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Research article

Dynamic simulation and assessment of the coupling coordination degree of the economy–resource–environment system: Case of Wuhan City in China

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ABSTRACT

The environmental and resource issues that accompany rapid economic growth have attracted the attention of the government and the public. Multiple non-linear and complicated interactions exist between the economy, resource and environment subsystem. Accordingly, understanding the operating mechanism of the economy–resource–environment (ERE) system and evaluating its coordination level are of immense significance for sustainable urban development. This study uses system dynamics (SD) to build a dynamic model of the ERE system. Furthermore, a coupling coordination degree model (CCDM) that focuses on the coordination of the ERE system is established using data from 2000 to 2015 for Wuhan City, China. Four typical scenarios (i.e., current, economy, resource and environment scenarios) are designed and simulated by the constructed SD model. Coordination assessment results based on the CCDM show that the coordination of the economy scenario performs the worst, the environment scenario performs best in the short term and the resource scenario is considerably effective for the coordinated development of the urban ERE system in the long term. We suggest that improvements in the energy structure and the natural environment are prior choices for sustainable urban development.

1. Introduction

Resource and environmental problems are receiving increasing attention with the increasingly rapid economic globalisation and urbanisation. Rapid economic growth and urban expansion substantially increase the demand for natural resources, including energy resource (Chen et al., 2016) and land resource (Lu and Ke, 2017). Meanwhile, irrational development leads to the degradation of the eco-environment (Millennium Ecosystem Assessment, 2005) and the emissions of various pollutants (Li et al., 2018; Balsalobre-Lorente et al., 2018). To achieve sustainable development, various environmental policies and regulations are formulated to coordinate the development of the economy, resource and environment subsystems. For example, the energy tax (Oueslati et al., 2017) and CO_2 tax (Filippini and Heimsch, 2016) were imposed to control emissions. The European Union Emission Trading System (Lundgren et al., 2015) was established to provide further incentives for technological upgrading. In China, a top–down land use planning system was implemented to protect natural ecological lands (Zhou et al., 2017). However, a scientific decision-making process requires the government and academia to considerably understand how the related factors of economy, resource and environment subsystems interact with one another under different policies (Guan et al., 2011). Therefore, the dynamic interactions amongst these factors should be explored and how to coordinate their developments must be investigated.

The coordinated development of the economy–resource–environment (ERE) system has been regarded by academia as an effective method to realise sustainable urban development (Guan et al., 2011; Sauvé et al., 2015; Sunderland and Butterworth, 2016; Zuo et al., 2017). The ERE system is complicated and massive and characterised by the involvement of multiple dynamics and interactions amongst the components within a single subsystem and multiple subsystems (Han and Zhu, 2011; Guan et al., 2011; Zuo et al., 2017). Fig. 1 shows the structure and main feedback of the ERE system. This system's specific operating rules are as follows. The resource subsystem comprises two main resources, namely, energy and land. Wang et al. (2018) and Gozgor et al. (2018) indicated that both resources are the essential conditions for economic development. However, the overexploitation and exhaustion of natural resources causes serious damage to the environment (Shafiei and Salim, 2014) and will ultimately lead to a blockage of economic development (Śmiech and Papież, 2014). To avoid unsustainable development, many countries, such as the

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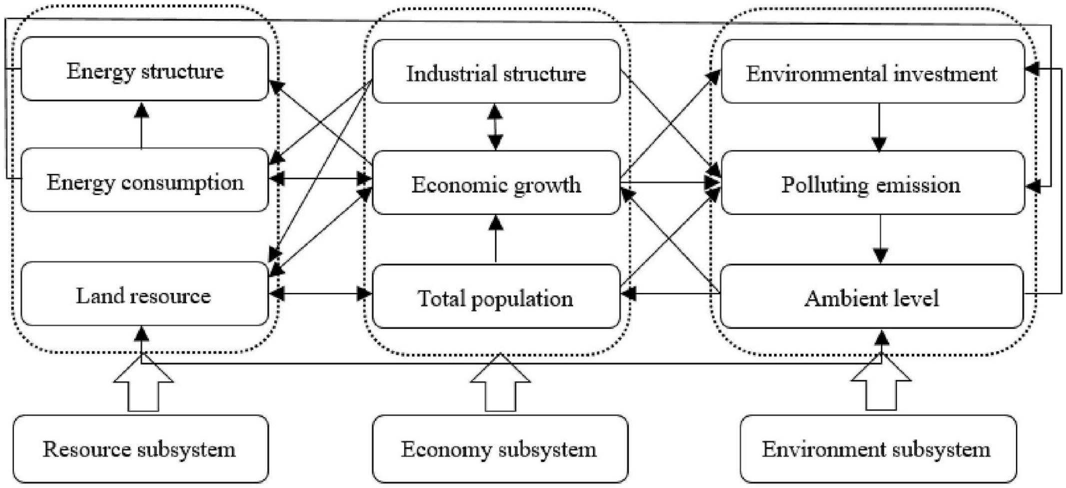

Fig. 1. Structure and main feedback sources of the ERE system.

members of Middle East and North Africa (MENA) (Kahia et al., 2016), Pakistan (Zafar et al., 2018) and China (Hu et al., 2018), have attempted to set goals and regulations to adjust their energy structures and introduce additional renewable energy. Therefore, energy structure is an important component in the resource subsystem and is consequently considered in the proposed model. In the economy subsystem, the total population provides the potential labour force for economic production. Meanwhile, labour productivity is influenced by regional pollution levels and the natural environment. Zivin and Neidell (2012) and Triguero-Mas et al. (2017) conducted thorough investigations to reveal that a bad ambient level had significant negative impact on labour productivity by harming the individuals' physical or mental health, thereby restraining economic growth. The hypothesis of the environmental Kuznets curve (Grossman and Krueger, 1995) indicates that economic growth has a negative impact on the environment at the primary stage of economic development. Upon reaching the inflection point, economic development can improve the environment through the adjustment of the industrial structure, technology upgrading and environmental policies (Shen, 2006; Xue et al., 2014). Zhao and Tang (2018) confirmed that China's industrial structure underwent substantial transformation from the traditional agricultural sector to the manufacturing and service sectors from 1995 to 2008. Mi et al. (2015) demonstrated that these transformations and upgrades have immense potential in energy saving and emission reduction. In the environment subsystem, numerous studies have explored the impact of energy consumption and economic growth on the environment (Herrerias et al., 2013; Omri, 2013; Xue et al., 2014; Chen et al., 2016). Soytas et al. (2007) and Arouri et al. (2012) determined that a unidirectional causal relationship exists from energy consumption to pollution emissions in the US and in 12 MENA countries. Additionally, natural or semi-natural lands have the ecosystem function of purifying the environment (Wang et al., 2017). Meanwhile, these lands are being gradually encroached upon by impermeable surfaces owing to rapid urbanisation (Wang et al., 2018). Therefore, feedback channels between land resource and the other two subsystems should be established.

As described above, the ERE system is a compound system with complex and dynamic interactions. At present, different methods have been developed and applied to investigate the performances or operating rules of the compound system. Generally, the ultimate goal of these studies is to provide suggestions for the coordination of the system, even though their foci differ from one another. Their features can be described in the following three aspects. Firstly, a few investigations aim to construct an index system for the compound system to evaluate the coordination degree. Wang et al. (2014) built an index system for the economy–energy–environment (3E) system and applied the proposed comprehensive evaluation model to evaluate the coordination degree of Shandong Province from 2004 to 2012. Sun and Cui (2018) constructed an index system for the social–economy–environment system of urban public transportation infrastructure and further evaluated the coordinated development of four Chinese autonomous municipalities. Secondly, other scholars have established different econometric models to investigate the causal relationships of key factors in the compound system. Omri (2013) used simultaneous equations models to reveal that bidirectional causal relationships exist between energy consumption and economic growth and between economic growth and CO_2 emissions in MENA countries. Belloumi (2009) applied a vector error correction model to the case of Tunisia and verified that a bidirectional causal relationship exists between energy consumption and income level over the period of 1971–2004. However, Ozcan (2013) used the panel cointegration model and determined a unidirectional causality from economic growth to energy consumption in the short-run based on materials from 12 Middle East countries. Similar studies and various conclusions are provided in the review of Tiba and Omri (2016) and Hajko (2017). These studies have demonstrated that complicated, non-linear and dynamic relationships are present amongst the key factors in the ERE system. Thirdly, other research focus on modelling and predicting the dynamic results of the compound system. System dynamics (SD) is popular for dealing with such problems. Zuo et al. (2017) described the modelling process of a 3E system and simulated the long-term development of the Beijing–Tianjin–Hebei region's 3E system. Guan et al. (2011) and Wu and Ning (2018) combined SD and a geographic information system to temporally and spatially model the dynamics of the 3E systems in Chongqing and Beijing. They also used the analytic hierarchy process to assess the sustainability of different scenarios.

Although the aforementioned developed methods are often used to investigate the performances, influential factors, interactions and dynamic changes of different compound systems, the compound ERE system is rarely studied. Meanwhile, existing models considerably focus on the energy aspect in the resource subsystem. Other resources, particularly land resource, are seldom considered. Wu et al. (2015) emphasised the importance of natural lands in sustainable urban development and constructed a coupled SD and the Conversion of Land Use and its Effects at Small Extent model to present the close relationships of land resource with economic development and the environment. Additionally, an index system approach for sustainability assessment can effectively integrate multiple factors that influence the ERE system into a comprehensive indicator. However, this method cannot reflect the dynamic interactions amongst these factors. Econometric models can only identify the causal relationships among a few factors of the

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