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Statistical-thermodynamics modelling of the built environment in relation to urban ecology

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ABSTRACT

Various aspects of the built environment have important effects on ecology. Providing suitable metrics for the built forms so as to quantify and model their internal relations and external ecological footprints, however, remains a challenge. Here we provide such metrics focusing on the spatial distribution of 11,418 buildings within the city of Geneva, Switzerland. The size distributions of areas, perimeters, and volumes of the buildings follow approximately power laws, whereas the heights of the buildings follow a bimodal (two-peak) distributions. Using the Gibbs–Shannon entropy formula, we calculated area, perimeter, volume, and height entropies for 16 neighbourhoods (zones) in Geneva and show that they have positive correlations ($R^2 = 0.43–0.84$) with the average values of these parameters. Furthermore, the entropies of area, perimeter, and volume themselves are all positively correlated ($R^2 = 0.87–0.91$). Deriving entropy from Helmholtz free energy, we interpret entropy as a measure of spreading or expansion and provide an analogy between the entropy increase during the expansion of a solid and the entropy increase with the expansion of the built-up area in Geneva. Compactness of cities is widely thought to affect their ecology. Here we use the density of buildings and transport infrastructure as a measure of compactness. The results show negative correlation ($R^2 = 0.39–0.54$) between building density and the entropies of building area, perimeter, and volume. The calculated length-size distributions of the street network shows a negative correlations ($R^2 = 0.70–0.76$) with the number of streets per unit area as well as with the total street length per unit area. The number of buildings as well as populations (number of people) show sub-linear relations with both the annual heat demand (MJ) and CO_2 emissions (kg) for the 16 neighbourhoods. These relations imply that the heat demand and CO_2 emissions grow at a slower rate than either the number of buildings or the population. More specifically, the relations can be interpreted so that 1% increase in the number of buildings or the population is associated with some 0.8–0.9% increase in heat demand and CO_2 emissions. Thus, in terms of number of buildings and populations, large neighbourhoods have proportionally less ecological footprints than smaller neighbourhoods.

1. Introduction

Cities can be regarded as thermodynamic systems. They are sources of water vapour, trace gases and aerosol, and modify the surface roughness (thereby affecting the magnitude and direction of wind) and the moisture content of the soil (e.g., Costanza et al., 1997; Wallace and Hobbs, 2006). In addition, urban areas impact on land use, biogeochemical cycles, and hydrosystems (Grimm et al., 2008). Perhaps the best-known climatic effect of cities is the urban 'heat island', whereby dense cities have higher temperatures, particularly minimum temperatures, than the surrounding rural areas (Grimm et al., 2008). The heat islands impact on air quality and water resources. These and many other aspects of cities influence local and global climate and contribute to pollution (Chen et al., 2014), all of which affect the general ecosystem. In particular, urban areas are marked by biodiversity decrease (e.g., Grimm et al., 2008; Sanford et al., 2008; MacDougall et al., 2013). Biodiversity loss is widely thought to increase the vulnerability of the ecosystem (e.g., Odum and Barrett, 2004; MacDougall et al., 2013). While the relation between reduced biodiversity and vulnerability may not be as clear-cut as once thought (e.g., Jørgensen and Svirezhev, 2004), there is no doubt that urbanisation results in decreased biodiversity, and this effect is certainly of general importance.

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There exist many methods of quantification and modelling in ecology as well as in urban systems (e.g., Maynard-Smith, 1978; Wilson, 2006; May and McLean, 2007; Alberti, 2008; Zhang, 2009). In particular, classical and statistical thermodynamics have been used extensively over many years for modelling complex systems in general (Prigogine, 1967; Kondepudi and Prigogine, 1998), complex urban systems (Allen and Sanglier, 1978; Portugali, 1997; Batty, 2005), as well as ecological systems (Svirezhev, 2000; Jørgensen and Fath, 2004; Jørgensen and Svirezhev, 2004; Filchakova et al., 2007; Dewar and Porte, 2008; Giudice et al., 2009; Jørgensen et al., 1995, 2007). For example, exergy (i.e., the maximum amount of useful work that a thermodynamic system can perform) analysis can be used for system optimisation in many engineering fields (Sciubba and Ulgiati, 2005). Similar methods of quantification and modelling, particularly using both classical thermodynamics and statistical thermodynamics, have been developed in urban systems. Examples include several works using thermodynamics and emergy concepts in urban systems (e.g., Odum, 1996; Huang, 1998; Brown et al., 2004; Huang and Chen, 2005; Bristow and Kennedy, 2013), gravity and maximum entropy models in transportation (Wilson, 1981; Wilson, 2006; Wilson, 2009; Simini et al., 2012), as well as information entropy (Zhang et al., 2006). While both emergy and exergy analysis quantitatively assess the resource consumption of physical systems using space and time integrated energy input/output models (Brown and Herendeen, 1997; Meillaud et al., 2004), recent comparisons suggest they are, as regards framework and approach, different (Sciubba and Ulgiati, 2005; Sciubba, 2010).

Despite all these studies, there has been little attempt to quantify the spatial distributions of the built environment and urban infrastructure using methods from statistical thermodynamics and information theory (Gudmundsson and Mohajeri, 2013; Mohajeri and Gudmundsson, 2014). In particular, there are hardly any studies on the size distributions of buildings within cities and between cities and how these size distributions relate to the ecological footprints of cities. The built-form parameters and their variation, under different ecological conditions, are thought to have strong impacts on the environment (Jabareen, 2006; Tratalos et al., 2007). It is also widely thought that compact urban forms are ecologically more sustainable than spread or dispersed forms (Alberti, 2007). This is because urban form, as reflected in the size distributions of buildings and transport infrastructures, affects energy use and energy efficiency of the built environment and thus the local climate, including the generation of heat islands. It is commonly argued that compact and mixed urban land use is more energy efficient and produces less pollution through reducing the average vehicle distances travelled (Alberti, 2007; Ewing and Cervero, 2010; Makido et al., 2012; Fragkias et al., 2013). In addition, the size distributions of buildings affect factors such as surface roughness, emission of greenhouse gases, and potential habitats for animals, particularly birds. All these factors, in turn, may affect biodiversity and vulnerability of the ecosystem (Alberti, 2007; Alberti and Marzluff, 2004).

One difficulty in making an objective assessment of how much the built environment impacts on various ecological processes is that quantitative methods and general models that embrace both urban and ecological systems are not well developed. One aim of this study is to show that the Helmholtz free energy can be related to the statistical distributions as an indication of the useful energy and derive the general entropy formula from the Helmholtz free energy. The results are then applied to new data on the building configurations of the city of Geneva in Switzerland. The second aim is to use concepts from general statistical physics/information theory as a framework for quantifying the complexities of built environment in relation to ecology. In particular, we propose metrics for the size distributions of buildings and populations and their relation to urban compactness/dispersal, heat demand, and CO$_2$ emissions. We also discuss the general ecological implications of the results.

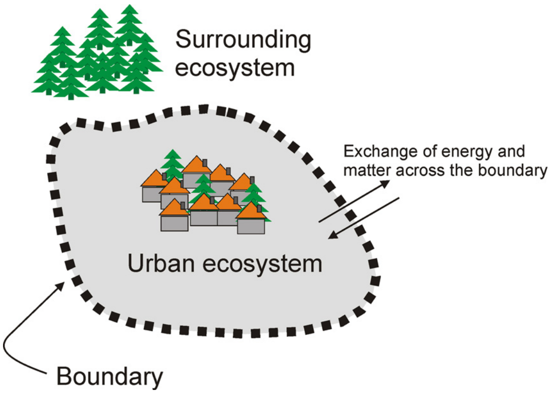

Fig. 1. City, as a thermodynamic system, is separated from its surroundings by a boundary (thick broken line) that allows the exchange energy and/or matter with the surroundings. A city is therefore an open thermodynamic system.

2. Statistical thermodynamics framework

Here we present the basic theory of statistical mechanics and, subsequently, information theory as related to the quantification of complex built environment systems. Statistical mechanics offers a microscopic basis for thermodynamics and a probabilistic treatment of all forms of matter so as to explain their bulk behaviour. In turn, information theory is presently widely regarded as offering a deeper foundation of statistical mechanics (e.g., Brillouin, 1956; Jaynes, 1957a,b; Ben-Naim, 2008; Volkenstein, 2009). All these three fields use the concept of entropy, originally measured as the input of heat at a given temperature to a system, and thus with the unit $\mathrm{J\,K^{-1}}$. Subsequently, when the concept was given a probabilistic interpretation by Boltzmann and Gibbs the original unit was maintained simply by multiplying the logarithm of probability by the Boltzmann constant k_B. The entropy introduced by Shannon in relation to information theory does not have any specific physical unit; the unit used depends on the base of the logarithm used. There are currently many entropy measures – commonly with arbitrary units – but these can generally be related to the original thermodynamics/statistical mechanics entropy concepts and units after suitable manipulation.

A thermodynamic system is that part of the universe that is of the main interest in a particular thermodynamic study. The surroundings of the system are, strictly speaking, the rest of the universe. For practical purposes, however, the system is commonly that portion of the universe where the thermodynamic measurements are made. An urban ecosystem is an open thermodynamic system since it exchanges energy and matter with its surroundings (Fig. 1). For an urban ecosystem, matter is primarily transported across its boundary, that is, in and out of the system, by human activities, whereas the system exchanges energy partly through natural processes (e.g., radiation) and partly thorough human activities. For a particular urban ecosystem such as the city of Geneva then, for practical purposes, the surrounding ecosystem could be the adjacent rural areas. Alternatively, the surrounding system could be the country (Switzerland) within which the city is located, or Europe, or the entire surface of Earth.

The first law of thermodynamics refers to the conservation of energy and is given by

$$\mathrm{d}U = \mathrm{d}Q + \mathrm{d}W \tag{1}$$