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THE EFFICIENCY OF SUSTAINABLE DEVELOPMENT GOALS 4 AND 8 IN CHINA: IMPACT OF LOW FERTILITY

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Abstract. China's declining birth rate is gradually eroding the demographic dividend, potentially affecting education, employment, and the economy. This study constructs a meta two-stage dynamic Directional Distance Function (DDF) Data Envelopment Analysis (DEA) model under exogenous variable. It considers the birth rate as an exogenous variable to assess the efficiency of 30 Chinese provinces in achieving SDGs 4 and 8. Key findings include: (1) Integrating the birth rate into the analytical framework has enhanced overall efficiency in most provinces, particularly in the central region. The average efficiency across 30 provinces was 0.8, with minimal regional disparities. (2) The birth rate positively influences both SDG 4 and SDG 8, notably boosting SDG 4 efficiency. (3) Efficiency varies by province: 17 exhibit high efficiency in both SDG 4 and SDG 8, one shows low SDG 4 but high SDG 8 efficiency, two have high SDG 4 but low SDG 8 efficiency, and ten are inefficient in both goals. (4) Hebei, Shandong, and Guangdong have significant redundancy in education and social security investments. Hebei, Henan, and Shanxi show considerable deficiency in economic growth and employment, while Xinjiang and Inner Mongolia require further enhancements in energy efficiency.

Keywords: low fertility, SDG4 efficiency, SDG8 efficiency, meta two-stage dynamic DDF DEA model under exogenous variable, efficiency optimization.

JEL Classification: I25, J13, O11.

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1. Introduction

In recent years, China's low fertility rate has become increasingly apparent, social transformation has altered traditional views on childbirth. According to data from the Seventh National Census, the number of births in China was 12 million in 2020, a decrease of 18% from 2019. In response to the declining birthrate, China introduced several measures, including the Two-Child Policy in 2015 and the Three-Child Policy in 2021, but population growth has not met expectations. By 2022, the birth rate fell below the death rate, marking the first negative population growth since 1962 (Figure 1). Over the past few decades, a large portion of the labor force has shifted from agriculture to urban industries, boosting overall productivity and contributing significantly to economic growth and modernization. However, in recent years, rising labor costs, coupled with the declining birthrate, have led China to gradually approach the Lewis Turning Point, highlighting emerging population challenges. In the future, China will face growing challenges in labor resource allocation and high-quality employment. Against the backdrop of a declining birthrate, addressing labor demand, improving education quality, and fully leveraging human capital will be more critical than ever.

In September 2015, the United Nations launched the 2030 Agenda for Sustainable Development, defining 17 Sustainable Development Goals (SDGs) with 169 targets and 231 indicators. This agenda aims to holistically address social, economic, and environmental challenges through 2030. SDG 4 emphasizes inclusive and equitable quality education, advocating for lifelong learning opportunities for everyone. SDG 8 aims to promote sustained and inclusive economic growth, full employment, and decent work for all. Achieving SDG 4 and SDG 8 helps secure quality education, provide decent jobs, and stimulate economic growth, advancing sustainable development.

One effective strategy to mitigate population decline is to offset the reduction in quantity by enhancing workforce quality. Consequently, China has placed greater emphasis on nine-year compulsory education and higher education, working to eliminate illiteracy and expand university enrollment capacity. By 2020, compared to the 2010 Sixth National Census, the proportion of people with university education per 100,000 increased by 73.2%, the average years of education for those aged 15 and above rose from 9.08 to 9.91 years, and the illiteracy rate dropped from 4.08% to 2.67% (National Bureau of Statistics, 2021).

China is currently at a critical juncture in transitioning from a population powerhouse to a human resources powerhouse. Human capital accumulation is a key driver of high-quality employment and economic transformation and upgrading. A declining birth rate will not only affect children's and higher education (SDG 4), but also drive changes in China's economic and industrial structure, ultimately influencing high-quality economic growth and decent employment (SDG 8). This study uses a sample of 30 Chinese provinces, covering the period from 2015 to 2020. It examines the efficiency of quality education (SDG 4) and decent work and economic growth (SDG 8) in relation to birth rates, offering theoretical and decision-making support to promote educational equity, address employment challenges, and drive economic transformation and high-quality development.

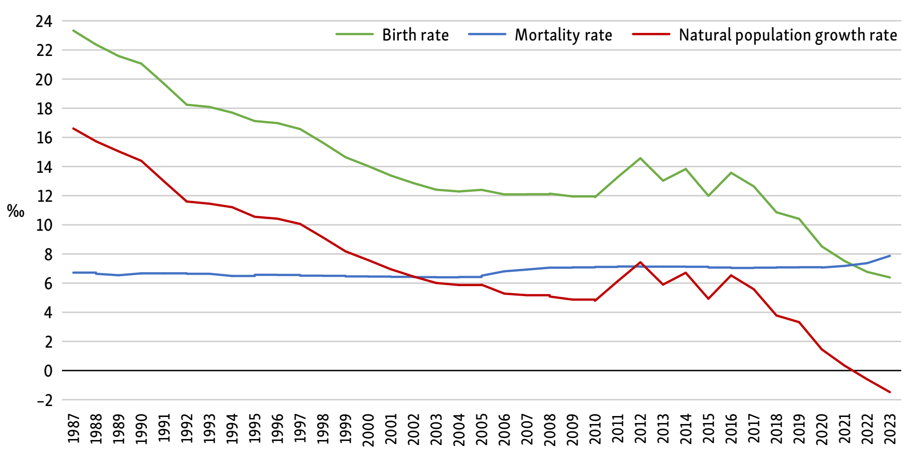


Figure 1. Birth rate, mortality rate, and natural population growth rate in China

The contributions of this paper are as follows: 1. This study empirically combines birth rates, education, and employment to examine the impact of the declining birth rate on economic and social development, analyzing the efficiency of SDG 4 and SDG 8 under the demographic transition in China. 2. The traditional model is modified by incorporating exogenous variables, and a meta two-stage dynamic DDF DEA model under exogenous variable is developed to ensure the accuracy of the evaluation. 3. Based on the efficiency performance of 30 provinces, the paper classifies and analyzes input redundancy and output insufficiency for key variables, explores the causes of inefficiency, and proposes differentiated improvement strategies.

The structure of this paper is as follows: Section 2 presents the literature review. Section 3 introduces the research methods. Section 4 is dedicated to empirical analysis. Section 5 is the discussion. Section 6 covers conclusions and policy recommendations.

2. Literature review

2.1. Population transition and human capital demand

Population plays a crucial role in driving economic and social development. The understanding of population transition and human capital demand in academia has evolved. In 1798, Lewis introduced the concept of population migration into economic theory, arguing that an excess of labor in rural areas leads to migration from the low-productivity agricultural sector to the higher-productivity urban industrial sector, continuing until the Lewis Turning Point, when the demographic dividend is fully realized. Romer (1986) proposed the endogenous growth theory, emphasizing the importance of knowledge capital. He argued that labor continuously generates knowledge capital through education and training, which in turn fosters endogenous technological progress and drives long-term economic growth. Bloom and Williamson (1998) demonstrated through a cross-national growth model that a population's age structure is a significant factor in economic growth.

Initially, research primarily focused on how changes in population size and age structure influence economic growth. Over time, scholars have recognized the role of human capital and begun to explore how educational improvements impact economic development (Jędrzychowska et al., 2024). Crespo Cuaresma et al. (2014) contended that age structure does not influence labor productivity; instead, educational improvements are crucial for productivity and income growth, suggesting that much of the demographic dividend is an education dividend. Lutz et al. (2019) analyzed data from 165 countries between 1980–2015, showing that human capital drives the demographic dividend and that enhancing education promotes economic growth more than adjusting age structures. Consequently, they recommend that global population policies prioritize the sustainable development of education.

In birth rate-related research, Becker and Lewis (1973), Becker and Tomes (1979), and de la Croix and Doepke (2003) each contributed to the substitution hypothesis between the quantity and quality of children, demonstrating that educational costs influence fertility intentions, leading to a preference for fewer but higher-quality children. Li et al. (2008) and Rosenzweig and Zhang (2009) further validated this hypothesis, finding that educational subsidies influence both the number and quality of births, thereby fostering a substitution effect and reducing overall fertility levels. Conversely, scholars like Omori (2009) and Fanti and Gori (2011) argue that public investment in education can increase fertility rates and enhance human capital accumulation.

2.2. SDG4 and SDG8

One of the key objectives of the SDGs is to ensure high-quality education for all learners (SDG 4). This goal seeks to provide comprehensive, equitable education and lifelong learning opportunities to all by 2030 (Ferguson et al., 2021; Saini et al., 2023). SDG 4 includes seven specific targets, addressing issues like gender inequality in education, dropout rates at various educational levels, and providing learning opportunities for vulnerable groups, such as persons with disabilities (Muff et al., 2017).

SDG 4 sets distinct targets for various educational stages, emphasizing the universal provision of quality preschool, primary, and secondary education (Haslip & Gullo, 2018; Murray, 2021). Many scholars assert that universities are crucial to achieving the SDGs, requiring a comprehensive approach that includes teaching, program and course development, research, and outreach activities to drive progress (Ferguson & Roofe, 2020; Menon & Suresh, 2020). SDG 4 aims to improve reading and math skills among youth and adults, contributing to better living standards, promoting human rights, gender equality, and appreciation of cultural differences (Hanemann, 2019; Grotlüschen et al., 2020).

SDG 4 advocates eliminating educational inequalities and discrimination based on gender, race, and socioeconomic status (Do et al., 2020). It underscores the need for equal access to higher education and vocational training, and supports varied educational pathways (Gregg, 2007; Owens, 2017; Avsec & Jagiełło-Kowalczyk, 2021). Friedman et al. (2020) analyzed global educational inequalities since 1970 and predicted progress towards achieving SDG 4 by 2030 using statistical models. They posit that although universal primary education may be achieved by 2030, significant challenges persist in extending this to secondary and higher education. Blázquez et al. (2024) argue that the digital platform economy can promote the growth of non-traditional employment, thereby enhancing well-being and effectively advancing progress toward SDG 4.

SDG 8 promotes sustained, inclusive economic growth, full employment, and decent work for all. Specifically, SDG 8.1 targets a minimum annual GDP growth of 7% in the least developed countries. Rai et al. (2019) maintain that SDG 8 fails to address gender equality issues, conflicting with SDG 5. Kreinin and Aigner (2021) propose evaluating SDG 8 through a new framework based on eight dimensions: well-being, participation, democracy and autonomy, economic growth dependence, material and energy use, footprint and intensities, decency of work, and international economic and social impact.

2.3. SDGs and DEA

DEA is extensively used to evaluate the efficiency of SDGs across one or several countries (Yan et al., 2018; Ehrenstein et al., 2020; Łącka & Brzezicki, 2022). Current research indicates synergistic effects among the SDGs, with interdependencies across various goals (Collste et al., 2017; Kroll et al., 2019; Huan et al., 2021). Numerous scholars propose different tools and methods to track SDGs progress, noting that most countries are unlikely to meet all goals by 2030 (Miola & Schiltz, 2019; Xu et al., 2020). This trend has intensified following the COVID-19 pandemic (Barbier & Burgess, 2020; Ranjbari et al., 2021).

Extensive research supports the notion that enhancing education levels yields a demographic dividend, thereby boosting economic growth. However, current literature scarcely evaluates the SDGs' efficiency from the perspective of population birth rate. Yet, fluctuations in birth rate significantly affect sustainable education development, ongoing economic growth, and decent employment. Investigating SDG 4 and SDG 8's efficiency from the birth rate perspective is highly relevant practically. This paper partially fills a literature gap and offers theoretical and empirical insights to help countries actively pursue the SDGs by 2030.

3. Research methods

3.1. Methodology

The DDF model is widely used to measure efficiency. Traditional radial DDF models tend to overestimate efficiency values. DEA facilitates the evaluation across different stages. Färe et al. (2007) introduced Network DEA, which views the production process as comprising several sub-production technologies, termed 'Sub-decision-making units (Sub-DMUs)'. Expanding on this, Tone and Tsutsui (2009) proposed the weighted slack-based measures (SBM) Network DEA model, analyzing DMU linkages and using the SBM approach for optimal solutions. Therefore, this paper uses a two-stage dynamic DDF model to assess DMUs over time, incorporating carry-overs to link stages across periods. This approach is extensively adopted by scholars (Tone & Tsutsui, 2014).

The traditional DEA model frequently faces limitations in efficiency evaluation due to variations in production technologies, influenced by geographic, policy, and socio-economic differences among DMUs. To overcome this, O'Donnell et al. (2008) implemented the meta-frontier in DEA, measuring the technology gap ratio (TGR) by the distance between the group and meta frontiers. Building on this, this study enhances the traditional DDF model by integrating Tone and Tsutsui's (2014) approach with Shannon's (1948) entropy method and O'Donnell et al.'s (2008) meta frontier concept. Furthermore, it accounts for exogenous variable in efficiency assessment, proposing a meta two-stage dynamic DDF DEA model under exogenous variable. This innovative model is applied to assess the SDG 4 and SDG 8 efficiency across China's 30 provinces.

3.2. Research framework and variables

This study focuses on the targets of SDG4 and SDG8, selecting variables that align with these goals. The evaluation system is structured into two stages: the first stage with SDG4 and the second with SDG8. Birth rate is considered an exogenous variable impacting the entire system. The analytical framework is depicted in Figure 2.

Each stage includes multiple input and output variables. The model applies the entropy method to process a broad range of input and output variables. The variables used in this model are detailed in Table 1.

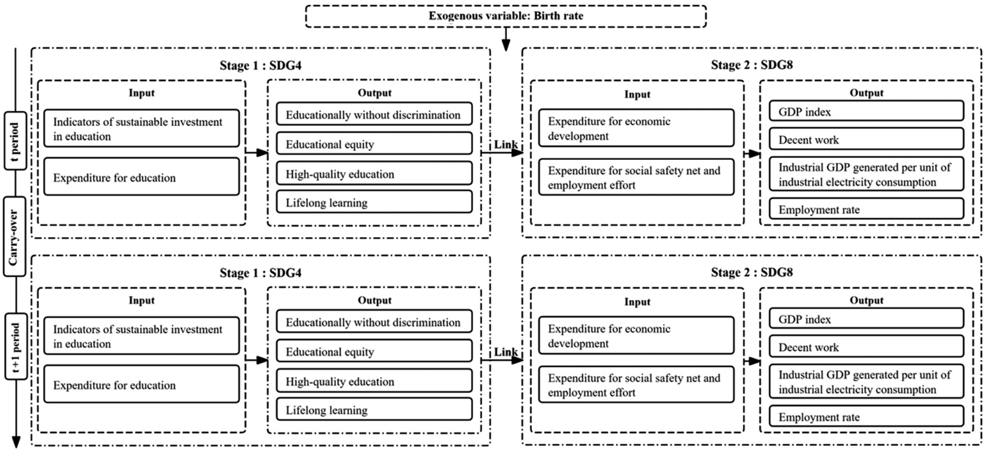


Figure 2. The research framework of the SDG4 and SDG8 assessment

Entropy methodology and steps:

Step 1: The original data is normalized to reduce dimensionality and magnitude effects through range standardization.

$$r_{mn} = \frac{\max_m x_{mn} - x_{mn}}{\max_m x_{mn} - \min_m x_{mn}} \left(m = 1, \ldots, 30;\ n = 1, \ldots, N\right), \tag{1}$$

where r_{mn} is the standardized value of the nth indicator for the m^{th} province; $\min_m x_{mn}$ is the minimum value of the nth indicator for the m^{th} province; $\max_m x_{mn}$ is the maximum value of the nth indicator for the m^{th} province.

Step 2: Calculate the proportion of each indicator for each evaluation object using normalized values.

$$P_{mn} = \frac{R_{mn}}{\sum_{m=1}^{30} R_{mn}} \ \left(m = 1, \ldots, 30,\ n = 1, \ldots, N\right). \tag{2}$$

P_{mn} represents the proportion of the m^{th} evaluation object on the n^{th} variable, where m is the total number of evaluation objects.

Step 3: Calculate the entropy value of the n^{th} indicator (e_n).

$$e_n = -k \sum_{m=1}^{30} \left[P_{mn} \ln\left(P_{mn}\right)\right] \ \left(m = 1, \ldots, 30,\ n = 1, \ldots, N\right). \tag{3}$$

e_n represents the entropy formula, where k is a constant, set as $\frac{1}{\ln m}$, to ensure that the entropy values range between 0 and 1. If the proportion P_{mn} for any indicator is 0, then $P_{mn} \ln\left(P_{mn}\right)$ is defined as 0.

Step 4: Calculate the weight of each variable.

$$w_n = \frac{1 - e_n}{\sum_{n=1}^{N} \left(1 - e_n\right)} \ \left(n = 1, \ldots, N\right). \tag{4}$$

N represents the total number of variables, and the weight w_n indicates the importance of indicator n. The term $1–e_n$ represents the difference coefficient, with a larger $1–e_n$ indicating a greater weight of the variable.

Table 1. Input and output variables

Stage	Variable			
SDG4	Input	Indicators of sustainable investment in education (ISIE)	Entropy	Number of colleges and universities
				Number of primary and secondary schools and high schools
				Ratio of teacher-to-student
		Expenditure for education (EFE)		
	Output (Link)	Educationally without discrimination (EWD)	Entropy	Primary School Enrollment
				Literacy rate of population over 15 years old
				High School Promotion Rate
		Educational equity (EE)	Entropy	Ratio of adult education students to general education students
				Ratio of female literacy rate to male literacy rate
				Ratio of country higher education rate to urban higher education rate
				Ratio of higher education rate for women to higher education rate for men
				Ratio of special education teachers to students
		High-quality education (HQE)	Entropy	Ratio of higher education
				Years of education per capita
				Total number of full professors and associate professors in universities
		Lifelong learning (LL)	Entropy	Rate of obtaining vocational skills qualification
				Rate of obtaining senior technician certificate
SDG8	Input	Expenditure for economic development (EED)		
		Expenditure for social safety net and employment effort (SSE)		
	Output	GDP index (GDPI)		
		Decent work (DW)	Entropy	The proportion of employees in high-tech enterprise
				The proportion of employees with college degree or above
				The proportion of female employees
				The proportion of employment in cultural industries
				The proportion of employment in financial industries
		Industrial GDP generated per unit of industrial electricity consumption (IGEC)		
		Employment rate (ER)		
Carry-over				Fixed assets
Exogenous variable				Birth rate

3.3. A meta two-stage dynamic DDF DEA model under exogenous variable

A decision-making unit (DMU) operating under the efficiency boundary selects the optimal weighted output. The efficiency for a DMU under the common boundary is determined using a linear programming process. This process utilizes specific equations to calculate the total efficiency of DMU_i, as well as the efficiency for each period, each stage, and each stage of each period.

Suppose there are two stages in each t period $\left(t=1,\ldots,T\right)$. In each period, there are two stages, including stage 1 (SDG 4) and stage 2 (SDG 8). As each DMU under the frontier chooses the most favorable final weighted output. In each period, there are two stages in each t periods, including the first and second stages.

The variables and expressions are listed in Table 2.

Table 2. The expression of the variable

Stage	Item	Variable	Expression
Stage1	Input	ISIE, EFE	$x1_{bj}^{t}\left(b=1,\ldots,B\right)$
	Output	EWD, EE, HQE, LL	$y1_{aj}^{t}\left(a=1,\ldots,A\right)$
	Link	EWD, EE, HQE, LL	$z_{hj}^{t}\left(h=1,\ldots,H\right)$
Stage 2	Input	EED, SSE,	$x2_{dj}^{t}\left(d=1,\ldots,D\right)$
	Output	GDPI, DW, GEC, ER	$y2_{sj}^{t}\left(s=1,\ldots,S\right)$
	Carry-over	Fixed assets	$C_{ljk}^{(t,t+1)}\in R_{+}\left(l=1\ldots l_k,\ t=1,\ldots,T\right)$
	Exogenous variable	Birth rate	$E_{vj}\left(v=1,\ldots,V\right)$

Meta-frontier efficiency (MFE):

Due to differences in management type, resources, regulations, or environment, all firms N (j = 1, ..., N) are composed of g groups of DMU under a common boundary $\left(N=N_1+N_2+\ldots+N_G\right)$. Under this boundary, DMU_i chooses the optimal final output weights that are most advantageous to it so as to maximize its efficiency. Therefore, the efficiency of DMU_i under the common boundary can be solved by the following linear programming procedure. The objective functions are as follows:

The efficiency of the DMU_i:

$$\max MFE=\theta^{*}=\sum_{g=1}^{G}\sum_{t=1}^{T}\left(w_{g1}^{t}\theta_{g1}^{t}+w_{g2}^{t}\theta_{g2}^{t}\right). \quad (5)$$

Stage 1: SDG4

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj1}^{t}x1_{gbj1}^{t}\le x1_{gbi1}^{t}-\theta_{g1}^{t}q_{gbi1}^{t}\ \forall b,\ t=1,2,\ldots,T,$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj1}^{t}y1_{gaj1}^{t}\ge y1_{gai1}^{t}+\theta_{g1}^{t}q_{gai1}^{t}\ \forall a,\ t=1,2,\ldots,T,$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj2}^{t}z_{ghj(1,2)}^{t} \geq z_{ghi(1,2)}^{t} + \theta_{g(1,2)}^{t}q_{ghi(1,2)}^{t} \ \forall h,$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj1}^{t} = 1,\ \lambda_{gj1}^{t} \geq 0\ \ \forall j,\ \ t = 1, 2, \ldots, T. \tag{6}$$

Stage 2: SDG8

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj2}^{t}X2_{gdj2}^{t} \leq X2_{gdi2}^{t} - \theta_{g2}^{t}q_{gdi2}^{t}\ \forall d,\ t = 1, 2, \ldots,\ T,$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj2}^{t}y2_{gsj2}^{t} \geq y2_{gsi2}^{t} + \theta_{g2}^{t}q_{gsi2}^{t}\ \forall s,\ t = 1, 2, \ldots, T,$$

$$\sum_{g=1}^{G}\sum_{j}^{n}\lambda_{gj2}^{t} = 1,\ \ \lambda_{gj2}^{t} \geq 0\ \forall j,\ \ t = 1, 2, \ldots, T. \tag{7}$$

The link of two periods: $\sum_{g=1}^{G}\sum_{j=1}^{n}\lambda_{j}^{t-1}c_{lj}^{t} = \sum_{g=1}^{G}\sum_{j=1}^{n}\lambda_{j}^{t}c_{lj}^{t}\ \ \forall l,\ \forall t,$

The exogenous variable: $\sum_{g=1}^{G}\sum_{j=1}^{n}\lambda_{jg}^{t}E_{gvj}^{t} = \sum_{g=1}^{G}E_{gvi}^{t}\ \ \forall V,\ \forall t.$ (8)

We set birth rate as the exogenous variable, in DEA model, exogenous variable refers to factors that are not directly under the control of the DMUs but may still influence efficiency. These variables typically represent external environmental factors or uncontrollable inputs/ outputs, yet they have a significant impact on efficiency evaluation. The use of exogenous variable helps improve the accuracy of the model, provides a more comprehensive analysis for efficiency assessment, and supports policy formulation.

q_{gbi1}^{t}, q_{gai1}^{t}, and $q_{ghi(1,2)}^{t}$ denote the direction vectors associated with stage 1 inputs, desirable output, and linking intermediate product from division 1 to division 2. q_{gdi2}^{t}, q_{gsi2}^{t}, and q_{goi2}^{t} denote the direction vectors associated with stage 2 inputs, desirable output and undesirable output.

In DEA models, ‘Group’ refers to a method of classifying DMUs based on certain specific characteristics or conditions. These characteristics may include technological conditions, environmental factors, regional differences, policy contexts, and more. In this study, we divide the 30 DMUs into three groups: eastern, central, and western regions.

Group-frontier efficiency (GFE):

The efficiency of the DMU_i is:

$$\max GFE = \theta^{i} = \sum_{t=1}^{T}\left(w_{1}^{t}\theta_{1}^{t} + w_{2}^{t}\theta_{2}^{t}\right). \tag{9}$$

Stage 1: SDG4

$$\sum_{j}^{n}\lambda_{j1}^{t}x1_{bj1}^{t} \le x1_{bi1}^{t} - \theta_{1}^{t}q_{bi1}^{t} \; \forall b, \; t = 1, 2, \ldots, T,$$

$$\sum_{j}^{n}\lambda_{j1}^{t}y1_{aj1}^{t} \ge y1_{ai1}^{t} + \theta_{g1}^{t}q_{ai1}^{t} \; \forall a, \; t = 1, 2, \ldots, T,$$

$$\sum_{j}^{n}\lambda_{j2}^{t}z_{hj(1,2)}^{t} \ge z_{hi(1,2)}^{t} + \theta_{(1,2)}^{t}q_{hi(1,2)}^{t} \; \forall h,$$

$$\sum_{j}^{n}\lambda_{j1}^{t} = 1, \; \lambda_{j1}^{t} \ge 0 \; \forall j, \; t = 1, 2, \ldots, T. \tag{10}$$

Stage 2: SDG8

$$\sum_{j}^{n}\lambda_{j2}^{t}X2_{dj2}^{t} \le X2_{di2}^{t} - \theta_{2}^{t}q_{di2}^{t} \; \forall d, \; t = 1, 2, \ldots, T,$$

$$\sum_{j}^{n}\lambda_{j2}^{t}y2_{sj2}^{t} \ge y2_{si2}^{t} + \theta_{2}^{t}q_{si2}^{t} \; \forall s, \; t = 1, 2, \ldots, T,$$

$$\sum_{j}^{n}\lambda_{j2}^{t} = 1, \; \lambda_{j2}^{t} \ge 0 \; \forall j, \; t = 1, 2, \ldots, T. \tag{11}$$

The link of two periods: $\sum_{j=1}^{n}\lambda_{j}^{t-1}c_{lj}^{t} = \sum_{j=1}^{n}\lambda_{j}^{t}c_{lj}^{t} \; \forall l, \; \forall t,$

The exogenous variables: $\sum_{j=1}^{n}\lambda_{j}^{t}E_{vj}^{t} = E_{vi}^{t} \; \forall v, \; t = 1, 2, \ldots, T.$ (12)

$\mathbf{q_{bi1}^{t}}$, $\mathbf{q_{ai1}^{t}}$, and $\mathbf{q_{hi(1,2)}^{t}}$ denote the direction vectors associated with stage 1 inputs, desirable output, and linking intermediate product from division 1 to division 2. $\mathbf{q_{di2}^{t}}$, $\mathbf{q_{si2}^{t}}$, and $\mathbf{q_{oi2}^{t}}$ denote the direction vectors associated with stage 2 inputs, desirable output and undesirable output.

3.4. Technology gap ratio (TGR)

The production frontiers of the g groups are encompassed within the meta-frontier. Technical efficiency under the meta-frontier is invariably lower than that under the group frontier. This ratio between the two frontiers is termed the TGR:

$$TGR = \frac{\theta^{*}}{\theta^{i}} = \frac{MFE}{GFE}. \tag{13}$$

3.5. Input efficiency and output efficiency

The gap between each DMU's actual input-output and its optimal target input-output index illustrates the potential for efficiency improvement from both input and output perspectives. As Hu and Wang (2006), in Figure 3, point B is the actual input set and point B′ is the projected

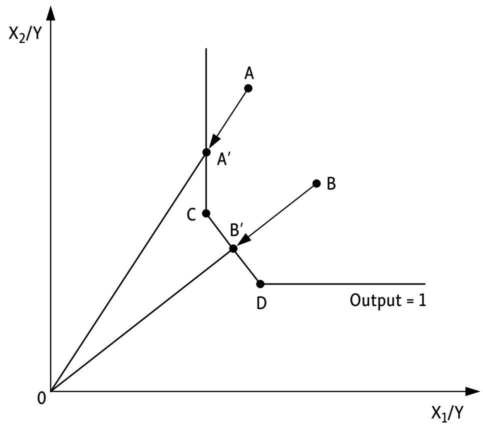


Figure 3. Radial adjustment and slack identified in the input-oriented DEA

point on the frontier for DMU B as the target in order to improve its efficiency according by reducing the radial adjustment BB′. Point A′ is the projected point on the frontier for another DMU A as the target to reach by reducing the radial adjustment AA′. However, the input level at point A′ could be further reduced to input. The amount CA′ that shall further be adjusted for the input level at point A′ along with the frontier is called 'slack'. The summation of slack (CA′) and radial adjustment (AA′) for inputs is called the amount of total adjustments (CA).

Hu and Chang (2016) further explained the input and output efficiency. Because actual input is always larger than or equal to target input, that is,

$$0 \le \frac{\text{Target input}}{\text{Actual input}} \le 1. \tag{14}$$

In addition, excess input is denoted as the gap between target input and actual input is slack. Thus, total slack, ranging from 1 to positive infinite, is equal to actual input minus target input. In Eqs. (10)–(11), $x1^t_{bi1}$ and $X2^t_{di2}$ denote actual input, $\theta^t_1 q^t_{bi1}$ and $\theta^t_2 q^t_{di2}$ denote total input slack, $\sum_j^n \lambda^t_{j1} x1^t_{bj1}$ and $\sum_j^n \lambda^t_{j2} X2^t_{dj2}$ denote target input, it can be illustrated by:

$$0 \le 1 - \frac{\text{Total input slack}}{\text{Actual input}} \le 1. \tag{15}$$

Then, output efficiency is defined as:

$$0 \le \frac{\text{Actual output}}{\text{Target output}} \le 1. \tag{16}$$

In Eqs. (10)–(11), $y1^t_{ai1}$ and $y2^t_{si2}$ denote actual output, $\theta^t_{g1} q^t_{ai1}$ and $\theta^t_2 q^t_{si2}$ denote total output slack, $\sum_j^n \lambda^t_{j1} y1^t_{aj1}$ and $\sum_j^n \lambda^t_{j2} y2^t_{sj2}$ denote target output, it also can be represented by:

$$0 \le 1 - \frac{\text{Total output slack}}{\text{Target desirable output}} \le 1. \tag{17}$$

For inputs, an actual input exceeding the target signifies an efficiency less than 1, labeled as inefficient. Conversely, when the actual input matches the target, efficiency is 1, termed efficient. For outputs, an actual output smaller than the target indicates an efficiency below 1, considered inefficient. If the actual output equals the optimal target, the efficiency is 1, deemed efficient.

4. Empirical analysis

4.1. Data description and statistical analysis

This study utilizes provincial-level sample data spanning from 2015 to 2020. Due to data unavailability in some provinces, the study focuses on 30 provinces across China. The 7th Five-Year Plan (1986–1990), ratified at the Fourth Session of the Sixth National People's Congress, categorizes the 30 provinces into eastern, central, and western regions. Inner Mongolia and Guangxi, having GDP per capita equivalent to the average of the 10 western provinces, are thus classified as part of the western region. Table 3 displays the regional divisions. Table 4 presents the mean, standard deviation, minimum, and maximum values of the variables.

Table 3. Regional division of China

Region	Provinces
Eastern	Beijing, Tianjin, Shanghai, Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Hainan
Central	Heilongjiang, Jilin, Henan, Shanxi, Anhui, Hubei, Hunan, Jiangxi
Western	Gansu, Guizhou, Ningxia, Qinghai, Shaanxi, Yunnan, Xinjiang, Sichuan, Chongqing, Guangxi, Inner Mongolia

Table 4. Statistical description of inputs and outputs

Stage	Variable	Unit	Mean	Std	Min	Max
SDG 4	ISIE		3634.48	2492.67	613.91	14690.35
	EFE	CNY10^8	982.75	583.02	142.51	3510.56
	EWD		75.99	25.84	55.76	411.76
	EE		39.93	4.98	25.67	54.60
	HQE		31.54	24.65	5.73	102.20
	LL		260.08	176.36	7.31	990.97
SDG 8	EED	CNY10^8	715.02	471.41	147.23	3225.41
	SSE	CNY10^8	817.31	394.91	146.23	1998.67
	GDPI	%	106.30	2.37	94.60	111.00
	DW		38.99	21.81	9.22	109.51
	IGEC	CNY/kWh	4.05	1.81	0.09	7.22
	ER	%	96.81	0.63	94.40	98.70
Carry-over	Fixed assets	CNY10^8	21244.39	14428.88	2736.29	58980.02
Exogenous variable	Birth rate	‰	10.75	2.88	3.75	17.89

4.2. Analysis of overall efficiency

Figure 4 compares overall efficiency under two scenarios: one excluding the exogenous variable (S) and the other including it (S*). Clearly, considering the birth rate's impact has led to varied improvements in the efficiency of most provinces. The average efficiency across the 30 provinces rose from 0.68 to 0.80. Regionally, efficiency improved as follows: in the eastern region from 0.66 to 0.79, in the central region from 0.67 to 0.80, and in the western region from 0.70 to 0.81. From 2015 to 2020, considering the exogenous variable, the western

Province	Overall		2015		2016		2017		2018		2019		2020	
	S	S*	S	S*	S	S*	S	S*	S	S*	S	S*	S	S*
Beijing	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tianjin	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Shanghai	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00
Liaoning	0.58	0.94	0.54	0.95	0.65	1.00	0.60	0.95	0.60	0.95	0.64	0.96	0.64	0.95
Hebei	0.37	0.41	0.46	0.52	0.49	0.54	0.42	0.48	0.42	0.48	0.41	0.46	0.36	0.43
Shandong	0.34	0.36	0.35	0.42	0.39	0.42	0.46	0.48	0.42	0.45	0.43	0.45	0.46	0.48
Jiangsu	0.40	1.00	0.50	1.00	0.51	1.00	0.62	1.00	0.57	1.00	0.53	1.00	0.52	1.00
Zhejiang	0.49	0.53	0.64	0.72	0.61	0.69	0.59	0.64	0.56	0.61	0.56	0.59	0.56	0.60
Fujian	0.78	1.00	0.77	1.00	0.79	1.00	0.82	1.00	0.77	1.00	0.74	1.00	0.77	1.00
Guangdong	0.35	0.43	0.40	0.50	0.42	0.54	0.46	0.54	0.49	0.55	0.45	0.57	0.49	0.55
Hainan	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Eastern	**0.66**	**0.79**	**0.70**	**0.83**	**0.71**	**0.84**	**0.73**	**0.83**	**0.71**	**0.82**	**0.70**	**0.82**	**0.71**	**0.82**
Heilongjiang	0.75	0.98	0.69	0.94	0.74	0.97	0.80	1.00	0.86	1.00	0.81	1.00	0.72	1.00
Jilin	0.80	1.00	0.77	1.00	0.92	1.00	0.74	1.00	0.84	1.00	0.76	1.00	0.83	1.00
Henan	0.59	0.61	0.62	0.66	0.68	0.71	0.70	0.73	0.66	0.68	0.62	0.64	0.58	0.59
Shanxi	0.58	0.73	0.61	0.69	0.64	0.73	0.70	0.83	0.65	0.82	0.58	0.81	0.52	0.76
Anhui	0.46	0.51	0.51	0.57	0.49	0.57	0.54	0.57	0.55	0.60	0.47	0.54	0.51	0.59
Hubei	0.63	1.00	0.64	1.00	0.66	1.00	0.80	1.00	0.77	1.00	0.70	1.00	0.70	1.00
Hunan	0.85	0.87	0.96	0.96	0.98	0.98	1.00	1.00	0.88	0.89	0.89	0.94	0.68	0.70
Jiangxi	0.66	0.69	0.73	0.76	0.72	0.75	0.66	0.68	0.66	0.67	0.70	0.74	0.61	0.65
Central	**0.67**	**0.80**	**0.69**	**0.82**	**0.73**	**0.84**	**0.74**	**0.85**	**0.73**	**0.83**	**0.69**	**0.83**	**0.64**	**0.79**
Gansu	0.85	0.86	0.66	0.66	0.70	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Guizhou	0.57	0.66	0.57	0.63	0.68	1.00	0.56	0.66	0.57	0.60	0.57	0.60	0.65	0.73
Ningxia	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Qinghai	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Shaanxi	0.98	1.00	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Yunnan	0.51	0.69	0.60	1.00	0.64	1.00	0.58	0.67	0.63	0.69	0.72	0.79	0.52	0.55
Xinjiang	0.42	0.65	0.53	0.55	0.45	0.50	0.49	0.90	0.74	1.00	0.47	0.72	0.42	0.75
Sichuan	0.43	0.89	0.48	0.61	0.51	1.00	0.60	1.00	0.59	1.00	0.54	1.00	0.51	1.00
Chongqing	0.95	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.96	0.96	0.98	0.99	0.87	1.00
Guangxi	0.54	0.56	0.57	0.58	0.60	0.61	0.62	0.63	0.61	0.62	0.68	0.68	0.49	0.54
Inner Mongolia	0.47	0.66	0.64	0.81	0.63	0.77	0.59	0.73	0.58	0.75	0.58	0.78	0.61	0.70
Western	**0.70**	**0.81**	**0.72**	**0.80**	**0.75**	**0.87**	**0.77**	**0.87**	**0.79**	**0.87**	**0.78**	**0.87**	**0.73**	**0.84**
Average	**0.68**	**0.80**	**0.71**	**0.82**	**0.73**	**0.85**	**0.74**	**0.85**	**0.75**	**0.84**	**0.73**	**0.84**	**0.70**	**0.82**

Figure 4. The overall efficiency under the two scenarios

region's overall efficiency demonstrated a rising trend, increasing from 0.80 to 0.84. This suggests that in terms of sustainable development, the western region has outperformed both the eastern and central regions.

Further analysis of the overall efficiency across the 30 provinces is detailed in Figure 5. In both scenarios, Beijing, Tianjin, Shanghai, Hainan, Ningxia, and Qinghai consistently achieved the efficiency value of 1. Under the S* scenario, Jiangsu, Fujian, Jilin, Hubei, and Shaanxi

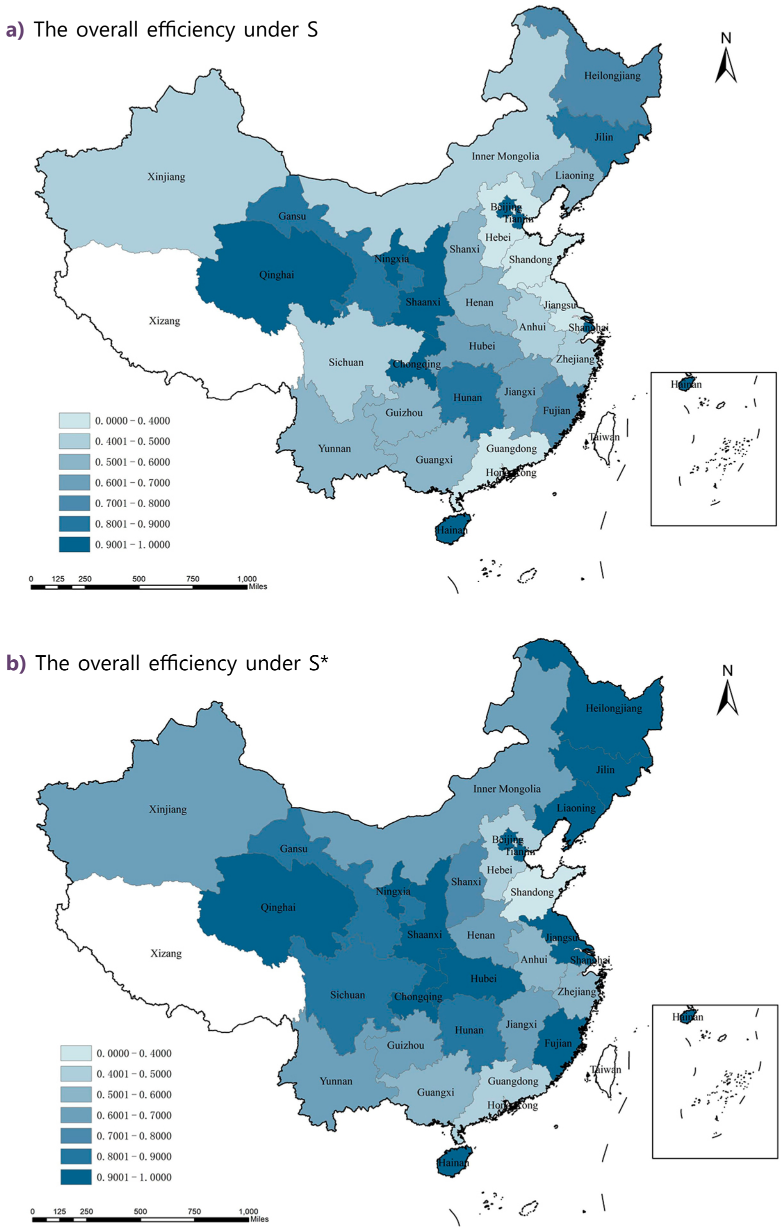


Figure 5. The overall efficiency of 30 provinces under S and S*

improved their efficiency to the optimal score of 1. Liaoning, Heilongjiang, and Chongqing achieved efficiency values ranging from 0.9 to 1. Shandong, Hebei, and Guangdong recorded the lowest performance among the provinces. Jiangsu exhibited the most dramatic improvement, increasing from 0.40 to 1.00, with Sichuan next, improving from 0.43 to 0.89. While efficiency improved across all provinces, these results underscore considerable regional disparities.

4.3. Analysis of SDG 4 and SDG 8 efficiency

Figure 6 illustrates that, excluding the impact of the birth rate, SDG 8's efficiency (0.74) exceeds that of SDG 4 (0.71). However, SDG 4's efficiency rises to 0.85, a gain of 0.14, whereas SDG 8 increases to 0.83, a gain of 0.09, thus rendering SDG 4 more efficient than SDG 8. This suggests that the birth rate positively influences both SDG 4 and SDG 8, with a notably stronger effect on SDG 4.

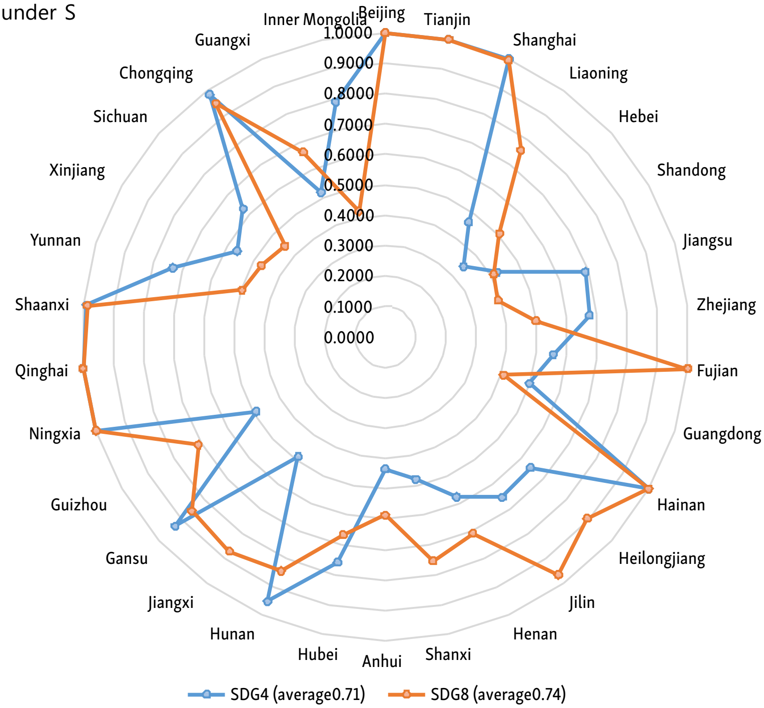
Figure 7 depicts the efficiency of SDG 4 and SDG 8 under S*. In the eastern region, SDG 4's average efficiency (0.85) exceeds SDG 8's (0.80). Moreover, from 2015 to 2020, the efficiencies of both SDG 4 and SDG 8 exhibited minimal fluctuations, maintaining essential stability. In the central region, the average efficiency of SDG 4, at 0.81, is lower than SDG 8's average of 0.85. Over the years, SDG 4's efficiency remained stable from 2015 to 2019, fluctuating slightly around 0.8, before markedly increasing to 0.84 in 2020. SDG 8's efficiency traced an inverted U-shaped curve, especially notable between 2019 and 2020, when it fell sharply from 0.86 to 0.73. In the western region, SDG 4's average efficiency (0.88) surpasses that of SDG 8 (0.84). Over the years, SDG 4's efficiency in the western region has consistently increased, rising from 0.83 in 2015 to 0.89 in 2020, demonstrating a stable upward trend. Similarly, SDG 8's efficiency in the western region mirrors that in the central region, following an inverted U-shaped trajectory. Notably, from 2019 to 2020, its efficiency notably declined, falling from 0.86 to 0.80.

The analysis clearly shows that the central and western regions saw significant declines in SDG 8 efficiency from 2019 to 2020, which we attribute to the impact of COVID-19. Notably, efficiency declines were confined to the central and western regions, while the eastern region maintained its stability. This disparity stems from the later economic development in the central and western regions, which still have considerable potential for enhancement in their industrial, resource, and energy structures. Despite recent rapid development, the economic vulnerabilities of these regions were exposed by COVID-19, resulting in a substantial drop in SDG 8 efficiency. In contrast, the eastern region, benefiting from an earlier start in economic development, greater openness, and stronger innovation capabilities, demonstrated resilience during COVID-19, maintaining stable SDG 8 efficiency.

4.4. Analysis of Technology Gap Ratio (TGR)

The TGR is defined as the ratio between technical efficiency at the meta-frontier and that at the group frontier. TGR facilitates the comparison of regional technological efficiency changes before and after grouping. A TGR of 1 signifies no gap between meta-frontier and group frontier technologies, according to Tian and Lin (2018).

a) SDG4 and SDG8 under S



b) SDG4 and SDG8 under S*

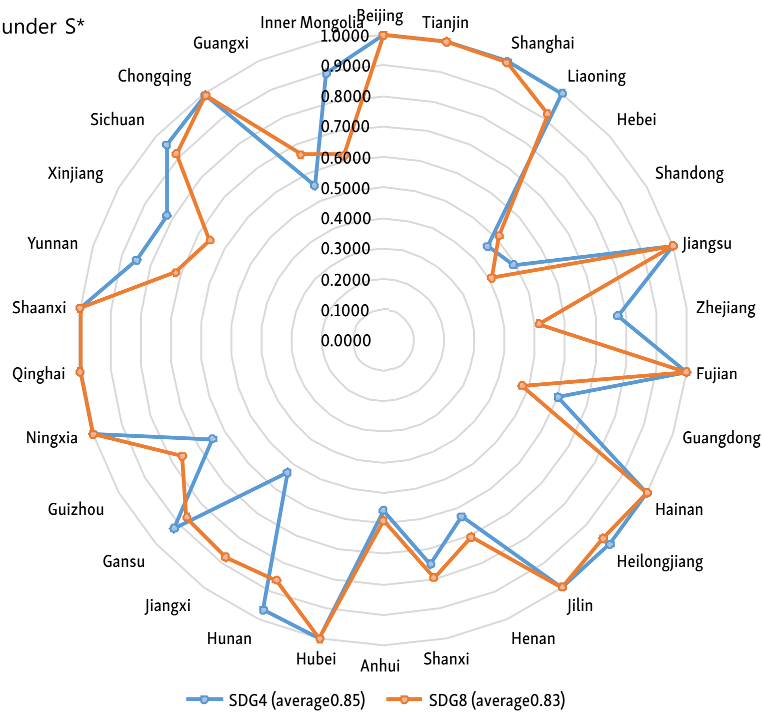


Figure 6. The efficiency comparison between SDG 4 and SDG 8 under S and S*

Province	SDG 4							SDG 8						
	Mean	2015	2016	2017	2018	2019	2020	Mean	2015	2016	2017	2018	2019	2020
Beijing	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tianjin	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Shanghai	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00
Liaoning	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	0.90	1.00	0.89	0.91	0.91	0.89
Hebei	0.46	0.47	0.47	0.44	0.47	0.43	0.47	0.51	0.57	0.61	0.52	0.48	0.49	0.39
Shandong	0.49	0.46	0.45	0.50	0.51	0.49	0.55	0.41	0.38	0.40	0.46	0.38	0.41	0.41
Jiangsu	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Zhejiang	0.77	0.84	0.86	0.81	0.77	0.71	0.65	0.51	0.61	0.52	0.46	0.45	0.48	0.55
Fujian	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Guangdong	0.60	0.60	0.65	0.59	0.57	0.59	0.61	0.48	0.41	0.43	0.48	0.52	0.54	0.50
Hainan	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Eastern	**0.85**	**0.85**	**0.86**	**0.85**	**0.85**	**0.84**	**0.84**	**0.80**	**0.81**	**0.82**	**0.80**	**0.79**	**0.80**	**0.80**
Heilongjiang	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.88	0.94	1.00	1.00	1.00	1.00
Jilin	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Henan	0.63	0.65	0.66	0.63	0.60	0.61	0.64	0.71	0.68	0.76	0.83	0.77	0.67	0.53
Shanxi	0.75	0.57	0.65	0.73	0.81	0.85	0.89	0.80	0.81	0.81	0.93	0.84	0.76	0.63
Anhui	0.56	0.54	0.61	0.50	0.48	0.52	0.69	0.59	0.60	0.53	0.65	0.72	0.56	0.49
Hubei	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hunan	0.97	1.00	1.00	1.00	1.00	0.96	0.85	0.86	0.93	0.97	1.00	0.79	0.93	0.55
Jiangxi	0.54	0.53	0.56	0.49	0.46	0.52	0.65	0.88	0.98	0.94	0.86	0.88	0.96	0.65
Central	**0.81**	**0.79**	**0.81**	**0.79**	**0.79**	**0.81**	**0.84**	**0.85**	**0.86**	**0.87**	**0.91**	**0.87**	**0.86**	**0.73**
Gansu	0.92	0.76	0.78	1.00	1.00	1.00	1.00	0.87	0.57	0.63	1.00	1.00	1.00	1.00
Guizhou	0.65	0.59	1.00	0.68	0.53	0.52	0.56	0.76	0.68	1.00	0.64	0.67	0.67	0.90
Ningxia	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Qinghai	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Shaanxi	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Yunnan	0.85	1.00	1.00	0.82	0.78	0.78	0.72	0.72	1.00	1.00	0.53	0.60	0.79	0.37
Xinjiang	0.82	0.60	0.59	1.00	1.00	0.83	0.90	0.66	0.51	0.41	0.80	1.00	0.61	0.61
Sichuan	0.96	0.74	1.00	1.00	1.00	1.00	1.00	0.91	0.48	1.00	1.00	1.00	1.00	1.00
Chongqing	0.99	1.00	1.00	1.00	0.98	0.98	1.00	0.99	1.00	1.00	1.00	0.95	1.00	1.00
Guangxi	0.56	0.53	0.51	0.51	0.54	0.55	0.69	0.67	0.64	0.70	0.75	0.71	0.80	0.39
Inner Mongolia	0.89	0.92	0.95	0.83	0.76	1.00	0.91	0.62	0.70	0.58	0.64	0.73	0.56	0.50
Western	**0.88**	**0.83**	**0.89**	**0.89**	**0.87**	**0.88**	**0.89**	**0.84**	**0.78**	**0.85**	**0.85**	**0.88**	**0.86**	**0.80**

Figure 7. The efficiency of SDG4 and SDG8 under S*

According to Figure 8, the western region demonstrates a pronounced technological advantage, with TGR values exceeding 0.9 in both scenarios. The eastern region is next, with the central region showing the largest technological gap, indicative of a significant technological disadvantage. Considering the exogenous variable, the birth rate significantly improved the central region's efficiency (from 0.66 to 0.80), while the eastern and western regions saw marginal declines.

From 2015 to 2020, under the S* scenario, TGR fluctuations indicate a notable decline in the eastern and central regions, while the western region exhibits a slight increase. This implies that population growth, fueled by an increasing birth rate, may boost the development efficiency of the western region, effectively reducing the technological gap and possibly overtake the eastern region in technological progress.

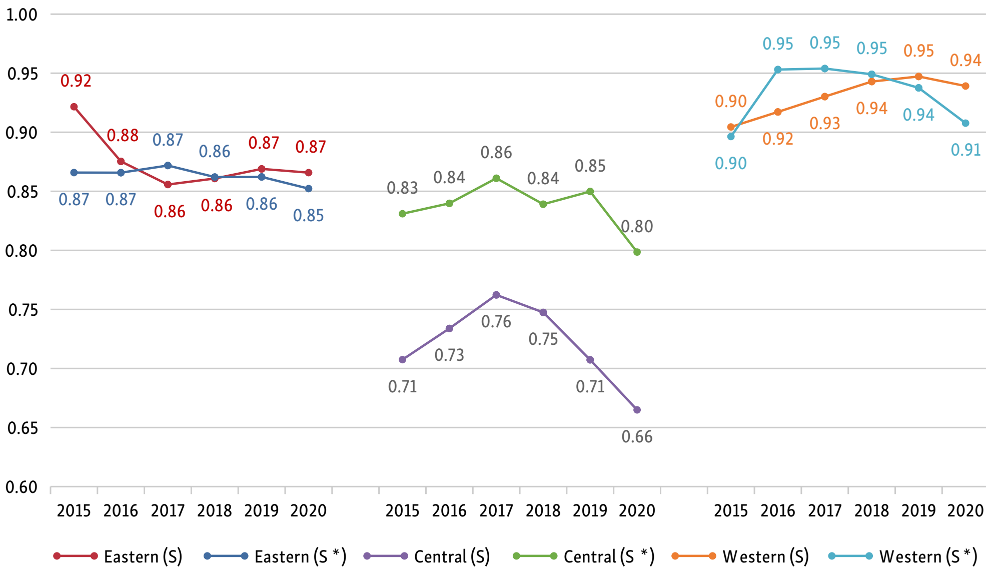


Figure 8. TGR in eastern, central, and western from 2015 to 2020

4.5. Efficiency optimization analysis

Following Zuo et al. (2022), We employed a two-dimensional scatter plot to categorize the 30 provinces and suggest paths for efficiency improvement. We designated the efficiency of SDG 4 as the horizontal axis and SDG 8 as the vertical axis. The mean efficiency of SDG4 is 0.85, while that of SDG8 is 0.83. The mean efficiency serves as the boundary for dividing the quadrants. Provinces with efficiency values above the mean are considered to perform better. Based on these values, a combined matrix is constructed, as illustrated in Figure 9.

Based on efficiency distribution, we classified the 30 provinces into four quadrants: Quadrant I for provinces with high efficiency in both SDG4 and SDG8, Quadrant II for those with low SDG4 and high SDG8 efficiency, Quadrant III for those with low efficiency in both, and Quadrant IV for those with high SDG4 but low SDG8 efficiency. This classification aids in pinpointing specific areas for improvement in each province to boost their SDG performance effectively.

Seventeen provinces are located in Quadrant I, serving as benchmarks. These provinces should preserve their advantages to continue efficient development in both SDG 4 and SDG 8. As the benchmark, Shanghai has prioritized vocational education reform to align with industrial and technological demands. The city has established over 100 industry-education integration projects, partnering with leading enterprises to develop tailored curricula and training programs. Additionally, Shanghai has implemented modern apprenticeship models, benefiting more than 10,000 students annually. The city's vocational education system emphasizes innovation, with a focus on emerging fields such as artificial intelligence and green energy. These efforts have resulted in a graduate employment rate exceeding 95%, showcasing Shanghai's success in integrating education with industry needs and supporting sustainable economic development.

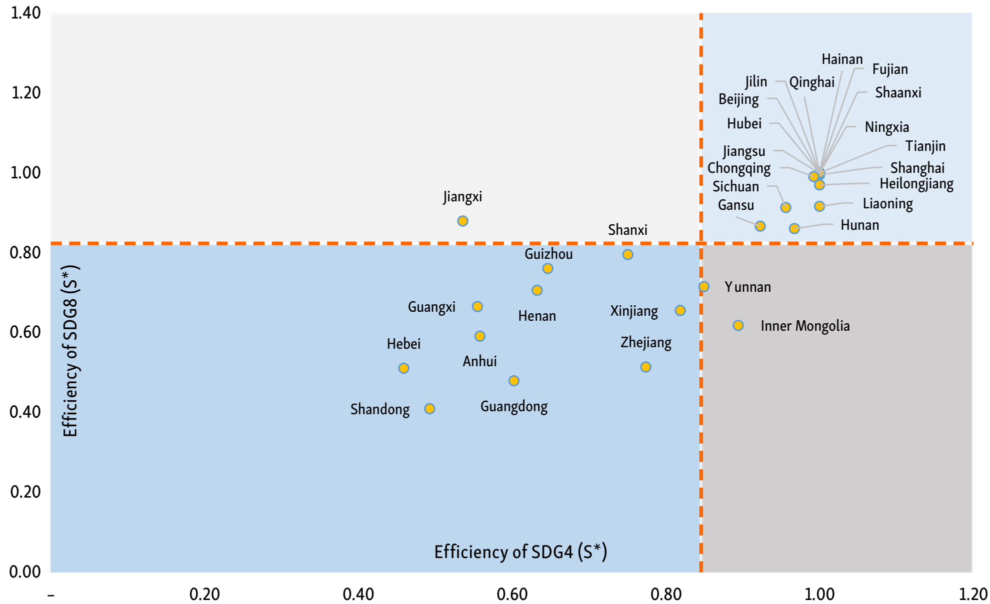


Figure 9. Distribution of SDG 4 efficiency and SDG 8 efficiency in the 30 provinces

Jiangsu Province has deepened education reforms by fostering industry-academia collaboration. It established 200 industry-integrated majors, 53 key bases, and 200 top courses, with over 6,000 graduate workstations hosting 10,000 students annually. Additionally, 4,000 industry experts have been appointed as professors, bridging gaps between education and sectors like smart manufacturing and integrated circuits. These efforts have enhanced innovation and talent development, driving the transformation of scientific achievements into real-world productivity.

Jiangxi, the sole province in Quadrant II, faces a significant disparity in educational resources between urban and rural areas, with urban schools boasting superior staff and facilities. Jiangxi must enhance sustainable educational development awareness, boost educational investment in rural areas, and offer regular training for rural teachers to reduce educational resource imbalances.

Ten provinces are in Quadrant III, where significant investments in human, material, and financial resources have not translated into effective outcomes, leading to low SDG 4 efficiency. In the second stage, these provinces also failed to achieve a balanced input-output ratio, resulting in low SDG 8 efficiency. As China's largest manufacturing hub, Guangdong has implemented innovative vocational education reforms to meet industrial labor demands. The province established 526 modern industrial colleges, launched over 4,000 enterprise-tailored classes, and piloted modern apprenticeships across 310 fields through partnerships with 207 companies. Additionally, 1,223 industry-education integrated enterprises were cultivated. Despite current inefficiencies, Guangdong's efforts provide valuable insights for aligning education with industrial needs.

The provinces in Quadrant IV, Yunnan and Inner Mongolia, must address geographical challenges and correct inefficiencies in their economic structures. Yunnan, for example, depends heavily on agriculture with underdeveloped industrial and service sectors, which constrain job creation and economic diversification. Conversely, Inner Mongolia's overreliance on mineral resource exploitation limits its sustainable development potential. Targeted strategies are necessary for these regions to overcome their challenges and achieve balanced, sustainable growth.

To delve deeper into the causes of inefficiency and identify potential improvements, we analyzed the efficiency of input and output variables, as depicted in Figure 10. In this analysis, red indicates input redundancy, signaling a need to reduce inputs, and blue denotes output insufficiency, suggesting an increase in outputs is necessary. The deeper the color, the greater the redundancy or insufficiency ratio. It becomes evident that provinces with higher efficiency demonstrate improved performance in managing their input and output variables. In these provinces, instances of input redundancy and output insufficiency are relatively mild.

Province	SDG4						SDG8					
	ISIE	EFE	EWD	EE	HQE	LL	EED	SSE	GDPI	DW	IGEC	ER
Beijing	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tianjin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shanghai	0.00	0.00	0.00	0.00	0.00	0.00	−0.11	−0.07	0.01	0.00	0.00	0.01
Liaoning	0.00	0.00	0.00	0.00	0.00	0.00	−0.06	−0.51	0.05	0.37	0.04	0.04
Hebei	−0.72	−0.63	0.24	0.15	0.37	0.74	−0.34	−0.55	0.22	0.75	0.27	0.23
Shandong	−0.55	−0.48	0.37	0.33	0.12	0.34	−0.39	−0.38	0.34	0.63	0.35	0.34
Jiangsu	0.00	0.00	0.00	0.00	0.00	0.00	−0.04	−0.05	0.00	0.06	0.00	0.00
Zhejiang	−0.31	−0.41	0.30	0.16	0.13	0.00	−0.41	−0.36	0.27	0.49	0.24	0.27
Fujian	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guangdong	−0.47	−0.54	0.41	0.30	0.14	0.29	−0.59	−0.34	0.39	0.47	0.30	0.38
Hainan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heilongjiang	0.00	0.00	0.00	0.00	0.00	0.00	−0.02	−0.14	0.03	0.04	0.01	0.02
Jilin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Henan	−0.74	−0.49	0.27	0.21	0.14	0.12	−0.20	−0.40	0.19	0.49	0.13	0.19
Shanxi	−0.49	−0.30	0.06	0.05	0.28	0.48	−0.14	−0.43	0.08	0.65	0.10	0.07
Anhui	−0.65	−0.51	0.25	0.25	0.16	0.07	−0.25	−0.34	0.21	0.40	0.18	0.21
Hubei	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hunan	−0.17	−0.04	0.24	0.21	0.11	0.34	−0.09	−0.14	0.21	0.15	0.05	0.22
Jiangxi	−0.60	−0.53	0.13	0.21	0.21	0.12	−0.07	−0.13	0.10	0.28	0.04	0.10
Gansu	−0.18	−0.10	0.04	0.08	0.07	0.22	−0.11	−0.14	0.05	0.06	0.09	0.05
Guizhou	−0.46	−0.40	0.18	0.17	0.10	0.04	−0.22	−0.18	0.13	0.42	0.13	0.14
Ningxia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Qinghai	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shaanxi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yunnan	−0.39	−0.19	0.18	0.13	0.15	0.00	−0.19	−0.19	0.13	0.41	0.22	0.14
Xinjiang	−0.26	−0.16	0.11	0.10	0.14	0.09	−0.26	−0.22	0.14	0.08	0.43	0.13
Sichuan	−0.05	−0.04	0.06	0.05	0.07	0.02	−0.06	−0.06	0.05	0.05	0.05	0.05
Chongqing	−0.01	−0.01	0.04	0.06	0.00	0.10	−0.01	−0.05	0.03	0.10	0.00	0.03
Guangxi	−0.64	−0.54	0.18	0.08	0.10	0.51	−0.25	−0.36	0.15	0.40	0.18	0.15
Inner Mongolia	−0.13	−0.08	0.08	0.13	0.27	0.18	−0.28	−0.34	0.15	0.67	0.41	0.14

Figure 10. Annual average slack adjustment ratios for the input and output in two stages

In the SDG 4 stage, provinces including Hebei, Shandong, Guangdong, Shanxi, and Guangxi show notable input redundancy and output insufficiency. Despite substantial investments, these provinces experience low conversion rates in promoting educational equity and lifelong learning. To remedy this, establishing and enhancing an education quality assessment system with regular inspections can ensure that investments translate into measurable improvements in educational quality and equity.

Furthermore, consolidating educational resources in neighboring regions can minimize duplication and waste by sharing teaching facilities and pooling teacher resources. The use of modern information technologies, like online education platforms, can broaden the accessibility of high-quality educational resources, thereby enhancing their flexibility and efficient use.

In the SDG 8 stage, Hebei, Shandong, Zhejiang, and Guangdong exhibit excessive spending on economic development and social safety nets, coupled with inadequate outputs in regional GDP and quality employment. To prevent wastage of public resources, these provinces should consider scaling back government investments. Efforts should be directed towards transitioning industrial structures to high-tech and high-value-added industries to enhance production efficiency and economic quality.

Supporting innovation and employment can generate more high-quality opportunities. Optimizing the allocation of social security funds to prioritize critical areas like unemployment insurance and vocational training ensures more effective use of resources. Promoting economic diversification to lessen dependence on traditional industries will foster service and high-tech industries, creating more high-quality jobs.

Xinjiang and Inner Mongolia also exhibit poor performance in energy-efficient production. These regions should prioritize technological advancements and upgrades to improve the energy efficiency of industrial production. Additionally, renewable energy industries, such as wind and solar power, should be vigorously developed to reduce dependence on fossil fuels and facilitate the transformation of the energy structure.

5. Discussion

China is approaching the Lewis Turning Point and is gradually losing its demographic dividend, posing new challenges for the country's sustainable development. Regional variations in birth rates in China are influenced by differences in resource endowments and fertility norms. Our findings indicate that the birth rate positively influences both SDG 4 and SDG 8, with a stronger effect on SDG 4. This paper constructs a more comprehensive indicator system to measure the development efficiency of SDG 4 and SDG 8, incorporating the impact of the birth rate into the research framework, which distinguishes it from existing literature. We examine the current state of education quality and employment performance in China while exploring pathways for optimization and improvement. It provides robust decision-making support to policymakers for achieving SDG 4 and SDG 8.

The research findings reveal a significant decline in the efficiency level of SDG 8 in 2020, primarily attributed to the impact of COVID-19, with notable regional disparities. This is consistent with the findings of Markowska and Strahl (2024). In response to this shock, the eastern region exhibited greater economic resilience, with SDG 8 efficiency remaining relatively stable. In contrast, the central and western regions, due to their shorter development histories and the need for further optimization of industrial structures, displayed greater economic vulnerabilities when confronted with external shocks. COVID-19 resulted in a decline in both global and domestic demand, directly affecting China's exports and, subsequently, GDP growth. In 2020, China's GDP growth rate fell to 2.3%, the lowest in several years. Furthermore, lockdown measures and factory closures led to widespread unemployment and disruption to work, particularly in the service and manufacturing sectors. In the short term, COVID-19 presented significant challenges for China in achieving SDG 8. However, in the long term, the Chinese government has accelerated economic structural adjustments, promoted digital transformation, and fostered emerging industries such as remote work, online education, and e-commerce. These measures have contributed to economic recovery and the generation of new employment opportunities.

Globally, declining birth rates and population aging are major issues in developed countries, with Japan, Italy, Germany, and South Korea serving as notable examples. In contrast, China's population challenges emerged later, largely due to the long-term implementation of the one-child policy, which gradually led to declining birth rates and an aging population. While China still has much to learn from developed countries in addressing these challenges, it has also offered valuable insights to other nations, particularly through innovations in community-based elderly care services in urban-rural fringe areas and the gradual implementation of delayed retirement policies (Table 5).

China's demographic dividend is gradually waning, and the declining birth rate presents unique challenges for achieving the SDGs, particularly those related to SDG 4 and SDG 8. The next areas require further research and are key to promoting long-term social and economic sustainability. First, we will analyze the impact of population structure shifts on school distribution, teacher allocation, and educational resource investment using spatial econometric models and GIS to optimize resource allocation and improve educational quality. Second, we will forecast labor demand across industries and regions, employing machine learning algorithms and input-output analysis to evaluate the alignment between the education system and labor market needs, guiding targeted reforms. Finally, we will establish predictive models, such as system dynamics or agent-based modeling, to simulate the long-term effects of policy combinations on educational quality and employment outcomes, identifying optimal policy mixes. These approaches will provide actionable insights and robust recommendations for sustainable development.

Table 5. Common and highlight policy by selected countries to address population issues

Common policy	Highlight policy
1. Pro-natalist policy 2. Introduce baby-rearing allowances 3. Expand childcare facilities 4. Support young parents in balancing family and career responsibilities 5. Improve the work environment for women	1. Encourage elderly employment (Japan) 2. Tax exemptions and priority housing (Korea) 3. Policies to stimulate fertility (Italy) 4. The nationwide governance system ensures the effectiveness of policies (China) 5. Relax immigration policies (Germany)

6. Conclusions and policy recommendations

There are significant imbalances in birth rates across China's 30 provinces. In light of this disparity, this study treats birth rate as an exogenous variable and applies a meta two-stage dynamic DDF DEA model to evaluate the efficiency of SDG 4 and SDG 8, as well as the impact of birth rate on these goals. The main conclusions are as follows:

First, in overall efficiency, after considering the impact of birth rate, all provinces showed varying degrees of improvement, with the central region experiencing the most significant enhancement. After accounting for birth rate, the efficiency differences between regions became smaller, with values of 0.79 for the eastern region, 0.80 for the central region, and 0.81 for the western region. Between 2015 and 2020, the eastern and central regions showed a declining trend in efficiency, while the western region displayed an upward trend.

Second, the impact of birth rate on both SDG 4 and SDG 8 is positive, with a more pronounced effect on SDG 4. In the eastern region, the efficiency of SDG 4 (0.85) exceeds that of SDG 8 (0.80), with relatively stable performance from 2015 to 2020. In the central region, the efficiency of SDG 4 (0.81) is lower than that of SDG 8 (0.85). From 2015 to 2020, SDG 4's efficiency showed an upward trend, while SDG 8 followed an inverted U-shaped curve. In the western region, the efficiency of SDG 4 (0.88) is higher than that of SDG 8 (0.84).

Third, 17 provinces exhibit high efficiency in both SDG 4 and SDG 8, 1 province shows low efficiency in SDG 4 but high efficiency in SDG 8, 10 provinces display low efficiency in both SDG 4 and SDG 8, and 2 provinces demonstrate high efficiency in SDG 4 but low efficiency in SDG 8. Hebei, Shandong, Guangdong, Shaanxi, and Guangxi exhibit significant education input redundancy and output insufficiency. Hebei, Shandong, Zhejiang, and Guangdong exhibit dual redundancies in government economic expenditures and social security spending, with insufficient outputs in regional GDP and high-quality employment. In addition, Xinjiang and Inner Mongolia perform poorly in energy-efficient production.

According to the main findings above, as depicted in Figure 11, the following policy recommendations are provided:

First, draw on the experiences of developed countries to develop comprehensive fertility policies that minimize the opportunity costs associated with family childbearing. Measures should include providing childbirth subsidies, tax reduction, offering housing discounts, and broadening maternity insurance coverage to encompass flexible workers and the unemployed. Specifically, this could involve improving childcare markets, extending leave periods, introducing parental leave, upgrading the legal status of fertility-related regulations, and increasing their practical effectiveness.

Second, focus on prioritizing resource allocation for the nine-year compulsory education system. Regional collaboration within the Yangtze River Delta, Pearl River Delta, and Beijing-Tianjin-Hebei regions should be strengthened to facilitate the integration and sharing of educational resources. Digital technologies, including artificial intelligence and 5G, should be leveraged to enrich educational content and expand access to online learning. Lifelong learning reforms should also be advanced by offering diverse educational opportunities and skills training to meet the evolving needs of an aging society.

Third, design and implement macroeconomic policies that promote both economic development and job creation. Specifically, the eastern region should capitalize on its advantage in

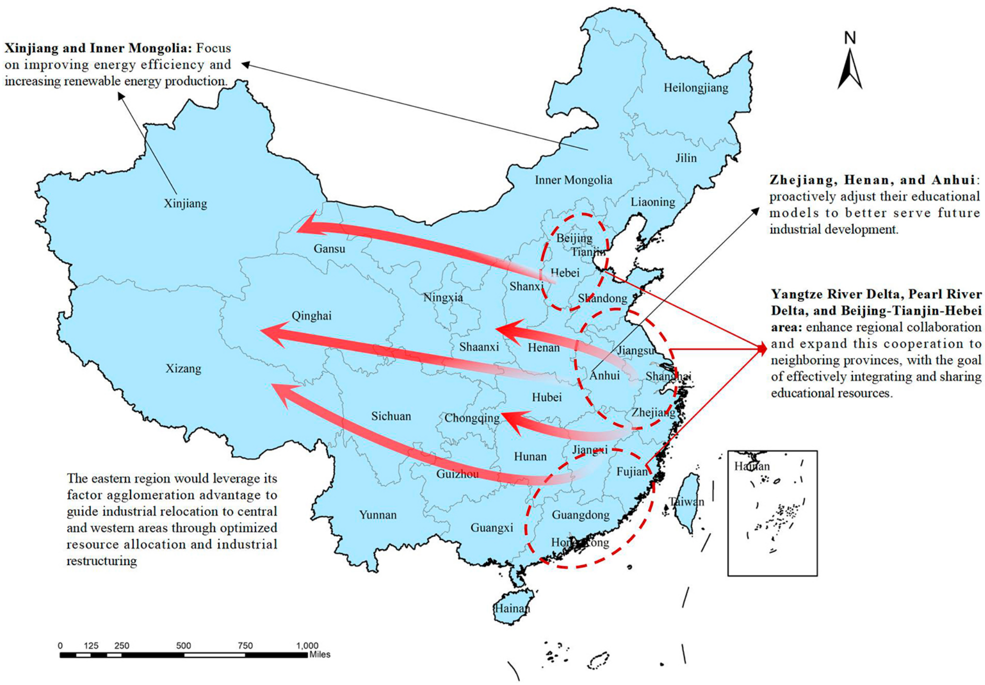


Figure 11. The suggestions in different regions

factor agglomeration and guide industries to relocate to the central and western regions by optimizing resource allocation and restructuring industrial sectors. This approach will create more job opportunities in provinces such as Hebei and Shandong. By fostering regional economic and educational cooperation, a more efficient flow of talent and resources can be achieved, promoting the coordinated development of regional economies.

Fourth, harness the potential of high-quality education to drive technological progress and foster independent innovation, thereby promoting economic growth and generating decent employment opportunities. It is essential to strengthen the integration of higher education with the nation's strategic technological development, emphasizing cutting-edge fundamental research and the development of core technologies in critical sectors. Simultaneously, higher education should be closely aligned with the technological transformation and upgrading of industries, optimizing the structure and direction of educational programs. Specifically, provinces such as Zhejiang, Henan, and Anhui should actively adapt their educational models to the needs of industrial development, ensuring better alignment with the demands of industrial transformation and regional economic growth.

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