Ecological Modelling 325 (2016) 84–88

Contents lists available at ScienceDirect

Ecological Modelling

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

The input-state-output model and related indicators to investigate the relationships among environment, society and economy

Simone Bastianoni, Luca Coscieme*, Federico M. Pulselli

Ecodynamics Group, Department of Earth, Environmental and Physical Sciences, University of Siena, Pian dei Mantellini 44, Siena 53100, Italy

ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 8 October 2014
Accepted 10 October 2014
Available online 22 October 2014

Keywords:
Sustainability
Systemic approach
National economies
Emergy
Gini index of income distribution
Gross domestic product

ABSTRACT

Economic systems can be studied as thermodynamic open systems that rely upon inputs of energy and materials, processed through human labor and a structured organization, and eventually transformed into useful outputs (i.e., goods and services). In this vein, a generic input-state-output model can be used to represent the relations among environment, society, and economy as well as their dynamics. This approach, that implies the use of holistic and systemic approaches, allows the description and understanding of the evolution of the level of sustainability of national economies through the use of three different metrics computed for world countries in time-series: emergy flow as input-based indicator, Gini index of income distribution as a state descriptor, and gross domestic product as a measure of outputs produced by the economic system. This whole framework depicts a synthetic representation of the environmental, social, and economic dimensions that characterize national systems. It aims at being highly informative to better understand complex relationships between quality and amount of energy and resources used, equity in income distribution, and the overall value of economic production.

1. Introduction

An input-state-output model has been proposed by Coscieme et al. (2013a) in order to characterize ecosystems in a socio-ecological context. Three different indicators were used to account respectively for the energy and matter inputs to the ecosystem (the emergy flow; Odum, 1988), the ecosystem organization (eco-exergy; Jørgensen, 2008), and the useful outputs provided by the ecosystem to humans (ecosystem services; MA, 2005). In the input-state-output model, the mutual relationships between different indicators have been investigated, highlighting how effectively ecosystems transform resources, self-organize by processing them, and produce goods and services that represent fundamental benefits to our well-being. This analysis can be extended to investigate other kinds of open systems, such as cities, social systems and economies, by using appropriately different indicators. In fact, these systems, though characterized by different dynamics, have many similarities with ecological ones: they are open, use energy and matter inputs, and are organized through human labor to process and transform resources into goods and services. In this paper, an application of the input-state-output model to national economic systems is presented (Fig. 1).

Various combinations of indicators can be adapted to this framework in order to account for inputs in both quantitative and qualitative terms, describe the state organization, and give a measure of outputs (Pulselli et al., 2011). This input-state-output model supports the integration of different disciplinary approaches to the study of economic systems.

In general, each part of the input-state-output model should be described with the most appropriate indicator relative to the kind of information needed to assess the various aspects of an open system functioning. Regarding national economies, the choice of proper indicators may help identify emergent properties and the relationships among different dimensions of sustainability, namely, the environmental, social, and economic ones. Improvement and information refinement may derive from data availability (that depends on the type of indicator), statistical computation of indicators and measures (e.g., rankings, quartiles, scales), and data aggregation (e.g., cluster analysis). These considerations led us to select a triad of indicators that is representative of each part of the framework. Here, the Emergy flow has been chosen as an input-based indicator, being able to account for the convergence of different kinds of energy and matter forms to an economy (Odum, 1996); the Gini index of income distribution is used as a descriptor

* Corresponding author. Tel.: +39 577232011; fax: +39 577232004.
E-mail address: coscieme2@unisi.it (L. Coscieme).

http://dx.doi.org/10.1016/j.ecolmodel.2014.10.015
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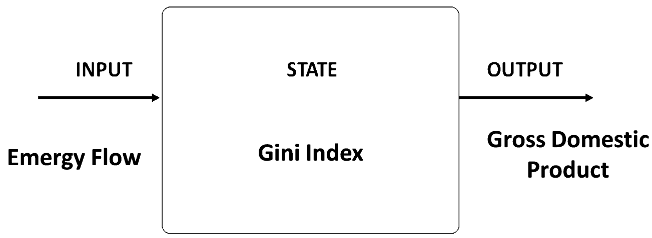

Fig. 1. Input, state and output representation of an economic system.

of the organization of the system; the gross domestic product (GDP) is used as a measure of the economic production.

2. Methods and data

2.1. Emergy evaluation of national economies

In thermodynamic terms we can state that an economy, to maintain itself, has to exchange energy and matter (including wastes) with an external source-sink system (Fath, 2008). A particular mix of energy and matter inputs is somewhat specific for economies based on different transformation processes (Brown et al., 2009). The concept of energy quality derives from arranging all the energy transformation of the geo-biosphere in an ordered series, forming a hierarchy, from the more diluted forms (i.e., the solar energy) to the more concentrated ones, with different abilities to perform work and different flexibility to be used. The emergy synthesis (Odum, 1996) is an accounting method able to sum together the different energy forms, expressing them in a common unit, and can thus be able to properly represent the resource requirement of different economies at different development levels.

Solar energy can be considered the basis upon which energy transformations in the biosphere occur. Emergy is defined as the quantity of solar energy directly or indirectly necessary to produce a flow or a product and is expressed in solar emergy joules (seJ). Unit emergy values (UEVs) are utilized to compare all kinds of energy on the common basis of solar energy. The UEVs are defined as the solar energy directly or indirectly required to generate 1 J of a product. A UEV is a conversion factor that takes into account the position of one energy form in the thermodynamic hierarchy of energy quality. The UEV of the sunlight absorbed by the Earth is 1 seJ/J by definition (Brown and Ulgiati, 2004). The UEV increases moving from sunlight to very concentrated forms of energy such as fossil fuels or electric energy.

To measure the emergy necessary to support a national economy during a certain period, for example a year, the emergy flow per unit time (also called ëmpower̈) is used. The emergy flow is intended as the quantity of equivalent solar energy necessary to maintain the system (Odum, 1996, 2000; Odum et al., 2000). All the inputs to the economic system must be quantified and expressed in seJ by means of suitable UEVs. Emergy flow therefore represents the convergence of different kinds of energy to a system times the emergy per unit energy of each one of them. This method enables to identify, quantify, and weighs the inputs used by economic systems.

A quasi global database of emergy for nations has been compiled by Sweeney et al. (2007): the National Environmental Accounting Database (NEAD; http://www.cep.ees.ufl.edu/nead/). The NEAD includes a wide variety of data extracted from a number of sources. This database represents the most comprehensive list of countries and their emergy accounting available for three different years, i.e., 2000, 2004, and 2008. In particular, in the proposed input-state-output model (Fig. 1), the total emergy flow (i.e., total emergy use per year) is considered. This indicator accounts for the renewable emergy flow, plus indigenous dispersed non-renewable resources used (forestry, fisheries, water, topsoil loss, and organic matter), plus indigenous concentrated non-renewable resources used (coal, natural gas, oil, minerals, and metals), plus imported goods and electricity, fuels, metals and minerals imported, and imported services.

Starting from NEAD data, Coscieme et al. (2013b) presented a method based on satellite observations of the Earth at night that uses nocturnal lights data as a proxy measure for the evolution of the non-renewable fraction of national emergy flow. In fact, on the one hand, as night lights observation are available for a long period, this approach allows to derive time-series reference measures and profiles; on the other hand, Coscieme et al. (2013b) found a strict correlation between the intensity of lights and the non-renewable component of national emergy flow for more than 100 countries. Moreover, in the case of Italy presented here, the proxy-based estimations of non-renewable emergy have been compared with the calculated values from NEAD for 2000, 2004, and 2008, showing a difference lower than 5% (Coscieme et al., 2013b). Despite the uncertainties intrinsic in any indirect proxy measure of a phenomenon, this method allows to study changes in the amount of non-renewable resources used by the world countries during the last 20 years, being night-time satellite observed lighting data archived since 1992 (at the NOAA National Geophysical Data Center – NGDC; Elvidge et al., 2009). However, when available, actual calculated emergy values have to be used in order to account for the resource inputs used by a system.

Other indicators of pressure on environmental resources or environmental quality can be used as input indicators. Some examples can be the energy or material flows feeding a national economy, the ecological footprint that is directly related to human consumption, or the greenhouse gas inventory.

2.2. The Gini index of income distribution

An economy cannot become organized and produce services without performing work (Prigogine, 1980; Ayres, 1998). In an economy all the transformation processes need human labor to some extent. Labor organizes the economy and paid employment is the main form of inclusion of a subject into the economic system. The distribution of income, as indicated by the Gini index, describes the organization of a national economy by considering societal aspects of equality/inequality. In the input-state-output model (Fig. 1) it can be viewed as a pre-requisite for a proper economic functioning. Moreover, societal aspects are dependent on the environmental basis of energy forms, resources, and healthy ecological processes that feed the economy (Fig. 1; Costanza et al., 1997, 2014a).

The calculation of Gini index is based on a Lorenz curve where the cumulative percentages of total income received are plotted against the cumulative number of recipients (The World Bank, 2014). The index is a measure of the area between the Lorenz curve and a hypothetical line of perfect equality. It is expressed as a percentage of the maximum area under the line and thus assumes values between 0 and 100% (or, alternatively, between 0 and 1). A Gini index of 0 means absolute equality, while an index of 100% implies absolute inequality. Information on income inequality for the world countries is stored in the World Development Indicators database (WDI), held by the World Bank. However, a more complete list for the Gini index can be found in the “All the Ginis” database (http://econ.worldbank.org/projects/inequality) that includes Gini coefficients derived from eight different sources (Luxembourg Income Study – LIS, Socio-Economic Database for Latin America – SEDLAC, Survey of Living Conditions – SILC by Eurostat, World Income Distribution – WYD, World Bank Europe and Central Asia dataset, World Institute for Development Research – WIDER, World Bank Povcal, and Ginis from individual long-term