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A multilevel and multistage efficiency evaluation of innovation systems: A multiobjective DEA approach

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ABSTRACT

Evaluating the efficiency of innovation systems can serve as a substantial enabling tool for policymaking serving to identify best practices and develop potential improvements of actions and strategies. It also serves to provide valuable insight in understanding the nature and dynamics of innovation process at its different stages and levels. The main aim of the paper is to present an integrated assessment and classification framework for national and regional innovation efficiency. The proposed model is based on Data Envelopment Analysis and is formulated as a multiobjective mathematical program in order to consider the objectives and constraints of the different stages and levels of the innovation process. Additionally, the model copes with DEA inconsistencies when ratio measures are employed. In the second part of the study, a multicriteria decision aid approach, based on an ordinal regression model, is applied in order to study how environmental factors on innovation and entrepreneurship affect the estimated efficiency scores. The proposed approach is applied to a set of 23 European countries and their 185 corresponding regions. The results show that there are large differences regarding the efficiency scores of the different stages and levels, implying the existence of significant divergences from the expected norm concerning innovation efficiency. The contribution of the paper lies (i) in the proposed multiobjective model, which is able to model the multiple stages and levels of the innovation process and handle ratio measures without requiring the same set of inputs and outputs at different levels and (ii) in the presented application of the model in the efficiency evaluation of innovation systems, including a meta-analysis of the results based on the framework of the Quadruple Innovation Helix. Such an approach may provide a valuable tool for country/region comparison and policy formulation.

1. Introduction

The study of innovation systems has been receiving significant attention, due to the important role of innovation policies in the economic growth, welfare, and competitiveness of nations and regions. Innovation should be considered as a complex and dynamic, socio-technical, socio-economic, socio political phenomenon. In this context, measuring the performance and the efficiency of innovation systems remains a high priority in order to develop integrated benchmarking systems in the knowledge-based economies. Such benchmarking systems are able to comparatively evaluate the efficiency/performance of innovation systems, identify best practices, and develop potential improvements of innovation performance enhancing theories, policies, and practices. Specifically, this may concern innovation policy formulation enhancements, as well as innovation policy implementation improvements concerning the different stages and levels of the innovation phenomenon.

There are multiple quantitative approaches for the study of national, regional, and sectoral innovation systems at the macro, meso, and micro levels. For instance, Carayannis and Provance (2008) propose a composite indicator approach for the study of innovation at the micro level pivoting around the 3Ps (Posture, Propensity, and Performance). Also, Cai (2011) refers to three major quantitative approaches in studying national (or regional) innovation systems at the macro level: composite indicators, econometric analysis, and data envelopment analysis. The composite indicators approach focuses mainly on aggregating –using different schemes– a set of innovation indicators, which should cover various aspects of the examined innovation systems (e.g., indicators that reflect the different stages of innovation process, organization pattern of

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innovation activities, institutional arrangements). The econometric analysis, on the other hand, is mainly used to analyze the factors influencing the national (or regional) innovation capacity. Using economic theory and empirical data, researchers in this field try to identify the determinants of innovation capacity or estimate how specific factors affect national/regional innovation capacity (see for example Furman, Porter, & Stern, 2002; Hu & Mathews, 2008).

The efficiency of innovation systems cannot be considered in the aforementioned approaches because only the final results are evaluated and not the efficiency of the design of the process leading to those results. Thus, it is not possible to study how effectively innovation resources have been used in the whole innovation process. In general, the efficiency of national or regional innovation systems is defined as the maximization of innovation outputs through the effective internal resource allocation and system operation under the given factor inputs, such as Research and Development (R&D) funding, human capital, etc. (Zhang, 2013).

In contrast to the previous approaches, Data Envelopment Analysis (DEA) focuses just on that, namely the efficiency of the design of the innovation process. DEA is the most widely used approach for measuring the relative efficiency of a number of Decision Making Units (DMUs) that transforms multiple inputs to multiple outputs in a similar context. Thus, DEA models focus exactly on input-output efficiency of innovation systems, where each country or region is considered as an independent DMU (Cai, 2011).

Studying separately innovation inputs and outputs may give misleading results (Carayannis & Provance, 2008; Cruz-Cázares, Bayona-Sáez, & García-Marco, 2013), e.g., innovation inputs may involve short-term costs and those investments that do not result in innovations are sunk costs. Moreover, innovation should not be modeled as a single stage process. Numerous researchers, following Schumpeter's (1934) definition for innovation, consider a knowledge exploration (recognition and development), and a knowledge exploitation (production and commercialization) stage. As noted by Kaihua and Mingting (2014), this can be considered as a consecutive process, which, in the case of technological innovation efficiency, may include both an upstream sub-process (transformation of technological investments to incremental technological knowledge) and a downstream sub-process (transformation of incremental technological knowledge to technological market profits). Adopting the existence of a complex knowledge production function in the innovation process, other scholars study not only the process of creating and disseminating knowledge, but also the creation and exploitation of skills, new technologies, and material products (such as the Mode 3 knowledge production system discussed in Carayannis & Campbell, 2009). Given the existence of several involved actors, (universities, research institutions, business enterprises, governmental organizations, etc.), innovation should be considered as an interactive, networking and collaboration process (Zhang, 2013). In any case, efficiency in knowledge production does not necessarily imply efficiency in commercialization, and thus studying the efficiency (or inefficiency) of the different innovation stages may support policy formulation (Carayannis, Goletsis, & Grigoroudis, 2015).

Furthermore, innovation is also a multilevel concept, since national and regional innovation systems coexist and coevolve. As noted by Carayannis et al. (2015), national innovation systems form the framework where a country's innovation is produced, while regions may follow different regimes and exploit innovation inputs in a different way. Each region has its own assets, strengths, competitive advantages, and capabilities. However, each national or regional innovation strategy should share some important common features that form the overall national contextual environment where innovation takes place.

The main aim of this paper is to present a framework for estimating national and regional innovation efficiency. The proposed approach considers the multiple stages of the innovation process (i.e., knowledge creation and commercialization), as well as the multiple levels of innovation systems (i.e., national and regional innovation systems). The approach is based on DEA modeling and its main characteristic is its ability to handle different inputs and outputs at different levels. The problem is based on a soft hierarchy modeling proposed by Carayannis et al. (2015), but it is modelled as a Multiobjective Linear Program (MOLP) in order to consider the objectives and the constraints of the different stages and hierarchies of the innovation process. Furthermore, in order to study how additional innovation and entrepreneurship variables affect the efficiency scores, a Multicriteria Decision Aid (MCDA) approach is applied based on the Quadruple Innovation Helix (QIH) framework (Carayannis & Campbell, 2009). The MCDA approach is based on an ordinal regression model (UTASTAR) that has the ability to handle ordinal data, such as the estimated efficiency scores, and model the nonlinear nature of the selected QIH indicators.

The originality of the paper is twofold: first, a multiobjective DEA model is proposed in order to model the multiple stages and levels of DMUs, without requiring the same set of inputs and outputs at different levels; moreover, our model overcomes limitations of ratio values which are quite common in the innovation case, this being an issue not adequately addressed in literature; second, an application of the model in the efficiency evaluation of innovation systems is presented, including a meta-analysis of the results based on MCDA tools.

The rest of paper is organized in four more sections. The literature review regarding the efficiency evaluation of innovation systems with DEA models is discussed in Section 2. Section 3 presents the proposed multistage and multilevel DEA approach, including the assessment of national and regional innovation sub-processes and the selection of necessary data. Section 4 is devoted to the most important results of the MOLP DEA model, including a comparison analysis between the different stage efficiencies. Also, a meta-analysis for the estimated efficiencies is presented in this section based on a MCDA approach. Finally, Section 5 summarizes our concluding remarks and discusses limitations, as well as potential extensions of the research.

2. Evaluating innovation systems with DEA

Innovation is a complex process and it should be evaluated as such, not as a single input-output activity (Tidd & Bessant, 2009). Non-parametric methods, with DEA as the most prominent one, manage to effectively combine the multiple facets and factors of innovation without the need for a specific production function.

Starting with Nasierowski and Arcelus (2003) DEA has been successfully applied to measure the efficiency of National Innovation Systems (see for example Matei and Aldea (2012), Sharma and Thomas (2008)). Some of these studies applied a second level econometric analysis to examine the effect of environmental factors to efficiency scores (Afzal (2014), Cai (2011), Chen and Guan (2010), Cullmann, Schmidt-Ehmcke, and Zloczysti (2011), Guan and Chen (2012), Nasierowski and Arcelus (2003)). Tobit has been mostly used while more recently Matei and Aldea (2012) and Afzal (2014) employed bootstrap for getting bias corrected estimations. Superefficiency that can produce complete country rankings has been also applied by Chen and Guan (2010), Guan and Chen (2012), Pan, Hung, and Lu (2010)).

Network DEA approaches have been applied to focus on the interaction of the two distinct processes i.e, the technological/knowledge development process and the commercialization