



# Assessing regional sustainable development through an integration of nonlinear principal component analysis and Gram Schmidt orthogonalization



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## ABSTRACT

The regional sustainable development level (SDL), sustainability of regional development (SRD) and system coordination (SC) make up the triangular truss of regional sustainable development assessment, but it is debated how should traditional practice best weight and calculate the whole sustainable development system level. The Bohai Rim, covering three provinces and two municipalities in China, lies in a region that is sensitive to profound conflict between socioeconomic development and environment pollution in the process of sustainable development. Considering the defects of traditional models and the multidimensionality of regional sustainability issues, we proposed an integrated model of nonlinear principal component analysis and Gram Schmidt orthogonalization and presented a novel regional sustainable development assessment method and framework from three perspectives for the society–economy–environment system of the Bohai Rim region. The results show that: (a) the integration of nonlinear principal component analysis and Gram Schmidt orthogonalization can well remedy the defects of traditional methods and provide a more objective conceptual framework; (b) the sustainability of regional development and system coordination models graphically demonstrate the essence and connotation of a dynamic sustainable development system; (c) the empirical study demonstrated that the Bohai Rim region has experienced a distinct development period in which the SRD experienced a steady decline and the SDL and SC generally increased; (d) the coordination ability can be improved by a decline in the environmental sustainability, which reveals the importance of environment subsystem optimization; and (e) the weight distribution of variables demonstrates that the most significant factors affecting sustainable development are the indicators from the dimensions of people's standard of living, economic structure and environmental pollution. This study enriches the sustainable development assessment theory and methodology, and lays the foundation for further sustainable development research in the Bohai Rim region.

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## 1. Introduction

According to McMichael et al. (2003), sustainability refers to actions taken to ensure that the environmental and social conditions support human security, wellbeing and health by transforming people's lifestyles and production models. How to measure and evaluate sustainability (Zhang et al., 2014; Silvestre et al., 2015;

Shaker and Zubalsky, 2015) is one of the most fundamental issues of sustainability research, as put forward by Kate et al. (2001), as the evaluation process is the first challenge that must be navigated to enable the transition toward sustainability and achieve a sustainable development strategy (Bebbington et al., 2007; Singh et al., 2012). Thus, the purpose of a sustainable development assessment is to provide decision-makers with an evaluation of 'from global to local' integrated society–economy–environment systems in short-term and long-term perspectives to assist them in determining whether actions should or should not be taken in the process of sustainable development (Ness et al., 2007). The compound system should be analyzed and dissected from the three perspectives of sustainable development level, sustainability of regional

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development and system coordination. For instance, when developing an urban sustainability index the researchers usually consider the overall urban sustainability (Singh et al., 2012), which contains three dimensions: the dimension of urban status, the dimension of urban potential and the dimension of urban coordination.

General ecological and environmental concerns gave rise, approximately 20 years ago, to the emergence of the sustainable development idea (Marques et al., 2009), but researchers in different disciplines have attempted to define more a precise meaning of the term and to more objectively quantify performance in the social, economic and environmental fields (Yu et al., 2010). Due to the multifaceted overlapping contents of the society–economy–environment complicated system's components on various geographical scales, measuring sustainable development and exploring the relationships among indices at the national and regional scales poses a formidable task (Salvati and Carlucci, 2014; Böhringer and Jochem, 2007). The current sustainable development assessment approach contains four main categories: socioeconomic, ecological, systematic and emerging methods. Typical methods include green GDP accounting (Eugeniom et al., 2010), genuine saving measure (Pillarissetti, 2005) and human development index (Mori and Christodoulou, 2012), ecological footprint (Jia et al., 2009), energy analysis (Vega-Azamar et al., 2013), the comprehensive index system method (Salvati and Carlucci, 2014), the fuzzy mathematical method (Erol et al., 2011), the system dynamic method (Jin et al., 2009), neural networks and other optimized algorithms (Li, 2007). Among these quantitative methods and models, the comprehensive index assessment method is especially popular with researchers due to its virtues in reflecting and covering economic, environmental, and social conditions together (Ness et al., 2007; Marques et al., 2009). Meanwhile, Agenda 21, which was put forward at the United Nations Conference on Environment and Development in 1992, clearly identified three critical building components of sustainable development: economic, environmental and social pillars. Therefore, to provide a scientific basis for decision-makers, it is essential to comprehensively assess the status of regional development with regard to these fields comprehensively (UNDP, 2007). The three pillars must be integrated and interlinked in a comprehensive manner (Hosseini and Kaneko, 2011), allowing for the robust application of a comprehensive evaluation method.

The most notable comprehensive assessment techniques are the analytic hierarchy process, discriminate analysis, factor analysis and principal component analysis (Singh et al., 2012). Principle component analysis (PCA), a very well-studied data analysis approach that aims to reduce the dimensionality and identify linear trends (Hosseini and Kaneko, 2011; Douka et al., 2012), can provide an objective way to aggregate indicators so that the data variations are accounted for as precisely as possible (Jollands et al., 2004). It has widespread applications in sustainable development assessment, involving society, economy and environment subsystems, while the sustainable development level (Shi et al., 2004; Zhou et al., 2007; Zhou and Zang, 2009) or coordination (Yang and Shi, 2011) is always directly judged on the basis of the PCA results of each subsystem. However, there are several innate easily neglected deficiencies. The traditional PCA is more suitable for the linear mapping case and its results are usually affected by the degree of inter-relatedness among indicators (Sun and Qian, 2009; Xu and Hua, 2009). Moreover, if sample groups are in different subsystems, the principal components and variance contributions will be different, so the assessment results will subsequently be unstable, whether the correlation matrix or covariance matrix is adopted in the process. In principle, the traditional principal component analysis is actually only suitable for a one-time evaluation of each subsystem individually (Abdi and Williams, 2010). Therefore, assessing

the compound system by principal component analysis may not consider the essential drawbacks of directly using the integrated results of the individual subsystems.

In view of the defects of PCA and the multidimensionality of regional sustainability issues, a coupled model based on non-linear principal component analysis (NLPCA) and Gram Schmidt orthogonalization (GSO) may better track and explore the accurate regional sustainable development level (SDL), providing a more objective procedure and better conceptual framework to analyze the society–economy–environment system (Salvati and Carlucci, 2014). Due to the nature of the complex sustainable development system described above, which is similar to the development of the urban sustainability index (Singh et al., 2012), we also need to incorporate in the design the perspectives of the regional development potential and coordination degree among the three subsystems to dissect the complex system, which are presented by the sustainability of regional development (SRD) model and system coordination (SC) models, respectively. The consideration of combining the two aspects together with the SDL model can help provide insights into the importance of the regional sustainable development change pattern.

In this study, an integration model of NLPCA and GSO was proposed to assess the SDL, and subsequently, SRD and SC models were established. The Bohai Rim region was selected as a case study characterized by its social, economic and environmental contexts. The Bohai Rim region (containing two municipalities and three provinces), one of the leading economic zones in China as well as the political, economic and cultural center, has achieved a relatively high urbanization level and economic development degree. However, profound conflict exists between socioeconomic development and environmental pollution, restraining the overall regional sustainable development tremendously (Tan and Lu, 2015). The following main objectives are pursued: the proposal and construction of SDL, SRD and SC models based on NLPCA–GSO; the application and analyses of the assessment framework and process in the Bohai Rim region; and the presentation of the overall sustainable development assessment and weight distribution of variables in the case.

## 2. Material

### 2.1. Study area

The target area (the Bohai Rim region, 34°22′–43°26′N, 113°04′–125°46′E) in this study (Fig. 1) surrounds the Bohai Sea in China and contains two municipalities (Beijing and Tianjin) and three provinces (Hebei, Shandong and Liaoning). The land area, population and total gross domestic product of the Bohai Rim region account for approximately 5.75%, 18.18% and 25.26% of the total value for China as of 2010, respectively. Although economic growth is clearly perceived in the region, the traditional development pattern has brought about severe resource shortage and ecological environment problems, leading to restrict socioeconomic development. Following the Pearl River Delta and the Yangtze River Delta, it is indispensable to assess the sustainable development situation to provide a relevant proposal.

### 2.2. Data resources and the sustainable development index system

The variables used in the relevant calculations of each subsystem in the Bohai Rim region were derived from official statistical sources, such as standard yearbooks compiled by central government and subordinate ministries (CSY, 2002–2011; BSY,

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