Ecological Modelling 250 (2013) 155–164

Contents lists available at SciVerse ScienceDirect

Ecological Modelling

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

Maximizing the use of energy in cities using an open systems network approach

David N. Bristow*, Christopher A. Kennedy

Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario, Canada

ARTICLE INFO

Article history:
Received 22 August 2012
Received in revised form 30 October 2012
Accepted 1 November 2012
Available online 11 December 2012

Keywords:
Thermodynamic sustainability
Urban energy systems
Scale-free networks
Random networks
Open systems

ABSTRACT

The ability of cities to extract useful work from energy imports is analyzed by considering all of the flows of energy within the city as an ecological network and by accounting for the role the second law of thermodynamics plays in open systems such as cities. We construct a new procedure for generating a variety of flow balanced random networks to test the role that the network structure has on the city's ability to constructively destroy exergy, the useful component of energy in a process. We consider two network types, Erdös–Rényi and scale-free networks, and illustrate how these types, and the various realizations of these types as defined by their control parameters, impact the quantity of exergy destroyed. Specifically we find that the Erdös–Rényi network is best equipped to destroy exergy, but that the scale-free network provides more certainty in this ability for networks that are sparsely connected. This trade-off between the exergy destruction and certainty is observed in a study of Toronto. Overall the findings suggest that the selection of network topology in the development of open systems is an important factor (among others) in the successful development of open systems, their sustainability, and their ability to achieve maximum work extraction from energy imports.

1. Introduction

There are many indications that energy scarcity may become a serious problem (Darley, 2004; Simmons, 2005; National Petroleum Council, 2007) especially for cities (Newman, 2007; Peter and Swilling, 2012). Indeed, peak oil – the apex of supply from which follows ever smaller maximum possible supplies – is already causing impacts to society (Murray and King, 2012). Couple this with the fact that cities drive 75% of global energy demand (Ash et al., 2008) but tend to have an overall efficiency around 10–20% (Keirstead et al., 2010), it becomes clear that improving how energy is used in cities is of global importance.

In general, the energy imported into cities proceeds through a series of transformations and exchanges to provide for the energy services that cities need such as the heating of buildings, operation of machinery and the moving of freight and people. The transformations, such as from chemical potential of natural gas to heat, and the exchanges, such as from the electricity grid to buildings, form a network within cities. This network includes the infrastructure that converts and conveys energy in desirable forms, such as the electricity grid and natural gas distribution networks; and the movement of energy via transportation systems to desired locations.

More generally cities are open systems that destroy exergy in pursuit of a thermodynamic goal to produce entropy. The conduct of this procedure can be conceptualized as a network of flows of exergy resources. Each node of the network represents a site of energy transformation such as an industrial process. Each edge represents a transfer of exergy between two nodes such as the exchange of natural gas from the distribution pipes to a household, or of gasoline from a service station to a vehicle. Cities in this way do not differ significantly from ecosystems and other open systems as the literature of thermodynamics and network studies reveals.

The relevant thermodynamics to this inquiry on cities include: (1) the implications of the second law of thermodynamics on the efficient use of energy; and (2) the self-organization of open thermodynamic systems. The second law necessitates that any real thermodynamic change must produce entropy and thus limits the utility of energy gradients by requiring their destruction in any real process. An effective tool for capturing this limit is exergy, the useful portion of energy in a process (Bejan, 2006; Sciubba and Wall, 2007). Since energy is never destroyed and gradients are destroyed all the time, the more commonly used first-law efficiency (energy input divided by desirable energy output) provides a limited assessment of the efficiency of processes. An efficiency based on exergy accounts for the destruction of the gradients by comparing the output of a process to the ideal output (e.g. exergy output of an actual process divided by maximum exergy output by ideal process). Any output less than the ideal results in wasteful destruction of gradients and thus provides a meaningful reference point for efficiency.

* Corresponding author. Tel.: +1 416 978 5972.
E-mail addresses: david.bristow@mail.utoronto.ca (D.N. Bristow), christopher.kennedy@utoronto.ca (C.A. Kennedy).

0304-3800/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecolmodel.2012.11.005

Extending these principles to open systems free to exchange matter and energy with their surroundings it is observed that the existence of external gradients and waste sinks support the self-organization of structure within open systems (Nicolis and Prigogine, 1977; Schneider and Kay, 1994). The work by Schneider and Kay (1994), Nielsen and Ulanowicz (2000), and Ulanowicz and Hannon (1987) provide further important foundations to the understanding of complex open thermodynamic systems. Schneider and Kay (1994) link the development of these systems to their rates of energy dissipation, exergy destruction, and entropy production. Nielsen and Ulanowicz (2000) provide a thermodynamic framework considering the network of flows in open system development and Ulanowicz and Hannon (1987) were perhaps the first to suggest how strategies of open systems are related to their thermodynamics, introducing an energy discount rate to explain how the quantity of energy stored in internal structures is chosen based on the availability of energy.

The structure of open systems is often represented by networks, though the study of networks in general is not necessarily tied to thermodynamics. The modern study of networks falls roughly into two camps. One, referred to here as network science due to its agnostic approach to subject matter, was popularized by the works of Barabasi and Watts on scale-free and small world networks respectively (Watts and Strogatz, 1998; Barabási and Albert, 1999; Barabási, 2002; Watts, 2004). The other approach, ecological network analysis involves a variety of techniques and owns its foundations largely to the input–output works of Hannon (1973) and Finn (1976) and has more often intersected with open system thermodynamics (Nielsen and Ulanowicz, 2000; Jørgensen et al., 2007). Both areas of inquiry have sometimes shared a variety of roots including various aspects of graph (Erdös and Rényi, 1959; Patten, 1985; Newman et al., 2006) and information (Ulanowicz, 1980; Kay, 1984) theory.

The ecological network approach is often concerned with the structure and relationships between components within networks. This is echoed in the work by Zhang et al. (2009) whom provide a method using emergy analysis of an urban ecologic network to consider the utility or disutility that the compartments of a city (industry, agriculture, domestic or residential, local environment, external environment) have on each other. They examine mutualism between pairs of compartments, defined as a state in which compartments have positive utility in relation to each other. In cases where mutualism does not exist it is an indicator of a problematic relationship. For example, it is shown that the development of agriculture in the regions of Beijing and Shanghai is occurring at the expense of the local environment, while in the case of Tianjin and Chongqing, agriculture pollution has had such damage on the local environment so as to also hamper agriculture itself.

The efforts within network science often surround the dynamics of formation of the linkages in large networks. In the case of the scale-free network the addition of new edges occurs with the preference of attaching to nodes that already have a large number of edges. The result is a sparsely connected network (i.e. low connectance) where many nodes have few connections and a few nodes have many connections. This degree distribution pattern follows a power-law.

An early exception to the differing efforts of these two camps is a novel though somewhat overlooked finding from an ecological network study that observes an important pattern of development (Ulanowicz and Wolff, 1991). This work, predating that of the Barabási group by a number of years, shows that the flow magnitudes along the edges in ecosystem networks must exhibit a certain class of distribution whereby the mean and higher order moments are undefined. Power-laws exhibit this behavior in certain ranges of the parameters, as do Cauchy distributions in general. Interestingly this finding is reached using randomly generated networks with degree distributions that resemble Erdös–Rényi networks whereby the degree distribution is generated with a uniform probability distribution (Erdös and Rényi, 1959) as opposed to the power-law degree distribution of the scale-free topology.

With the wide occurrence of the Barabási scale-free network in a variety of systems and the work on ecological networks up until recently not having considered alternative topologies it became a question of interest to determine whether the scale-free topology existed in ecosystem networks. Dunne et al. (2002) provide convincing evidence that this can be the case in food webs, but it is not a general rule. Specifically they note that the degree distribution varies with connectance such that low connectance networks have near scale-free topologies; high connectance networks have uniform distributions like the Erdös–Rényi network; and in-between are exponential distributions.

The works of Ulanowicz and Wolff (1991) and Dunne et al. (2002) are of significant importance to the understanding of the structure of networks of open thermodynamic systems. Ulanowicz and Wolff describe in effect the distribution of flows among the nodes that can be expected when an ecosystem network is of the Erdös–Rényi topology and Dunne et al. describe the food web topology that can be expected based on the connectance of the network.

Given that different topologies are exhibited by open systems, such as ecosystems, this work considers the role that the topological differences can have on the system's ability to retain and use locally imported exergy. This role is examined with respect to cities.

Specifically, the objective of this work is to relate network topology and connectance to the ability of open systems to extract a maximum of useful energy from the energy that it imports. Following some background on thermodynamics, we first illustrate that the city of Toronto (population of 2.6 million in 2011) exhibits near-scale free topology and connectance. We then proceed to examine, through simulation, how networks of scale-free and Erdös–Rényi topology (the extremes found by Dunne et al. (2002) for food webs) differ in their capacity to successfully destroy exergy. By studying different topologies we are able to determine how cities could evolve to improve their use of energy.

2. Thermodynamic background

Considering the optimization of the use of energy imports in cities requires application of several thermodynamic concepts. The first is exergy to account for the irreversibilities of energetic processes. Next, important aspects of urban exergy use are introduced in relation to maximizing the usefulness of energy imports in cities. How these aspects of exergy use relate to the development of exergy flows in cities is explained by introducing pertinent thermodynamic behaviors common to all complex open systems such as cities. The study of these behaviors is served well by a network approach, a review of which is provided. The behaviors also establish the foundation upon which the ensuing simulation is developed to pursue maximization of the usefulness of energy imported to a city.

2.1. The usefulness of an exergy approach in providing a reference point

The concept of exergy is of importance in dealing with energy efficiency and maximizing the usefulness of energy in systems. Extensive reviews can be found in Fraser and Kay (2004), Bejan (2006) and Sciubba and Wall (2007). For the purposes of this work, a brief explanation is sufficient.

Exergy represents the maximum usefulness (maximum work) that can be extracted from energy in a given process. Consider for