburban retired couple (R2-SUB) is also a 170 m^2 detached wood frame house (DH-170). The single suburbanite (SI-SUB) is assumed to be living in a 130 m^2 detached wood frame house (DH-130). The housing for the urban family (F4-URB) is assumed to be of a similar construction as the suburban alternative, realized as a 140 m^2 attached row house (RH-140). The urban retired couple (R2-URB) is assumed to live in a 1.00 m^2 apartment in a multi-floor apartment building (AP-100). The single person in the urban environment (Sl-URB) lives in a 100 m^2 apartment (AP-100).

Social unit	Home type	Trips			
		Work	**Shops& Errands**	**Day care**	**Recreation**
F4-Sub	DH-170	C: 600 km	C: 280 km	C: 200 km	C: 200 km
R2-	DH-	none	C: 280 km	none	C: 200 km

SUB	170				
S1-SUB	DH-130	C:200 km	C: 200 km	none	C: 200 km
F4-URB	RH-140	PT: 100 km W: 10 trips	C: 35 km PT: 40 km W: 3 trips	W: 10 Trips	C: 100 km PT: 50 km W: 1 trip
R2-URB	AP-100	none	C: 20 km PT: 30 km W: 7 trips	none	C: 50 km PT: 100 km W: 1 km
S1-URB	AP-100	W: 10 trips	C: 20 km car PT: 30 km W: 3 trips	none	C: 100 km PT: 50 km W: 1 trip

Table 1: Summary of case study assumptions. Legend: F4-SUB: suburban family of four; R2-SUB: suburban retired couple; S1-SUB: suburban single; F4-URB: urban family of four; R2-URB: urban retired couple; S1-URB: urban single; DH: detached house; RH: urban row house; AP: apartment; C: car; PT: public transport; W: walking

3.2.3 Environmental Load, Energy Use, and Population Density

Table 2 summarizes the annualized aggregate (production and operation) assumptions for air load, water load, and energy use of the three housing alternatives. Table 3 summarizes the aggregate (production and operation) assumptions for the two transportation alternatives in terms of air load, water load, and energy use. The assumptions regarding the population density (10 persons/hectare for the suburban setting and 50 persons/hectare for the urban context) are derived based on data in a publication of the World Resources Institute (WRI 1996).

House	**Air load [$10^6.m^3$]**	**Water load [m^3]**	**Energy [MWh]**
Detached (DH-170)	128,3	315	36
Detached (DH-130)	103,2	280	32
Row house (RH-140)	100,7	235	27
Apartment (AP-100)	52,8	165	19

Table 2: Annualized production and operation air load, water load, and energy use indicators for three home types

Transportation	**Air load [$10^6.m^3$]**	**Water load [m^3]**	**Energy [MWh]**
Car (C)	5,8	19	1
Public Transport (PT)	4	3	0,5

Table 3: Production and operation air load, water load, and energy use for two transportation alternatives (for 1000 person-km)

3.3 Results

The results (aggregate relative environmental impact indicators for the two settlement types in terms of air load, water load, energy use, and land use) are presented in Figure 1 and Figure 2. Figure 1 illustrates that, for this specific set of assumptions (demography, settlement types and housing features, travel patterns, and emission and energy use data), the indicators in the urban case are about 30% of the value of the suburban case, on average. Figure 2 shows the results for each family type in both the suburban and urban locations. The indicators for all urban cases are all well below their suburban counterparts.

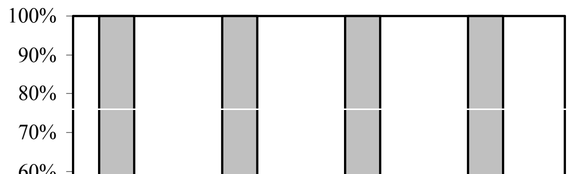

Figure 1: Relative values of the indicators for the sample population

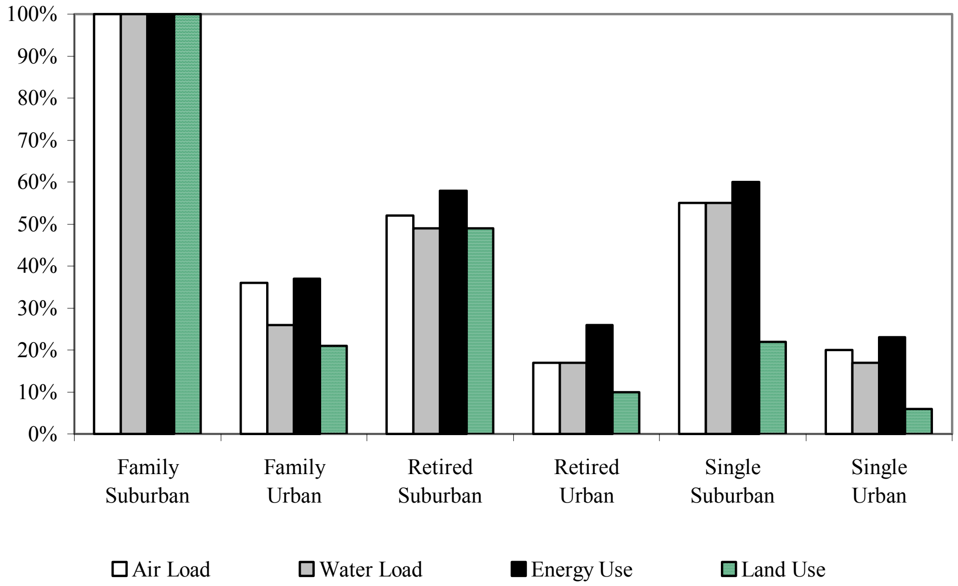

Figure 2: Relative values of the indicators for each social unit type and habitat pattern

3.4 Discussion

The above case study admittedly included a number of simplifications and was based on assumptions that are not meant to be generalized. Rather, the intention was to demonstrate the highly critical consequences of decision making in regional planning and urban design for the long term environmental sustainability of human habitats. The results do indicate the necessity to collect, analyze, and evaluate pertinent data on the environmental impact of alternative strategies and schemes for regional and urban development. Furthermore, such comparative models must become an integral part of high level strategic planning and social policy decisions pertaining to economy, population, and environment.

4 A COMPUTATIONAL PERSPECTIVE

4.1 Background

We argued that building artifacts must be modeled within a context and over time so that the interactions and dependencies between the region and building can be adequately explored. This requires support for an integrated life-cycle anylsis approach. Using computational design and evaluation tools is necessary to facilitate such context-sensitive analysis.

Numerous tools and methods have been developed that allow designers to compare the relative environmental impact of alternative systems, components, and materials. However, a number of limitations remain, two of which will be addressed here. First, environmental assessment tools for buildings are based less on what would typically be called a simulation than on an "accounting" approach. This approach multiplies a factor or group of factors that represent unit environmental impact and the quantity of the system, component, or material used in a building. Second, the majority of impact assessment evaluation methods are based on temporally and spatially aggregated values in an inventory of emissions over the project life cycle that does not consider the characteristics of the context where the releases occur.

A review of representative impact analysis methods and tools (Ries and Mahdavi 2001b) illustrates the progression of impact analysis since the early energy and pollutant mass methods. However, a number of limitations remain. General environmental impact factors cannot account for differences in the location and context, which are therefore not included in the analysis. In current LCA practice, impact analysis is often based on the life cycle inventory stage, which is a mass- or intensity-only accounting of pollutant emissions and material and energy use. This type of aggregation does not take into consideration the varying intensities (e.g., emission or use per unit time) that occur in actuality. A short-term high intensity emission release may aggregate to the same mass as a long-term low intensity release, although the environmental impact may not be equivalent. Aggregation also does not take into account the spatial distribution of an emission release. Emission releases equivalent in mass terms could be distributed over different volumes of media, result in different concentrations and therefore potentially different environmental impact. Emission inventories also do not consider the characteristics of the context or region where releases occur. As a result, the sensitivity of the context to an emission release cannot be included in the analysis. Additionally, most LCA impact assessment methods require a comparison of alternatives, but do not necessarily determine whether either of them are within the ability of the ecosystem to sustain the environmental loading over a period of time.

Current environmental impact assessment tools for buildings do not fulfill the strict definition of a simulation as a model of the functioning of a system so that information can be gained about a problem. Simulation of environmental impact that is based on more than an accounting method (i.e., a factor representing environmental impact applied to a given quantity of a component or material) requires the following capabilities. First, the tool must have the capability to model the activities relevant to environmental impact that occur in the building life cycle. These are the processes associated with material production, construction, operation, maintenance, and decommissioning. Second, the tool must have the capability to model the aspects of the environment that are relevant to impact assessment. A broad categorization of environmental impacts in the building life cycle are: impacts from the emissions of substances and energy related to an activity, whose effects include global warming, human health, noise, etc.; impacts from land use, whose effects include habitat and species diversity, and impacts from non-renewable resource use. Both of these sets of models are required to represent the interactions of the building and the environment that are relevant for environmental assessment and to evaluate the environmental impacts of buildings. The framework should be able to allow the user to construct life cycle models of systems from basic components. The designer can assemble process descriptions and then use these descriptions to calculate the relative environmental impact. Aggregate models can be available in libraries. Aggregate models could correspond to an LCA's of building components or systems generated by experts or by individual manufacturers.

4.2 The ECOLOGUE approach

The limitations outlined above have motivated the work toward ECOLOGUE (Ries and Mahdavi 2001a, 2001b). ECOLOGUE is the computational tool for life cycle environmental impact assessment in the SEMPER integrated building design and simulation system (Mahdavi 1999, Mahdavi et al. 1999). ECOLOGUE contains a building model and an environmental model. The building model is automatically derived from the shared building model of the SEMPER system. The environmental model is a combination of a representation of the processes and emissions occurring in the life cycle of buildings and an impact assessment model. The impact assessment model is a combination of a context model of the physical characteristics of a region and a sub-regional fate and transport model based on the fugacity concept (Mackay 1991, Mackay and Patterson 1981).

ECOLOGUE embodies an impact assessment method called affordance (Mahdavi 1998). Affordance is an indicator which calculates a spatial allocation for emissions and resource usage and has units expressed in $kg \cdot m^{-2} \cdot yr^{-1}$. The implementation of affordance described here uses a model evaluative environment, which allows for the consideration of the emission rate and the spatial distribution of an emission release in the indicator calculation. The evaluative environment models the characteristics of the context or region where releases occur. As a result, the sensitivity of the context to an emission release can be included in the indicator calculation. In addition, the affordance concept is similar to carrying capacity in that it evaluates the ability of the ecosystem to sustain the emission rates over a period of time. Lastly, the allocation of an emission rate per unit area makes the indicator useful for land use and resource planning.

For example, to illustrate the use of the affordance indicator, consider the evaluation of CO_2 production during a building's operation, wherein the production of CO_2 is compared to a spatial and temporal affordance. The affordance value is derived from the annual anthropogenic carbon production that is estimated would produce a target atmospheric concentration (WRI 1996). For example, a target concentration of 650 ppm translates into an estimated worldwide production of $7\ Gt\ C \cdot yr^{-1}$. Given global land use patterns, and the fraction of urban land in the United States (WRI 1996), the mean affordance for a US urban area is estimated to be $4\ kg \cdot m^{-2} \cdot yr^{-1}$. If the example building has an annual C contribution from operational CO_2 production equal to $6\ kg \cdot m^{-2} \cdot yr^{-1}$, the estimated impact would be 1.5.

Determining the environmental impact value of a process in a context using the affordance method requires the modeling of the fate and transport of the process-related emissions, and the estimation of the resulting concentrations in the context. Processes represent activities in the environment, and are related to an element of the ECOLOGUE domain model (Figure 3). Each process can be composed of multiple "sub-processes", each with a set of related emissions and one related context. Emissions are modeled in terms of a set of chemical and physical attributes. The interrelationship of the characteristics of the emission and the context together determine the distribution and concentrations of the emission in that context. The regional or context model in ECOLOGUE is a multi-compartment model (Figure 4). A compartment is defined by its physical characteristics, such as the size (area and volume) and the rates of advective flow of the media. A fugacity-based model is used within each compartment. Fugacity is a property of a substance that is used for predicting mass and concentration distributions, reaction characteristics, and persistence of a chemical released into an environment. Fugacity is an "escaping tendency" or "driving force" with units of pressure [Pa]. When the escaping tendencies from two media are equal, they are in equilibrium. Fugacity is linearly proportional to concentration, i.e., one molecule exerts one-tenth the escaping tendency of ten.

Fugacity models have been developed in four levels (Mackay and Patterson 1981). The Level III model in this implementation is non-equilibrium steady-state: a system with non-equilibrium distribution in which each media may have a different fugacity, and the emission releases are steady-state. Emissions may occur in one or more media. The media in this level are air, soil, water, and sediment. The fate and transport processes modeled (see Figure 4) are emissions to air, soil, and water (E_i), transmissions between media (D_{ij} representing diffusion, deposition, and runoff), reactions (R_i), and advection (A_i). Mass balance equations are used to determine the distribution tendency and concentration. The evaluative environment is not intended to simulate the real environment, but is intended to provide the behavioral characteristics of the substance in terms of partitioning among the media (air, water, soil, and sediment).

The context is modeled as a bounded system, and therefore no transfers of mass occur across the boundary. A regional context model can correspond to a naturally defined area, such as a watershed. Larger models can be assembled from multiple contexts by linking the individual models together through the transfers across their boundaries, allowing the construction of a larger system. This coupled model can then be solved iteratively.

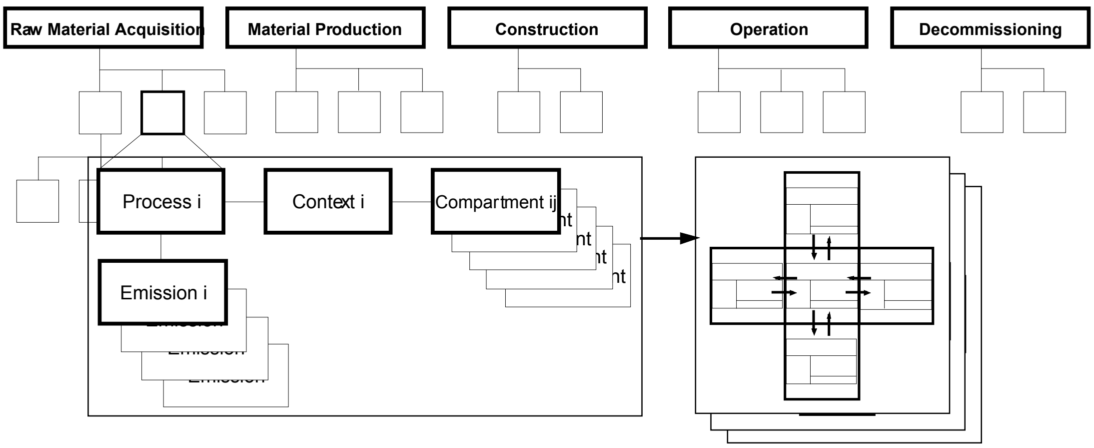

Figure 3: A representational scheme for environmental impact assessment in case of built environment

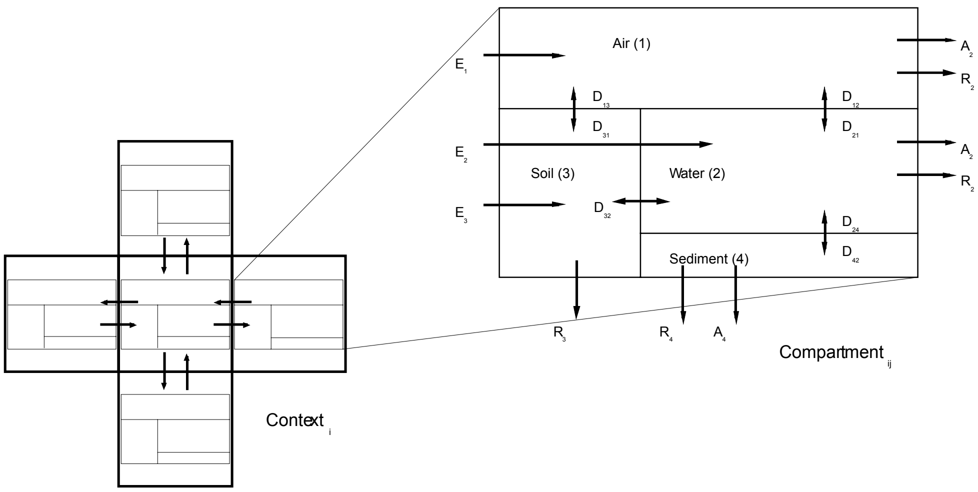

Figure 4: Illustration of a five compartment context model

In the affordance method, the allowable emission rate for each emission in each process in the context is calculated using the above model. The calculation procedure evaluates each emission-context pair. The combination of the context characteristics, including the transfer between compartments, the emission properties, and the emission rates determines the allowable concentrations. The model is calculated iteratively and the allowable emission rate is found when the concentration in one of the media in a compartment reaches the target concentration range (Sittig 1994, 1981) within a tolerance factor. The allowable emission rate is then divided by the developable area in the process compartment, resulting in the allocation of the emission rate per unit area.

Although requiring further development, the embodied process model and the implementation of the affordance-based methodology using a fate and transport model in ECOLOGUE may be seen as an alternative to current environmental impact assessment instruments for buildings. The approach addresses some of the limitations of the "accounting" of materials and environmental factors and is a initial step towards a computational environment that adopts a genuinely simulation-based approach toward the environmental assessment of buildings and related infrastructures.

5 CONCLUSION

Although very different in their scope, domain, objectives, and tools, LCA methods generally attempt to accomplish a two-fold aggregation of *i)* multiple environmental impact measures into a small group of indicators (occasionally into only one super-indicator) and *ii)* multiple environmental impacts over a certain time horizon. It appears that most LCA methods attempt to accomplish this two-fold aggregation via means that display an "entropic touch", even though they rarely entail an explicit reference to an entropy-inspired terminological framework, nor do they provide for a coherent "operationalization" of entropic eco-indicators (Mahdavi 1998). For example, the "Critical Volume" in the eco-balance method (Etterlin et al. 1992) represents a measure of dilution (contamination, dispersion) which may be seen as corresponding to entropy increase.

Needless to say, there is still a long way from simple measures such as critical volume to a more comprehensive and coherent entropy-based eco-indicator. Certain intermediate improvements are not difficult to bring about, as the aforementioned concept of affordance illustrated. Beyond such incremental improvements, future research that would build upon works such as Ayres 1994, Ayres and Martinas 1994, Brillouin 1964, 1956, and Georgescu-Roegen 1971 may well lead to the formulation of a new generation of substantially refined, comprehensive, and computationally supported entropy-based eco-indicators.

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