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Data envelopment analysis of cities – Investigation of the ecological and economic efficiency of cities using a benchmarking concept from production management

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ABSTRACT

To better understand the economic performance of cities and the accompanying social and environmental implications, one focus of research has been on ways to quantify performance advantages of growth and size while considering the impact of economies of scale. An important aspect of the current discussion is the introduction of the merely environmental driven concept of resource efficiency, defined as minimizing resource consumption while enhancing the quality of life. However, as yet there is no commonly agreed method on how best to measure efficiency. In order to contribute to this debate, an approach is described here of applying Data Envelopment Analysis (DEA) to study the resource efficiency of cities. Originating in the field of economics, DEA is a non-parametric, deterministic method to measure the efficiency of economic production, specifically the relative efficiency of Decision Making Units (DMUs).

Here we test the usefulness of DEA to analyze urban efficiency by applying it to an investigation of 116 cities throughout Germany. This entailed the development of two separate economic and ecological models in order to allow more precise identification of the relevance of individual parameters during the evaluation process. The results allow a ranking of cities as well as an estimation of the ratios of economic and ecological efficiencies of the investigated cities, realized with the aid of a nine-field matrix (portfolio).

DEA is at the same time a promising heuristic tool to help draw the basic outlines of a resource efficient city and to shed light on the underlying factors that boost or reduce efficiency. We recommend a three-step approach. First, two separate models should be defined (ecological, economic) and used to feed the DEA computation. Second, the results are spread in a portfolio to give an overview of the ecological and economic efficiency scores. This provides a basic overview of the DEA results for the selected cities following a basic and abstract model without determination of causal relationships between these values. Third, the field-dependent commonalities between the cities are considered. Additional indicators that also characterize the selected cities (but which were not selected as inputs to the algorithm) can now be examined. In this way, it is possible to understand the common factors that determine the level of efficiency as well as to learn about the qualitative difference and specific features of cities in the particular matrix quadrants.

1. Introduction

Discussion of the eco-efficiency of services and products has widened to include the issue of efficiency of regions and cities (www.futurecities.ethz.ch, Weisz and Steinberger, 2010; Moavenzadeh et al., 2002). Indeed, the European Union Research Programme funds various projects to investigate the energy efficiency of cities and to promote sustainable urban metabolism (see SUME http://www.sume.at/abstract). In June 2012, the UNEP launched a global programme aimed at promoting resource efficient cities (see also UN SDGs (United Nations Sustainable Development Goals, 2015): http://www.un.org/sustainabledevelopment/cities/). Several cities have taken part

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in global initiatives, voluntarily committing themselves to improving energy efficiency (see Breuste, 2012; Joss, 2012, p. 11; Joss, 2011a, 2011b). Resource efficiency plays a vital role in the sustainable development of cities. Thus a primary aim of the German National Sustainability Strategy (*Nationale Nachhaltigkeitsstrategie*, p. 17ff.) is to minimize resource consumption (input) while ensuring the same or an increased level of construction activity and delivered services (output). Against this backdrop, some very basic questions must be answered: What do we mean when we say that a city is efficient? How can the efficiency of cities be measured and evaluated? In everyday language, the term *efficiency* is tied to the notion of minimizing input while maintaining a certain output or, conversely, maximizing output for a given input (Bohr, 1993). This is a basic concept in the field of economics, especially in production theory. The starting point of all theories of efficiency is how to deal with conditions of scarcity. The general concept of efficiency, which focuses on the thrifty use of resources, can therefore also be termed an "economic principle". It implies "a continual balancing of costs and returns" (Streit, 1991, p. 3). Classical concepts of efficiency encompass technical efficiency, micro-economic efficiency (Rivera, 1986, p. 3) as well as costs efficiency and the Pareto efficiency (after Dichtl and Issing, 1994, p. 493). Economists have developed a number of models to measure the efficiency of products and processes. Data Envelopment Analysis (DEA) is one tool that has been developed to measure relative efficiency. This investigation of the transferral of the DEA method from the field of economics to the urban context is motivated by the discussion of resource-efficient cities. Hitherto, the application of DEA to spatial units has only been attempted sporadically; there are some examples from China (Fang et al., 2013; Bian and Yang, 2010; Gu and Xiao Song, 2009), Finland (Kuosmanen and Kortelainen, 2005; Loikkanen and Susiluoto, 2002), the United States (Raab and Lichty, 1997), Turkey (Bal and Örkcü, 2011), Portugal (Morais and Camanho, 2010), Lithuania (Galiniene and Dzemydaite, 2012), Italy (Suzuki et al., 2011) and Israel (Hadad et al., 2010). Kuosmanen and Kortelainen (2005) have applied DEA to measure the eco-efficiency of cities, where eco-efficiency is defined as the ratio of (economic) value added to environmental damage. Other investigations have used DEA to compare the suitability of plots of land for the siting of public and non-profit facilities (Thompson et al., 1986; Takamura and Tone, 2003).

The questions we intend to answer here are: (1) is DEA a viable method to compare the efficiencies of cities? (2) Does the application of DEA provide some insight into the nature of an efficient city? (3) To which extent can this model be simultaneously applied to the study of the economic AND ecological efficiency of cities? (4) How do the scale properties of each city affect the level of efficiency? (5) Which characteristics are indicative of efficient as opposed to relatively inefficient cities? The paper primarily examine the questions (1) to (3) and gives some indicative answers to the questions (4) and (5).

2. Methods

2.1. Applying the model to cities

Data Envelopment Analysis (DEA) is a non-parametric, deterministic model developed as a benchmark concept in production economics to measure relative efficiency. No particular functional relationship between inputs and outputs is posited; instead, the model simply takes the combinations of inputs and outputs of all DMUs (Decision Making Units) as given, and subjects them to a process of comparison. DEA thus serves to compare the relative efficiency of DMUs. The Units can be any objects characterized by their inputs and outputs, which should be measurable in absolute values. The DMUs should be homogeneous in regard to their basic features in order to enable comparability. Efficiency values are determined for every DMU (Charnes et al., 1978). Depending on the observed inputs and outputs, these efficiency (or indeed inefficiency) values measure the distance to the optimal graphical envelope drawn by the most efficient units. DEA identifies a DMU as efficient if it reaches a certain desired level of output at the smallest possible level of input (input-oriented model). If this condition is met, then no higher output can be realized with the selected combination of inputs, or conversely the achieved output level will be lower for any other combination of inputs. All objects laying on the efficiency envelope create a benchmark, so that each DMU can be compared to their neighbouring "best-practice" unit (the so-called "peer"). Thus, the model is able to incorporate individual framework conditions. So-called "targets" are calculated in multi-dimensional space. The resulting measurements of efficiency are ratios laying between 0 and 1. An efficiency score of 1 characterizes a Benchmark DMU, whilst 0 is a theoretical value implying a unit with no output whatsoever (Kletzan and Url, 2003). The management team of a particular DMU can make direct use of the efficiency score to pinpoint potential areas for improvement.

In our study, we define built-up land (settlement and traffic areas) and soil-sealed areas as environmental "damage", although the focus is in fact on the consumption of the resource "land". These function as the model inputs for the ecological and economic models (assumption: settlement and traffic areas as fundamental "factor of production"). In the current investigation, the Decision Making Units (DMUs) of the DEA are 116 large and medium-sized cities (so-called Kreisfreie Städte [urban districts]) with independent administrations, whose populations vary from approx. 36,000 to 3.5 million. These meet the definition of DMUs in possessing an own scope for action, allowing them to greatly influence their internal development processes. We chose to look at the efficiency of land-use planning as a major factor in municipal planning with regard to environmental issues and in regulating the local economy. In this way, knowledge gained of the impact of settlement development and urban structures through DEA can quickly be incorporated into municipal decision-making processes (Arlt et al., 2001, Fig. 1).

In this study the professional software tool PIM DEASoft was used for the Data Envelopment Analysis. PIM DEASoft permits the calculation of different model types. Furthermore, the model provides weightings for individual indicators as well as statistical evaluations (Performance Improvement Management Ltd, 2014). The efficiency scores of the cities were calculated within PIM DEASoft by means of input-oriented DEA. Here the inputs were taken to be land use and land coverage, as the city administrations (the basic Decision Making Units) possess a measure of control over these inputs. The input and output parameters used in the model are clearly defined and regularly surveyed by relevant agencies in Germany. Data was drawn from own surveys (Arlt et al., 2001, 2005; Hennersdorf (1998)) as well as from regional databanks (Regionaldatenbank Deutschland, 2015) maintained and regularly updated by statistical agencies at the national and federal state level (https://www.regionalstatistik.de/genesis/online). The comparability of these sources is ensured by their similar methods of data capture. These data sources were selected as providing the best quality data.

To identify economies of scale (and consequently scale efficiencies) constant and variable returns to scale were considered. Constant returns to scale means that a change in input is reflected by a proportional change in output. In the case of variable returns to scale, a change in input can result in a disproportionate change in output (higher or lower than expected) as well as a proportional change in output (Walshaw, 2014, p. 8ff.).