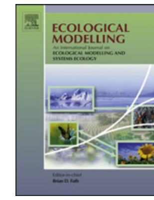
Ecological Modelling 222 (2011) 2825–2834

Contents lists available at ScienceDirect

Ecological Modelling

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



Ecological network determination of sectoral linkages, utility relations and structural characteristics on urban ecological economic system

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ARTICLE INFO

Article history:
Received 19 October 2010
Received in revised form 14 April 2011
Accepted 20 April 2011
Available online 12 June 2011

Keywords:
Ecological network analysis
Extended exergy analysis
Structure
Utility
Urban ecological economic system

ABSTRACT

Analyzing the structure and functioning of the urban system revealed ways to optimize its structure by adjusting the relationships among compartments, thereby demonstrating how ecological network analysis can be used in urban system research. Based on the account of the extended exergy utilization in the sector of urban socio-economic system, which is considered as the composition of extraction (Ex), conversion (Co), agriculture (Ag), industry (In), transportation (Tr), tertiary (Te) and households (Do) sectors, an urban ecological network model is constructed to gain insights into the economic processes oriented to sustainable urban development. Taking Beijing city as the case, the network accounting and related ecological evaluation of a practical urban economy are carried out in this study in the light of flux, efficiency, utility and structure analysis. The results showed that a large quantity of energy and resources have to be consumed to maintain the structure and function of a city. The thermodynamic efficiencies of individual sector in Beijing remain at a low level. The social system in Beijing is a highly competitive network, and there are 8 competitive relations and only two mutualistic ones. The Domestic and Agricultural sector are the major controlling factors of the system. Moreover, the assessment results of Beijing are compared with the other three socio-economic systems, Norway, UK and Italy, and the ecological network function and structure comparisons are correspondingly illuminated and discussed. The conclusions indicate that the exergy-based network analysis can be refined to become an integrative tool for evaluation, policy-making and regulation for urban socio-economic system management concerning structure and efficiency at urban levels.

1. Introduction

The paradigm of urban ecological economic system has been formulated in an attempt to focus thinking towards a balanced co-evolution of the economic, natural and social environments while living within the carrying limits of the supporting ecosystems (World Conservation Union, 1991). Frosch and Gallopoulos (1989) proposed that socio-economic systems could become more sustainable if they were organized like biological ecosystems after considering the natural system as an integral part of the urban system. It immediately follows, since the mid-1980s, a lot of experts and scholars have carried out thorough and meticulous researches into the urban sustainable operation. However, the main urban study fields have been focused on the fluxes of single elements and on 'nutrition' with respect to that element, while analysis of urban structure, function and utility are seldom mentioned (Fischer-Kowalski, 1998; Huang et al., 2006). Analyzing the structure and functioning of the urban system revealed ways to optimize its structure by adjusting the relationships among compartments, thereby demonstrating how ecological network analysis can be used in urban system research. In particular, urban ecology brings into focus the sustainability of physical resource use patterns and how they may drive changes in the system. Relational structures develop and change through the interactions among the urban sectors and exogenous forces acting on the system. Despite criticisms that ecological metaphors are inadequate to understand urban systems, the remarkable similarities between the attributes of the structure of regional economies and those of biological ecosystems render their analogies meaningful (Taylor, 1998). Moreover, for these attributes, an ecological perspective introduces additional concepts or quantitative measures that could improve understanding of the urban systems.

No satisfactory tool was available to measure the system function objectively until the adaptation of network analysis to natural systems. One of the popular ways of representing the activities taking place in an ecosystem is to depict them as networks of flows of material and/or energy. The process which began with the quantitative analysis of interconnections was pioneered by Leontief (1941) as input–output (I–O) analysis and since then has also been applied to study energy flows in the economic system

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doi:10.1016/j.ecolmodel.2011.04.034

(Costanza, 1980; Costanza and Herendeen, 1984). Network analysis affords an ecosystem researcher or manager several new avenues for extracting heretofore unavailable information about the flows of material or energy in the ecosystem (Wulff et al., 1989). More ecological network properties such as cyclic pathways, link density and connection have revealed new patterns and insights (Patten, 1985; Ulanowicz, 1986). Structural analysis of ecological food webs has received considerable attention of late (Dunne, 2006; Fath and Halnes, 2007). Patten and Fath applied this method to develop a paradigm of ecological network analysis including indirect effects, network amplification, network homogenization and network synergism (Patten, 1991; Fath, 2004; Scharler and Fath, 2009; Patten, 2010). The methods mentioned above construct the theoretical underpinning of ENA, and the related analysis methods and indices have been addressed explicitly (Ulanowicz, 1997, 2004; Fath, 2007; Tollner et al., 2009; Shevtsov et al., 2009).

Scholars are paying increasing attention to the social and organizational forces at work in social and economic systems (Fath, 2006; Fath et al., 2008). Ji (2010) took a network accounting and related ecological evaluation of a practical urban economy based on embodied cosmic exergy. Zhang et al. (2010a) developed an ecological network model for the urban energy metabolic system, and used four Chinese cities as examples of how the integration of throughflow analysis and ecological network utility analysis provides insights into the flows within the system at both high and low levels of detail. Zhang et al. (2010b) developed another ecological network model for the urban water metabolic system. Using a network utility matrix, the relationships and degrees of mutualism among six compartments were determined. This integrated network analysis framework presents an approach for a more holistic understanding of the interaction between natural and socio-economic systems by placing them within a complex systems framework. A reference can be established in urban economic scale to obtain insights into the structure and functioning of urban ecosystems and explore the consequences of various ecosystem change scenarios. Current studies viewed in the direct and indirect structure and function in an interconnected web based upon different inflows (such as flows of materials, energy, population or monetary). To consider the integrated image of interactions and connectedness both proximate and distal of urban socio-economic system, however, a quantitative method is needed to integrate the value of free environment investment, goods, services and labor forces in a common unit based on the principle of holism, where the whole has the greater affects for system behaviour than the sum of the parts.

A variety of techniques have attempted to quantify the flux of exchange and the contribution of ecosystems to economic activity. As an indicator of the distance from thermodynamic equilibrium, exergy provides a unified measure of various forms of materials and energy carriers, and thus qualified as a basic medium used in the bookkeeping to qualify ecological networks of exchange (Chen et al., 2008). It can capture various quality aspects of streams as indicated by their mass, energy, concentration, velocity and location. Thus, exergy can characterize both mass and energy streams, and is the truly limiting resource on this planet (Sciubba, 2001; Wall, 2002). The application of the exergy method for a society was to account for the use and conversion of natural resources including both energy carriers and materials was introduced by Wall (1977) and carried out for many countries (Wall, 1990; Scheffer et al., 2000; Ertesvåg, 2001, 2005; Chen and Qi, 2007; Zhang and Chen, 2010). Extended Exergy Accounting (EEA) proposed by Sciubba determines cumulative exergy consumption associated with not only raw material inputs but also labor and capital inputs and non-energetic externalities (Sciubba, 2001; Sciubba et al., 2008). The proposed thermodynamic approach is not meant to replace, but to complement an economic approach.

The goals of this study were to determine the sectoral linkages, utility relations and structural characteristics of urban ecological economic system, and provide the implications of these attributes for system sustainability. The urban ecological network model was designed to describe the structure of an urban system, collect data addressing the attributes of the framework throughout the desired period and evaluate what processes brought about these characteristics. Finally, the assessment results of Beijing are compared with three other socioeconomic systems, Norway, the UK and Italy. It may present an initial diagnosis of resource utilization efficiency, input/output structure and environmental impact on the urban scale and priority on funding of the whole sectors.

As a continuation of our earlier efforts of unified analysis based on extended exergy for quantifying the flux of exchange in Beijing society (Liu et al., 2011) and ecological network model for the urban metabolic system (Zhang et al., 2010a,b) the present work provides an ecological network determination of sectoral linkages, utility relations and structural characteristics on the urban ecological economic system, with emphasis on a joint application of the extended exergy synthesis and ecological network analysis methods and regional comparison.

2. Methodology

2.1. The urban ecological network model

In urban systems, sectors consume the materials (goods and services) produced by others, and can be modelled as a food web with trophic structure (Hardy and Graedel, 2002). At the urban level, the system compartments have been chosen following Wall's and Sciubba's approach. The analysis is also based on the earlier work of Chen and Qi (2007) and Zhang and Chen (2010) for the societal exergy utilization of Chinese society. A typical systems diagram can be shown in Fig. 1. The urban system is divided into seven sub-systems, including: (a) Extraction (Ex), including mining and quarrying, oil refining and processing, and the inflow of energy carriers from the external environment; (b) Conversion (Co), comprising heat and power plants; (c) Agriculture (Ag), including harvest, forestry, fishery, and food processing; (d) Industry (In), manufacturing industry except food industry and oil refineries; (e) Transportation services (Tr); (f) Tertiary sector (Te), including construction and other services; (g) Domestic sector (Do), households. The domestic sector has changed from a final consumption to an important labor exergy inflow transferring to other sectors. In this study, capital flows would not be accounted into extended exergy in order to avoid double-counting because a part in capital flows is a relatively equivalent value of resource, commodity and labor exergy and the other part in capital flows used in banks and governments would not be accounted due to the lack of reliable data. Thus the boundary of the model is the whole city without regard to the bank system and government.

2.2. Extended exergy accounting of inter-sectional flows

To quantify the network, flows of the chosen exergy into and out of each compartment should be determined. The input fluxes include imports from abroad (resources such as primary and secondary fuels, electricity, ores, and products) and free local resources (natural resources such as agricultural products, livestock, and wood), which are combined in the pathway crossing the system boundary and in the system, respectively. The yield (products and services, etc.) and exergy loss are represented by the pathway to the other sectors and the environment.

A system networks described by the direct flow matrix, **F**, which includes all flows between *n*-compartments inside a system but