Urban Atmospheric Environmental Capacity and Atmospheric Environmental Carrying Capacity Constrained by GDP–PM_{2.5}

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Abstract: China faces a contradictory period of economic development and environmental protection, with it being essential to control total emissions within the limit of atmospheric environmental capacity (AEC) by promoting atmospheric environmental carrying capacity (AECC). This implies that well-calculated AEC and AECC values are the key macro-criteria for improving environmental quality and supporting the challenging coordinated development of economy and environment. When considering compound air pollution characterised as fine particulate matter (PM_{2.5}), conventional methods are not capable of calculating AEC and AECC, but the system dynamics (SD) method retains the advantage of simplicity in resolving complex problems. In the present study, we first describe the background and definitions of AEC and AECC, which are different from Western concepts, and their dialectical relationships. Then, with the statistical data from Wuhan city in 2014, we establish an ‘economy–energy–atmospheric environment’ dynamic model using the SD method, which does not need to simulate the complicated physicochemical processes of atmospheric transmission and diffusion. Instead, it uses the pollutants’ proportionality factors and conversion rates to establish quantitative connections among different types of variables. Finally, we simulate the dynamic trends of gross domestic production (GDP), PM_{2.5}, and six air pollutant emissions between 2015 and 2030 in four different scenarios and calculate the results of AEC and AECC constrained by GDP and PM_{2.5}.

Keywords: GDP; PM_{2.5}; Atmospheric environmental capacity; Atmospheric environmental carrying capacity; System dynamics; Wuhan city

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1 Introduction

China's rapid and extensive economic development over the past three decades has caused serious environmental pollution, with compound air pollution characterised as fine particulate matter (PM_{2.5}) being especially conspicuous in recent years. PM_{2.5} is the particulate matter floating in the air for an extended period whose diameter is less than 2.5 μm . PM_{2.5} is formed by a variety of air pollutants such as sulphur dioxide (SO₂), nitrogen oxides (NO_x), non-methane volatile organic compounds (VOCs), ammonia (NH₃) and dust, thus severely affecting people's health and social and economic development (Pui et al., 2014; Kiesewetter et al., 2015; Oxley et al., 2015; Li et al., 2016). The Chinese government has implemented the Interim Targets 1 of the Air Quality Guidelines (the lowest) established by the World Health Organization (WHO) as the 'qualified' level of PM_{2.5} concentration according to the present conditions (WHO, 2005). In 2012, the new Chinese National Ambient Air Quality Standard (NAAQS) was amended and issued by the Ministry of Environmental Protection of China (MEP). In the NAAQS, the annual average PM_{2.5} concentration Grade II limit is 35 $\mu\text{g}/\text{m}^3$, with the 24-h average concentration Grade II limit being 75 $\mu\text{g}/\text{m}^3$ (MEP, 2012).

Currently, in the background of the economic slowdown (called 'new normal' in China), the Chinese government would like to improve environmental quality and ensure a coordinated development of economy and environment through the utilisation of total emission control systems and environmental quality control systems (Zhang et al., 2013; Zhang et al., 2014). Essentially, the calculation of environmental capacity is the key connection between these two systems. In 2015, an important document, the Integrated Reform Plan for Promoting Ecological Progress, issued by the Communist Party of China Central Committee and the State Council emphasised that regional development must be constrained within its environmental capacity and that the use of the restricted environmental carrying capacity supports greater social and economic development for the future. This implies that a well-calculated atmospheric environmental capacity (AEC) and atmospheric environmental carrying capacity (AECC) establish the

1 foundation for controlling total emissions, improving environmental quality and guaranteeing
2 coordinated economic development (Wang et al., 2015; Zhang and Hao, 2016).

3 However, the current calculations of AEC and AECC have some complications. On the one
4 hand, a minority of government administrators still consider gross domestic production (GDP)
5 growth to be more important and ignore environmental protection. The environment-related
6 statistical and monitoring data are usually inaccessible and some historical data may be missing.
7 Moreover, no effective laws demand that mandatory information be made public, which results in
8 difficulty in analysing AEC and AECC. On the other hand, some environmental scholars regard
9 the AEC and AECC analysis as technically cumbersome because the traditional physicochemical
10 methods are not suitable for calculating AEC characterised as compound air pollution. For
11 example, the A-P value method, a widely used AEC calculation method in China, is apt only for
12 the determination of air pollutants produced by burnt coal and is not suitable for compound
13 pollutants. The third-generation air quality models such as the Community Multiscale Air Quality
14 model are widely used by weather departments and are a tool for early warning forecast of air
15 quality. These models can also be used to predict the short-term AEC characterised as PM_{2.5},
16 however, they are not suitable for long-term predictions, which require a large quantity of data
17 such as emission source data and meteorological data and a large amount of computer processing
18 (Xue et al., 2013; Djalalova et al., 2015; Zhang et al., 2016). Moreover, timely control of air
19 pollutant emissions after early warning signals and forecasting is not enough. Annual average
20 PM_{2.5} concentrations, not daily concentrations, are preferable as the first consideration when
21 measuring the regional long-term air quality. The AEC and AECC calculations that are constrained
22 by GDP and PM_{2.5} are a complicated systematic problem that needs to be analysed so that it
23 considers all aspects of the complex system, such as reference to economy, society, energy use and
24 the environment. When dealing with complex systems, physicochemical methods have an
25 inevitable disadvantage, namely that the economic and social systems cannot be integrated into an
26 environmental model (Vafa-Arani et al., 2014), and these methods are unable to calculate AECC
27 thresholds. Therefore, a system dynamics (SD) method is an appropriate approach for the study of
28 complex systems, because it retains the advantage of simplicity in resolving complex problems
29 (Radzicki and Taylor, 1997; Neuwirth et al., 2014).

1 To date, in the literature, we have not found any explicit calculations for the annual regional
2 AEC and AECC thresholds constrained by $PM_{2.5}$ using the SD method (Feng et al., 2013;
3 McKnight and Finkel, 2013; Chateau et al., 2015; Gao et al., 2016; Sahin et al., 2016). In 2014,
4 we created an ‘economy–atmospheric environment’ dynamic model for the ‘Pollution
5 Characteristics and Prevention Counter Measures of $PM_{2.5}$ ’ project in Dongguan City, Guangdong
6 province. The predicted results had a well-guiding significance, concluding with a good evaluation.
7 Appointed by the Wuhan Environment Protection Science Research Institute (WEPSRI) in 2015,
8 we commenced a study of AEC and AECC analysis for Wuhan city. Compared with Dongguan,
9 Wuhan city has a larger geographical area, greater population and more complicated
10 circumstances. The subsystems of economy and atmospheric environment in the model for this
11 city were improved, and an energy subsystem was added to the SD model. By adjusting the energy
12 consumption and industrial growth rates, the development of industry and energy can be directly
13 predicted. Improvements made to the model optimised the operability of the model, i.e. the
14 readability of the AEC and AECC thresholds. This shows that adjusting the structure of industry
15 and energy plays an important role in improving environmental quality.

16 In the present study, we clarify the definitions of AEC, atmospheric environmental stress (AES)
17 and AECC, expand the concept of AECC and describe its dialectical relationship that is
18 constrained by GDP and $PM_{2.5}$. We also establish an ‘economy–energy–atmospheric environment’
19 dynamic model using the SD method based on the data of Wuhan city’s economical,
20 meteorological, energy and environmental statistical data in 2014. An SD model does not require
21 simulation of the complicated physicochemical processes of atmospheric transmission and
22 diffusion; instead it exploits the pollutants’ proportionality factors and conversion rates to
23 establish quantitative connections among different kinds of variables such as GDP, annual $PM_{2.5}$
24 concentration and six air pollutant emissions (SO_2 , NO_x , VOCs, NH_3 , primary PM_{10} and primary
25 $PM_{2.5}$). Assuming a stable climatic environment over the next several years, changing the control
26 variables of economy, energy and emission reduction enables us to forecast GDP, pollutant
27 emissions and annual concentrations of $PM_{2.5}$ and PM_{10} from the year 2015 to 2030 in four
28 scenarios. This was then used to calculate AEC and AECC thresholds (PM_{10} is also particulate
29 matter whose diameter is less than $10\ \mu m$ and having a tight relationship with $PM_{2.5}$).

1

2 **2 Background, concepts and technology roadmap**

3 The concepts of environmental capacity and environmental carrying capacity are different
4 between Western countries and China; because different countries are at different stages in their
5 environmental protection plans. Developed countries have progressed from the contradictory
6 period of economic development and environmental protection towards a period that contains
7 environmental quality protection. These countries have no need for a considerable emission
8 reduction scheme and maintain their environmental status through supervision and regulation.
9 With reference to the two concepts of environmental capacity and environmental carrying capacity,
10 the majority of researchers from Western countries do not differentiate between them. Instead,
11 they generally study the capacity of ecological and urban resources from the perspective of the
12 ecological or environmental system itself, such as forests, land use, marine, mineral and
13 transportation capacity (Zeng et al., 1991; Arrow et al., 1995; Saveriades, 2000; Furuya, 2004;
14 Mondino et al., 2014; Martire et al., 2015).

15 However, these two concepts in China are very different. Several Chinese researchers study
16 them from the perspective of environmental carrying variables such as social, economic,
17 technological development and the accompanying pollution. Developing countries, including
18 China, are still located in the climb portion of the Environment–Economy Kuznets curve
19 (‘Inverted-U’ curve), where a number of environmental indicators fail to reach the established
20 standards. It is therefore necessary to distinguish the bottom line that the environment can bear, i.e.
21 the environmental capacity, as well as determine the scale of social and economic activities within
22 a reasonable scope of lower effect to the environmental quality, i.e. environmental carrying
23 capacity, for China and other developing countries. Additionally, the Chinese government has
24 powerful macro-control, and is capable of regulating the social and economic activity to ensure
25 better development.

26 Thus, environmental capacity is generally defined as the maximum total pollutant load that the
27 environment can receive according to the environmental quality standard in a certain geographical
28 range. This is a prototype of the concept of environmental carrying capacity theory (Wang et al.,
29 2005; Li, 2007). However, environmental issues are complex, and have close relationships with

social and economic development. This means that merely discussing the assimilative capacity of the environment itself cannot meet China's future developmental needs. Conceptually, on the basis of the environmental capacity, the environmental carrying capacity needs to be extended to include not only capacity, but also the scale of human activities. The environmental carrying capacity refers to the appropriate thresholds of the environmental system that support human activity in maintaining the environmental system structure without qualitative change, the environment function without destruction within a certain geographical area and over a certain period.(Ye et al., 1992; Zeng et al., 1998; Liu et al., 2009). In the present study, the concepts of AEC, AES and AECC are described as follows.

2.1 Atmospheric Environmental Capacity (AEC)

AEC is the maximum allowable quantity of pollutant emissions when an air pollutant's concentration is no greater than its environmental target in an area's atmospheric environment, and is an important component of AECC. In the present study, AEC refers to the maximum allowable discharged volume of certain air pollutants, including SO₂, NO_x, VOC, NH₃, primary PM_{2.5} and primary PM₁₀, when PM_{2.5} concentration reaches Grade II of NAAQS (average annual limit of 35 µg/m³).

2.2 Atmospheric Environmental Stress (AES)

AES is the produced volume of atmospheric pollutants owing to human social and economic activities. The produced volume includes the discharged and reduced volume. AES in the present study is defined as the predicted discharged volume of six air pollutants according to the pollutants' discharged volumes, concentrations, emission inventories and sources apportionment in Wuhan city in 2014, on the premise of maintaining the current level of economy, energy and environmental protection and ensuring the standard growth of GDP.

2.3 Atmospheric Environmental Carrying Capacity (AECC)

In our definition, AECC is composed of two sections: 'recessive' and 'expressive' indicators. The 'recessive' component is the actual ability for maintaining environmental quality such as a regional economic state, industrial structure, energy structure, technological level, natural resources, geographical and meteorological factors, investments of environmental protection or

1 other factors (Wang and Xu, 2015). The ‘expressive’ component is the external comprehensive
 2 performance of the ‘recessive’ portion. It is the accumulative reduced discharged volume shown as
 3 the sum of the stock and increment that counteracts a part of AES (see Fig. 1). In the present study,
 4 AECC explicitly refers to eight recessive indicators, namely a city’s GDP; its production value of
 5 primary, secondary and tertiary industries, and the consumption of coal, petroleum, natural gas
 6 and new energy; and six expressive indicators, i.e. six air pollutants’ accumulative reduced volume,
 7 namely SO_2 , NO_x , VOC, NH_3 , primary $\text{PM}_{2.5}$ and primary PM_{10} .

Fig.1 An illustrated explanation for the expressive component of AECC.

10 We chose these indicators for the following reasons. First, to ensure coordinated economic and
 11 environmental development, adjusting the energy and economic structure has great significance in
 12 improving the environmental quality, which concerns the government the most. Using the eight
 13 recessive indicators in the SD model can reflect this change. The recessive indicators also include
 14 variables such as population, but these contribute little to this research. Different researchers are
 15 able to use other indicators as they require them. Second, the more variables embedded into the
 16 model, the more complicated is the SD model. Additional variables need to establish dynamic
 17 quantitative relationships with the main variables such as GDP and $\text{PM}_{2.5}$, which need more
 18 statistical data to support the SD model building.

19 Figure 2 shows the dynamic dialectical relationships between AEC, AES and AECC. In the
 20 first scenario (Fig. 2a), when a traditional GDP growth mode is based on fossil fuel use, AECC is
 21 always less than AES and the air pollution (Combined curve) is over AEC, which leads to the
 22 deterioration in environmental quality. In the second scenario (Fig. 2b), where AECC is eventually
 23 greater than AES, the air pollution (Combined curve) converges to AEC, which leads to the

1 improvement in the environmental quality (Zeng et al,1991; Zeng et al, 1998; Liu et al, 2009;
2 Wang et al, 2010; Zhang and Hao, 2016).

3
4 Fig.2 Dialectical relationships of AES, AEC and AECC illustrated in two scenarios. The 'Combined curve', which
5 could be regarded as the annual $PM_{2.5}$ concentration, is a synthetic result of AECC's expressive component and
6 AES.

7 2.4 Technology roadmap

8 The following are the steps taken in the present study to build and study the SD model.

- 9 1) Focus on the research targets, i.e. the AEC and AECC, when confronting a complex objective;
- 10 2) Establish the indicators of targets to be investigated;
- 11 3) Confirm the SD model border;
- 12 4) Describe the causality of the SD model system;
- 13 5) Build the SD model flow diagram and test its usability;
- 14 6) Obtain the economy, meteorology, energy and the source apportionment (air pollution emission
- 15 inventory) data;
- 16 7) Determine the SD model's parameters and write the model's equations;
- 17 8) Conduct the SD model check and reality test;
- 18 9) Allocate four scenarios – S1 Basic, S2 Moderate, S3 Enhanced and S4 Intense. The parameters
- 19 in the four scenarios are in accordance with the requirements of WEPSRI. The specific parameter
- 20 adjustment values of the economy, energy and environment in the SD model are given in Section
- 21 4.4;
- 22 10) Predict Wuhan city's GDP, the annual concentrations of $PM_{2.5}$ and PM_{10} , and the changes in
- 23 six pollutant emissions in the four scenarios;
- 24 11) Predict the AEC and AECC thresholds when the annual $PM_{2.5}$ concentration reaches Grade II
- 25 of NAAQS ($35 \mu g/m^3$). The main progression of the research in the present study is illustrated in

1 Figure 3.

Fig.3 Technology roadmap in the AEC and AECC research

3 Building the SD model

3.1 Causal description of the SD model system

The entire SD model system is divided into energy, economic and environmental subsystems.

The basic causal relationships in each subsystem are as follows:

1) From an energy point of view, in the traditional developmental mode, economic growth will lead to increased fossil fuel energy use, resulting in increased air pollutant emissions and greater annual average PM_{2.5} concentrations (Zhang et al, 2013; Wang et al, 2015; Chen et al, 2016).

However, to protect the environment, people will limit polluting energy consumption, including the use of coal, petroleum and so on, which also limits the traditional economic development based on the consumption of fossil energy, characterised as an 'environment → energy → economy' restraining pollution process.

2) From an economic point of view, the deterioration in the environment confines the growth of the polluting industry; instead new service industries grow, which will control the pollution of the environment, characterised as an 'environment → economy → environment' restraining pollution process.

3) From an environmental point of view, the end-treatment mode reduces emissions resulting in pollution abatement.

The SD model focuses on the causality of restraining the pollution process. The above relationships are illustrated in Figure 4.

Fig.4 Description of cause and effect in three subsystems

3.2 Variables of the SD model

Each subsystem of the SD model consists of a series of variables, which can be divided into five types characterised by function, i.e. variables of level, rate, auxiliary, constant and control.

The classification of all the SD model variables is listed in Table 1.

Table 1 Classification of all variables in the SD model

Subsystems	Level variables	Rate variables	Auxiliary variables	Constant variables	Control variables
Environment	Discharged volume of VOC, SO ₂ , NO _x , NH ₃ , primary PM _{2.5} and primary PM ₁₀ ; Annual concentration of PM _{2.5} and PM ₁₀ ,	Increment in VOC, NO _x , SO ₂ , NH ₃ , primary PM _{2.5} , primary PM ₁₀ , PM _{2.5} and PM ₁₀ ; Decrement in VOC, SO ₂ , NO _x , NH ₃ , primary PM _{2.5} , primary PM ₁₀ , PM _{2.5} and PM ₁₀	<Time>, Proportionality factor of SO ₂ , NO _x , VOC, NH ₃ , primary PM ₁₀ and primary PM _{2.5} ; Conversion rate SO ₂ -PM _{2.5} , NO _x -PM _{2.5} , VOC-PM _{2.5} , NH ₃ -PM _{2.5} , primary PM ₁₀ , primary PM _{2.5} and PM _{2.5} volume; Conversion rate SO ₂ -PM ₁₀ , NO _x -PM ₁₀ , VOC-PM ₁₀ , NH ₃ -PM ₁₀ and City volume under boundary layer	Contribution rate SO ₂ for PM _{2.5} , NO _x for PM _{2.5} , VOC for PM _{2.5} and NH ₃ for PM _{2.5} and primary PM _{2.5} ; Contribution rate SO ₂ for PM ₁₀ , NO _x for PM ₁₀ , VOC for PM ₁₀ , NH ₃ for PM ₁₀ and primary PM ₁₀ , City area and Height of boundary layer	Emission reduction factor of SO ₂ , NO _x , VOC, NH ₃ , primary PM ₁₀ and primary PM _{2.5}
Energy	Annual consumption	Increment in coal,	<Time>, Energy growth rate, Energy	Energy consumption	Growth rate of

	of coal, natural gas , petroleum and new energy	natural gas, petroleum and new energy	adjustment factor of SO ₂ , NO _x , primary PM _{2.5} , primary PM ₁₀ and VOC; Growth rate of NO _x , particulate matter, Energy consumption of discharging NO _x and discharging particulate matter	elasticity coefficient	coal, natural gas, petroleum and new energy
Economy	GDP of primary, secondary and tertiary industries	Increment in primary, secondary and tertiary industries	<Time>, GDP, polluting GDP, increment of polluting GDP and growth rate of GDP	None	Growth rate of primary, secondary and tertiary industries

1

2 3.3 Flow diagram of the SD model

3 The flow diagram of the SD model describes a precise state of the entire system. We can
4 simulate and predict economic, energy and environmental trends and indicators of AEC and
5 AECC after creating the SD model, by setting each variable's parameters and equations in the
6 model. Apart from the control and constant variables, all other variable values are dynamically
7 changing throughout the operation of the SD model. Vensim PLE software provides SD modelling
8 and simulation capabilities (Yeh et al., 2006; Mao et al., 2013). The most essential mathematical
9 description of the SD model is given in the following equation (Wang, 2009):

$$10 \quad lv.S(t) = S(t_0) + \int_{t_0}^t rate.S(t) dt = S(t_0) + \int_{t_0}^t [inflow.S(t) - outflow.S(t)] dt$$

11 where $lv.S(t)$ (level variables) is the state of a level variable at (t) moment; $S(t_0)$ is this level
12 variable's initial value; and the 'rate' in $\int_{t_0}^t rate.S(t) dt$ is the rate variables, describing the rate's
13 accumulation from time t_0 to t .

14 The entire system diagram (Fig. 5) is too large to display on one page, instead, three
15 subsystems are shown, namely the environmental subsystem (Fig. 5a), the energy subsystem (Fig.
16 5b) and the economic subsystem (Fig. 5c), which are not independent and have tight connection
17 with each other. Detailed equations of the SD model system are given in the Appendix.

(a) Environmental subsystem

(b) Energy subsystem

(c) Economic subsystem

Legend

Fig.5 Flow diagram of the SD model

1

2 The basic simulating logical process of the SD model is that according to the requirement of a
3 region's GDP growth rate, GDP growth promotes the increment of a certain pollutant-discharged
4 volume through the dynamic proportionality factor in the SD model. Next, the increment in a
5 certain pollutant's discharged volume makes the annual PM_{2.5} concentration increase by the
6 variable of a pollutant's conversion rate, which is a link for connecting discharged volumes to
7 concentrations.

8 There are three specific control measures in the model to reduce emissions and improve
9 environmental quality by simulating the variation trend of GDP, the concentration of PM_{2.5} and
10 discharged volumes: (1) the changed proportion of pollution GDP through adjusting the growth
11 rates of primary, secondary and tertiary industries shows the optimisation of industrial structure; (2)
12 the reduced pollution increment per unit of GDP through adjusting different energy consumption
13 growth rates portrays the optimisation of energy structure; and (3) the pollution end-treatment is
14 realised by the emission reduction factors.

15

16 **3.4 Explanation of important variables**

17 1) The proportionality factor— μ

18 The proportionality factor, μ , is a specific air pollutant discharged volume per billion Yuan of
19 GDP. Its function is to convert the increment of GDP to the increment of a discharged volume
20 quantitatively in a SD model dynamic simulation. The mathematical expression for μ is given as
21 Equation (1). Its physical meaning can be regarded as an enterprise referred limit emissions per
22 unit of GDP:

$$23 \quad \mu = Dv_i / \text{GDP} \quad (1)$$

24 where Dv is the discharged volume (t); i is a specific air pollutant; and GDP is a region's gross
25 domestic production (billion Yuan).

26

27 2) The annual average height of the atmospheric boundary layer— h

28 The atmospheric boundary layer, a meteorological term, is an atmospheric layer that is
29 affected by diurnal heat, moisture or momentum transfer to or from the surface in the troposphere,

usually maintaining a 1–1.5 km thickness from the ground. Like a ‘hat’ covering a city, the PM_{2.5} usually exists under the boundary layer. During different periods and under different meteorological conditions the height of the boundary layer changes. Generally, the maximum diurnal height of the mixed layer is at 1500 m or greater, and the nocturnal stable boundary layer stays at 100 m (Hu et al., 2014).

3) The PM_{2.5} volume V.PM_{2.5}

The PM_{2.5} volume is described as an annual average state that is a precise total mass of PM_{2.5} existing in a city space. The mathematical expression for V.PM_{2.5} is given as Equation (2):

$$V.PM_{2.5} = C.PM_{2.5} \times S \times h \quad (2)$$

where C.PM_{2.5} is the annual concentration of PM_{2.5} (μg/m³); S is a city’s administrative area (km²) and h is the annual average height of the atmospheric boundary layer.

In Equation (2), the annual concentration of PM_{2.5} is equal to its concentration at a previous time, adding the increment in the PM_{2.5} concentration to this time difference. The calculation method for the volume of PM₁₀ is the same as for the PM_{2.5} volume.

4) The contribution rate of a certain air pollutant to PM_{2.5} or PM₁₀—θ

The contribution rate, θ, is the proportion of chemical composition in source apportionment of PM_{2.5} or PM₁₀. According to the general features of atmospheric particulate matter, sulphate comes from the transform contribution of SO₂. This means that the contribution rate of SO₂ in the model is approximately equal to the chemical composition proportion of sulphate, which is the same for nitrate and ammonium salts. Non-methane VOCs are relatively complex, but the majority of the organic matter (OM) in the chemical composition proportion is from the transition of VOCs. In the present study, we set the contribution rate of VOC to be equivalent to the OM’s proportion for convenience. The primary particulate matter’s constitution is also complex, usually including black carbon, metal particles, mineral substances and so on (Huang et al, 2014; Yao et al., 2016; Zhou et al., 2016). Therefore, the contribution rate of primary particulate matter is equal to the sum of these substances’ chemical composition proportions.

5) The conversion rate from a certain air pollutant to PM_{2.5} or PM₁₀— η

The conversion rate, η , refers to the ratio of the contributed component derived from the annual discharged volume of a specific air pollutant to PM_{2.5} volume and this discharged volume itself. The mathematical expression for η is given as Equation (4):

$$\eta = V \cdot PM_{2.5} \times \theta_i / Dv \quad (4)$$

In the SD model system, η is a very important auxiliary variable and is the key factor in the present study, which constructs a link between the annual discharged volume and the annual PM_{2.5} concentration in the quantitative relationship. The η is based on the statistical data and does not have any actual physical and chemical significance; it is only used for the SD model.

6) The polluting GDP— P_{GDP}

In reality, not all economic activities cause heavy pollution; instead, some heavier polluting industries contribute to most of the air pollution. With this in mind, we proposed the concept of ‘polluting GDP’, which can be defined for those GDP generated specifically by the industries that discharge a major amount of air pollutants. In the SD simulation, by adjusting the primary, secondary and tertiary industries’ GDP growth rate, the economic development could be influenced by the change in the industrial structure. In the process, we reduce the dirtier secondary industry ratio and increase the cleaner tertiary industry ratio to restrict the ‘polluting GDP’ while maintaining gross GDP growth. To achieve this, it is necessary to separate the ‘polluting GDP’ from the gross GDP, otherwise it would not be possible to analyse the environmental quality change after adjusting the industrial structure. The ‘polluting GDP’ equation is given as Equation (5):

$$P_{GDP} = \alpha_1 \cdot GDP1 + \alpha_2 \cdot GDP2 + \alpha_3 \cdot GDP3 \quad (5)$$

where P_{GDP} refers to the gross ‘polluting GDP’. GDP1, GDP2 and GDP3 represent the city’s primary, secondary and tertiary industry outputs, respectively. α_1 , α_2 , α_3 represent different industrial weighted coefficients of ‘polluting GDP’, and they are a variable of time, but are not expected to fluctuate much in a certain period of time. To simplify the analysis, they are valued as constants. In the paper, we estimated the values of the three coefficients as 0.1, 0.9 and 0.1, respectively, using the data from the Urban Statistical Yearbook.

1

2 7) The sum of discharging a certain air pollutant— E_i

3 The sum of discharging a certain air pollutant, E_i , is an important transitional variable for
 4 calculating the energy adjustment factor. This value is equal to the sum of discharging a certain air
 5 pollutant caused by different types of energy consumption. The mathematical expression for E_i is
 6 given as Equation (6):

$$7 \quad E_i = \sum_{j=1}^n E_j \quad (6)$$

8 where E is the energy consumption; i is a specific air pollutant; j is a specific energy resource
 9 and n is the number of energy resources.

10

11 8) The growth rate of a specific air pollutant— r_i

12 The growth rate of a specific air pollutant, r_i , caused by different kinds of energy consumption
 13 is an important transitional variable for calculating the energy adjustment factor. r_i is a weighted
 14 average value of growth rates of different energy consumptions in a process of discharging a
 15 specific air pollutant. The mathematical expression for r_i is given as Equation (7):

$$16 \quad r_i = \sum_{j=1}^n E_j r_j / E_i \quad (7)$$

17 where r is the growth rate, and the other symbols are the same as for the previous equations.

18

19 9) The energy adjustment factor— EF

20 The energy adjustment factor, EF , is a ratio of the energy use after adjusting the energy
 21 structure and before adjusting it to the base year. The mathematical expression for EF is given as
 22 Equation (8):

$$23 \quad EF_i = 1 - (1 + r_i) / (1 + \lambda r_{GDP}) \quad (8)$$

24 where i stands for a specific air pollutant; λ is the energy consumption elasticity coefficient
 25 and r_{GDP} is the growth rate of GDP.

26

10) The emission reduction factor— RF

The emission reduction factor, RF , refers to the reduction rate of a specific air pollutant's discharged volume based on the sum of stock and increment for reducing the total emissions. In other words, this reduction rate not only emphasises the reduction in the stock of discharged volume, but also on reducing the increment in discharged volume caused by the GDP growth. The mathematical expression for RF is given as Equation (9):

$$RF_i = r_{GDP} + \left(\sqrt[m]{1 + r_{i,target}} - 1 \right) + EF_i \quad (9)$$

where i stands for a specific air pollutant; m is the year number from the base year to the planning target year and $r_{i,target}$ is the accumulated reduction percentage that is normally a planning target for the Chinese government from the base year to the planning target year.

4 Case study and results

4.1 An introduction to Wuhan city

Wuhan city, the capital of Hubei province, China, is a metropolis located in the middle of China, with a population of 10.3 million people. In 2014, the region's GDP was 1006.9 billion Yuan and the annual concentrations of $PM_{2.5}$ and PM_{10} were 82 and 113 $\mu g/m^3$, respectively. On the one hand, to comply with the requirements of the most recent National 13th Five-year Plan (FYP), the Wuhan Environmental Protection Bureau proposed stricter $PM_{2.5}$ control objectives, i.e. the days of achieving air quality standards should be over 80% in a full year by 2020, and the annual $PM_{2.5}$ and PM_{10} concentrations should decrease by 40%, with annual $PM_{2.5}$ concentration decreasing to 42 $\mu g/m^3$ by 2020. On the other hand, Wuhan city is currently experiencing a critical period of economic development. On the basis of the city's social and economic development planning, the government wants to increase GDP to 2000 billion Yuan and emphasises that the economic growth rate should remain at 8.5% during the 13th FYP. Trying to achieve both these objectives simultaneously is a massive challenge.

According to the meteorological data for Wuhan city over the past 50 years, the average annual temperature has remained at approximately 17 °C, with a slight upward trend. The average annual rainfall fluctuated between different years, but maintained approximately 1300 mm. The

average annual humidity was approximately 78%, but in the past 20 years, this has slowly decreased. The average annual wind speed has remained at approximately 2 m/s and for the past 20 years, there has been a slight downward trend (Qin, 2009; Shi et al., 2015). Generally, as a region, the changes seen in the climate over the past 15 years has been very small. In an economic–environmental system prediction process, the weather factors are considered stable and unchanging.

The chemical composition of PM_{2.5} or PM₁₀ annual average concentrations and their external and internal source proportions are affected by many factors, including meteorology and human activities, as well as changes over time. Changes in these factors are random and independent of each other. In a one-year period, each factor has only a very slight influence on the overall result, which can be regarded as a stationary random process. Faced with a stationary random process, without further data, it can be considered acceptable that the sample statistics for 2014 represent the average results of chemical composition for a number of years.

Therefore, assuming a stable regional background, such as the annual average temperature, rainfall, wind speed and wind direction, the height of the atmospheric boundary layer, the proportion of source contribution from PM_{2.5} or PM₁₀ inside or outside the city, and the chemical composition in source apportionment of PM_{2.5} and PM₁₀ for the future 15 years, we established an SD model over the territorial extent of the whole city (8494 km²), with simulation for the period 2015–2030.

Four scenarios were set for the case study to obtain a relatively precise prediction: S1 Basic, S2 Moderate, S3 Enhanced and S4 Intense; these enabled to predict the different development situations and calculate the AEC and AECC results.

4.2 Main data sources

From Wuhan's research programme 'Main Environmental Problems and Counter Measures in Wuhan City', we obtained the main datasets for developing the SD model and predicting the AEC and AECC:

- 1) Wuhan statistical yearbook in 2014;
- 2) White book of energy construction in 2014;

- 1 3) Environmental protection planning in the period of 13th FYP (2016–2020, first draft);
- 2 4) Technical report of the air pollutants' source apportionment of Wuhan city in 2014; and
- 3 5) Technical report of Wuhan city's air pollutant emissions inventory in 2014.

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5 4.3 The SD model test

6 1) Reality test

7 The PM₁₀ concentration and GDP were regarded as the reality test objects, excluding the PM_{2.5}
 8 concentration because the statistical data of PM_{2.5} concentration have only been recorded for two
 9 years since 2012. The steps undertaken for the reality test were as follows. First, check syntax,
 10 model check and units check are employed for the automatic detection of SD model via Vensim
 11 PLE. Second, the reality tests of PM₁₀ concentration and GDP from year 2001 to 2013 were the
 12 main and important working steps. In the process of reality testing, the initial values in the model
 13 were based on the data from 2001. The values for three types of control variables, namely GDP
 14 growth rates, energy consumption rates and emission reduction factors, were based on the
 15 precedent data over 13 years.

16 The reality testing results indicated that the maximum error of GDP between the reality value
 17 and the simulated one was –10.1%, the minimum error 1.1%, the mean error –1.5%, the
 18 correlation coefficient $r = 0.99$, the maximum error of PM₁₀ concentration was –14.5%, the
 19 minimum error was –0.8%, the mean error was 0.36% and the correlation coefficient $r = 0.80$. In
 20 short, the accuracy and correlation of GDP and PM₁₀ predicted results were reasonable (Fig. 6).

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Fig.6 Model reality test of (a) GDP and (b) PM₁₀.

2) Sensitivity analysis

The sensitivity analysis refers to an uncertainty analysis in which the degree of change in certain factors affects one or a set of key indicators from the view of quantitative analysis (Pannell, 1997).

The sensitivity test in the SD is aimed to assess the SD model's parameters settings or structure designs. Generally, the sensitivity test is widely used because the unknown variables usually overwhelm the known ones in the process of modelling. As known, the data obtained from project investigation and expert analysis are not always reliable for a research, but this can be mitigated through the sensitivity test. In the SD model, different parameters have different influence on a system; some are sensitive and some are not. The sensitive parameters are required to be verified and confirmed carefully and this is very important for modelling (Zhong et al, 2013).

In this model, there are 16 constants, among which the values of the energy consumption elasticity coefficient, the conversion rates of pollutants to PM_{2.5}, the city's area and the height of boundary layer are based on the facts. However, the α_1 , α_2 , and α_3 are estimated according to the related statistical data. These three values should be in a reasonable range in dealing with such a complex system. It would be interesting to know the simulation result if we change these values. The α_1 is attributed to agriculture, and it is characterised to have a relative small scale and small influence. Therefore, we analyse only α_2 and α_3 , and Table 2 summaries the simulation result.

Table 2 Sensitivity analysis results for constant variables. Two tests are compared with the results from the S4 Intense scenario.

	α_2				α_3			
	Value	Change (%)	PM _{2.5} ($\mu\text{g}/\text{m}^3$)	Change (%)	Value	Change (%)	PM _{2.5} ($\mu\text{g}/\text{m}^3$)	Change (%)
Test1	0.7	-23	22.1	3.2	0.15	50	22.7	6.0
Test2	0.8	-12	21.7	1.4	0.2	100	23.9	11.6
S4	0.9	0	21.4	0	0.1	0	21.4	0

In Table 2, the predicted PM_{2.5} concentration in 2030 changes to 22.1 $\mu\text{g}/\text{m}^3$ and 21.7 $\mu\text{g}/\text{m}^3$ respectively, when the α_2 , the polluting weighted coefficient, is decreased from 0.9 to 0.7 and 0.8. Compared to S4, the decreasing range of α_2 is -23 and -12% and the change range of PM_{2.5} result in 3.2 and 1.4%, respectively. In another group, the predicted PM_{2.5} concentrations in 2030 are 22.7 and 23.9 $\mu\text{g}/\text{m}^3$, respectively, when the α_3 is increased to 0.15 and 0.2 from 0.1. Compared to S4, the increasing range of α_3 is 50% and 100% and the change range of PM_{2.5} results in just 6.0% and 11.6%, respectively.

From the sensitivity analysis results, we conclude that the change rate of the predicted PM_{2.5} concentration is significantly less than the adjustment range of α_2 or α_3 during a 15-year simulation period. With this in mind, we believe that the SD model has a good stability, which meets the robustness requirement of a complex system.

4.4 Input data

Precise and credible predicted results depend on the actual and valid input variable data in the prediction process of the SD model. All the input data of level, control and constant variables in the SD model are based on the statistical data of 2014, as given in Tables 3, 4 and 5.

Table 3 Initial values in level variables.

Level variables	Initial values	References	Notes
GDP of primary industry	35 billion Yuan	Environmental protection 13 th FYP (first draft)	
GDP of secondary industry	478.5 billion Yuan		
GDP of tertiary industry	493.3 billion Yuan		
Annual consumption of coal	34.54 million tonnes	White book of energy construction in 2014 and the	

Annual consumption of petroleum	1.85 million tonnes	latest data by WEPSRI	Not including crude oil
Annual consumption of natural gas	2.40 million tonnes		Liquefied gas and natural gas
Annual consumption of new energy	2.45 million tonnes		From the National Development and Reform Commission in Wuhan city plan
Discharged volume of SO ₂	109 604 tonnes	Technical report of Wuhan city's air pollutants' emission inventory in 2014	
Discharged volume of NO _x	181 486 tonnes		
Discharged volume of VOC	208 558 tonnes		
Discharged volume of NH ₃	16 496 tonnes		
Discharged volume of primary PM _{2.5}	77 251 tonnes		
Discharged volume of primary PM ₁₀	171 630 tonnes		
Annual concentration of PM _{2.5}	82 µg/m ³	Environmental protection 13 th FYP (first draft)	
Annual concentration of PM ₁₀	113 µg/m ³		

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Table 4 Values of control variables.

Control variables	S1 Basic		S2 Moderate		S3 Enhanced		S4 Intense		References
Time periods	T1	T2	T1	T2	T1	T2	T1	T2	
Growth rate of primary industry	0.04	0.03	0.04	0.03	0.035	0.03	0.03	0.025	Environmental protection 13 th FYP (first draft)
Growth rate of secondary industry	0.065	0.04	0.055	0.04	0.045	0.03	0.035	0.03	
Growth rate of tertiary industry	0.105	0.07	0.11	0.07	0.115	0.08	0.125	0.08	
Emission reduction factor of SO ₂	0.105	0.08	0.11	0.08	0.115	0.09	0.14	0.1	
Emission reduction factor of NO _x	0.08	0.07	0.09	0.08	0.1	0.08	0.105	0.08	Latest requirements provided by WEPSRI
Emission reduction factor of VOC	0.11	0.08	0.115	0.08	0.12	0.09	0.125	0.09	
Emission reduction factor of primary PM ₁₀	0.09	0.07	0.095	0.07	0.1	0.07	0.105	0.07	
Emission reduction factor of primary PM _{2.5}	0.1	0.08	0.105	0.08	0.11	0.08	0.115	0.08	
Emission reduction factor of NH ₃	0.085	0.07	0.09	0.07	0.095	0.08	0.1	0.08	
Growth rate of coal	0	-0.005	-0.01	-0.01	-0.02	-0.015	-0.03	-0.02	Latest requirements provided by WEPSRI
Growth rate of petroleum	0.08	0.04	0.05	0.02	0.02	0.01	0.01	0.005	
Growth rate of natural gas	0.16	0.1	0.18	0.11	0.2	0.12	0.22	0.13	
Growth rate of new energy	0.14	0.1	0.17	0.11	0.2	0.12	0.25	0.13	

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Footnote: T1 stands for the period 2015–2020, T2 stands for 2021–2030.

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Table 5 Values of constant variables.

Variables	Values	References	Notes
Energy consumption elasticity coefficient	0.5	Environmental protection 13 th Five Year plan (first draft)	
α1 in polluting GDP	0.1	Wuhan statistical yearbook in 2014	Estimated values, i.e. ratio coefficient of polluting production output in a certain industry and its industrial production.
α2 in polluting GDP	0.9		
α3 in polluting GDP	0.1		

Contribution rate SO ₂ for PM _{2.5}	0.21	Technical report of Wuhan city's air pollutants' source allotment in 2014	
Contribution rate NO _x for PM _{2.5}	0.15		
Contribution rate VOC for PM _{2.5}	0.3		
Contribution rate NH ₃ for PM _{2.5}	0.1		
Contribution rate of primary PM _{2.5}	0.15		
Contribution rate of primary PM ₁₀	0.21		
Contribution rate SO ₂ for PM ₁₀	0.2		
Contribution rate NO _x for PM ₁₀	0.13		
Contribution rate VOC for PM ₁₀	0.26		
Contribution rate NH ₃ for PM ₁₀	0.08		
City area	8494 km ²	Network data	baike.baidu.com
Height of boundary layer	1000 m	No exact data	Used for computing

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2 4.5 Predicted results

3 The predicted results showed that the annual PM_{2.5} concentration in year 2020 in S1 Basic,
4 S2 Moderate, S3 Enhanced and S4 Intense are 66, 57, 49, and 42 µg/m³, respectively. These
5 annual concentrations in year 2030 were calculated to be 45, 35, 25, and 21 µg/m³, respectively. In
6 the four scenarios, it is only in S4 Intense that the annual PM_{2.5} concentration can meet the latest
7 requirement of environmental protection planning in Wuhan city. In S4, the annual concentration
8 of PM_{2.5} scarcely reaches 35 µg/m³ when the simulation year is 2023.75. This means that the
9 following thresholds are all corresponding results of level variables (see in Fig. 7 except for the
10 annual concentration of PM_{2.5}) when simulation year is 2023.75 in S4 Intense:

11 1) Results of AEC in Wuhan city

12 The AEC results of SO₂, NO_x, VOC, primary PM₁₀, primary PM_{2.5} and NH₃ constrained by
13 GDP and PM_{2.5} on the basis of S4 simulation are 29 679, 87 391, 86 643, 64 029, 26 336, and 10
14 649 t, respectively (see Fig. 7a).

15 2) Thresholds of AECC in Wuhan city

16 (i) Thresholds of economic indicators ('recessive' component)

17 In S4, the thresholds of economic indicators, GDP and its production value of primary, secondary
18 and tertiary industries are 1969, 45, 640.3, and 1283.9 billion Yuan, respectively (see Fig. 7b).

19 (ii) Thresholds of energy consumption ('recessive' component)

1 In S4, the thresholds of energy consumption, including the consumption of coal, petroleum,
 2 natural gas and new energy are the standard coal consumption of 27.28, 1.99, 12.33, and 14.92
 3 million t, respectively (see Fig. 7c).

7 Fig.7 (a) AEC results of six air pollutants, (b) thresholds of economic indicators and (c) thresholds of energy

consumptions. The results are marked by black dots when annual concentration of PM_{2.5} (black lines) reaches 35 µg/m³ (the red dashed line) at simulated time 2023.75.

(iii) Emission reduction thresholds (‘expressive’ component)

On the premise of keeping the composition of economic structure, energy and environmental protection level basically unchanged and GDP growth as normal, the predicted discharged volume of SO₂, NO_x, VOC, primary PM₁₀, primary PM_{2.5} and NH₃ in 2023.75 beginning in 2015 were 213 278, 353 153, 405 832, 333 974, 150 322, and 32 099 t, respectively, based on the data from 2014. After they were subtracted from the AEC results, the accumulative emission reduction thresholds were 183 599, 265 762, 319 189, 269 945, 123 986, and 21 450 t, respectively. In other words, the six air pollutants would need to be reduced by 20 400, 29 529, 35 465, 29 994, 13 776, and 2383 t, respectively, each year based on the 2014 data (see Table 6).

Table 6 Emission reduction thresholds of AECC. To understand how the emission reduction thresholds should be calculated, predicted AES and S4 Intense AEC are also listed.

Scenario	SO ₂ (t)	NO _x (t)	VOCs(t)	Primary PM ₁₀ (t)	Primary PM _{2.5} (t)	NH ₃ (t)
Predicted AES	213 278	353 153	405 832	333 974	150 322	32 099
AEC of S4	29 679	87 391	86 643	64 029	26 336	10 649
Accumulative emission reduction thresholds	183 599	265 762	319 189	269 945	123 986	21 450
Annual average emission reduction thresholds	20 400	29 529	35 465	29 994	13 776	2383

4.6 Discussion

1) Credibility of the predicted results

The credibility of the predicted results depends on three aspects. First, the model logic is correct and its structure is reliable. Second, the initial values of level variables are accurate. Third, the control variables’ parameter settings are reasonable. After the model structure and validity testing, input data proofreading and the reality testing and sensitivity analysis, the predicted results in the present case study are aligned with the development trends of the city with a high credibility.

2) Limitations in traditional physicochemical methods

If there is a lack of data on the layouts and patterns of pollution sources and pollutant quantities, then the A-value method is an easy way of calculating the AEC in a region (MEP, 1991). To compare these two methods, we used the A-value method to estimate the AEC of SO₂, NO_x and PM₁₀ in Wuhan city. However, the VOC and NH₃ cannot be calculated using the A-value method. According to the 13th FYP of environmental protection in Wuhan city, the development area belonging to type II category is 4926.5 km² in size, with an occupation rate of 58% in the city; however, the limited development ecological area belonging to type I category is 3567.5 km² in size, with an occupation rate of 42% in the city. The value of coefficient 'A' ranges from 3.6 to 4.9 in the Hubei province, and from these values, it was calculated that the AEC of SO₂ ranges from 143 329 to 195 069 t; NO_x ranges from 132 696 to 180 614 t; and PM₁₀ ranges from 190 422 to 259 185 t.

Therefore, the AEC results from the A-value method are higher than those calculated using the SD method. The AEC results from the A-value method are 4.8~6.5, 1.5~2 and 2.9~4.0 times the amount obtained from the SD method for SO₂, NO_x and PM₁₀, respectively. This reveals that the AEC results constrained by GDP-PM_{2.5} are much stricter than the results calculated from a single pollutant. In brief, the traditional AEC method has limitations when dealing with complex air pollution characterised as PM_{2.5}.

3) The same AEC results in different scenarios

However, regardless of the degree of control in the model by control variables, the same reduction scale when assessing different pollutants can lead to the same pollutant AEC results appearing in different scenarios. In other words, the AEC is only related to polluted objects, the ambient air quality standard and a region's pollution dissipation capability.

4) A further optimisation of the SD model

The predicted results for the PM_{2.5} concentration may be relatively lower because the sum of proportion in five pollutants, SO₂, NO_x, VOC, NH₃ and primary PM_{2.5} is only 91% of the total chemical composition. There is another unknown 9%, and this has not been considered in the SD

model. Therefore, it is necessary for future studies to determine ways of predicting $PM_{2.5}$ concentrations with greater accuracy. With improvements in the development of monitoring ability of authorities, the conversion rate can be dynamically based on the updated source apportionment and emission inventory. This will ensure that the SD model is more reasonable and consistent with the reality. Moreover, more precise height of the atmospheric boundary layer could be obtained in cooperation with the meteorological department.

5) Research prospect

Deriving the AEC and AECC calculations in relation to compound air pollution, $PM_{2.5}$, is a complicated task and a systematic project work that is unprecedented in China's history. Currently, this pollution was commonly ignored in the field of environmental protection. The calculation of environmental capacity and environmental carrying capacity is an essential work of top planning departments to improve environmental quality. This implies that besides the AEC and AECC, water and soil environmental capacity and their carrying capacities are also important for future research. At present, the related research about water is carried out at a fast pace (Cheng, 2010; Liu and Shao, 2015; Li et al., 2016). Generally, water capacity is calculated using the water quality analysis models based on hydrology data and the positions of discharging sources and quantities. However, this is a difficult work with a great amount of analysis and calculation and does not involve economic and social systems. Although both the theoretical and practical research has begun for the soil, these areas are facing many problems in China (Zhou et al., 2006). In relation to these, we hope to establish water and soil SD models for analysing their environmental capacity and carrying capacity by using macro statistical data that avoid simulating the complex physicochemical processes. We believe that this work has a great significance in remedying the vague, fragmented current situation and bridging some of the current gaps in the research of environmental capacity and its carrying capacity.

5 Conclusions

When researching environmental capacity and its carrying capacity, the influence of social economy cannot be excluded, something which the current physicochemical methods barely

include; however, the SD method easily does. The SD method provides a powerful tool to establish quantitative links between different types of variables (such as emissions and the annual concentration of PM_{2.5}) in the ‘society–economy–environment’ complex system. Compared to the physicochemical methods, using SD models does not require the inclusion of the physical and chemical processes of a complex system (e.g. the ecological massive system is too complex to determine all its internal contacts for researchers). A number of effective statistical and monitoring data help us to investigate the intrinsic logical relationship between complex objects from the outcome of things. This is a much simpler and more effective way than the physicochemical analysis methods.

The predicted results from the present study indicate that in the S4 Intense scenario, the annual PM_{2.5} concentration of Wuhan city reaches the target (35 µg/m³) at the simulated year 2023.75. The corresponding AEC results of SO₂, NO_x, VOC, primary PM₁₀, primary PM_{2.5} and NH₃ are 29 679, 87 391, 86 643, 64 029, 26 336, and 10 649 t, respectively. The thresholds of economic indicators, GDP, and its production value of primary, secondary and tertiary industries are 1969, 45, 640.3, and 1283.9 billion Yuan, respectively. The thresholds of energy consumption, including coal, petroleum, natural gas and new energy are the standard coal consumption of 27.28, 1.99, 12.33, and 14.92 million tonnes, respectively. The 9-year accumulative emission reduction thresholds of six air pollutants are 183 599, 265 762, 319 189, 269 945, 123.986 and 21 450 t, respectively. The environmental capacity results provide a reference for the Chinese government to formulate environmental protection planning, and the thresholds of carrying capacity help to determine the direction for the environmental-friendly social and economic development to occur.

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Appendix

The equations in the SD model system

- (001) Annual concentration of PM₁₀= INTEG (Increment in PM₁₀-Decrement in PM₁₀, 0.113), Units: mg/m³
- (002) "Annual concentration of PM_{2.5}"= INTEG ("Increment in PM_{2.5}"-"Decrement of PM_{2.5}", 0.082), Units: mg/m³
- (003) Annual consumption of coal= INTEG (Increment of coal, 34.54), Units: million tonnes
- (004) Annual consumption of natural gas= INTEG (Increment of natural gas, 2.4), Units: million tonnes
- (005) Annual consumption of new energy= INTEG (Increment of new energy, 2.45), Units: million tonnes
- (006) Annual consumption of petroleum= INTEG (Increment of petroleum, 1.85), Units: million tonnes

1 (007) City area= 8.494e+009, Units: m²

2 (008) City volume under boundary layer= City area*Height of boundary layer, Units: m³

3 (009) "Contribution rate (NH3 for PM₁₀)"= 0.08, Units: Dmnl

4 (010) "Contribution rate (NH3 for PM_{2.5})"= 0.1, Units: Dmnl

5 (011) "Contribution rate (NOx for PM₁₀)"= 0.13, Units: Dmnl

6 (012) "Contribution rate (NOx for PM_{2.5})"= 0.15, Units: Dmnl

7 (013) "Contribution rate (SO2 for PM₁₀)"= 0.2, Units: Dmnl

8 (014) "Contribution rate (SO2 for PM_{2.5})"= 0.21, Units: Dmnl

9 (015) "Contribution rate (VOC for PM₁₀)"= 0.26, Units: Dmnl

10 (016) "Contribution rate (VOC for PM_{2.5})"= 0.3, Units: Dmnl

11 (017) Contribution rate of primary PM₁₀= 0.21, Units: Dmnl

12 (018) "Contribution rate of primary PM_{2.5}"= 0.15, Units: Dmnl

13 (019) "Conversion rate (NH3 to PM₁₀)"= PM₁₀ volume*"Contribution rate (NH3 for PM₁₀)"/Discharged volume of NH3, Units: Dmnl

14 (020) "Conversion rate (NH3 to PM_{2.5})"= "PM_{2.5} volume*"Contribution rate (NH3 for PM_{2.5})"/Discharged volume of NH3, Units: Dmnl

15 (021) "Conversion rate (NOx to PM₁₀)"= PM₁₀ volume*"Contribution rate (NOx for PM₁₀)"/Discharged volume of NOx, Units: Dmnl

16 (022) "Conversion rate (NOx to PM_{2.5})"= "PM_{2.5} volume*"Contribution rate (NOx for PM_{2.5})"/Discharged volume of NOx, Units: Dmnl

17 (023) "Conversion rate (SO2 to PM₁₀)"= PM₁₀ volume*"Contribution rate (SO2 for PM₁₀)"/Discharged volume of SO2, Units: Dmnl

18 (024) "Conversion rate (SO2 to PM_{2.5})"= "PM_{2.5} volume*"Contribution rate (SO2 for PM_{2.5})"/Discharged volume of SO2, Units: Dmnl

19 (025) "Conversion rate (VOC to PM₁₀)"= PM₁₀ volume*"Contribution rate (VOC for PM₁₀)"/Discharged volume of VOC, Units: Dmnl

20 (026) "Conversion rate (VOC to PM_{2.5})"= "PM_{2.5} volume*"Contribution rate (VOC for PM_{2.5})"/Discharged volume of VOC, Units:

21 Dmnl

22 (027) Conversion rate of primary PM₁₀= PM₁₀ volume*Contribution rate of primary PM₁₀/Discharged volume of primary PM₁₀, Units:

23 Dmnl

24 (028) "Conversion rate of primary PM_{2.5}"= "PM_{2.5} volume*"Contribution rate of primary PM_{2.5}"/Discharged volume of primary PM_{2.5}",

25 Units: Dmnl

26 (029) Decrement of NH3= Discharged volume of NH3*Emission reduction factor of NH3, Units: tonne/Year

27 (030) Decrement of NOx= Discharged volume of NOx*Emission reduction factor of NOx, Units: tonne/Year

28 (031) Decrement of PM₁₀= Decrement of NH3*"Conversion rate (NH3 to PM₁₀)"*1e+009/City volume under boundary layer

29 +Decrement of NOx*"Conversion rate (NOx to PM₁₀)"*1e+009/City volume under boundary layer +Decrement of primary

30 PM₁₀*Conversion rate of primary PM₁₀*1e+009/City volume under boundary layer +Decrement of SO2*"Conversion rate (SO2 to

31 PM₁₀)"*1e+009/City volume under boundary layer +Decrement of VOC*"Conversion rate (VOC to PM₁₀)"*1e+009/City volume

32 under boundary layer, Units: mg/(Year*m³)

33 (032) "Decrement of PM_{2.5}"=Decrement of NH3*"Conversion rate (NH3 to PM_{2.5})"*1e+009/City volume under boundary layer+

34 Decrement of NOx*"Conversion rate (NOx to PM_{2.5})"*1e+009/City volume under boundary layer+ Decrement of SO2*"Conversion

35 rate (SO2 to PM_{2.5})"*1e+009/City volume under boundary layer+ Decrement of VOC*"Conversion rate (VOC to PM_{2.5})"*1e+009/City

36 volume under boundary layer+ "Decrement of primary PM_{2.5}"*"Conversion rate of primary PM_{2.5}"*1e+009/City volume under

37 boundary layer, Units: mg/(m³*Year)

38 (033) Decrement of primary PM₁₀=Discharged volume of primary PM₁₀*Emission reduction factor of primary PM₁₀, Units: tonne/Year

39 (034) "Decrement of primary PM_{2.5}"= "Discharged volume of primary PM_{2.5}"*Emission reduction factor of primary PM_{2.5}", Units:

40 tonne/Year

- 1 (035) Decrement of SO₂= Emission reduction factor of SO₂*Discharged volume of SO₂, Units: tonne/Year
- 2 (036) Decrement of VOC= Discharged volume of VOC*Emission reduction factor of VOC, Units: tonne/Year
- 3 (037) Discharged volume of NH₃= INTEG (Increment of NH₃-Decrement of NH₃, 16496), Units: tonne
- 4 (038) Discharged volume of NO_x= INTEG (Increment of NO_x-Decrement of NO_x, 181486), Units: tonne
- 5 (039) Discharged volume of primary PM₁₀= INTEG (Increment of primary PM₁₀-Decrement of primary PM₁₀, 171630), Units: tonne
- 6 (040) "Discharged volume of primary PM_{2.5}"= INTEG ("Increment of primary PM_{2.5}"-"Decrement of primary PM_{2.5}", 77251), Units:
- 7 tonne
- 8 (041) Discharged volume of SO₂= INTEG (Increment of SO₂-Decrement of SO₂, 109604), Units: tonne
- 9 (042) Discharged volume of VOC= INTEG (Increment of VOC-Decrement of VOC, 208558), Units: tonne
- 10 (043) Emission reduction factor of NH₃=IF THEN ELSE(Time<2021, 0.1 , 0.08),Units: 1/Year
- 11 (044) Emission reduction factor of NO_x=IF THEN ELSE(Time<2021, 0.105, 0.08)+Energy adjustment factor of NO_x, Units: 1/Year
- 12 (045) Emission reduction factor of primary PM₁₀=IF THEN ELSE(Time<2021, 0.105, 0.07)+Energy adjustment factor of primary
- 13 PM₁₀, Units: 1/Year
- 14 (046) "Emission reduction factor of primary PM_{2.5}"=IF THEN ELSE(Time<2021, 0.115 , 0.08)+"Energy adjustment factor of primary
- 15 PM_{2.5}", Units: 1/Year
- 16 (047) Emission reduction factor of SO₂=IF THEN ELSE(Time<2021, 0.14, 0.1)+Energy adjustment factor of SO₂, Units: 1/Year
- 17 (048) Emission reduction factor of VOC=IF THEN ELSE(Time<2021, 0.125, 0.09)+Energy adjustment factor of VOC, Units: 1/Year
- 18 (049) Energy adjustment factor of NO_x=1-(1+Growth rate of NO_x)/(1+Energy growth rate), Units: Dmnl
- 19 (050) Energy adjustment factor of primary PM₁₀=1-(1+Growth rate of particulate matter)/(1+Energy growth rate), Units: Dmnl
- 20 (051) "Energy adjustment factor of primary PM_{2.5}"=1-(1+Growth rate of particulate matter)/(1+Energy growth rate), Units: Dmnl
- 21 (052) Energy adjustment factor of SO₂=1-(1+Growth rate of coal)/(1+Energy growth rate), Units: Dmnl
- 22 (053) Energy adjustment factor of VOC=1-(1+Growth rate of petroleum)/(1+Energy growth rate), Units: Dmnl
- 23 (054) Energy consumption elasticity coefficient= 0.5, Units: Dmnl
- 24 (055) Energy consumption of discharging NO_x=Annual consumption of coal+Annual consumption of natural gas+Annual consumption
- 25 of petroleum, Units: million tonnes
- 26 (056) Energy consumption of discharging particulate matter= Annual consumption of coal+Annual consumption of petroleum, Units:
- 27 million tonnes
- 28 (057) Energy growth rate= Energy consumption elasticity coefficient*Growth rate of GDP, Units: 1/Year
- 29 (058) FINAL TIME = 2031, Units: Year, The final time for the simulation.
- 30 (059) GDP=GDP of primary industry+GDP of secondary industry+GDP of tertiary industry, Units: billion Yuan
- 31 (060) GDP of primary industry= INTEG (Increment of primary industry, 35), Units: billion Yuan
- 32 (061) GDP of secondary industry= INTEG (Increment of secondary industry, 478.5), Units: billion Yuan
- 33 (062) GDP of tertiary industry= INTEG (Increment of tertiary industry, 493.3), Units: billion Yuan
- 34 (063) Growth rate of coal=IF THEN ELSE(Time<2021, -0.03 , -0.02), Units: 1/Year
- 35 (064) Growth rate of GDP=Growth rate of primary industry*GDP of primary industry/GDP+Growth rate of secondary industry*GDP of
- 36 secondary industry/GDP+Growth rate of tertiary industry*GDP of tertiary industry/GDP, Units: 1/Year
- 37 (065) Growth rate of natural gas=IF THEN ELSE(Time<2021, 0.22 , 0.13), Units: 1/Year
- 38 (066) Growth rate of new energy=IF THEN ELSE(Time<2021, 0.25, 0.13), Units: 1/Year
- 39 (067) Growth rate of NO_x= Growth rate of natural gas*Annual consumption of natural gas/Energy consumption of discharging NO_x
- 40 +Growth rate of coal*Annual consumption of coal/Energy consumption of discharging NO_x +Growth rate of petroleum*Annual

1 consumption of petroleum/Energy consumption of discharging NO_x, Units: 1/Year

2 (068) Growth rate of particulate matter= Growth rate of coal*Annual consumption of coal/Energy consumption of discharging

3 particulate matter +Growth rate of petroleum*Annual consumption of petroleum/Energy consumption of discharging particulate matter,

4 Units: 1/Year

5 (069) Growth rate of petroleum= IF THEN ELSE(Time<2021, 0.01 , 0.005), Units: 1/Year

6 (070) Growth rate of primary industry= IF THEN ELSE(Time<2021, 0.03, 0.025), Units: 1/Year

7 (071) Growth rate of secondary industry= IF THEN ELSE(Time<2021, 0.035 , 0.03), Units: 1/Year

8 (072) Growth rate of tertiary industry= IF THEN ELSE(Time<2021, 0.125 , 0.08), Units: 1/Year

9 (073) Height of boundary layer= 1000, Units: m

10 (074) Increment of coal= Growth rate of coal*Annual consumption of coal, Units: million tonnes/Year

11 (075) Increment of natural gas= Annual consumption of natural gas*Growth rate of natural gas, Units: million tonnes/Year

12 (076) Increment of new energy= Annual consumption of new energy*Growth rate of new energy, Units: million tonnes/Year

13 (077) Increment of NH₃= Increment of polluttional GDP*Proportionality factor of NH₃, Units: tonne/Year

14 (078) Increment of NO_x=Energy adjustment factor of NO_x*Increment of polluttional GDP*Proportionality factor of NO_x, Units:

15 tonne/Year

16 (079) Increment of petroleum= Annual consumption of petroleum*Growth rate of petroleum, Units: million tonnes/Year

17 (080) Increment of PM₁₀=Increment of NH₃*"Conversion rate (NH₃ to PM₁₀)"*1e+009/City volume under boundary layer+Increment

18 of NO_x*"Conversion rate (NO_x to PM₁₀)"*1e+009/City volume under boundary layer+Increment of SO₂*"Conversion rate (SO₂ to

19 PM₁₀)"*1e+009/City volume under boundary layer+Increment of VOC*"Conversion rate (VOC to PM₁₀)"*1e+009/City volume under

20 boundary layer+Increment of primary PM₁₀*Conversion rate of primary PM₁₀*1e+009/City volume under boundary layer, Units:

21 (mg/m³)/Year

22 (081) "Increment of PM_{2.5}"=Increment of NH₃*"Conversion rate (NH₃ to PM_{2.5})"*1e+009/City volume under boundary

23 layer+Increment of NO_x*"Conversion rate (NO_x to PM_{2.5})"*1e+009/City volume under boundary layer+Increment of

24 SO₂*"Conversion rate (SO₂ to PM_{2.5})"*1e+009/City volume under boundary layer+Increment of VOC*"Conversion rate (VOC to

25 PM_{2.5})"*1e+009/City volume under boundary layer+"Increment of primary PM_{2.5}"*Conversion rate of primary PM_{2.5}*1e+009/City

26 volume under boundary layer, Units: mg/(m³*Year)

27 (082) Increment of polluting GDP= 0.1*Increment of primary industry+0.9*Increment of secondary industry+0.1*Increment of tertiary

28 industry, Units: billion Yuan/Year

29 (083) Increment of primary industry= GDP of primary industry*Growth rate of primary industry, Units: billion Yuan/Year

30 (084) Increment of primary PM₁₀=Energy adjustment factor of primary PM₁₀*Increment of polluttional GDP*Proportionality factor of

31 primary PM₁₀, Units: tonne/Year

32 (085) "Increment of primary PM_{2.5}"="Energy adjustment factor of primary PM_{2.5}"*Increment of polluttional GDP*Proportionality factor

33 of primary PM_{2.5}", Units: tonne/Year

34 (086) Increment of secondary industry=GDP of secondary industry*Growth rate of secondary industry, Units: billion Yuan/Year

35 (087) Increment of SO₂=Increment of polluttional GDP*Energy adjustment factor of SO₂*Proportionality factor of SO₂, Units:

36 tonne/Year

37 (088) Increment of tertiary industry= GDP of tertiary industry*Growth rate of tertiary industry, Units: billion Yuan/Year

38 (089) Increment of VOC=Energy adjustment factor of VOC*Increment of polluttional GDP*Proportionality factor of VOC, Units:

39 tonne/Year

40 (090) INITIAL TIME = 2015, Units: Year, The initial time for the simulation.

- 1 (091) PM_{10} volume= Annual concentration of PM_{10} *City volume under boundary layer*1e-009, Units: tonne
- 2 (092) "PM_{2.5} volume"="Annual concentration of PM_{2.5}"*City volume under boundary layer*1e-009, Units: tonne
- 3 (093) Polluting GDP=0.1*GDP of primary industry+0.9*GDP of secondary industry+0.1*GDP of tertiary industry, Units: billion Yuan
- 4 (094) Proportionality factor of NH₃= Discharged volume of NH₃/Pollutional GDP, Units: tonne/billion Yuan
- 5 (095) Proportionality factor of NO_x= Discharged volume of NO_x/Pollutional GDP, Units: tonne/billion Yuan
- 6 (096) Proportionality factor of primary PM₁₀= Discharged volume of primary PM₁₀/Pollutional GDP, Units: tonne/billion Yuan
- 7 (097) "Proportionality factor of primary PM_{2.5}"="Discharged volume of primary PM_{2.5}"/Pollutional GDP, Units: tonne/billion Yuan
- 8 (098) Proportionality factor of SO₂= Discharged volume of SO₂/Pollutional GDP, Units: tonne/billion Yuan
- 9 (099) Proportionality factor of VOC= Discharged volume of VOC/Pollutional GDP, Units: tonne/billion Yuan
- 10 (100) SAVEPER = TIME STEP, Units: Year [0,?]. The frequency with which output is stored.
- 11 (101) TIME STEP = 0.25 Units: Year [0,?], The time step for the simulation.
- 12