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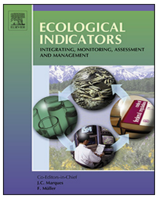

Structural optimization for industrial sectors to achieve the targets of energy intensity mitigation in the urban cluster of the Pearl River Delta

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ABSTRACT

An integrated approach was developed through incorporating a copula-based violation risk analysis into a programming model for optimizing industrial structures of urban clusters in uncertain conditions. Also, this approach can be used to support decision making about promoting advanced manufacturing sectors (AMSs) and mitigating industrial energy intensity. The advantages and the improvements of this approach lie in (a) reflecting the relationships between energy consumption and economic benefits in industrial sectors, and (b) incorporating the violation risk of the targets in energy-intensity mitigation into an optimizing model. A case study was conducted to illustrate the application of this approach in the Pearl River Delta of China, a highly urbanized area that includes the cities of Guangzhou, Shenzhen, Zhuhai, Dongguan, Huizhou, Zhaoqing, Foshan, and Jiangmen. The results indicated that under the desired industrial structures, violation risk of energy-intensity mitigation in the urban cluster of the Pearl River Delta would be indistinctive in the single-city perspective. Also, except Dongguan, Jiangmen and Zhaoqing, the cities of the urban cluster would achieve the goal for developing AMSs, based on the Industrial Plans for the 13th Five Year.

1. Introduction

The management of energy resources is an integral component of regional economic development and environmental protection (Zhou et al., 2015). The generation, consumption, and conservation of energy are central to economic activities which are measured as the growth of gross domestic product (GDP) (Bian et al., 2016; Sreekanth, 2016). Energy consumption is a major contributor to global climate change (Liu et al., 2016; Zhao et al., 2018). Approximately 70% of China's total energy consumption derives from the industrial sectors (Liu et al., 2015a; Wang et al., 2013). The International Energy Agency predicted that the energy used by industrial sectors would continue to increase, and the energy use would approximately double by 2050, assuming present trends continue (Edelenbosch et al., 2017). The Chinese government has thus proposed that the energy intensity (i.e., energy consumption per value added) in 2020 should be 15% less than its level in 2015 (Li and Lin, 2016; Liu et al., 2015b). As well as reducing the energy intensity, it is worth noting that energy consumption and economic benefits may face correlated variations in the process of industrial development (Zhou et al., 2015). Industrial agglomeration among urban cluster would also lead to complexities for mitigating energy intensity (Pan et al., 2015). Energy intensity reduction would become a tough constraint in the background of urban or urban-cluster development (Xu et al., 2017). Therefore, novel methods are required to consider how the energy intensity would be reduced over the long-term industrial development.

At the global level, industrial activities were responsible for over a third of the total energy demand (Fais et al., 2016). Industrial activities in China have had an enormous impact on energy consumption (Mi et al., 2015; Xu et al., 2014). China's industrial energy consumption has been the focus of various studies in recent years (Li and Shi, 2014). For example, Lu et al. (2015) used the decomposition technique and the decoupling method to determine the main influences on the energy consumption of industries. Yang et al. (2017) validated the inverted U-shaped relationship between the GDP per capita and the economy-related GHG emissions per capita. The mining and manufacturing sectors have a great effect on the energy intensity at both the national and provincial scales (Cai et al., 2016). Against the backdrop of the current energy mitigation goal in China, most industrial sectors need to reduce their energy intensity (Wu et al., 2016). In this context, the reduction of energy intensity poses a great challenge to China, especially for energy-intensive industrial sectors (Feng and Wang, 2017).

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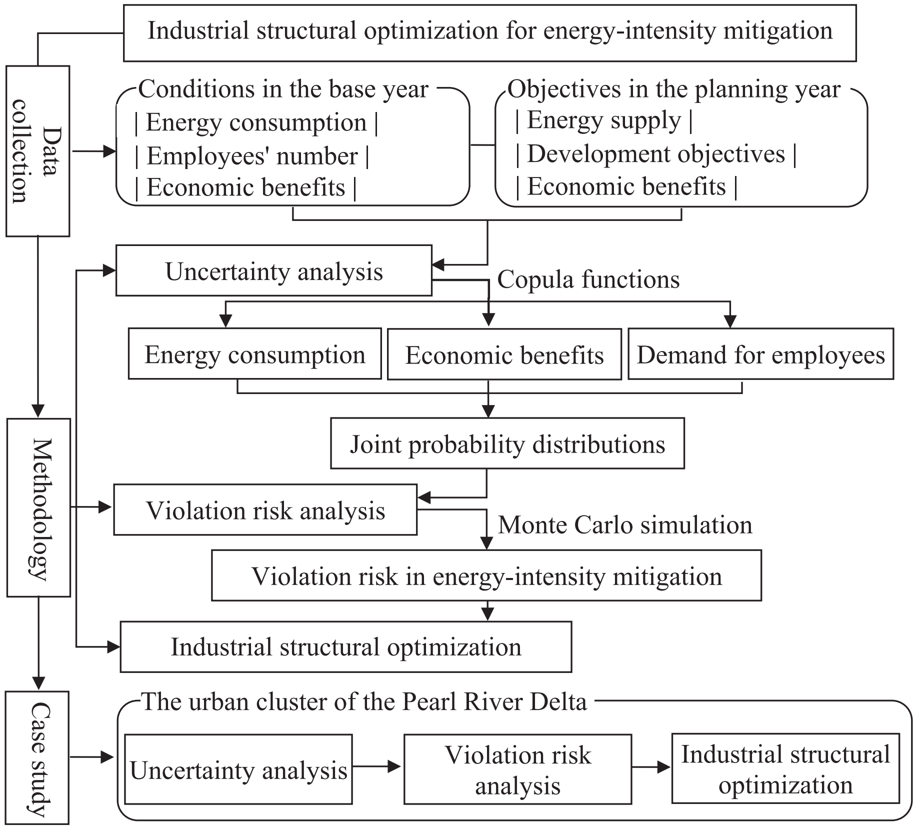

Fig. 1. Framework of industrial structural optimization in the background of energy-intensity mitigation.

Table 1
Equations of Copula function.

Family*	Parameter	$C_\theta(x,\ y)$
Gaussian copula	$\theta \in [-1,\ 1]$	$\frac{\phi_\theta(\Phi^{-1}(x), \Phi^{-1}(y))}{\phi(\Phi^{-1}(x))\phi(\Phi^{-1}(y))}$
Gumbel-Hougaard	$\theta \in [1, +\infty]$	$\exp\{-[(-\ln x)^\theta + (-\ln y)^\theta]^{1/\theta}\}$
Clayton	$\theta \in [-1, \infty]\backslash\{0\}$	$\max[(x^{-\theta} + y^{-\theta} - 1)^{-1/\theta}, 0]$
Frank	$\theta \in [-\infty, +\infty]\backslash\{0\}$	$-\frac{1}{\theta}\ln\left[1 + \frac{(e^{-\theta x}-1)(e^{-\theta y}-1)}{e^{-\theta}-1}\right]$
Student t	$\theta = \begin{bmatrix} 1\cdots\theta_{d1} \\ \vdots\ \ddots \\ \theta_{1d}\cdots 1 \end{bmatrix} \theta_{ij} = \begin{cases} 1, & i = j \\ \theta_{ij}, & i \neq j \end{cases}$	$\int_{-\infty}^{t_k^{-1}(x)} \int_{-\infty}^{t_k^{-1}(y)} \frac{1}{2\pi\sqrt{1-\theta^2}} \left[1 + \frac{s^2 - 2\theta st + t^2}{k(1-\theta^2)}\right]^{-(k+2)/2} dsdt$

* References: Nelsen (2006) and Zhang et al. (2016).

The energy intensity was influenced by many factors in industrial sectors (Ang, 1999). Over recent decades, some researchers have studied the effect of energy intensity in industrial sectors. Li and Lin (2015) used a meta-frontier network to measure the energy intensity performance of 30 provinces in China. Wang and Wei (2014) applied data envelopment analysis (DEA) to evaluate the regional energy efficiencies and the energy saving potentials of the industrial sectors in major cities. Wu et al. (2016) suggested that a DEA approach could be used to allocate the total national energy intensity reduction targets to China's provincial industrial sectors, for the purpose of sustainable development. Concurrently, structural effects in industries were revealed to be the dominant factors in reducing energy intensity of China (Liu et al., 2015a). Structural transformation in industrial sectors can help mitigate energy intensity (Liu and Xiao, 2018; Shi and Li, 2018). To achieve mitigation targets in energy intensity, optimizing models can provide the desired strategies for industrial structural transformation (IST) (Dong et al., 2014a,b). For example, Mi et al. (2015) developed an multi-objective optimization model based on the input-output method to obtain the adaptive industrial structures, considering the energy-intensity mitigation and economic benefits. In addition to industrial structural transformation, fuel prices and the number of employees can also influence the energy intensity of industrial sectors (Kander et al., 2017).

To realize the targets for energy-intensity mitigation in the future, the links between the environmental and economic performance of industrial sectors need to be considered (Cheng et al., 2018; Segura et al., 2018). Such relationships directly affected the mitigation of energy intensity in industrial sectors. For example, some researchers revealed the relationship between the economic growth and environmental protection in the framework of Environmental Kuznets Curves (Wang et al., 2016a,b). Previously, approaches for correlation analysis (e.g., fuzzy rough set model, threshold analysis, and gray relational analysis) were introduced to indicate the relationship among energy consumption, CO_2 emissions and mitigation options (Chen et al., 2018;