## Modeling the interaction between energy source enterprises and industrial enterprises as "Nature-Technology" closed-loop control systems

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**Abstract**. This paper focuses on models of interaction between energy source enterprises and industrial enterprises in order to minimize and control atmospheric emissions. Based on these models, computer simulations of "Nature-Technology" closed-loop control systems-energy source enterprises and industrial enterprises at the meta, macro and mini-models are carried out within the concept of "Nature-Technology" closed-loop control systems, taking into account the existing constraints of China norms and standards with inputs from the Beijing region of China. The simulations are based on a combined heat and power plant and a steel (cement) plant. Overall energy consumption and emissions monitoring based on computer modelling of energy source enterprises and industrial enterprises, including consideration of standards and guidelines for environmental and energy policies and plans in the Beijing region of China.

**Keywords:** energy source enterprises; industrial enterprises; emissions; closed-loop control systems; meta, macro and mini-models

#### 1. Introduction

Metamodels of the interaction between energy source enterprises (ESE) and industrial enterprises (IE) as "Nature-Technology" closed-loop control systems (NTCLCS) are presented in the authors' works and serve for a qualitative assessment of such a control system. Such assessments according to the criteria of: achievability of control objectives (in this case minimizing emissions), variability of output coordinates and parameters (pollutants in the atmosphere), feasibility of the "Nature-Technology" closed-loop control systems-energy source enterprises and industrial enterprises (NTCLCS-ESEIE), are carried out by means of computer modelling in Matlab. Further development of the qualitative assessments of the "NTCLCS-ESEIE" is envisaged on the basis of system dynamics theory [3,4]. At the next development stage, the "NTCLCS-ESEIE" metamodels evolve into macromodels and mini-models of ESE and IE, in which the control objects and the control system (measuring, amplifying-transforming, telecommunication, actuating and other devices) and the corresponding criteria, limitations, characteristics are highlighted. For the industrial enterprise, these are production orders, production workflow, CO<sub>2</sub> monitoring documentation, components of the automated process control system (APCS) of that enterprise. The ESE include the energy requirements of the IE, the energy production process, CO<sub>2</sub> monitoring and the components of the enterprise's APCS. An integrated decision-making model for energy and emission planning in Beijing was proposed in 1991 and is mainly used to quantitatively describe the influence between atmospheric quality and energy planning <sup>[5]</sup>. Wang Liang et al. constructed a comprehensive evaluation framework for regional resource and ecological carrying capacity <sup>[6]</sup>. Zhou Lin combined the energy structure optimization model with the air pollution control model to optimize the energy structure and air pollution control<sup>[7]</sup>.

Metamodels based on the balance equations are proposed based on these data <sup>[2]</sup>. Macromodels are represented by a vector-matrix differential control of a multidimensional "NTCLCS-ESEIE", designed to analyze such a system in n-dimensional Euclidean space. Going to the micro-model level "NTCLCS-ESEIE" includes specific devices: sensors measuring CO<sub>2</sub> (or other pollutants), amplifying and converting (e.g. Analogue to digital converters, digital-to-analog converter),

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microprocessors, switching elements of the ESMC, actuators, emission compensation devices (mechanical, electromagnetic, pneumatic, etc.). Mathematical models of ESE and IE at this level are represented by input-output operators, which are linearly reduced to the transfer functions of the individual links.

# 2. Analysis of Energy Consumption And Emissions in the Beijing Region of China

With the rapid development of China's economy, the country's overall energy consumption increases. As the capital, political and cultural center of China, economic output in Beijing has increased by a factor of 10 compared to the past 20 years, the number of vehicles has increased 3.5 times, energy consumption has increased by almost 90% and the population has grown by almost 80%, with rapid development putting serious pressure on air quality <sup>[8]</sup>. Fossil energy sources such as coal and oil account for the vast majority of energy consumption in Beijing, and carbon emissions, as measured by energy activities, also dominate fossil energy consumption. In this paper, the selection of energy facilities is based on those that are mainly used daily in Beijing and have high carbon emissions (coal, oil, natural gas) <sup>[9]</sup>. Figures 1 and 2 are statistical charts of the data retrieved from the Beijing Statistical Yearbook 2010-2020<sup>[10]</sup>.







Figure 2 The consumption of various categories of energy in Beijing from 2010 to 2020.

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As can be seen from the figure above, in order to cope with the air pollutant emissions caused by energy consumption in Beijing, a neutralisation and cleaning system for pollutants will be a key area of research.

#### 3. Modelling and Analysis of the "NTCLCS-ESEIE" at the Meta-level

Establishing links between the functioning of ESE and IE at the meta-level comes down to the construction of appropriate mathematical models of the system dynamics of the flows in question.

Models such as the interaction of ESE and IE, the emissions of these enterprises and the environment of "nature" proceed as follows

$$\frac{dZ_1^i}{dt} = K_i^{(1)} X_i - K_i^{(2)} Y_i, 
\frac{dZ_2^j}{dt} = K_j^{(1)} Z_1^i - K_j^{(2)} Y_j + K_j^{(3)} X_j,$$
(1)

where:  $Z_1^i$  [MJ] - the amount of energy from the *i*-th ESE;  $X_i$  [kg] - the amount of fuel (coal) at the input of the ESE;  $Y_i$  [kg] - the amount of CO<sub>2</sub> emitted to the atmosphere by the ESE;  $Z_2^j$  [kg] the amount of IE products (steel, cement);  $X_j$  [kg] - the amount of raw materials (iron ore, limestone) at the input of the IE;  $Y_j$  [kg] - the amount of CO<sub>2</sub> emitted to the atmosphere by the IE;  $K_i^{(1)}$  - the conversion factor for fuel to energy;  $K_i^{(2)}$  - the conversion coefficient of coal combustion to CO<sub>2</sub> emissions;  $K_j^{(1)}$  - the conversion coefficient of energy to products;  $K_j^{(2)}$  - the conversion coefficient of production to CO<sub>2</sub> emissions;  $K_j^{(3)}$  - the conversion coefficient for standard coal so the energy content of one tonne of standard coal is 29307 MJ<sup>[11]</sup>.

$$\frac{dY_i}{dt} = K_i^{(4)} Z_1^i - K_i^{(5)} Y_i, 
\frac{dY_j}{dt} = K_j^{(4)} Z_2^j - K_j^{(5)} Y_j,$$
(2)

where:  $K_i^{(4)}, K_j^{(4)}, K_i^{(5)}, K_j^{(5)}$  - appropriate conversion coefficients for energy flows from ESE product flows from IE, offsetting emissions flows from ESE and IE by natural and anthropogenic means <sup>[1]</sup>.

#### 4. Modelling and Analysis of the "NTCLCS-ESEIE" at the Macro-level

In the form of an "NTCLCS-ESEIE" is shown in Figure 3.

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Figure 3 Block diagram of the "NTCLCS-ESEIE".

The following is an expression of the relationship between each block in the above scheme. L<sub>1</sub>:

 $\mathbf{6}_{1} = \mathbf{X}_{1} - \mathbf{6}_{_{1}}^{*}, \ \mathbf{Y}_{1}^{(1)} = [\mathbf{0}\mathbf{y}]_{1} \cdot \mathbf{6}_{_{1}}, \ \mathbf{Y}_{2}^{(1)} = [\mathbf{u}_{_{3}}\mathbf{y}]_{_{1}} \cdot \mathbf{Y}_{1}^{(1)}, \ \mathbf{6}_{_{1}}^{*} = [\mathbf{u}\mathbf{y}]_{_{1}} \cdot \mathbf{U}_{_{1}}, \ \mathbf{U}_{_{1}} = [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \Delta\mathbf{Y}_{_{1}}, \ \Delta\mathbf{Y}_{_{1}} = [\mathbf{C}\mathbf{D}]_{_{1}} \cdot \Delta\mathbf{Y}, \ \mathbf{C}_{_{1}} = [\mathbf{C}\mathbf{D}]_{_{1}} \cdot \mathbf{U}_{_{1}}, \ \mathbf{C}_{_{1}} = [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}}, \ \mathbf{U}_{_{1}} = [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}} + [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}} = [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}} + [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}} + [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}} = [\mathbf{C}\mathbf{L}]_{_{1}} \cdot \mathbf{U}_{_{1}} + [\mathbf{C}\mathbf{$  $\Delta Y = Y_0 - Y_2^{(1)} - Y_2^2,$ 

$$\begin{split} L_{1}^{\delta_{1},Y_{2}^{(l)}} &= [u_{3}y]_{l} \cdot [oy]_{l} \cdot \left\{ [E] - [u_{3}y]_{l} \cdot [oy]_{l} \cdot [uy]_{l} \cdot [CL]_{l} \cdot [CD]_{l} \right\}^{-1}, \\ L_{1}^{\delta_{1},\Delta Y_{1}} &= [u_{3}y]_{l} \cdot [oy]_{l} \cdot [ypy]_{l} \cdot \left\{ [E] - [u_{3}y]_{l} \cdot [oy]_{l} \cdot [uy]_{l} \cdot [CL]_{l} \cdot [CD]_{l} \right\}^{-1}; \\ L_{2}: \\ \delta_{2} &= X_{2} - \delta_{2}^{*}, Y_{1}^{(2)} = [oy]_{2} \cdot (\delta_{2} + Z_{2}), Z_{2} = [AC] \cdot Z_{1}, Z_{1} = [oy]_{l} \cdot \delta_{1}, Y_{2}^{(2)} = [u_{3}y]_{2} \cdot Y_{1}^{(2)}, \delta_{2}^{*} = [uy]_{2} \cdot U_{2}, \\ U_{2} &= [CL]_{2} \cdot \Delta Y_{2}, \Delta Y_{2} = [CD]_{2} \cdot \Delta Y, \\ L_{2}^{\delta_{2},Y_{2}^{(2)}} &= [u_{3}y]_{2} \cdot [oy]_{2} \cdot \{[E] - [u_{3}y]_{2} \cdot [oy]_{2} \cdot [uy]_{2} \cdot [CL]_{2} \cdot [CD]_{2} \}^{-1}, \\ L_{2}^{\delta_{2},\Delta Y_{2}} &= [u_{3}y]_{2} \cdot [oy]_{2} \cdot \{[E] - [u_{3}y]_{2} \cdot [oy]_{2} \cdot [uy]_{2} \cdot [CL]_{2} \cdot [CD]_{2} \}^{-1}. \\ Eigure 3 shows: \end{split}$$

Figure 3 shows:

 $(u_3y)_1$ - measuring devices for ESE,  $(oy)_1$ - the object of the device in the ESE,  $(uy)_1$ - actuators for ESE, (CD)<sub>1</sub>- control devices for ESE, (CL)<sub>1</sub>- control law for ESE, (AC) - analog converters, L<sub>1</sub>control system for ESE,  $\delta_1$ ,  $\delta_1^*$ ,  $Y_1^{(1)}$ ,  $Y_2^{(1)}$ ,  $\Delta Y_1$ - error arising from individual blocks in the ESE, $(\mu_3 y)_2$ - measuring devices for IE,  $(oy)_2$ - the object of the device in the IE,  $(uy)_2$ - actuators for IE, (CD)<sub>2</sub>- control devices for IE, (CL)<sub>2</sub>- control law for IE, L<sub>2</sub>- control system for IE,  $6_{2}, 6_{2}^{*}, Y_{1}^{(2)}, Y_{2}^{(2)}, \Delta Y_{2}$ - error arising from individual blocks in the IE, Y<sup>o</sup>- maximum permissible error standard,  $\Delta Y(1,2)$ - the error results for ESE and IE,  $u_1, u_2$ - the control action from the actuator,  $X_1$ - Fuel (coal) preparation after crushing or other preparation,  $X_2$ - raw material preparation,  $Z_1$ - the energy flow from the ESE output, Z<sub>2</sub>- the energy flow converted for IE.

#### Modelling and Analysis of the "NTCLCS-ESEIE" at Mini-level 5.

In the next stage to develop APCS, corresponding to the considered concept of NTCLCS for the design object ESE-i and IE-j, the analysis, synthesis and calculation are carried out for each loop automatic control system represented in the operators  $L_1(p)$ ,  $L_2(p)$  in Figure. 3.

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Figure 4 Schematic diagram of a one-dimensional 3CYIIT.

To evaluate the dynamics of the ESE-emission (CO<sub>2</sub>) system in first approximation for the outer loop, L<sub>2</sub>(p), as a one-dimensional system, the structural diagram is presented in Figure. 4<sup>[1]</sup>.

In Figure. 4 the following symbols are shown:

 $W_1(p)$  - the transfer function linking the mismatch signal  $\sigma(t)$  to the CO<sub>2</sub> output,  $y_1(t)$ ,

$$\mathbf{p} = \frac{\mathrm{d}}{\mathrm{d}t}; y_1(t) = \mathbf{W}_1(\mathbf{p})\sigma(t); \sigma(t) = x(t) - u(t), \tag{3}$$

where: x(t) - compensated component of the CO<sub>2</sub> output flow;  $u_1(t)$  - the control action from the actuator;  $W_2(p)$  - the transfer function of the CO<sub>2</sub> concentration (weight) conversion in the composition, flow, when transferred from their output to the measuring point;  $W_3(p)$  - the transfer function of the measuring device;  $W_4(p)$  - the transfer function of the data-converter and measurement devices;  $W_5(p)$  - the transfer function of the control unit;  $W_6(p)$  - the transfer function of the cleaning unit together with the actuator;  $y_{1,2,3,4}(t), u(t), u_1(t)$  - the expressions for the results of the mathematical model for each control module;  $y_{20}$  - the setting of the permissible value at the output of the measuring device.

 $L_2(p)$  operator in the form of a transfer function linking the "error" z(t) to the perturbation x, at controlling  $W_5(p) = k_6 + k_7 p + k_8 \frac{1}{p}$  (Proportional-Integral-Differential), the following formula can

be obtained:

$$\frac{z(t)}{x} = \frac{k_1 k_2 k_3 e^{-p(\tau_1 + \tau_2 + \tau_3)} p(1 + T_4 p)(1 + T_5 p)}{p(1 + T_1 p)(1 + T_2 p)(1 + T_3 p)(1 + T_4 p)(1 + T_5 p) +},$$

$$+ k_1 k_2^* k_3 k_4 k_5 (k_6 p^2 + k_7 p + k_8) e^{-p(\tau_1 + \tau_2 + \tau_3 + \tau_4 + \tau_5)}$$
(4)

where:  $k_{1,2,3,4,5,6,7,8}$  - coefficients,  $k_2^* = e^{-k_2\tau}$ ,  $T_{1,2,3,4,5}$  - time constants,  $\tau_{1,2,3,4,5}$  - the average value of the lag time, the p-operator of Laplace. This model serves to analyse the stability, and control quality of the ESE as a one-dimensional system.

The inner loop operator  $L_2(p)$  is constructed similarly with the input of the outer and inner loops of the system, "ESE and IE" leads to the construction of the operator  $L_1(p)$ , including  $L_1(p)$  and  $L_2(p)$  as components.

#### 6. Conclusion

The next stage in the design of the facilities considered here is the construction of an appropriate APCS(NTCLCS-ESEIE) using a computer-aided design system. This design phase includes the implementation of proposed mathematical models for analysis, synthesis, calculation; the formation

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of process flow diagrams, a set of standard measuring, regulating and visualization tools; set of components included in the circuit; set of electrical and mechanical connections. All this leads to the task given to the formation of a knowledge base of a computer-aided design system for the APCS, the ESE and the IE. All these factors lead to the task of forming a knowledge base of a computer-aided design system, APCS, NTCLCS-ESEIE. This knowledge base is built on the basis of individual databases (components, schematic sets, connections etc.) the database management system and the state knowledge base management system as applied to the needs of the design user.

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