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Urban resource use and environmental performance indicators. An application of decomposition analysis

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ABSTRACT

An evaluation of interlinkages and synergies among the different resources and performance patterns in the city of Rome (Italy) was accomplished by means of decomposition equations, in order to identify the major drivers of change in the investigated period as well as future low-resource scenarios. A half-a-century historical series (1962–2008) of energy and resource consumption in the city of Rome (Italy) was investigated in order to ascertain the links between resource use and complexity change. Environmental, material and energy inputs were firstly evaluated as actual energy and mass flows, then converted to emergy units to provide an assessment on a common ground. Results show that the sustainability of the urban system decreased steadily in the investigated period, as confirmed by both intensive and extensive parameters. The demand for abiotic matter, water, energy and emergy (environmental work) was accounted for over time and referred to the population (per-capita indicators) and current prices economic product generated by the city (GVA, Gross Value Added). Moreover, the effects associated with the emissions were evaluated, with a special focus on global warming and acidification potential. The changes in the urban metabolism occurred within the investigated period were analyzed considering the variation of different inputs necessary to drive the city (electricity, fuels, goods, machineries, etc.).

Finally, a decomposition analysis was performed to identify the main causes and drivers associated with the changes in the city metabolism. Decomposition results show that the increased fraction of imports compared to local sources, of non-renewable resources compared to renewables, as well as of population and per capita income not accompanied by sufficient increase of energy and material efficiency are the major drivers of such unsustainability pattern and call for policies that focus on optimization of production and consumption patterns in times of unavoidable shrinking of resource basis.

1. Introduction

Urbanization promotes rapid social and economic development, urban resource consumption and waste production. For this reason urban issues are not about sustaining cities per se, but reflect concerns over the role of cities in global sustainable development (Satterthwaite, 1997). According to this perspective cities present both unique problems and opportunities in closing the sustainability gap. Eco-system thinking emphasizes the concept of the city as a complex system which is characterized by a network of interactions and processes. Thus, cities can no longer be defined as static built spaces to manage, but instead as living organisms with a metabolism to control and support. The concept of metabolism has been adopted from biology and refers to physiological processes within living things. Similar to human metabolism, "cities transform raw materials, fuel, and water into the built environment, human biomass and waste" (Decker et al., 2000). In fact as all organisms, cities could be described as highly dependent open systems which rely on the provision of energy, food, materials and information from other systems at different scales (municipal, regional, national) (Ramos-Martin et al., 2009). Cities would not exist without these inputs and the metabolic processes can be described in terms of the transformation of inputs (sunlight, chemical energy, nutrients, water, and air) into useful products and wastes. An extreme view of urban metabolism was given by Odum (1971) by underling the parasitic character of cities, which strongly impact on natural and domesticated environment. Moreover, Odum and Odum (1981) have related the complexity of cities to ecological principles (hierarchies, feedbacks, maximum power) and energy flows. They described the growth of urban hierarchical

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structures in terms of uptake and transformation of resources as well as cities' regulatory role with feedbacks to the lower levels.

1.1. Integrating qualitative and quantitative indicators

The use of an ecosystem approach to urban environment, emphasizing the city as a complex system, provides a framework that enables a deep understanding of urban internal dynamics, absolutely needful to move toward a circular sustainable metabolism (Girardet, 2008). The problem of attaining urban sustainable development is thus an important challenge and the development of a method for assessing the status of urban sustainable development requires the definition of scientific and effective assessment indicators and their integration in a sound way. During the latest decades, several studies have developed a variety of urban ecosystem assessment indicators (Huang et al., 2009; Scipioni et al., 2009; Shen et al., 2010; Zellner et al., 2008) and have investigated the performance of different urban spatial structures against sustainability criteria (e.g. Næss, 1993, 2001; Tjallingii, 1995; Newman and Kenworthy, 1999; Williams et al., 2000; Schremmer et al., 2011; Ulgiati et al., 2011a,b). According to Ascione et al. (2009, 2011) a point that is still missing in most urban development studies is the integration among the assessment of quantitative (energy and material inputs) and qualitative (hierarchies, structure, information and environmental services) indicators, the evolution of such indicators over time in order to evaluate the improved standard of living, and the time change of the mix of products used by a city's population. Odum (1996) introduced the emergy concept in order to account for the quality of incoming energy and resources, i.e. for the environmental services supporting a process as well as for their convergence through a chain of energy and matter transformations in both space and time. In this work, the material, energy and environmental performance and sustainability of the city of Rome are assessed within a joint emergy and LCA perspective, in order to highlight both the complexity of urban systems and the quality of supporting resources. Moreover, the major drivers of changes occurred in the study period (1992–2008) are investigated by means of a decomposition analysis technique, based on the Advanced Sustainability Analysis (ASA) tool (Vehmas et al., 2012). The main goal of the present work is to provide indicators capable to integrate different methods within a life cycle perspective, in order to describe the urban metabolism and at the same time to identify the main underlying causes associated with the city metabolic changes occurred over the investigated period. To this purpose, the decomposition approach is used to point out the drivers of changes and provide useful information for policy and planning toward a more sustainable city management

2. Materials and methods

The complex interactions and metabolism of urban systems require the development of an integrated analysis model able to take into account the amounts of all imported and local flows (energy and materials), their supply side quality (environmental cost of resource generation), the parameters and rates of resources use, land use and land use change, emissions, process and system's configuration, interrelations of socioeconomic and natural systems, and finally decomposition of obtained indicators to support policy choices.

2.1. The accounting framework: Extended LCA approach

Life Cycle Assessment (LCA) has been widely adopted by the European Commission in support of the implementation of the EU Thematic Strategies on the Prevention and Recycling of Waste and on the Sustainable Use of Natural Resources, the Integrated Product Policy (IPP) Communication and Sustainable Consumption and Production (SCP) Action Plan. LCA is also used worldwide to assess the environmental burden related to resource use, to provide a basis for sustainable production, consumption and disposal. LCA provides interesting information about the resource and environmental cost of a given product and/or process but it only accounts for matter and energy flows occurring under human control, whereas flows outside of market dynamics (such as environmental services) and flows which are not associated to significant matter and energy carriers (such as labor, culture, information) are not generally included. Moreover, the quality and renewability of resources, in terms of biosphere activity generation processes and times are not generally taken into account in LCA evaluations. When sustainability comes into play as a major concern, these flows and qualities become relevant and cannot be disregarded. Emergy accounting (Odum, 1988, 1996; Brown and Ulgiati, 2004a,b) was suggested as a way to expand the focus of LCA in order to properly account for the contribution given by environmental flows to a system/process sustainable dynamics (Ulgiati et al., 2011a,b). By means of emergy accounting, all resources are referred to the spatial and time scales of biosphere and their usefulness and quality are quantified on the same value basis and then compared with the product(s) generated. The emergy method includes, and brings into the LCA accounting, the free environmental flows provided by nature, the time needed for resource generation within biosphere processes, the economic and societal infrastructures and dynamics supporting the process (in terms of flows of labor and services), and finally the optimization strategies simultaneously carried out at all levels of the biosphere hierarchical network.

In order to apply the emergy accounting in association with other methods, an extended LCA approach was developed by Ulgiati et al. (2006, 2011a,b) as SUMMA—Sustainability Multiscale Multimethod Assessment. This evaluation framework (Fig. 1) synergically merges several upstream methods, such as the Material Flow Accounting (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998; Bargigli et al., 2004), the Embodied Energy Analysis (Slesser, 1978; Herendeen, 1998), the emergy accounting (Odum, 1988, 1996; Brown and Ulgiati, 2004a,b), and a selection of downstream impact assessment methods (e.g. the CML2 baseline (Leiden, 2000); and the emergy-based environmental impact assessment of airborne emissions, according to Ulgiati and Brown (2002)). The latter methods stem from stoichiometric evaluations or actual measures of output airborne, waterborne and solid waste chemical releases for the identification and characterization of specific impact categories.

The analyzed system or process is treated as a “black box” and an inventory of foreground input and output flows is performed on its local scale. This inventory forms the common basis for all subsequent background impact assessments, which are carried out in parallel, thus ensuring the maximum consistency of the input data and inherent assumptions (Brown et al., 2012). Inventory data are converted into cumulative material demand, cumulative energy demand, environmental support (emergy), and cumulative emissions, in order to generate performance and sustainability indicators. The raw foreground inventory amounts, f_i, are multiplied by suitable conversion coefficients specific of each method applied, c_i, which express the “intensity” of the flow, i.e. quantify to what extent a background material, energy, or environmental cost is associated to each flow. Such coefficients are available in published life cycle assessment, energy and environmental accounting literature. Material, energy, and environmental “costs” associated to each flow are calculated, according to the following generic equation:

$$C = \Sigma C_i = \Sigma f_i \times c_i \quad i = 1, \ldots, n \tag{1}$$