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Sustainability Evaluation of Railways in China Using a Two-Stage Network DEA Model with Undesirable Outputs and Shared Resources

Haibo Zhou and Hanhui Hu *

Department of Economics and Management, Southeast University, Nanjing 210096, China; zhouhb0920@126.com
* Correspondence: huhh@seu.edu.cn; Tel.: +86-138-0902-1156; Fax: +86-25-520-90166

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Abstract: This paper constructs an additive two-stage network DEA (data envelopment analysis) model with consideration of undesirable outputs and shared inputs. Following the triple bottom line standard of sustainability, we calculate both the overall and sub-stage sustainability performance of railway transportation in China from 2002 to 2013, from the aspects of economy, environment and society. The results show that the overall sustainability of China's railway presents a character of first declining, then rising and declining again. Moreover, the railway sustainability of China's eastern areas are much better than that of the western and central areas, and the gap has become much larger since 2009. As for the sub-stage efficiency, neither the production stage nor the service stage of the railway is efficient in sustainability, and the efficiency of the production stage is lower than that of service stage and plays a greater impact on the overall sustainability. Therefore, in order to improve the overall sustainability of China's railways, it is essential to improve the level of railway engineering construction and develop technological innovations in railway production.

Keywords: sustainability; two-stage network DEA; shared input; undesirable output; railway

1. Introduction

Since the Reform and Opening in 1978, the average annual growth rate of China's GDP is reaching 9.9%, which creates a miracle in the history of human economic development. Among all of the explanations to this "China miracle", the advanced development of the transportation infrastructure is regarded as an accelerator of economic growth. Thanks to tax system reform and governance transition of local governments in the 1990s, especially in the two proactive fiscal policies after financial crises in 1998 and 2008, significant funds flowed into transportation infrastructure construction. Currently, China is making a national effort to implement the strategy of "One Belt and One Road", and transportation infrastructure is the prior field of this strategy, which plays a leading and facilitating role in realizing regional integrated development. As an important form of transportation, the railway is the backbone of a comprehensive transportation system, which has comparative advantages, such as high transport capacity, low cost, less land occupation, energy conservation, environment protection, high safety and so on. Railways have made a non-negligible contribution to regional sustainable development. However, existing railway-related research mainly concentrates on railways' effects on economic growth, including the multiplier effect of investment, spillover effects of stock, and the influence of railways' network attributes to the space layout of economic activity. Rarely is there literature that studies the sustainability of railways. However, only when it is in a good status of sustainability can the railway effectively promote the sustainable development of regional economy.

The book "Sustainable Transport: Priorities for Policy Reform" edited in 1996 first proposes the concept of "sustainable transport", which refers to accomplishing economic sustainability and finance, sustainability of the environment and ecology, and sustainability of society in transportation. With the increasing shortage of natural resources and the severity of environmental pollution, sustainable transport has attracted more and more attention from the public and the governments. Since the Reform and Opening in 1978, the railway transportation industry in China has made remarkable achievements: railway mileage reached 97,600 km by 2012, which ranks second in the world. Additionally, both the mileage of high-speed railways and its growth rate now rank first in the world. However, those achievements depend on high input and high consumption of production factors, which is unsustainable. According to the "China's Medium and Long-term Railway Network Planning" issued in 2008, railway mileage in China would reach 120,000 km by 2020. Without sustainable development, such large-scale railway construction will bring extremely adverse influence to the environment and the ecology of the areas along the railways. Hence, we should review railway development from the perspective of sustainability in order to obtain a more profound understanding about the relationship between railways and regional sustainable development.

Based on whether constructing a production frontier, the methodologies for the evaluation of railway operation efficiency can be divided into the frontier analysis method and the non-frontier analysis method. Here, the production frontier is a curve depicting all maximum output possibilities for two goods, given a set of inputs consisting of resources and other factors, which shows how much an economy can produce given existing resources and technology. The production frontier represents the point at which an economy is most efficiently producing its goods and services and, therefore, allocating its resources in the best way possible. If the economy is not producing the quantities indicated by the production frontier, resources are being managed inefficiently and the production of society will dwindle. Commonly used non-frontier analysis methods include partial factor productivity [1] and total factor productivity [2]. However, frontier analysis methods need to construct a production frontier to make sure that all input-output observation points are located below the frontier and as close as possible to it. Based on whether knowing the form of frontier production function, frontier analysis methods can be divided into the parameter analysis method and non-parameter analysis method. The former is represented by stochastic frontier analysis [3], and the latter is represented by data envelopment analysis (DEA). Oum et al. conducted a review about the application of those methods in railway efficiency evaluation [4]. Among all these methods, DEA, proposed by Charned et al., is a kind of systemic analysis method to measure relative efficiency of a set of decision-making units (DMUs) that apply multiple inputs to produce multiple outputs by linear programming. DEA has two basic models—the CCR model and the BCC model. The CCR model, introduced by Charnes, Cooper, and Rhodes [5], applies only to technologies characterized by constant returns to scale. The BCC model, proposed by Banker et al. [6], extends the CCR model to accommodate technologies that exhibit variable returns to scale.

The following DEA model is an input-oriented version of CCR (Charnes, Cooper, and Rhodes [5–7]) model, in which it tries to find the maximum possible reduction of inputs while keeping the output level constant:

$$\begin{aligned} E_k^{CCR} = \quad & \max. \quad \sum_{r=1}^{s} u_r Y_{rk} \\ & s.t. \quad \sum_{i=1}^{m} v_i X_{ik} = 1 \\ & \qquad \sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \leq 0,\ j = 1, \ldots, n \\ & \qquad u_r, v_i \geq 0,\ r = 1, \ldots, s,\ i = 1, \ldots, m \end{aligned} \tag{1}$$

where inputs X_{ij}, $i = 1, \ldots, m$, are utilized to produce outputs Y_{rj}, $r = 1, \ldots, s$, for each DMU_j, $j = 1, \ldots, n$, u_r and v_i are weights with respect to each output and input respectively. Larger values of E_k^{CCR} imply a better performance, and a value of 1 is considered as efficient.

By adding a scalar u_k to the CCR model, we can get the input-oriented BCC (Banker, Charnes, and Cooper) model, which is expressed as:

$$
\begin{aligned}
E_k^{BCC} = \quad & \max. \quad \sum_{r=1}^{s} u_r Y_{rk} + u_k \\
& s.t. \quad \sum_{i=1}^{m} v_i X_{ik} = 1 \\
& \qquad \sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} + u_k \leq 0, \; j = 1, \ldots, n \\
& \qquad u_r, v_i \geq 0, \; r = 1, \ldots, s, \; i = 1, \ldots, m, \; u_k \; free \; in \; sign
\end{aligned}
\tag{2}
$$

where u_k may be positive or negative (or zero). If u_k takes negative values in all optimal solutions to this model, then increasing returns-to-scale prevails at the DMU(x_k, y_k); if u_k takes a zero value in some optimal solutions to this model, then constant returns-to-scale prevails at the DMU(x_k, y_k); and if u_k takes positive values in all optimal solutions to this model, then decreasing returns-to-scale prevails at the DMU(x_k, y_k).

The DEA method does not need to know the concrete form of the production frontier. It only requires the input and output data, and could deal with the conditions of multiple inputs and multiple outputs. Compared with other methods, DEA has obvious superiority in avoiding subjective factors, simplifying algorithm and reducing errors. Therefore, DEA has been widely used in the evaluation of railway operation efficiency.

Oum and Yu [8] first evaluated the railway operation efficiency of 19 OECD countries from 1978 to 1989 using two-stage contextual factors analysis: evaluating the efficiency with the DEA method in the first stage and finding the impact factors of efficiency with Tobit regression [9] method in the second stage. Their pioneering research attracted more and more scholars to evaluate railway operation efficiency with various DEA models. Chapin and Schmidt used a DEA model to measure operation efficiency of American class 1 railway after deregulation [10]. Cowie adopted DEA method to compare the technology and management efficiency of public railway and private railway in Switzerland by separately constructing efficiency frontier of technology and management [11]. Lan and Lin separated the progress of production and consumption in railway for the first time, and used various DEA methods, such as the traditional CCR DEA model, exogenous fixed-input DEA model, and the category DEA method, to compare the technology efficiency and the service efficiency of 76 railways in the world [12]. However, the previous DEA models treated the railway operation process as a "black-box", neglecting the operations and interrelations of the processes within the system, until Yu and Lin proposed to use the network DEA model to evaluate the production efficiency and the service effectiveness of railway system with the consideration of different stages of production process [13]. In conclusion, existing works on the evaluation of railway efficiency mainly focus on the interior of railway system and assess the technology and management efficiency. However, the interaction of the railway system and the external environment and society has not been involved, which is to say current research has not involved environmental and social impacts of railway transportation in DEA models to assess the sustainability of railway transportation. Furthermore, sustainability assessment of railways plays an important role in the governments' choosing and improving of railway construction projects, which, in turn, influences regional sustainable development. Hence, this paper firstly divides railway operation processes into two stages: the production stage and the service stage, and constructs a revised additive two-stage network DEA model with undesirable outputs and shared resources for the first time. Then we use this model to evaluate the overall and sub-stage sustainability of railways in various areas in China based on the triple bottom line standard. Through this study, we can find the sustainability status of railway transportation in China and discover the main causes of the inefficiency, which will help the governments and railway enterprises in future railway development.

The remainder of the paper proceeds as follows: Section 2 deals with a discussion on the development of undesirable outputs DEA models and shared resource DEA models. Section 3 proposes the DEA methodology for assessing overall and sub-stage efficiency with undesirable outputs and shared inputs. Section 4 describes the concept of railway sustainability and uses the model proposed in Section 3 to estimate the overall and sub-stage sustainability of railway transport in different areas of China, then discusses the results. Section 5 provides some concluding remarks.

2. Undesirable Output and Shared Resource in DEA

2.1. Undesirable Output in DEA

Since Färe et al. [14] first discussed undesirable outputs in production processes, there has been extensive DEA literature studying this issue and developing various DEA models. The undesirable output research in DEA can be divided into two research dimensions: one is about adopting data transformation to transform the undesirable outputs into desirable outputs, and the other is about the production process, which is based on black-box processes or multi-stage processes.

From the perspective of data transformation, those works that adopted data transformation aimed at transforming undesirable outputs into desirable outputs to apply to the traditional DEA models. The most widely used transfer approach is taking the opposite number of undesirable outputs and then adding a large positive number to the opposite number [15–17]. There is also the method of directly taking the opposite number [18], implementing the reciprocal method [19,20]. However, those who did not use data transformation mainly adopted the attribute transformation method, which regarded undesirable output as desirable input [21].

From the perspective of stage properties of the production process, undesirable output research in DEA has developed from the early black-box production research to multi-stage research. In black-box process research, the DEA methods dealing with undesirable output mainly include radial measurement [17], direction distance function (DDF) [22], slack-based measure (SBM) [23], and slack-based inefficiency measure (SBI) [24]. Liu et al. [25] made a detailed review about undesirable output research in black-box DEA model, but when it comes to the multistage process, the former methods are no longer applicable. Hence, Liu et al. extended the radial measurement to a network radial analysis model [26]. Lozano et al. [27] extended the DDF method to a network direction distance function (NDDF). Tone and Tsutsui put forward a network SBM model [28], and Fukuyama and Weber extended the SBI method to a network SBI [24].

2.2. Shared Resource in DEA

In recent years, shared resources in DEA research have been receiving more and more attention from scholars. Shared resources mainly refer to those resources that are shared by two or more stages in a multistage production process. However, no shared resources exist in traditional DEA models. Regarding works on shared resources, Yu and Lin first allocated shared inputs by setting a subjective proportion in a multi-activity network DEA (MNDEA) model [13]. Following this, Chen et al. [29] proposed an additive linear two-stage shared inputs DEA model based on Kao and Hwang [30] and limited the interval of the shared proportion. The endogenous decomposition weight used in Chen's model is biased, which may lead to inaccurate evaluation results of overall efficiency, so there is a need to improve it.

However, few DEA works have ever comprehensively considered situations with undesirable outputs and shared resources existing at the same time, except for Wu et al. [31], who used non-cooperative efficiency measures and proportion weight to analyze the reuse of undesirable intermediate outputs in a two-stage production process with a shared resource. However, Wu et al.'s specification of decomposition weights may lead to biased evaluation, which is to say that the earlier stages would obtain higher decomposition weights and have a greater influence on the overall efficiency. We will discuss this problem in detail in the methodology section. However, undesirable outputs and shared resources are common in the real world, especially when evaluating environment technology efficiency of multistage production process. When considering undesirable outputs and shared resources simultaneously, existing models need to be revised so as to enlarge their scope of application. In the following section, we will propose a revised network DEA model to simultaneously deal with undesirable outputs and shared inputs, which is different from Wu et al. in the specification of decomposition weights and solution algorithms.

3. Methodology

In this section, we will introduce undesirable outputs into Chen et al.'s additive two-stage network DEA model with shared inputs [29], and replace the endogenous decomposition weights with invariant decomposition weights, and finally come up with a revised additive two-stage network DEA model.

Figure 1 shows a generic two-stage process where some inputs are shared by both stages and there are some undesired outputs in the second stage. Suppose that there is a set of n DMUs, denoted by $DMU_j(j = 1, \ldots, n)$, and that each $DMU_j(j = 1, \ldots, n)$ has m inputs denoted by $x_{ij}(i = 1, \ldots, m)$ to the entire process. Parts of these m inputs are the only inputs to the first stage, denoted by $x_{i_1 j}(i_1 \in I_1)$, while others are shared as inputs in both stages, denoted by $x_{i_2 j}(i_2 \in I_2)$, where $I_1 \cup I_2 = \{1, 2, \ldots, m\}$. Suppose, also, that each $DMU_j(j = 1, \ldots, n)$ has t outputs denoted by $z_{dj}(d = 1, \ldots, t)$ from the first stage, which then become inputs to the second stage and are referred to as intermediate measures. In the second stage, there are two kinds of outputs: ones that are desired outputs, denoted by $y_{rj}(r = 1, \ldots, s)$ and the other ones that are undesired outputs, denoted by $b_{qj}(q = 1, \ldots, Q)$.

Since inputs $i_2 \in I_2$ are shared by both stages, we assume that all $x_{i_2 j}(i_2 \in I_2)$ are divided into $\alpha_{i_2 j} x_{i_2 j}$ and $(1 - \alpha_{i_2 j}) x_{i_2 j}$ $(0 \leq \alpha_{i_2 j} \leq 1)$, corresponding to the portions of shared inputs used by the first and the second stage, respectively. Similar to the constraints in Cook and Hababou [32], all $\alpha_{i_2 j}$ $(i_2 \in I_2, j = 1, \ldots, n)$ will be required to be within certain intervals, namely $L^1_{i_2 j} \leq \alpha_{i_2 j} \leq L^2_{i_2 j}$.

The outputs b_{qj} are modeled as undesired outputs in subsystem 2, and have been transformed into normal output variables based on the linear transformation approaches proposed by Seiford and Zhu [17]. The core idea of their transformation method is firstly to multiply each undesirable output by "-1". Then, a proper translation vector M is constructed to make all negative undesirable outputs become positive. That is, $\bar{b}_{qj} = -b_{qj} + M > 0$.

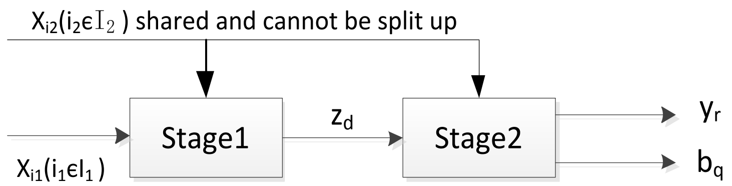

Figure 1. Two-stage process with shared inputs and undesired outputs.

Based upon the variable returns to scale (VRS) model of Banker et al. [6], the input-oriented VRS efficiency scores for DMU$_o$ in the first stage θ^1_0 and in the second stage θ^2_0 are calculated respectively by:

$$
\begin{aligned}
\theta^1_0 \quad &= Max \frac{\sum_{d=1}^{t} n^1_d z_{do} + u^A}{\sum_{i_1 \in I_1} v_{i_1} x_{i_1 0} + \sum_{i_2 \in I_2} v^1_{i_2} \alpha_{i_2 0} x_{i_2 0}} \\
s.t. \quad & \frac{\sum_{d=1}^{t} n^1_d z_{dj} + u^A}{\sum_{i_1 \in I_1} v_{i_1} x_{i_1 j} + \sum_{i_2 \in I_2} v^1_{i_2} \alpha_{i_2 j} x_{i_2 j}} \leq 1, \ \forall j \\
& L^1_{i_2 j} \leq \alpha_{i_2 j} \leq L^2_{i_2 j}, \ \forall j \\
& n^1_d, v_{i_1}, v^1_{i_2} \geq 0, \ d = 1, \cdots, t; \ i_1 \in I_1, i_2 \in I_2, u^A free.
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\theta_0^2 \quad &= Max \frac{\sum\limits_{r=1}^{s} u_r y_{ro} + \sum\limits_{q=1}^{Q} \varphi_q \bar{b}_{q0} + u^B}{\sum\limits_{i_2 \in I_2} v_{i_2}^2 (1-\alpha_{i_20}) x_{i_20} + \sum\limits_{d=1}^{t} n_d^2 z_{d0}} \\
s.t. \quad & \frac{\sum\limits_{r=1}^{s} u_r y_{rj} + \sum\limits_{q=1}^{Q} \varphi_q \bar{b}_{qj} + u^B}{\sum\limits_{i_2 \in I_2} v_{i_2}^2 (1-\alpha_{i_2j}) x_{i_2j} + \sum\limits_{d=1}^{t} n_d^2 z_{dj}} \leq 1, \forall j \\
& L_{i_2j}^1 \leq \alpha_{i_2j} \leq L_{i_2j}^2, \ \forall j \\
& u_r, \varphi_q, n_d^2, v_{i_2}^2 \geq 0, \forall r, q, d, \ i_2 \in I_2, u^B free.
\end{aligned}
\tag{4}
$$

As pointed out in a number of studies (e.g., Chen and Zhu [33]), the method of using Equations (3) and (4) separately to evaluate the efficiencies of different stages do not correctly model the intermediate outputs $z_{dj}(d = 1, \cdots, t)$. Since Equation (4) tries to reduce z_{dj}, which are assumed to be kept at their current level in Equation (3). An alternative approach to measure the efficiency of the two-stage process is to view them from a centralized perspective, and determine a set of optimal weights on the intermediate measures that maximize the aggregate or global efficiency score, as would be true where the manufacturer and retailer jointly determine the price, order quantity, etc. to achieve maximum profit [34]. Therefore, similar to Kao and Hwang's assumption [30] and the centralized model in Liang et al. [35], we assume that $n_d^1 = n_d^2 = n_d$ for all $d = 1, \cdots, t$ in Equations (3) and (4). We also assume that $v_{i_2}^1 = v_{i_2}^2 = v_{i_2}$ for all $i_2 \in I_2$ because these are the same types of inputs.

We propose to combine the two stages in a weighted average of efficiency scores of stages 1 and stage 2 as follows:

$$
w_1 \cdot \frac{\sum\limits_{d=1}^{t} n_d^1 z_{do} + u^A}{\sum\limits_{i_1 \in I_1} v_{i_1} x_{i_10} + \sum\limits_{i_2 \in I_2} v_{i_2} \alpha_{i_20} x_{i_20}} + w_2 \cdot \frac{\sum\limits_{r=1}^{s} u_r y_{ro} + \sum\limits_{q=1}^{Q} \varphi_q \bar{b}_{q0} + u^B}{\sum\limits_{i_2 \in I_2} v_{i_2} (1 - \alpha_{i_20}) x_{i_20} + \sum\limits_{d=1}^{t} n_d^2 z_{d0}} \tag{5}
$$

where w_1 and w_2 are user-specified weights which we refer to as the decomposition weights, as they decompose the overall efficiency into stage efficiencies and $w_1 + w_2 = 1$.

About the specification of decomposition weights, many works (e.g., Cook et al. [36]) chose the endogenous weights that define the weights w_p as the virtual inputs (outputs) of stage p divided by total virtual inputs (outputs), representing the relative importance or contribution of the performance of each stage, respectively, to the overall performance of the DMU in the whole process. However, Ang and Chen [37] found that these endogenous weights implied that upstream stages (regardless the stage efficiency scores) in the model would obtain higher priority in efficiency decomposition, which meant that the earlier stages would obtain higher decomposition weights and have a greater influence on the overall efficiency. In the two-stage model, for example, this means that the decomposition weight of the first stage will be at least as high as 0.5. It is easy to find examples in which managers may find that this property is at odds with the actual production process. In order to overcome this problem, in this paper, we use an additive model with constant decomposition weights and specify $w_1 = w_2 = 1/2$.

Thus, under VRS, the overall efficiency score of the two-stage process for DMU_o can be evaluated by solving the following fractional program:

$$\begin{aligned}
\theta_0 \quad &= Max\frac{1}{2}\cdot\frac{\sum\limits_{d=1}^{t} n_d^1 z_{do}+u^A}{\sum\limits_{i_1\in I_1} v_{i_1}x_{i_1 0}+\sum\limits_{i_2\in I_2} v_{i_2}\alpha_{i_2 0}x_{i_2 0}}+\frac{1}{2}\cdot\frac{\sum\limits_{r=1}^{s} u_r y_{ro}+\sum\limits_{q=1}^{Q}\varphi_q \overline{b}_{q0}+u^B}{\sum\limits_{i_2\in I_2} v_{i_2}(1-\alpha_{i_2 0})x_{i_2 0}+\sum\limits_{d=1}^{t} n_d^2 z_{d0}} \\
s.t. \quad &\frac{\sum\limits_{d=1}^{t} n_d^1 z_{dj}+u^A}{\sum\limits_{i_1\in I_1} v_{i_1}x_{i_1 j}+\sum\limits_{i_2\in I_2} v_{i_2}\alpha_{i_2 j}x_{i_2 j}} \le 1,\ \forall j \\
&\frac{\sum\limits_{r=1}^{s} u_r y_{rj}+\sum\limits_{q=1}^{Q}\varphi_q \overline{b}_{qj}+u^B}{\sum\limits_{i_2\in I_2} v_{i_2}(1-\alpha_{i_2 j})x_{i_2 j}+\sum\limits_{d=1}^{t} n_d^2 z_{dj}} \le 1, \forall j \\
&L_{i_2 j}^1 \le \alpha_{i_2 j} \le L_{i_2 j}^2,\ \forall j \\
&u_r, \varphi_q, n_d, v_{i_1}, v_{i_2} \ge 0, \forall r, q, d, i_1 \in I_1, i_2 \in I_2, u^A, u^B free
\end{aligned} \tag{6}$$

Here we have:

Definition 1. *DMU_j is said to be overall efficient if and only if θ_j = 1, $j = 1, \ldots, n$.*

Definition 2. *The stage k sub-DMU is said to be efficient if θ_j^k = 1, k = 1, 2.*

Notice that these two definitions ensure that DMU_0 is overall efficient if and only if each stage is efficient, which is proved in Wu et al.

To solve Equation (6), we adopt Ang and Chen's method [37]. In the first step, we calculate the bounds for the optimal efficiency scores of two stages. In the second step, we use the bounds from the first step to specify the value of one of the stage efficiency scores, and then we can solve the problem as a linear programming problem to obtain the efficiency score of the other stage.

Step 1. Calculating the bounds of the optimal values for θ_0^1 and θ_0^2 in Equations (3) and (4).

To compute the ranges for θ_0^1 and θ_0^2, we calculate the maximal efficiency scores for stage 1 and stage 2 as follows:

$$\theta_0^{1+} = Max\frac{\sum\limits_{d=1}^{t} n_d^1 z_{do}+u^A}{\sum\limits_{i_1\in I_1} v_{i_1}x_{i_1 0}+\sum\limits_{i_2\in I_2} v_{i_2}\alpha_{i_2 0}x_{i_2 0}}, \text{subject to the constraints of } (6) \tag{7}$$

$$\theta_0^{2+} = Max\frac{\sum\limits_{r=1}^{s} u_r y_{ro}+\sum\limits_{q=1}^{Q}\varphi_q \overline{b}_{q0}+u^B}{\sum\limits_{i_2\in I_2} v_{i_2}(1-\alpha_{i_2 0})x_{i_2 0}+\sum\limits_{d=1}^{t} n_d^2 z_{d0}}, \text{subject to the constraints of } (6) \tag{8}$$

where θ_0^{1+} and θ_0^{2+} are the upper bounds of the optimal values for θ_0^1 and θ_0^2. Then we can obtain the lower bounds of θ_0^1 by maximizing stage 1's efficiency given stage 2's efficiency score θ_0^{2+}, and vice versa.

$$\theta_0^{1-} = Max\frac{\sum\limits_{d=1}^{t} n_d^1 z_{do}+u^A}{\sum\limits_{i_1\in I_1} v_{i_1}x_{i_1 0}+\sum\limits_{i_2\in I_2} v_{i_2}\alpha_{i_2 0}x_{i_2 0}}$$

s.t. the same constraints of Equation (6):

$$\frac{\sum\limits_{r=1}^{s} u_r y_{ro} + \sum\limits_{q=1}^{Q} \varphi_q \overline{b}_{q0} + u^B}{\sum\limits_{i_2 \in I_2} v_{i_2} \left(1 - \alpha_{i_2 0}\right) x_{i_2 0} + \sum\limits_{d=1}^{t} n_d^2 z_{d0}} = \theta_0^{2+}$$
$$\theta_0^{2-} = Max \frac{\sum\limits_{r=1}^{s} u_r y_{ro} + \sum\limits_{q=1}^{Q} \varphi_q \overline{b}_{q0} + u^B}{\sum\limits_{i_2 \in I_2} v_{i_2} \left(1 - \alpha_{i_2 0}\right) x_{i_2 0} + \sum\limits_{d=1}^{t} n_d^2 z_{d0}} \tag{9}$$

s.t. the same constraints of Equation (6):

$$\frac{\sum\limits_{d=1}^{t} n_d^1 z_{do} + u^A}{\sum\limits_{i_1 \in I_1} v_{i_1} x_{i_1 0} + \sum\limits_{i_2 \in I_2} v_{i_2} \alpha_{i_2 0} x_{i_2 0}} = \theta_0^{1+} \tag{10}$$

The optimal objective values of Equations (9) and (10) are denoted by θ_0^{1-} and θ_0^{2-}, respectively, which are the lower bounds of θ_0^1 and θ_0^2.

Step 2. Searching the optimal solutions of Equation (6) based on the range obtained from Step 1.

Given the ranges obtained from Step 1, we can express Equation (6) as a parametric programming problem with $\theta_0^1 \in \left[\theta_0^{1-},\ \theta_0^{1+}\right]$ as the parameter:

$$\theta_0 = Max \frac{1}{2} \cdot \theta_0^1 + \frac{1}{2} \cdot \frac{\sum\limits_{r=1}^{s} u_r y_{ro} + \sum\limits_{q=1}^{Q} \varphi_q \overline{b}_{q0} + u^B}{\sum\limits_{i_2 \in I_2} v_{i_2} \left(1 - \alpha_{i_2 0}\right) x_{i_2 0} + \sum\limits_{d=1}^{t} n_d^2 z_{d0}}$$

s.t. the same constraints of Equation (6):

$$\theta_0^1 \in \left[\theta_0^{1-}, \theta_0^{1+}\right] \tag{10}$$

With θ_0^1 assigned to a value, Equation (11) maximizes the stage 2 efficiency score $\frac{\sum_{r=1}^{s} u_r y_{ro} + \sum_{q=1}^{Q} \varphi_q \overline{b}_{q0} + u^B}{\sum_{i_2 \in I_2} v_{i_2}^2 \left(1 - \alpha_{i_2 0}\right) x_{i_2 0} + \sum_{d=1}^{t} n_d^2 z_{d0}}$. By applying the Charnes-Cooper transformation, the fractional program shown in Equation (11) can be converted to the model in Equation (12). Let $t = \frac{1}{\sum_{i_2 \in I_2} v_{i_2} \left(1 - \alpha_{i_2 0}\right) x_{i_2 0} + \sum_{d=1}^{t} n_d^2 z_{d0}}$, $\mu_r = t u_r$, $\psi_q = t \varphi_q$, $\pi_d = t n_d$, $\omega_{i_1} = t v_{i_1}$, $\omega_{i_2} = t v_{i_2}$.

$$
\begin{aligned}
\theta_0 = \quad & Max\tfrac{1}{2}\cdot\theta_0^1 + \tfrac{1}{2}\cdot\left(\sum_{r=1}^{s}\mu_r y_{ro} + \sum_{q=1}^{Q}\psi_q \bar{b}_{q0} + u^2\right) \\
s.t. \quad & \sum_{d=1}^{t}\pi_d z_{dj} + u^1 - \sum_{i_1\in I_1}\omega_{i_1}x_{i_1j} - \sum_{i_2\in I_2}\omega_{i_2}\,\alpha_{i_2j}x_{i_2j} \le 0, \forall j \\
& \sum_{r=1}^{s}\mu_r y_{rj} + \sum_{q=1}^{Q}\psi_q \bar{b}_{qj} + u^2 - \sum_{i_2\in I_2}\omega_{i_2}(1-\alpha_{i_2j})x_{i_2j} - \sum_{d=1}^{t}\pi_d z_{dj} \le 0, \forall j \\
& \sum_{d=1}^{t}\pi_d z_{do} + u^1 - \theta_0^1\cdot\left(\sum_{i_1\in I_1}\omega_{i_1}x_{i_10} + \sum_{i_2\in I_2}\omega_{i_2}\alpha_{i_2o}x_{i_20}\right) = 0, \\
& \theta_0^1 \in \left[\theta_0^{1-},\ \theta_0^{1+}\right], \\
& \sum_{i_2\in I_2}\omega_{i_2}(1-\alpha_{i_20})x_{i_20} + \sum_{d=1}^{t}\pi_d z_{d0} = 1, \\
& L_{i_2j}^1 \le \alpha_{i_2j} \le L_{i_2j}^2, \\
& \mu_r, \psi_q, \pi_d, \omega_{i_1}, \omega_{i_2} \ge 0, \forall r, q, d,\ i_1 \in I_1, i_2 \in I_2, u^1, u^2\ free.
\end{aligned} \tag{11}
$$

Equation (12) is still non-linear since there are the non-linear items $\sum_{i_2\in I_2}\omega_{i_2}\alpha_{i_2j}x_{i_2j}$ in some constraints. By specifying $\beta_{i_2j} = \omega_{i_2}\alpha_{i_2j}(j = 1,\cdots,n)$, Equation (12) is linearized as:

$$
\begin{aligned}
\theta_0 = \quad & Max\tfrac{1}{2}\cdot\theta_0^1 + \tfrac{1}{2}\cdot\left(\sum_{r=1}^{s}\mu_r y_{ro} + \sum_{q=1}^{Q}\psi_q \bar{b}_{q0} + u^2\right) \\
s.t. \quad & \sum_{d=1}^{t}\pi_d z_{dj} + u^1 - \sum_{i_1\in I_1}\omega_{i_1}x_{i_1j} - \sum_{i_2\in I_2}\beta_{i_2j}x_{i_2j} \le 0, \forall j \\
& \sum_{r=1}^{s}\mu_r y_{rj} + \sum_{q=1}^{Q}\psi_q \bar{b}_{qj} + u^2 - \sum_{i_2\in I_2}(\omega_{i_2}-\beta_{i_2j})x_{i_2j} - \sum_{d=1}^{t}\pi_d z_{dj} \le 0, \forall j \\
& \sum_{d=1}^{t}\pi_d z_{do} + u^1 - \theta_0^1\cdot\left(\sum_{i_1\in I_1}\omega_{i_1}x_{i_10} + \sum_{i_2\in I_2}\beta_{i_20}x_{i_20}\right) = 0, \\
& \theta_0^1 \in \left[\theta_0^{1-}, \theta_0^{1+}\right], \\
& \sum_{i_2\in I_2}(\omega_{i_2}-\beta_{i_20})x_{i_20} + \sum_{d=1}^{t}\pi_d z_{d0} = 1, \\
& L_{i_2j}^1\omega_{i_2} \le \beta_{i_2j} \le L_{i_2j}^2\omega_{i_2}, \\
& \mu_r, \psi_q, \pi_d, \omega_{i_1}, \omega_{i_2} \ge 0, \forall r, q, d,\ i_1 \in I_1, i_2 \in I_2, u^1, u^2\ free.
\end{aligned} \tag{12}
$$

To obtain the optimal overall efficiency θ_0, we start by solving Equation (13) with θ_0^1 equal to its upper bound θ_0^{1+}. Then we stepwise reduce θ_0^1 by ε (ε = 0.0001 for example), namely $\theta_0^{1k} = \theta_0^1 - \varepsilon \times k$, $k = 1, 2, \ldots$, until the lower bound θ_0^{1-} is reached. We denote the corresponding optimal objective value for model (13) as $\theta_0 = \max\left\{\frac{1}{2}\cdot\theta_0^{1k} + \frac{1}{2}\cdot\left(\sum_{r=1}^{s}\mu_r y_{ro} + \sum_{q=1}^{Q}\psi_q\bar{b}_{q0} + u^2\right)\right\}$, which is the optimal overall efficiency. Then the corresponding optimal efficiency for stage 1 is θ_0^{1k} associated with the optimal overall efficiency θ_0, and the optimal efficiency for stage 2 can be calculated by $\theta_0^{2k} = 2\times\left(\theta_0 - \frac{1}{2}\cdot\theta_0^{1k}\right)$.

4. Empirical Study

According to the definition of sustainability (WCDE, 1987), the railway sustainability in a region can be expressed as that the railway development can meet the social transportation demand without destroying the living quality of future generations. The most widely accepted measurement standard of sustainable development is the triple bottom line (TBL) standard. The TBL standard was suggested by Elkington [38], which means the coordinated development of economy, environment, and society. The better sustainability efficiency the railway obtains, the better economic output and social welfare it will generate and the less negative effects it will make to the environment. Hence, this paper studies railway sustainability from the economy, environment, and society aspects simultaneously, on the basis of TBL standard, then chooses appropriate indicators and uses a two-stage network DEA model proposed above to evaluate the sustainability efficiency.

4.1. The Variables

The final product that a railway provides is the transportation service, including transportation of people and transportation of goods. The premise of transportation service is the construction of the railway track, which is a layered system, composed of a traditional ballast layer, an asphalt concrete sub-ballast layer, and a frost protective layer, and the reader is referred to Di Mascio et al. [39] for detailed technical contents about railway tracks. Thus, the railway transportation process presents an obvious network structure, from inputting factors to outputting transportation service. Referring to Yu and Lin [13], we divide the production and operation process of a railway into two stages, exactly the production stage and the service stage sequentially. As showed in Figure 2, in the first stage—production stage, railway enterprises use three inputs—investment in fixed assets, land and labor, to obtain intermediate products—railway mileage and density. In the second stage—service stage, railway enterprises use the intermediate products and labor input to obtain the final outputs—transportation of passengers and goods, along with undesirable output dust. Meanwhile, the wage growth of railway workers as social welfare can also be regarded as a final output. Therefore, according to the TBL standard, we choose inputs, outputs, and intermediate outputs as follows:

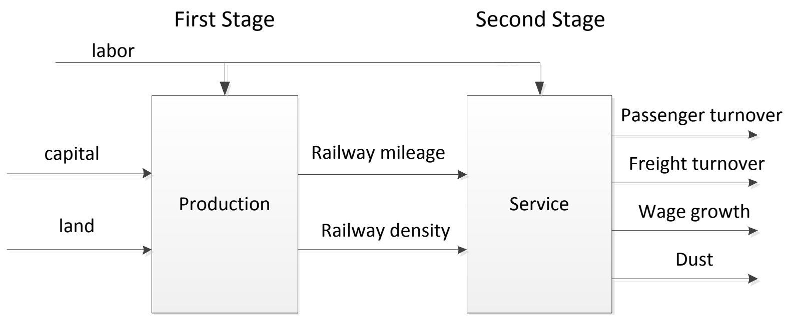

Figure 2. Two-stage production process of railway transportation.

(1) Inputs. Referring to the existing representative literature, we select three input factors—capital, land, and labor. Capital input is the economic input and we choose the annual fixed asset investment of railway in a region as the indicator and adjust the price index by taking 2002 as base period. Land input is environmental input and we choose the area covered by railway in a region as the indicator. Labor input is social input, which is shared by both two stages and we choose the annual total number of railway workers in a region as the indicator.

(2) Intermediate outputs. Railway mileage, which is the total length of main lines that conduct the business of passenger and freight transportation, is taken as the output in the first stage and input in the second stage. Railway density, defined as the railway mileage per 100 square kilometers, is also taken as an intermediate output.

(3) Final outputs. As to desirable outputs, we select the passenger turnover and freight turnover of a railway as economic output indicators [13], to measure the serving ability of railway transportation. We choose average wage growth of urban transportation employees as social output indicator. Due to the availability of the data, we use the average wage in transportation to approximately represent average wage in railway transportation and to measure social output of railway. As to undesirable output, we choose the total dust generated in the railway operation process as an environmental undesirable output.

All variables and their indicators' definitions are shown in Table 1.

Table 1. Inputs, outputs, and intermediate outputs indicators.

Types	Variables	Indicators
Input	Capital Land Labor	Regional annual railway fixed asset investment Regional annual railway covered area The annual total number of railway workers in a region
Intermediate output	Railway mileage Railway density	Regional annual railway operation mileageAnnual railway operation mileage/Regional land area
Desirable output	Passenger turnover Freight turnover	Regional passenger person-kilometers Regional rotation volume of freight transportation
	Average salary growth	(average wage of regional urban transportation employee in current year—average wage of regional urban transportation employee in last year)/average wage of regional urban transportation employee in last year
Undesirable output	Dust	Regional annual total dust generated in railway operation process

4.2. The Data

This paper assesses the railway sustainability using the panel data of 30 provinces in China from 2002 to 2013. The data mainly comes from annual China Railway Yearbook, China Environment Statistics Yearbook, China Land and Resources Yearbook, and related province statistical yearbooks. In all of the above three kinds of China yearbooks, there are the related statistical indicators by province. Specifically, the indicators for *Capital*, *Labor* and *Railway mileage*, are coming from the annual China Railway Yearbooks, the indicators for *Land* are coming from the annual China Land and Resources Yearbooks, the indicators for *Dust* are coming from the annual China Environment Statistics Yearbooks, and the indicators for *Passenger turnover*, *Freight turnover* and *Average salary growth* are coming from the annual statistical yearbooks of every province. Descriptive statistics of all sample variables are showed in Table 2.

Table 2. Descriptive statistics of inputs and outputs.

Variables	Mean	Std. Dev	Min	Max
Capital	10.1869	12.2458	0.0432	74.4785
Land	36,721.0300	41,036.15	156.0000	254,679.5000
Labor	58,149.5500	34,012.1800	1811.0000	151,764.0000
Railway mileage	2760.9890	1636.6630	213.9000	10203.3100
Railway density	1.9197	1.5699	0.1520	8.0843
Passenger turnover	4842.3070	3276.7580	13.0000	17,658.4400
Freight turnover	10,394.8000	12,663.0700	288.0000	73,181.4900
Average salary growth	0.1230	0.0717	−0.2504	0.3541
Dust	6.5946	6.0201	0.0400	32.2000

Note: Capital is in 100 million of Chinese yuan, land is in 0.1647 acres, mileage is in kilometer, density is in kilometers per 100 square kilometers, passenger turnover is in 10,000s, freight turnover and dust are in 10,000 thousand tons.

4.3. The Results

Based on the additive two-stage network DEA model with shared inputs and undesirable outputs, we estimate the overall and sub-stage sustainability of railway of 30 provinces in China from 2002 to 2013 by using LINGO software. We set the weight of each stage to be: $w^1 = w^2 = 0.5$. The lower and upper bounds of proportion of shared labor in first stage are specified as $0.2 \le \alpha_i \le 0.4$, according to the reality of China's railways. By solving Equation (13) through the two-step method discussed in the methodology section, we can get the average evaluation result for overall sustainability of railway transportation, which is showed in Table 3 (the detailed descriptive statistics for overall sustainability performance can be found in Appendix A).

Table 3. Overall sustainability performance of railway in different regions of China (2002–2013).

Year	Nationwide	Eastern Area	Central Area	Western Area
2002	0.7097	0.8182	0.6851	0.6044
2003	0.6717	0.7348	0.6799	0.5854
2004	0.6831	0.7619	0.6326	0.6428
2005	0.5737	0.6583	0.5155	0.5350
2006	0.6634	0.7053	0.6957	0.5764
2007	0.6118	0.6776	0.5495	0.5561
2008	0.6795	0.7139	0.6548	0.6648
2009	0.7703	0.7740	0.7585	0.7789
2010	0.7190	0.7256	0.6957	0.7367
2011	0.6990	0.7366	0.6653	0.6903
2012	0.6677	0.7188	0.5983	0.6825
2013	0.6817	0.7471	0.5940	0.6993
2002–2013	0.6775	0.7310	0.6471	0.6460

(1) The changing trend of the overall sustainability performance of railway transportation across the country. The results in Table 3 indicate that the overall sustainability of railway transportation in China is slightly above the middle level from 2002 to 2013, specifically locating in a high growth interval of 0.5737–0.7703 centered at 0.6775, which still has a large amount of room for improvement. The overall sustainability of railway transportation in China is inefficient, and as we discussed in the methodology section, this means that at least one stage is inefficient: either the production stage or the service stage, or both of them. We will identify the exact inefficient stage in the sub-stage analysis part. From the changing trend in Figure 4, we can find that the sustainability of railway transportation across the country presents a trend of declining first, rising after, and declining again, during the study period:

Firstly, it gradually declines from 2002 to 2005 and reaches the bottom by 2005. In 2002, China's Ministry of Railways put forward the strategy of "Railway Leap-forward Development", hoping to expand railway mileage by increasing investment and to improve railway technical equipment to reach the most advanced level in the world. This strategy leads to every province's large investment in railway projects in China: the annual growth of fixed asset investment of railways is up to about 40% during that period. During the "11th Five-Year Plan" period, the national total railway operating mileage reached 91,000 km and the total length of rapid passenger transportation network reached to more than 20,000 km. However, after three decades of increasing marginal returns, the marginal return of railway investment starts to decline. To pursue the growth of GDP, some regional governments invest in many railway projects, which exceed their needs and have inconspicuous economic and social benefits. Those excessive railway projects result in a waste of resources and cause much pollution to the environment. Hence, the sustainability performance keeps falling in that period.

Afterwards, the sustainability of railway transportation keeps rising from 2005 to 2009, which benefits from the transformation of the direction of government regulation and the development of high-speed railway technology. China's State Council promulgates the "Mid-to-Long Term Railway Network Plan" in 2005, highlighting the importance of railway technology innovation. Following it, the Ministry of Railways issues the "Mid-to-Long Term Railway Network Plan (Adjusted in 2008)" in 2008, shifting the railway construction orientation from emphasizing on quantity to emphasizing on quality, which leads to the steady increase of the sustainability of railway transportation. Moreover, with the Sixth Round Speed-up Campaign of railways in 2007, China officially entered the era of high-speed railways. The Leapfrog development of high-speed rail technology brings great economic and social benefits, and creates breakthroughs both in energy-saving and environmental protection in China.

However, sustainability performance presents a descending trend after 2009. This is partly because of the follow-up effect of the "Four-trillion Economic Stimulus Plan" after the international financial crisis in 2008. In addition, different regions in China have been increasing investment to railway infrastructure so as to stimulate economic growth. Until 2014, the new scale of railway production in China hits a record size, and the railway mileage exceeds 112,000 km, among which the high-speed railway mileage reaches more than 16,000 km and ranks first in the world. Although the total amount of railway infrastructure expands obviously, the planning of railway network in some places is unreasonable. In order to pursue high standard and high-speed railway, some investment projects become difficult to control. The growth rate of railway investment is then much larger than that of transportation revenue. Additionally, the investment in technology innovation of railway is far from enough, the environment pollution generated in railway construction is not well controlled, and the execution of environmental regulation is inadequate, which all result in the increasing of environmental pollution year by year. All of the above factors cause the declining of the sustainability of railway transportation during this period.

(2) The regional difference analysis of the overall sustainability of railway transportation. According to the partition method used by China Statistics Bureau on 13 June 2011, in this paper, we divide the 30 provinces into three groups: eastern area, central area, and western area (the eastern area includes Beijing, Tianjin, Shanghai, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Liaoning, Hainan; the central area includes Shanxi, Henan, Hubei, Anhui, Hunan, Jiangxi, Inner Mongolia, Guangxi, Heilongjiang, Jilin; and the western area includes Xinjiang, Ningxia, Shanxi, Gansu, Qinghai, Chongqing, Sichuan, Guizhou, Yunnan), and the location of these provinces can be seen from the map of China in Figure 3. We then estimate and compare the changing trend of the sustainability of railway transportation in these three areas (shown in Figure 4). During the observation period, the average sustainability performance values of railway transportation in eastern, central and western areas are respectively 0.7310, 0.6471, and 0.6460, which reflects that the sustainability of eastern railway transportation is much better than that of the central and western areas. The latter two areas' sustainability performance values of railways are similar and the central area is slightly better.

Figure 3. Map of the People's Republic of China.

To further investigate the difference of the sustainability of railway transportation among these three areas, we adopt the Mann-Whitney U-tests [40] to verify the difference between each of them. If the *p*-value of the Mann-Whitney U-tests are less than 0.05, we will reject the null hypothesis that there is no difference between the medians of the two populations. The results shown in Table 4 present that there are obvious differences between the eastern areas and the other two areas, while the latter two are close. The differences reflect that the level of economic development has a great influence in the sustainable development of railway transportation, which is to say that provinces with higher levels of economic development (like the eastern areas) pay more attention to the sustainability of railway transportation, while provinces with relative lower level of economic development (like the central and western areas) have the relative low level of railway sustainable development. In fact, the relationship between regional economic development and railway transportation is a reciprocal causation: economically developed provinces have larger demand for railway investment, as well as a higher request for the sustainability of railway transportation, and sustainable railway transportation, in turn, will promote economic growth.

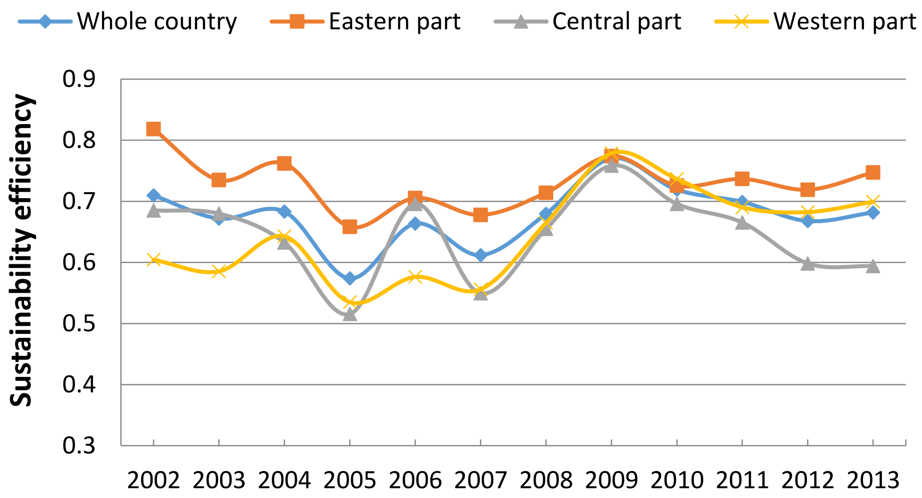

Figure 4. Overall sustainability of railway transportation in China.

Table 4. Mann–Whitney U tests of railway sustainable performance value differences in different areas.

Null Hypothesis (No Significant Difference between the Two Objects)	East and Central	East and West	Central and West
p-value (double tail)	0.0018	0.0079	0.9539

The distribution of the numbers of effective DMUs (sustainability performance value = 1) in different years also proves the above conclusion. Evaluation results show that effective DMUs mainly concentrate in eastern coastal provinces (Beijing, Tianjin, Shanghai, and Hainan), among which the sustainability of railway transportation in Tianjin has reached the effective status for 10 consecutive years (2002–2011) during the study period. The sustainable development of railway transportation in eastern coastal areas firstly benefits from the sufficient investment provided by the developed economy and finance there. Then the innovation of railway technology, such as the upgrading of locomotives, which is represented by high-speed railways, reduces the negative impact to the environment. Additionally, in these areas, there are denser populations and thriving businesses that generate great demand for railway transportation, so railway development can bring obvious social welfare effects. Finally, the local governments there pay more attention to energy conservation and environmental protection than the governments in other areas of China. All of these factors bring about the harmonious development of railways, population, and economy.

From the dynamic perspective of the differences, we can find that the gap of sustainability performance between the eastern areas and the other areas narrows gradually from 2002 to 2009, but it amplifies again after 2009. This reveals that the strategies Rise of Central China Plan and China's Western Development Program applied before 2009 contribute to the reduction of the gap. The central and western areas have much poorer railway infrastructure compared with the eastern area in the beginning, which means greater marginal economic and social benefit of railway investment and larger resource and environment space to be utilized; therefore, the gap in sustainability gradually becomes narrower. However, after 2009, this later-mover advantage of the central and western areas gradually disappears, and lots of investment in railway infrastructure there still does not pays attention to the coordinated development of railway transportation with the economy, population, and environment, leading to the decline in sustainability. By contrast, the new round of infrastructure investment in the eastern area pays more attention to the quality of railway infrastructure, environmental protection, and social development. Thus, the sustainability of railways there can be improved and the gap between the two areas becomes wider. It is noteworthy that the sustainability of western areas surpasses that of central areas after 2009. On the one hand, this may be caused by the significant support of the central government to the western area; on the other hand, it also indicates that the western areas pay more attention to the coordinated development on economy, environment protection, and society than the central areas. The central areas need to learn advanced experiences from other areas in railway transportation development and break the dilemma of "Central Depression".

(3) The sub-stage sustainability performance of railway transportation. Railways are a complicated and large system, and the interaction between sub-stages plays a significant role in the overall sustainability of railway transportation. If and only if both of the two sub-stages are effective can the overall sustainability of railway transportation be effective. Thus, when the optimal overall efficiency θ_0 is obtained, we can get the corresponding optimal efficiency for stage 1, θ_0^{1k} associated with the optimal overall efficiency θ_0, and then calculate the optimal efficiency for stage 2 as $\theta_0^{2k} = 2 \times \left(\theta_0 - \frac{1}{2} \cdot \theta_0^{1k}\right)$. Table 5 shows the average evaluation results for the sub-stage sustainability of railway transportation in different areas of China (the detailed descriptive statistics for sub-stage sustainability performance can be find in Appendix A).

From Table 5, we can see that the sustainability of railway production and service stages both present inefficient (efficiency value < 1) during the sample period. The efficiency of production stages is lower than that of service stage, which means production stage has a greater impact on the overall sustainability of railway transportation. In the production stage of railway in China, the construction technology is not mature enough, the equipment is not advanced and the overall level of project construction is not high enough. Therefore, the cost benefit ratio of railway construction is low, but its damage to environment is serious, which eventually becomes the main cause of inefficiency of the production stage. However, the inefficiency in service stage is mainly because of the use of non-renewable energy (coal) during the operation process of railway, which then causes serious pollution to the environment. The noises of railways during their operation should also be considered. In addition, the irrationality of the planning of railway routes in China also causes the waste of resources in the process of railway operation and finally results in the inefficient state of sustainability.

From the national perspective, Figure 5 shows that sustainability efficiency in the first stage declines first, then rises, and finally declines. This is consistent with the overall changing trend of sustainability, and the corresponding inflection points are also consistent. However, the changing trend of the sustainability in the second stage showed in Figure 6 presents different characteristics: it declines from 2002 to 2007 and keeps rising since 2007. The results certify that the present overall sustainability efficiency of railway transportation in China is mainly affected by the first stage (the production stage), so the improvement of railway construction and technological innovation is the priority task in current China to improve the overall sustainability of railway transportation, and the enhancement of the service efficiency of railway after 2007 corresponds to the fact that China formally steps into the era of high-speed railway in 2007, which proves that the leapfrog development of high-speed railway technique prompts a significant improvement on railway service efficiency. Thus, China should unswervingly develop high-speed railway technology and enhance the sustainability of railway operation.

Table 5. Sub-stage sustainability of railway transportation in different areas of China.

Year	Nationwide		Eastern Area		Central Area		Western Area	
	Sub-process-1	**Sub-process-2**	**Sub-process-1**	**Sub-process-2**	**Sub-process-1**	**Sub-process-2**	**Sub-process-1**	**Sub-process-2**
2002	0.5703	0.8491	0.6979	0.9385	0.5508	0.8195	0.4361	0.7728
2003	0.5207	0.8227	0.5957	0.8739	0.4946	0.8652	0.4579	0.7129
2004	0.5044	0.8618	0.6063	0.9175	0.4427	0.8226	0.4483	0.8372
2005	0.4156	0.7318	0.5161	0.8006	0.3416	0.6895	0.3752	0.6948
2006	0.5299	0.7969	0.5770	0.8335	0.5811	0.8102	0.4155	0.7373
2007	0.5059	0.7176	0.5799	0.7752	0.4412	0.7378	0.4874	0.6247
2008	0.5387	0.8202	0.5312	0.8967	0.6112	0.69844	0.4675	0.8620
2009	0.6854	0.8552	0.6909	0.8570	0.6948	0.8222	0.6681	0.8896
2010	0.5474	0.8905	0.5667	0.8844	0.5286	0.8629	0.5447	0.9286
2011	0.5414	0.8565	0.6151	0.8582	0.5303	0.8002	0.4638	0.9168
2012	0.4631	0.8724	0.5092	0.9283	0.4211	0.7755	0.4534	0.9115
2013	0.5150	0.8485	0.6452	0.8489	0.4257	0.7622	0.4550	0.9437
2002–2013	0.5282	0.8269	0.5943	0.8677	0.5053	0.7889	0.4727	0.8193

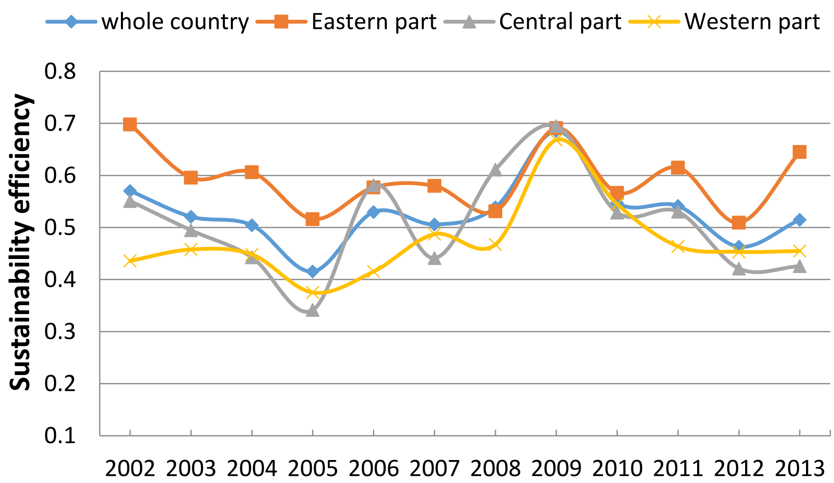

Figure 5. Efficiency of the railway production stage.

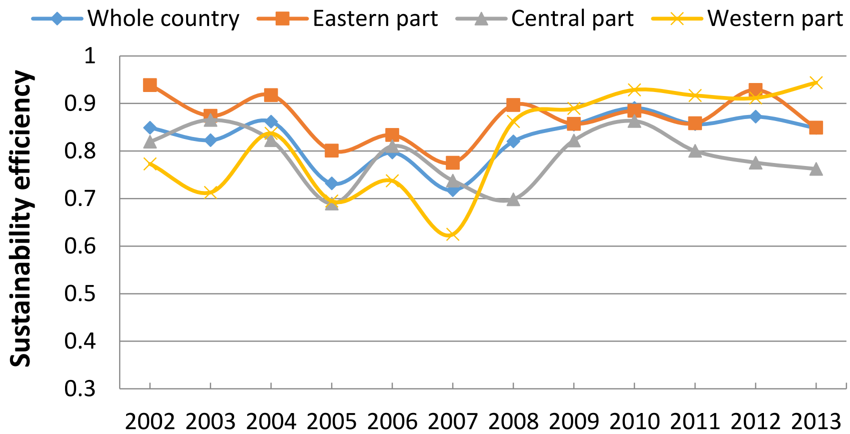

Figure 6. Efficiency of the railway service stage.

From the perspective of different areas, the average efficiency values of the first stage in the eastern, central, and western areas are separately 0.5943, 0.5053, and 0.4727 during the study period. The efficiency of eastern areas is better than that of central areas, and the latter is better than that of the western areas. The average efficiency values of the second stage in the eastern, central, and western areas are, separately 0.8677, 0.7889, and 0.8193, where the efficiency of the eastern area is better than that of the other areas, but the west is slightly better than the middle. From the view of changing trends, the changing trends of efficiencies of the three areas are almost the same in the first stage. Moreover, the gap between the eastern areas and the rest areas experiences a period of declining in early stage, and tends to expand since 2009, which is consistent with the changing trend of overall sustainability. However, in the second stage, the changing trends of the efficiency values are similar in the eastern and the central areas, while the western areas are different from them. The service efficiency in western areas overtakes that in eastern and central areas, which illustrates that the western areas do better in harmonious development of economy, environment, and society in the service process. This also indicates that the primary cause of the expansion of the gap in railway sustainability between the eastern and other areas is the expansion of the gap in production efficiency, which is brought by the gap in the technology level of railway construction. As a consequence, in order to narrow the gap, the central and western areas should make full use of national supportive policy, introduce and absorb the advanced green technology and management experiences from the eastern areas.

In summary, the inefficiency of the production stage contributes more to the inefficiency of the overall sustainability for China's railway transportation. There are two reasons for this observation. One reason is that the efficiency value of the production stage is much lower than that of the service stage, which means that the production stage has a greater impact on the overall sustainability, as the overall efficiency is the weighted mean of the two efficiencies with both weights being 0.5. The other reason is that the overall changing trend of the sustainability is consistent with the changing trend of the production stage, and their corresponding inflection points are also consistent; however, it is not the case between the changing trend of the service stage and the overall changing trend. Moreover, the inefficiency of the production stage of railway in China may be caused by the immature construction technology, the backward equipment, and the low level of project construction.

5. Concluding Remarks

This paper constructs a revised additive two-stage DEA model with consideration of undesirable outputs and shared inputs, which follows the triple bottom line standard of sustainability research. From the aspects of economy, environment and society, we calculate both the overall and sub-stage sustainability of railway transportation in various parts of China from 2002 to 2013. The results indicate that: (1) the overall sustainability of railway transportation in China shows a character of declining first, rising after, and declining again, and the overall sustainability values are located in a high growth interval of 0.5737–0.7703, centered at 0.6775, and still have great room to improve; (2) the sustainability of railway transportation in eastern areas is much better than that of the rest areas. The average sustainability values of railway transportation in eastern, central, and western areas are, respectively, 0.7310, 0.6471, and 0.6460. The sustainability efficiency gap between the eastern areas and the other areas narrows gradually from 2002 to 2009, but amplifies after 2009; (3) as for the sub-stage efficiency, neither the production nor service stage is efficient in sustainability, while the former is lower than the latter; and (4) the efficiency of the production stage plays a greater impact on the overall sustainability of railway transportation. Therefore, in order to improve the overall sustainability of China's railway transportation, it is an essential way to improve the level of railway engineering construction and to develop railway technical innovation.

The contribution of this paper is mainly manifested in the following three points: first, this paper for the first time evaluates the sustainability of regional railway transportation and measures the value of railway sustainability performance from three dimensions—economy, environment, and society. Second, we put forward a fixed decomposition weight additive two-stage network DEA model with considerations of undesirable outputs and shared inputs, which could be promoted to deal with those production conditions with undesirable outputs and shared inputs in the real world. Third, we find that the inefficiency of the overall sustainability for China's railway transportation is mainly caused by the inefficiency of the production stage, which points out the direction for enhancing the railway sustainability in China. Certainly, the sustainability of railway transportation still calls for further study. Industrial structure, population quality, and the policy system in a region can all influence the sustainability of local railway transportation. To find the more direct causes for the inefficiency of railway transportation sustainability, one needs to connect the DEA methods with other statistical analysis methods, such as the regression analysis, the correlation analysis, and so on. We will further study those significant themes in our subsequent research.

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Appendix A

Table A1. Overall sustainability performance of railway in different regions of China (2002–2013).

Year	Sustainability	Nationwide	Eastern Area	Central Area	Western Area
2002	Mean	0.7097	0.8182	0.6851	0.6044
	Max	1.0000	1.0000	1.0000	0.9905
	Min	0.3965	0.4126	0.3965	0.4152
	Std. Dev	0.2291	0.2317	0.2332	0.1803
2003	Mean	0.6717	0.7348	0.6799	0.5854
	Max	1.0000	1.0000	1.0000	0.7382
	Min	0.3869	0.3937	0.4000	0.3869
	Std. Dev	0.1973	0.2114	0.2276	0.1143
2004	Mean	0.6831	0.7619	0.6326	0.6428
	Max	1.0000	1.0000	1.0000	0.9271
	Min	0.3302	0.3522	0.3302	0.4136
	Std. Dev	0.2305	0.2486	0.2588	0.1626
2005	Mean	0.5737	0.6583	0.5155	0.5350
	Max	1.0000	1.0000	1.0000	1.0000
	Min	0.3035	0.3565	0.4032	0.3035
	Std. Dev	0.1915	0.2071	0.1189	0.2185
2006	Mean	0.6634	0.7053	0.6957	0.5764
	Max	1.0000	1.0000	1.0000	1.0000
	Min	0.3198	0.3224	0.3850	0.3198
	Std. Dev	0.2398	0.2308	0.2459	0.2482
2007	Mean	0.6118	0.6776	0.5495	0.5561
	Max	1.0000	1.0000	1.0000	0.8641
	Min	0.4110	0.4110	0.4223	0.4273
	Std. Dev	0.1917	0.2159	0.2034	0.1355
2008	Mean	0.6795	0.7139	0.6548	0.6648
	Max	1.0000	1.0000	1.0000	1.0000
	Min	0.3783	0.3860	0.3783	0.3934
	Std. Dev	0.2352	0.2584	0.2541	0.2046
2009	Mean	0.7703	0.7740	0.7585	0.7789
	Max	1.0000	1.0000	1.0000	1.0000
	Min	0.3942	0.3942	0.4116	0.5071
	Std. Dev	0.1819	0.1857	0.2010	0.1762
2010	Mean	0.7190	0.7256	0.6957	0.7367
	Max	1.0000	1.0000	0.9290	0.9598
	Min	0.4156	0.4156	0.5020	0.4923
	Std.dev	0.1863	0.2260	0.1603	0.1788
2011	Mean	0.6990	0.7366	0.6653	0.6903
	Max	1.0000	1.0000	1.0000	0.9870
	Min	0.4120	0.4556	0.4120	0.4427
	Std. Dev	0.1974	0.1907	0.2245	0.1886
2012	Mean	0.6677	0.7188	0.5983	0.6825
	Max	1.0000	1.0000	1.0000	1.0000
	Min	0.4123	0.4238	0.4123	0.4576
	Std. Dev	0.1817	0.1977	0.1697	0.1689
2013	Mean	0.6817	0.7471	0.5940	0.6993
	Max	1.0000	1.0000	0.8095	1.0000
	Min	0.4353	0.4353	0.4400	0.5135
	Std. Dev	0.1889	0.2348	0.1314	0.1584
2002–2013	Mean	0.6775	0.7310	0.6471	0.6460

Table A2. Sub-stage sustainability of railway transportation in different areas of China.

Year	Sustainability	Nationwide		Eastern Area		Central Area		Western Area	
		Sub-process-1	Sub-process-2	Sub-process-1	Sub-process-2	Sub-process-1	Sub-process-2	Sub-process-1	Sub-process-2
2002	Mean	0.5703	0.8491	0.6979	0.9385	0.5508	0.8195	0.4361	0.7728
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.1461	0.4961	0.1461	0.6442	0.2103	0.5009	0.1521	0.4961
	Std. Dev	0.3259	0.1942	0.3519	0.1371	0.3158	0.2101	0.2736	0.2118
2003	Mean	0.5207	0.8227	0.5957	0.8739	0.4946	0.8652	0.4579	0.7129
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.1249	0.1134	0.1600	0.5083	0.1617	0.5392	0.1249	0.1134
	Std. Dev	0.3008	0.2232	0.2955	0.1856	0.3206	0.1780	0.3002	0.2872
2004	Mean	0.5044	0.8618	0.6063	0.9175	0.4427	0.8226	0.4483	0.8372
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.1017	0.4551	0.1369	0.5289	0.1017	0.4551	0.1226	0.5611
	Std. Dev	0.3546	0.1836	0.3762	0.1656	0.3822	0.2116	0.3035	0.1752
2005	Mean	0.4156	0.7318	0.5161	0.8006	0.3416	0.6895	0.3752	0.6948
	Max	1.0000	1.0000	1.0000	1.0000	0.8867	1.0000	1.0000	1.0000
	Min	0.0969	0.2183	0.1049	0.3220	0.1061	0.2183	0.0969	0.4538
	Std. Dev	0.3128	0.2532	0.3153	0.2450	0.2636	0.2832	0.3601	0.2384
2006	Mean	0.5299	0.7969	0.5770	0.8335	0.5811	0.8102	0.4155	0.7373
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.0860	0.1127	0.1458	0.4989	0.0860	0.4713	0.1074	0.1127
	Std. Dev	0.3520	0.2441	0.3493	0.2127	0.3545	0.2218	0.3665	0.3131
2007	Mean	0.5059	0.7176	0.5799	0.7752	0.4412	0.7378	0.4874	0.6247
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9276
	Min	0.0785	0.1423	0.1106	0.3735	0.0785	0.4533	0.0982	0.1423
	Std. Dev	0.3424	0.2445	0.3695	0.2619	0.3064	0.2071	0.3681	0.2607
2008	Mean	0.5387	0.8202	0.5312	0.8967	0.6112	0.69844	0.4675	0.8620
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.0841	0.1039	0.0941	0.6208	0.1805	0.1039	0.0841	0.6237
	Std. Dev	0.3627	0.2298	0.3965	0.1661	0.3523	0.2977	0.3583	0.1691

Table A2. *Cont.*

Year	Sustainability	Nationwide		Eastern Area		Central Area		Western Area	
		Sub-process-1	Sub-process-2	Sub-process-1	Sub-process-2	Sub-process-1	Sub-process-2	Sub-process-1	Sub-process-2
2009	Mean	0.6854	0.8552	0.6909	0.8570	0.6948	0.8222	0.6681	0.8896
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.2562	0.1100	0.2562	0.4326	0.3813	0.1100	0.2947	0.7196
	Std. Dev	0.2494	0.2246	0.2824	0.2150	0.1982	0.3111	0.2850	0.1164
2010	Mean	0.5474	0.8905	0.5667	0.8844	0.5286	0.8629	0.5447	0.9286
	Max	1.0000	1.0000	1.0000	1.0000	0.8580	1.0000	1.0000	1.0000
	Min	0.1142	0.5310	0.1457	0.6855	0.1520	0.5310	0.1142	0.8237
	Std. Dev	0.3206	0.1438	0.3653	0.1386	0.2365	0.1958	0.3767	0.0721
2011	Mean	0.5414	0.8565	0.6151	0.8582	0.5303	0.8002	0.4638	0.9168
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.0847	0.5558	0.0847	0.5558	0.1320	0.5852	0.1406	0.6267
	Std. Dev	0.3042	0.1657	0.3124	0.1745	0.3133	0.1781	0.2976	0.1331
2012	Mean	0.4631	0.8724	0.5092	0.9283	0.4211	0.7755	0.4534	0.9115
	Max	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
	Min	0.0924	0.5096	0.0924	0.6569	0.1224	0.5096	0.1451	0.6951
	Std. Dev	0.2686	0.1486	0.3125	0.1202	0.2488	0.1656	0.2543	0.1157
2013	Mean	0.5150	0.8485	0.6452	0.8489	0.4257	0.7622	0.4550	0.9437
	Max	1.0000	1.0000	1.0000	1.0000	0.7008	1.0000	1.0000	1.0000
	Min	0.1508	0.4947	0.2145	0.6150	0.1508	0.4947	0.1681	0.7875
	Std. Dev	0.2786	0.1709	0.3170	0.1757	0.2038	0.1930	0.2677	0.0767
2002–2013	Mean	0.5282	0.8269	0.5943	0.8677	0.5053	0.7889	0.4727	0.8193

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