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Article

Policy for handling air pollution in Jakarta: Study using System Dynamics Simulation Models

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Abstract: Air pollution in Jakarta has become a severe concern in the last four months. IQAir, in August 2023, revealed that the level of air pollution had reached 161 points on the Air Pollution Standard Index (APSI). The negative impact on society has placed air pollution as a concern for environmental safety and survival in danger. This condition will encourage the development of a national policy agenda to integrate environmental welfare through various energy efficiency channels. This research analyzes the relationship between air pollutant elements that can reduce air quality. The analysis includes pollutant intensity measured by APSI per unit of pollutant as a measure of efficiency. The aim is to observe energy use, which causes an increase in pollutant levels. This research utilizes dynamic system modeling to produce relationships between parameters to produce factors that cause pollution. The parameters used are motorized vehicles, waste burning in landfills, industry, and power plants. The results of historical behavioral tests and statistical suitability tests show that the behavior is suitable for the short and long term. The simulation results show that the pollution level will worsen by the end of 2027, a hazardous condition for society. The optimistic scenario simulation model proposes immediate counter-measures to reduce pollution to 45.01, the ideal condition. To accelerate improvements in air quality, the Government can plan policies to reduce the use of coal by power plants and industry, as well as the use of electric motorized vehicles, resulting in an ideal reduction in pollution by 2024. In conclusion, pollution can be reduced effectively if the Government firmly implements policies to maintain that air quality remains stable below 50 points.

Keywords: public policy; air pollution; motor vehicle; power plan; waste burn; industrial pollution; dynamic system simulation

1. Introduction

The issue of air pollution in Jakarta has become a serious highlight in the last four months. The Ministry of the Environment and the Coordinating Minister for Political, Legal, and Security Affairs stated that motorized vehicles are the leading cause of this pollution. Some people blame motorized vehicles for high emissions and air pollution. However, experts believe the increase in motorized vehicles is not the only cause. Other causes also contribute, such as the concentration of factories operating in the Bodetabek Megapolitan area whose smoke disrupts the capital city, throwing rubbish carelessly in rubbish dumps and public places, and a dry climate that triggers increased air pollution. In 2022, Tomtom, a congestion index provider institution, conducted a survey and concluded that Jakarta was one of the most crowded cities in the world, with the number of motorized vehicles triggering an increase in air pollution (Clinten, 2023). It explained the conclusion of the survey results that Jakarta, as one of the most crowded cities in the world, was triggered by various factors, including limited roads, the behavior of motorized vehicle drivers, and the capacity of non-comparable motorized vehicles to the length of the road. Data from the Central Statistics Agency (BPS) shows that in early 2023, the population of motorized vehicles was 26,370,535. Of this number, 73.82% are motorbikes, 18.42% passenger cars, and 2.81% buses and trucks (4.95%) (BPS, 2022a).

The Provincial Government has issued a three-in-one policy to cope with traffic jams, but the implementation has not been successful (Hanna et al., 2017). Then, the Provincial Government innovated by issuing a replacement policy known as the policy in odd-even vehicle numbers (Supriana et al., 2020). This policy is an alternative and continuation of road management engineering, enacted based on Governor Regulation Number 164 of 2016 and amended by Governor Regulation Number 88 of 2019. In its implementation, this policy was found unsuccessful.

Furthermore, the Jakarta government formulated a new policy restricting motorized vehicles that will be implemented in 2025 (Sandi, 2022). The incumbent Governor of Jakarta issued instructions to restrict the age of motorized vehicles in operation. Vehicles over ten years old are not allowed to operate on the highway in early 2025. This Governor's Instruction No. 66 of 2019 becomes the basis of the vehicle restriction plan policy. If observed, this Governor's policy is based on considerations of the results of the Euromonitor International survey predicting that road traffic will be paralyzed in 2030 because only 13.3% of the total number of individual cars that switch to the busway (Rahadianto et al., 2019). However, this policy is considered a half-hearted policy until finally, the replacement of the Governor has not been realized, as well. On 20 March 2023, the Government officially published Presidential Instruction No. 7 of 2022. This policy requires central and local government agencies to adopt battery electric vehicles (BEV) as operational service vehicles or official vehicles (Bram et al., 2022). To support this policy, the Government provides subsidized aid for purchasing battery electric vehicles starting on 20 March 2023. However, along with the enactment of Presidential Instruction Number 7 of 2022, which was realized amidst March 2023, air quality in Jakarta was not improving but encountered a reduction in quality.

Cross-opinion between ministries and local Government in Jakarta occurred in August 2023. The Ministry of Environment and Forestry revealed two primary sources of air pollution, i.e., from motorized vehicles at 43% and steam power plants at 34%, while the Ministry of Maritime and Investment suggested that the air pollution derived from motorized vehicles at 75% and steam power plant at 25%.

On 25–27 August 2023, the Jakarta Provincial Government implemented a work-from-home policy. However, the concentration of PM 2.5 pollutants did not change. This policy trial changed the Government's perception, which had long considered motor vehicles the leading cause. The Jakarta government assumes that the cause may be coal-based power plants and industries. The Jakarta government's assumption was strengthened because the Center for Research on Energy and Clean Air (CREA) revealed on 30 August 2023, that the Central Government had exaggerated the role of transportation as a cause of pollution. CREA shows that pollutants from peripheral regions extremely influence the problem of air pollution in Jakarta. Observation is closer to the air mass path in Jakarta when the PM 2.5 level peaked at the American Embassy air quality monitoring station in Central Jakarta and South Jakarta. The results showed that most of the pollution was caused by coal power plants (CNN, 2023).

The assumption that motorized vehicles is a cause of pollution raises questions from experts, academics, and transportation consultants. The interesting question is why governments do not reduce part or one-third of the number of existing vehicles at present. What is the ideal percentage of reduction? Besides motorized vehicles, are there other factors that have a significant influence? Please note that the electricity capacity in Indonesia has experienced a surplus with a ratio of 99.68% (Puspaningtyas, 2023), which shows that Indonesia requires no additional power plants.

To better understand the conditions in Jakarta, the following is presented: the number of motorized vehicles and the air quality index in Jakarta as of July and August 2023, and research data sourced from BPS, Local Revenue Agency (BPS, 2022b), and IQAir, 2023.

The paradigm of reducing the number of motorized vehicles three decades ago was not the best option for the Jakarta government because it impacted a reduction in local income. However, this article reminds us that the road length in Jakarta is only 7208 km, with a number of motorized vehicles of 26,370,535 units. It explains that the ratio of the length of the road and the number of motorized vehicles makes no sense, i.e., 1 meter of highway is occupied by three motorized vehicles. This study aims to get a comprehensive policy by presenting two solution scenarios for analyzing the system dynamics model. The hypothesis is:

- Ha1: Every additional motor vehicle will impact poor air quality.
- Ha2: Motorized vehicles are not Jakarta's leading cause of poor air quality.
- Ha3: The ideal policy to reduce air pollution in Jakarta is to use an optimal scenario.

2. Methodology

2.1. Data source and collection

We obtained secondary data on the number of motorized vehicles and road length from the Ministry of Transportation and the Central Bureau of Statistics. Meanwhile, we obtained the number of landfills, industrial companies, and coal-fired power plants from the Provincial Government. Difficulties occur when estimating the current level of carbon emissions produced and discussing the Air Pollution Standard Index (APSI), calculated based on the upper and lower limit values, upper and lower environmental limits, and environmental concentrations measured. We need discussions with transportation and environmental experts to determine estimates and scenarios.

2.2. The dynamic systems concept

Simulation models with system dynamics refer to qualitative and quantitative approaches (Coyle, 2000). The use of a qualitative systems thinking approach (soft systems methodology) in operational processes is facilitated by the use of Powersim constructor software as a cognitive mapping tool or formulating models as a quantitative system thinking approach (system dynamics) (Staadt, 2015; Duggan, 2016a). The main objective of dynamic system analysis, according to Warren (2006), is to answer three questions: why pollution is increasing (why), where or in what position should action be taken so that air quality can be lowered according to quality standards (where), and how to change it (how), this last question is more likely to be about the policy that will be taken.

It can be said that system dynamics is a method for describing how a system changes over time (Şenaras, 2017). In each model, the feedback structure is expected to have several loops to meet the requirements of a model. Models tested many times will last long, even in extreme (strong) conditions. Esteso et al. (2023) added that the model must also have many points of contact with the real world, where repeated comparisons with the real world will strengthen the model.

Regarding system dynamics, the trend of increasing air pollution levels in Jakarta continually increases and decreases at certain times, then increases again, as depicted in Figure 1, containing a certain meaning called behavior or dynamics (Brennan and Molloy, 2020). Behavior arises from where or by whom. In system dynamics, the question is what the value or number of the quantity will be at a future point in time (Duggan, 2016b).

Figure 1. Number of motorized vehicles and air quality in Jakarta, 2023.

2.3. Initial values and parameters

Analyzing system dynamics modeling helps produce relationships between parameters and components of air pollution reduction models. This relationship can be estimated and made into a scenario if the data is available in numerical form. Secondary data resources generally acquire Initial values and parameters (Favereau et al., 2020). If secondary data is unavailable, this value can be estimated by processing supporting or numerical data on primary and secondary data. In order to cover the relationship model between variables, initial values need to be determined at constants, function tables, and indicator levels. For example, the auxiliary air quality index can be calculated from levels and constants, so complicated initial value calculations are not required.

Therefore, determining parameter values must consider the effect on model sensitivity. In this case, changes in the structural model will appear more sensitive than in the feedback model. Therefore, estimates in this study are only made at the required level of accuracy. For modeling purposes, this research will consider trends toward long-term changes, understanding the nature of system dynamics and alternative design policies. Therefore, behavioral sensitivity and policy sensitivity will be prioritized. (Hekimoglu and Barlas, 2016).

The initial values and parameters used in modeling are presented in the following Table 1. These values are mostly acquired from secondary data and must be from important references (Duggan, 2016a), and some values may be acquired in estimates based on reliable-considered qualitative information (Schoenenberger et al., 2021).

Table 1. Initial values and model parameters (2022).

No	Indicators	Initial Value/ Parameters (endogenous variable)	Unit	Source
A.	Motor vehicle:			
	Number of motor vehicles	26,370,535	Unit	S
	Buses	37,180	Unit	S
	Motorbike	17,304,447	Unit	S
	Truck cars	748,395	Unit	S
	Passenger cars	3,766,059	Unit	S
	Number of motor vehicles last year	21,289,309	Unit	S
	Number of new motor vehicles	566,772	Unit/year	C
	Average vehicle growth ratio	2.14	Percent/year	C
	Vehicle mutation	0.1	Percent/year	C
	The ideal ratio of the number of vehicles	15,839,900	unit	S
	Percentage of motor vehicle pollution	45	Percent//APSI	S
	Vehicle pollution reduction ratio	50	Percent/year/APSI	E
B.	Road length and traffic density:			
	Road length	7208	Km	S
	Vehicle ratio and road length	3:1	Vehicle/meter	C
	Ideal vehicle-length road ratio	1:2	unit/meter	C
C.	Industry:			
	Industrial number of residual gas exhaust chimneys	114	Company/unit	S
	Industry growth ratio	1.4	Percent/year	E
	Industrial pollution ratio	35	Percent/year	E
	Industrial pollution reduction ratio	50	Percent/year/APSI	E
	Percentage of pollution by industry	15	Percent//APSI	S
D.	Power plant:			
	Number of coal-based power plants	16	Company/unit	S
	Power plant growth ratio	1.2	Percent/year	E
	Coal combustion reduction ratio	50	Percent/year/APSI	E
	Power plant pollution percentage	20	Percent//APSI	S
E.	Landfill:			
	Number of Landfills	1004	unit	S
	Number of waste deposits	3.1	Million tons	S
	Landfill growth ratio	2.8	Percent/year	E
	The amount of waste burned in the Landfill	240.25	Gg/year	S
	The ratio of waste incineration in Landfill	20	Percent/year	E
	Waste incineration ratio: carbon	52.56	Gg/year	C

Table 1. (*Continued*).

No	Indicators	Initial Value/ Parameters (endogenous variable)	Unit	Source
	Waste incineration reduction ratio	50	Percent/year/APSI	E
	Percentage of pollution in Landfill	15	Percent/APSI	S
	The amount of carbon emissions produced today	12,627.34	Gg/year	S
	Maximal normal air quality index	50	APSI	S
	Current air quality index	161	APSI	S
F.	Scenario:			
	Scenario reduction in the number of vehicles	5–10	Percent	Sc
	Landfill burn Reduction Scenario	5–10	Percent	Sc
	Industrial exhaust gas reduction scenario	5–10	Percent	Sc
	The Power Plan Company coal combustion reduction scenario	5–10	Percent	Sc

Abbreviation: S = Obtained from secondary data, E = Estimation based on qualitative information, C = Calculated by accounting, Sc = Scenario model.

2.4. Parameter definitions

1) Growth in the number of motorized vehicles

The required data is the growth of the motorized vehicle population from 2018–2022 and the types of motorized vehicles, i.e., motorbikes, buses, trucks, and passenger vehicles. The increase in the motorized vehicle population is based on the type of vehicle calculated within a specified period. Data on the average growth rate of motorized vehicles is 2.12% per year, and data on the growth in the number of used motorized vehicles, transfers, and growth ratios. The number of used motorized vehicles is calculated on a unit basis, and the ratio is set at 1%. Meanwhile, the number of expired motorized vehicles is calculated within units, and the ratio is set at 1% per year. The transfer will remove the motorized vehicle from the ownership system by removing the file and registering it in another region. The average transfer rate is set at 1%.

2) Road length and density

The roads in Jakarta are 7208 km, and the number of vehicles is 26,370,535 units. According to the Ministry of Transportation, the ideal road length is 12,000,000 km. This information shows that the ideal number of vehicles is 15,839,900 (Adam, 2019).

3) Concentration of power plants and residual exhaust gas of industrial chimneys

Umasugi (2019) and Ramli (2023) revealed that 114 industries or factories in Jakarta were identified as having residual exhaust gas chimneys. This residual exhaust gas is considered ineligible to quality standards and pollutes the environment. This year’s inspections target 90 companies from 114 industrial activities identified as having residual exhaust gas chimneys: Steam Power Plants (SPP), Diesel Power Plants (DPP), and electronic and industrial waste.

4) Amount of waste, landfills, and burning of waste

Jakarta is the largest waste producer in Indonesia and contributes 7500 tons of waste per day or 3.1 million tons of Landfill. It is estimated that 5%–15% of the waste incinerated at the Landfill causes air pollution (Satispi and Samudra, 2022). Expert of Recycling Supply Chain from Waste4Change, Lathifah A. Mashudi, suggests that waste-incineration activities in the Bodetabek Megapolitan regions reach 240.25 Gg/year, producing 12,627.34 Gg/year for carbon emissions and 9.42% CO_2 from greenhouse gas emissions (Ramli, 2023). Emissions from waste-incineration activities are CO, SO_2, O_3, HC, CH_4, NO_2, PM 10, and PM 2.5. Air Pollutant Standard Index Categories are as follows.

5) Air pollutant standard index category

Indonesia uses APSI standards, i.e., the air pollution standard index that informs ambient air quality to determine air pollution standards. The APSI standard is determined at an average of 50 points of APSI. IQair data on August 2023 recorded pollution standards in the capital city were above the WHO standard, namely 161 points of APSI; finally, according to the World Air Quality Report from IQAir, Jakarta's air quality was classified as the worst compared to the capital city of ASEAN countries (Annur, 2023).

The Ministry of Environment and Forestry has prepared APSI (**Table 2**). The aim is to provide convenience from uniform information between ambient air to locations in community locations at a particular time and as a consideration in making efforts to control air contamination at the central Government and regional governments.

Table 2. Conversion of concentration values.

APSI	24 Jam (ug/m^3)						
	PM 10	PM 2.5	SO_2	CO	O_3	NO_2	HC
0–50	50	15.5	52	4000	120	80	45
51–100	150	55.4	180	8000	235	200	100
101–200	350	150.4	400	15,000	400	1130	215
201–300	420	250.4	800	30,000	800	2260	432
>300	500	500	1200	45,000	1000	3000	648

Additional information: 24-h continuous measurement data; Results of calculating APSI particulate parameters (PM 2.5) per hour for 24 h; The results of calculating APSI parameters of particulate matter (PM 10), sulfur dioxide (SO_2), carbon monoxide (CO), Ozone (O_3), Nitrogen dioxide (NO_2), and hydrocarbons (HC) are taken from the highest APSI parameter values and informed every hour.

The Air Pollution Standard Index (APSI) is calculated under upper and lower limit values, the upper and lower ambient limits, and the ambient concentration of the measurement results. The following is the mathematical equation:

$$I = \frac{I_a - I_b}{x_a - x_b}(x_x - x_b) + I_b$$

where: I = calculated APSI, I_a = APSI upper limit, I_b = APSI lower limit, X_a = upper limit of ambient concentration (µg/m^3), X_b = lower limit of ambient concentration (µg/m^3), X_x = real ambient concentration measurement results (µg/m^3).

This mathematical equation determines the parameters used to calculate APSI, namely particulates measuring 10 µm (PM 10), sulfur dioxide (SO_2), carbon monoxide (CO), oxidants in the form of ozone (O_3), and nitrogen dioxide (NO_2). The results will determine whether the air quality is a good or dangerous category.

- Good Category (1–50): The Air Pollution Standard Index in the Good category has a value range of 1 to 50 and does not negatively affect humans, animals, and plants.

- Medium Category (51–100): The Medium category APSI has a value range of 51 to 10, where the air quality level is still acceptable for human, animal, and plant health.
- Unhealthy Category (101–200): The APSI category for Unhealthy has a range of 101–200, meaning that the air quality level harms humans, animals, and plants.
- Very Unhealthy Category (201–300): The APSI category of Very Unhealthy ranges from 201 to 300, where air quality can increase health risks in some exposed population segments.
- Hazardous Category (>300): The Hazardous APSI category has a value range of more than 300, meaning that the air quality level can seriously harm the health of the population, and immediate treatment is needed (Wibawana, 2023).

6) Increase in carbon emissions

Indicators for measuring air quality are by using levels of Hydrocarbons (HC), Carbon monoxide (CO), Sulfur dioxide (SO_2), Nitrogen dioxide (NO_2), Ozone (O_3), and Particulates (PM 10 and PM 2.5). APSI defines good air quality as ranging from 0 to 50. Under normal conditions, ambient air quality standards consist of 20% oxygen, 78% nitrogen, 0.93% argon, and 0.03% carbon dioxide. Based on IQAir data, Jakarta's air quality index in August 2023 will reach 161 points. It means that the level of air pollution in Jakarta is very high, so the air quality is classified as unhealthy. The main pollutants in the air include carbon dioxide (CO_2), nitrogen oxides (NOx), particulate matter (PM) 2.5, particulate matter (PM) 10, and sulfur dioxide (SO_2). According to the Jakarta Air Pollution Emission Inventory report, in 2018, the air in the capital city assumed the burden of pollution from various types of pollutants with CO_2 volumes: 298,170 tons, NOx: 106,068 tons, PM 2.5: 8817 tons, PM 10: 7842 tons, and SO_2: 4257 tons. These various pollutants generally derive from the transportation sector and processing industry. The transportation sector is considered the main contributor of CO_2 (96.36% of the total pollution volume in Jakarta in 2018), NOx (72.40%), PM 2.5 (67.03%), and PM 10 (57.99%). On the other hand, the processing industry sector is the most significant source of pollutants for SO_2 (61.96%) and the second largest contributor for NOx (11.49%), PM 10 (33.9%), and PM 2.5 (26.81%) (Ahdiat, 2023). In this study, we did not concentrate on discussing the chemistry of pollutants, but the data helps us understand the dangers of high pollution levels.

3. Results

3.1. Model flowchart

In system dynamics analysis, the development of the number of motorized vehicles was illustrated in a flowchart diagram of new, used, and transferred vehicles. The flowchart diagram generated two loops and the Motorized Vehicles Population in Stock. Loop 1 was the growth of motorized vehicles; Loop 2 was represented by transfers, damaged cars, expired car documents, and no longer operating on the highway. The flowchart diagram (+)/Loops-1 shows that the growth of motorized vehicles increased by an average of 2.13% per year. This assumption was still below reports published by national news, where the growth rate has reached above 4%. Meanwhile, the flowchart diagram (−)/Loops-2 explained the balancing as indicated by a reduction in motorized vehicles caused by transfers, which was assumed to be around 1% of the total motorized vehicles.

From **Figure 2** below, the flowchart diagram of road density was expressed as Stock. The flowchart diagram for road density levels presented 1 loop, i.e., the road length addition and density ratio. The Vehicle Pollution flowchart diagram presented 2 Loops, where they are Stock. Loop 1 showed the nature of a pollution increase by vehicles. In loop 1, pollution levels increased due to various variables, for example, the growth rate of motorized vehicles, density, and traffic jams, while loop 2 was a reduction in pollution levels by vehicles as a balance.

The landfill flowchart diagram presented 2 Loops, and the Landfill was 'Stock'. Loop 1 showed the landfill growth. In loop 1, pollution levels increased due to uncontrolled waste incineration at a ratio of 20% per year. Loop 2 was a reduction in waste-incineration at the Landfill by 10% to halve the total pollution level of 15%/APSI.

Furthermore, the Industrial flowchart diagram was Stock with two loops. Loop 1 was the growth of the residual gas exhaust industry at 1.4% per year. Meanwhile, Loop 2 was a balancing or negative (−), i.e., a reduction in pollution from a residual gas exhaust industry is set at 15% for a total of 15%/APSI. Finally, the Power Plant flowchart diagram was Stock and had two loops. Loop 1 was the growth of the residual gas exhaust industry at 1.4% per year. Meanwhile, Loop 2 is balancing or negative (−), i.e., a reduction in pollution from a residual gas exhaust industry is set at 20% for a total of 15%/APSI (**Figure 2**).

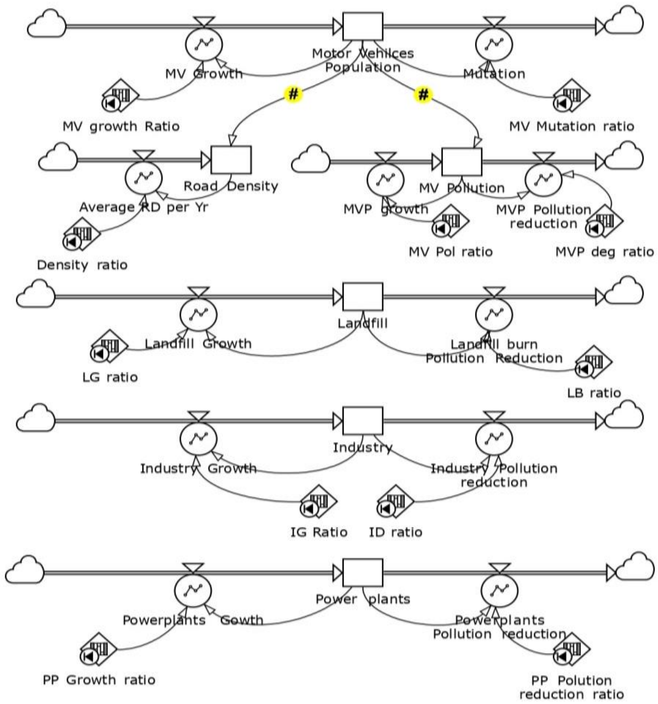

Figure 2. Polluting variable flow chart.

3.2. Modeling behavior

Initial values and parameters are used in generating the model the dynamic system requires (see **Table 1**). In order to acquire validity, the model was tested using the Historical Behavior Test Model and the Fitment (Conformity) Statistical Test

Model. This test model would stimulate air pollution reduction related to planned motorized vehicle restriction policies. The test results are presented in **Table 3** and **Figure 3**.

Table 3. Model conformity statistical test results.

No.	Variables	RMSPE	Theil Inequality Statistics		
			U^m	U^S	U^C
1.	Number of motor vehicles	0.0593	0.0156	0.0864	0.1538
2.	Traffic Density Level	0.1732	0.0752	0.4032	0.0363
3.	Waste Incineration in Landfill	0.0410	0.7524	0.5940	0.6622
4.	Coal Power Company	0.1848	0.0112	0.0048	0.2939
5.	Air Quality	0.3279	0.5516	0.3072	0.5569

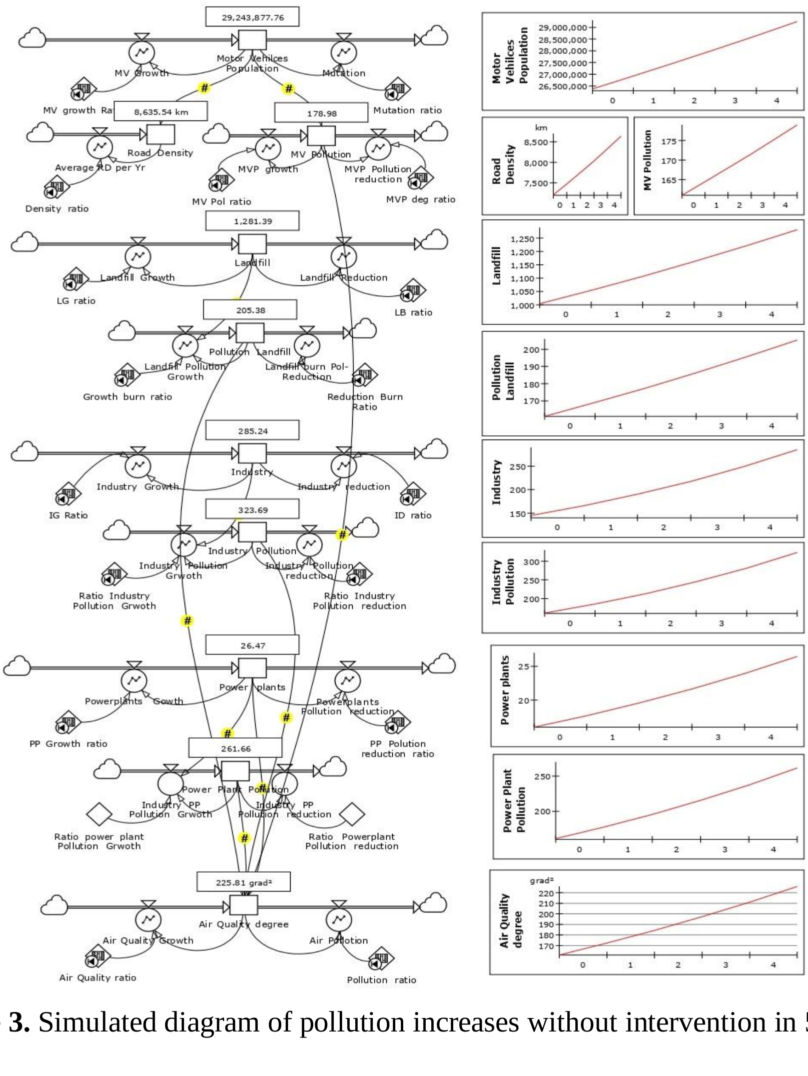

Figure 3. Simulated diagram of pollution increases without intervention in 5 years.

3.3. Behavioral test model

1) Historical behavioral test model

Testing was required to determine whether the model was developed following the existing system (historical behavior) by comparing the results of computer dynamic system simulations with empirical data in the field (Paine, 2022). The developed model is declared valid if the computer simulation results match and are similar to empirical data. A valid model can be used as an experimental tool to analyze government policy. Comparative analysis of historical behavior with the behavior of the simulation model resulted in a reduction in the number of motorized vehicles, pollution levels, and road density levels. The simulation results of the conformity test of the behavioral model with historical behavior showed the conformity of the behavior and were appropriate for use as a basis for long-term policy simulations.

2) Fitment (conformity) statistical test model

To measure the level of confidence of the model built in representing actual behavior, a set of statistical tests was used to test its validity. Given that in system dynamics modeling, historical data is not directly used to construct the model, the model size was adjusted to actual conditions (goodness-of-fit), and the significance tests that are always used in econometric modeling are not conformed to implement (Tezel et al., 2021). For this reason, the root mean square percent error (RMSPE) and Theil inequality statistics can be used to measure the magnitude and nature of the error (Chai and Draxler, 2014). RMSPE measures the root mean square of the proportion of differences between simulated and actual values (Narwane et al., 2021). Meanwhile, Theil's inequality statistics divide the mean square error (MSE) into components that measure the parts of the error caused by bias (the proportion of biased inequality), inequality of variance (the proportion of variance from inequality), and the covariance of unequal (covariance proportion of inequality). In order to apply Theil statistics in health model testing, the following items were considered:

a) Big U^m, U^S, small U^C: indicated error due to bias. This error was a systematic error between the model and reality or an error in determining specification parameters.
b) Errors caused by inequality of variances. This error was also systematic and had two types of error, namely:
   - Big U^S, small U^m, and correlated with U^C; the mean was the same, but the mean-variance differed. This situation showed that the simulated and actual values had different trends.
   - Big U^S and $U^m = 0$, and small U^C small, indicating that the value has cycles that are not present in the simulated value.
c) Big U^C, U^m, small U^S: indicated errors due to covariance inequality. According to Naumov Oliva (2018), this was caused by the simulated and actual average values being the same, but the phases were different, and these error corrections were required. In increasing model confidence to produce system behavior like the real situation, U^C and U^S errors and failures must be small; otherwise, models with significant errors are unacceptable (Schoenenberger and Tanase, 2017). Acceptable error variables in this model are summarized in **Table 3**.

Table 3 showed that there were root mean square errors (RMSPE) from the indicators tested, where the errors occurred systematically between the model and reality, or perhaps due to errors in determining the specification parameters (Schoenberg et al., 2023). The results showed a reduction in motorized vehicles of 15.38 U^C and a density level of 3.63 U^C, where these two values showed a tendency towards imperfect variance (U^S); the correlation was high, but the mean variance was different. Thus, the simulated values and the actual situation will always be different.

However, in actual conditions, the number of motorized vehicles, density levels, waste incineration at the Landfill, industrial pollution, and power plants are predicted always to have different influences each year and will greatly determine the value of Air Quality. For example, this difference occurs if the number of motorized vehicles, industrial and power plant pollution decreases, and the exegetical variable of climate change will greatly influence the reduction in air pollution by 80–50 points of APSI (half of the current pollution of 161 points of APSI, Indonesia IQAir indicator). In conclusion, the conformity value of the statistical test results was considered good in determining the validity of the model generated in imitating historical behavior. Even though errors occurred, they were still within the tolerance limits for this analysis, namely, not exceeding a value of 1.0 (Qudrat-Ullah and Seong, 2010).

4. Discussion

4.1. Current conditions and scenario determination

Figure 4 below simulates that in 2027, the number of motorized vehicles will reach 31,045,152 units, while the length of the road is assumed to remain 7213.77 km. The curve on the right illustrates a straight rising red line, which contains a 1-meter-long road—occupied by four motorized vehicles. The solution is that the level of road density must be loosened by reducing the number of motorized vehicles. The Government of the capital city of Jakarta has no other solution at present or in the future.

In the flowchart, logically, the number of motorized vehicles increases because of many indicators. For example, easy credit of ownership, discount promotions, low tax rates, and vehicle surcharge costs. This variable is called exogenous and is not the subject of this research, but can be intervened in further models of study. Weight is the carrying capacity of a motorized vehicle measured based on the total tonnage or cylinder volume, which is expressed with a coefficient of 1–1.3 and is different for each type of vehicle. Weight is a development of the surcharge tax concept (Zhao and Sun, 2022).

Regarding pollution by motorized vehicles, if we look closely, perhaps the increase in air pollution is caused by a lack of government anticipation with pro-public health policies, so the number of motorized vehicles is out of control. The impact of motor vehicles explains the increasing evidence of the negative impact of air pollution on health and well-being (Noël et al., 2022) and also by traffic density (Huang et al., 2021). A study in Iran describes stricter pollution standards and more attention focused on pollutants emitted from cars. As a very dangerous pollutant, NOx always triggers the sensitivity of relevant organizations. In the process of developing and designing machines, estimating the amount of these pollutants is critical to reducing future health costs. In order to determine dangerous levels, the determination uses the Zeldovich approach to calculate NOx values with an error of 20% (Keshavarzzadeh et al., 2023).

Study in Bogotá, Colombia, levels of fine particulate matter (PM 2.5) often exceed air quality guidelines, resulting in adverse health impacts. The main sources of PM 2.5 pollution was clearly identified by applying a modeling framework based on the Community Multiscale Air Quality Modeling System (CMAQ), where suspended dust from unpaved roads is the largest local source of PM 2.5 and can contribute more than 30% of seasonal average concentrations all over the city. Combined vehicles, industrial activity, and unpaved road dust are responsible for more than 60% of PM 2.5 pollution (East et al., 2021).

Most research on waste burning has occurred in India, Nepal, and Kathmandu, which causes severe air pollution with high concentrations of aerosols and gas pollutants (Saikawa et al., 2020; Islam et al., 2020). Apart from that, Bekun (2022) researched the case of emissions mitigation in India. As a developed industrial country and a large producer of carbon emissions, India should be able to overcome climate change and its impacts, which requires innovation in finding energy for sustainable development. Burning of rubbish in Pokhara, Nepal, reveals that open burning of rubbish has caused air pollution. This pollution is a cause for concern because of weak public awareness (Zhong et al., 2019; Choi et al., 2021). A study in Qatar examined the widespread use of landfills; even today, it is important to examine the environmental and health problems that cause carcinogenic and non-carcinogenic effects on exposed populations living nearby (Siddiqua et al., 2022).

Not only burning waste, heavy and coal-based industry is also a significant cause of air pollution. A study in China showed that the industrial sector was the cause of inorganic mercury pollution, and the cause could be traced to heavy industrial production in Tangshan City (Hu et al., 2022). Many studies in China highlight the influence of environmental factors on industrial pollution transfer. The results obtained indicate that industrial superiority is the main factor in increasing the transfer of industrial pollution in China (C Li et al., 2021). High air pollution from industry also has an impact on tourism (Hao et al., 2021), which entails environmental regulations and industrial restructuring is highly relevant to environmental governance and green development, and previously, some of this evidence was presented in research by Xu et al. (2021) and Wang and Zhou (2021).

Regarding pollution from coal-based power plants, research in China introduced a new Environmental Protection Tax Law in 2018, which taxes pollutants to a higher standard. Most existing studies have investigated the impact of environmental taxes (ET) at the city or provincial level, estimating their impact on pollutant reduction at fossil fuel power plants in 30 provinces in China. The results show that RE has a positive impact on reducing pollutant emissions compared to the pollution removal fee policy. Empirical evidence shows that sulfur dioxide (SO_2), nitrogen oxides (NOx), and dust from fossil fuel power plants have decreased significantly after the implementation of the policy (P Li et al., 2021; Wei and Yao, 2022). The environmental tax rate (ETR) is the environmental fee charged to companies for pollution emissions, while the corporate law tax rate (CTR) is the rate companies must pay on net income. These two factors have an explicit role in determining environmental performance (Farooq et al., 2023). The conventional methods applied so far are no longer possible to continue. However, the consideration of using the Leviathan hypothesis (Millsap et al., 2019) is still possible to increase vehicle taxes as implemented in several developed countries, such as Japan, and not follow the pressure group from the Vehicle Brand Holder Sole Agent (BHSA). Also, currently developing issues, such as global warming, environmental protection, and carbon emissions, can be used as indicators for increasing additional tariffs or similar taxes to reduce vehicle congestion or restrictions (Williams et al., 2021; Oderinwale and van der Weijde, 2017). These various alternatives can be formulated using beneficially strict calculations to reduce air pollution levels in Jakarta. On the other hand, this exogenous variable can be used to suppress the growth in the number of motorized vehicles plus the imposition of high emission costs. This study can be continued by subsequent researchers.

The four main causes described above occurred in Jakarta city and became a reference for developing the designed model scenario. From **Figure 2**, a scenario model is designed that can simulate air pollution reduction policies. The data used consists of:

- The simulation was set from 2022–2027 using two scenarios, i.e., moderate (25%) and optimistic (50%).
- The variables and indicators underlying the scenario were motorized vehicle growth (2.21% per year), air pollution (161 points of APSI); highway density, ratio of road length versus number of motorized vehicles (1:3), Landfill growth, industrial growth, power plant growth, landfill growth ratio, industrial growth ratio, and power plant growth ratio.

The simulation in **Figure 3** showed that the air quality would be very worrying in 2023–2027. Without intervention, air pollution reached 225.81 points of APSI, close to the hazardous category (>300). APSI described that the hazardous category had a value range of <300, where the air quality level could seriously harm the population’s health and required quick and immediate handling. **Figure 3** of the simulation included the following:

4.2. Moderate scenario simulation

The following scenario aimed to generate a problem-solving model based on the information in **Table 1**, where all indicators contributed to the model. The model was expected to have the capacity to describe predictions comprehensively and could anticipate adverse possibilities in the future.

The structure of the scenario model in **Figure 4** was a continuation of the simulation from the **Figure 3** model and showed two loops. The Air Quality scenario was Stock, while loop 1 was air quality growth, and loop 2 was air pollution. Loop 2 was considered as the balancing or negative (−). The stock value was 161 points of APSI and was influenced by four variables. The result was a reduction in air pollution to 112.01 points of APSI. This figure is still above the APSI standard specified as clean air. Therefore, the simulation needs to continue with the optimistic scenario in **Figure 4**.

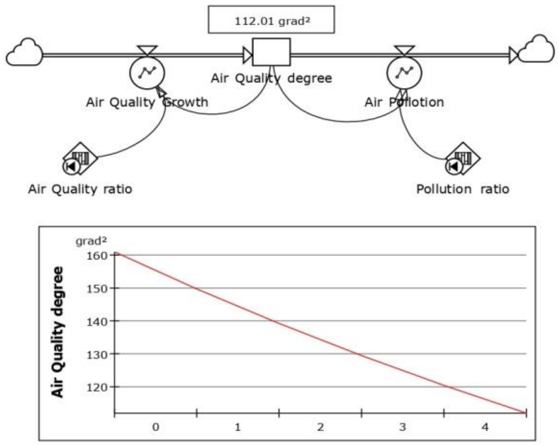

Figure 4. Simulated air pollution reduction intervention moderate scenario.

4.3. Optimistic scenario analysis

In the optimistic scenario analysis, the curve appeared to be increasingly sloping, and in 2027, air quality would have reached 50 points. Optimistic scenarios were intervened with a 50% reduction in the number of vehicles and a reduction of incineration at the landfills, industries, and power plants. Please note that a reduction in motorized vehicles has been done by implementing the odd-even system policy since 2022. It means the pollution causes were concentrated in incineration variables at the landfills, industries, and power plants. This scenario ignored the population growth at the landfills, industries, and power plants. If reduction interventions are conducted on these three variables, it can be predicted that in May 2024, air quality in Jakarta will reach 45.01 (**Figure 4**).

As a comparison, the moderate and optimistic simulation results are presented in the following **Table 4**.

Table 4. Comparison of 2023 polluters and air conditions and 2027 predictions.

Polluters	**2023**				**2027**			
	Current pollution level*	**Pollution percentage**	**Amount/Unit**	**Pollution/ Unit****	**Amount/Unit**	**Current pollution level***	**Scenario moderate***	**Scenario optimistic***
Motor Vehicle	161	45%	26,370,535	0.00000275	29,243,878	179	89	36
Landfill/Landfill	161	15%	1004	0.024	1281	205	103	41
Industri	161	15%	145	0.167	285	316	158	63
Power Plan	161	20%	16	2.013	26	262	131	52
Others/cigarette	161	5%	70,200,000	0.0000001	70,200,000	161	81	32
Average	161	100%	-	-	-	225	112	45

*APSI, **APSI/unit.

5. Conclusion

The results of this research explain that the leading causes of air pollution in Jakarta in calculation units come from power plants (2.013), industry (0.167), and Landfill (0.024). Motorized vehicles, considered the primary cause of pollution, contribute only 0.0000028 per unit. The dangerous pollution level calculated by IQAir is currently 161 points and will continue to rise if the Government fails to intervene with quick policies. A moderate simulation of 50% shows that it can only reduce pollution levels by 112.01 points in 2027, while an optimistic simulation shows a significant reduction in pollutants to 45.01 points. From the above scenario, a good choice is to use an optimistic scenario, which helps control the causes of air pollution from power plants and coal-based industries. The Government also needs to be careful in implementing motor vehicle reduction policies, which will reduce local government revenues. Further research needs to be carried out by adding other indicators influencing the model. The findings show that the three research hypotheses have been proven correct.

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References

Adam S (2019). Pantas Sering Macet, Panjang Jalan di Jakarta Cuma Segini, Ternyata Ini Idealnya. GridOto.Com.

Ahdiat A (2023). 5 Jenis Polutan Utama yang Mencemari Udara Jakarta. Katadata.Co.Id.

Annur CM (2023). Kualitas Udara Jakarta Lebih Buruk dari Ibu Kota ASEAN Lainnya. Katadata.Co.Id.

Bekun FV (2022). Mitigating Emissions in India: Accounting for the Role of Real Income, Renewable Energy Consumption and Investment in Energy. IJEEP 12(1): 188-192. doi: 10.32479/ijeep.12652

BPS (2022a). Jumlah Kendaraan Bermotor Menurut Jenis Kendaraan (unit) di Provinsi DKI Jakarta 2020–2022.

BPS (2022b). Realisasi Pendapatan Pemerintah Provinsi DKI Jakarta Menurut Jenis Pendapatan (ribu rupiah) 2018–2022.

Brennan C, Molloy O (2020). A system dynamics approach to sustainability education. Syst Res Behav Sci 37(6): 875-879. doi: 10.1002/sres.2755

Chai T, Draxler RR (2014). Root mean square error (RMSE) or mean absolute error (MAE)?—Arguments against avoiding RMSE in the literature. Geosci Model Dev 7(3): 1247-1250. doi: 10.5194/gmd-7-1247-2014

Choi E, Shrestha N, Bhandari TR (2021). Open waste burning contrary to other air pollution-related perceptions and practices in Pokhara, Nepal. Archives of Environmental & Occupational Health 77(9): 721-733. doi: 10.1080/19338244.2021.2004985

Clinten B (2023). Riset TomTom: Jakarta Kota Termacet Nomor 29 di Dunia. Kompas.Com.

CNN (2023). Bukan Kendaraan, Studi Ungkap Sumber Polusi Udara Sesungguhnya. CNN Indonesia.

Coyle G (2000). Qualitative and Quantitative Modelling in System Dynamics: Some Research Questions. System Dynamics Review 16: 225-244. doi: 10.1002/1099-1727(200023)16:3<225::AID-SDR195>3.0.CO;2-D

Duggan J (2016a). An Introduction to System Dynamics. In: System Dynamics Modeling with R. Springer International Publishing.

Duggan J (2016b). System Dynamics Modeling with R. Springer International Publishing. doi:10.1007/978-3-319-34043-2

East J, Montealegre JS, Pachon JE, Garcia-Menendez F (2021). Air quality modeling to inform pollution mitigation strategies in a Latin American megacity. Science of The Total Environment 776: 145894. doi: 10.1016/j.scitotenv.2021.145894

EREN ŞENARAS A (2017). Structure and Behavior in System Dynamics: A Case Study in Logistic. Isarder 9(4): 321-340. doi: 10.20491/isarder.2017.334

Esteso A, Alemany MME, Ottati F, Ortiz Á (2023). System dynamics model for improving the robustness of a fresh agri-food supply chain to disruptions. Oper Res Int J 23(2). doi: 10.1007/s12351-023-00769-7

Farooq U, Subhani BH, Shafiq MN, Gillani S (2023). Assessing the environmental impacts of environmental tax rate and corporate statutory tax rate: Empirical evidence from industry-intensive economies. Energy Reports 9: 6241-6250. doi: 10.1016/j.egyr.2023.05.254

Favereau M, Robledo LF, Bull MT (2020). Homeostatic representation for risk decision making: A novel multi-method simulation approach for evacuation under volcanic eruption. Nat Hazards 103(1): 29-56. doi: 10.1007/s11069-020-03957-2

Fisher D (2018). Reflections on Teaching System Dynamics Modeling to Secondary School Students for over 20 Years. Systems 6(2): 12. doi: 10.3390/systems6020012

Hanna R, Kreindler G, Olken BA (2017). Citywide effects of high-occupancy vehicle restrictions: Evidence from "three-in-one" in Jakarta. Science 357(6346): 89-93. doi: 10.1126/science.aan2747

Hao Y, Niu X, Wang J (2021). Impacts of haze pollution on China's tourism industry: A system of economic loss analysis. Journal of Environmental Management 295: 113051. doi: 10.1016/j.jenvman.2021.113051

Hekimoğlu M, Barlas Y (2016). Sensitivity analysis for models with multiple behavior modes: a method based on behavior pattern measures. System Dynamics Review 32(3-4): 332-362. doi: 10.1002/sdr.1568

Hertasning B, Samudra AA, Satispi E, et al. (2022). Strategi Zonasi Penggunaan Kendaraan Bermotor dengan Pendekatan Zona Parkir Progresif dan Zona Rendah Emisi dalam Mewujudkan Kota Ramah Lingkungan. JPTD 24(2): 119-126. doi: 10.25104/jptd.v24i2.2175

Hu S, Ren F, Jia J, et al. (2022). Exploring the environmental properties and resource utilization of construction waste in Beijing-Tianjin-Hebei region. Environ Sci Pollut Res. doi: 10.1007/s11356-022-23327-8

Huang Y, Lei C, Liu CH, et al. (2021). A review of strategies for mitigating roadside air pollution in urban street canyons. Environmental Pollution 280: 116971. doi: 10.1016/j.envpol.2021.116971

IQAir (2023). Air quality in Jakarta: Unhealthy for Sensitive Groups. IQAir.

Islam MdR, Jayarathne T, Simpson IJ, et al. (2020). Ambient air quality in the Kathmandu Valley, Nepal, during the pre-monsoon: concentrations and sources of particulate matter and trace gases. Atmos Chem Phys 20(5): 2927-2951. doi: 10.5194/acp-20-2927-2020

Keshavarzzadeh M, Zahedi R, Eskandarpanah R, et al. (2023). Estimation of NOx pollutants in a spark engine fueled by mixed methane and hydrogen using neural networks and genetic algorithm. Heliyon 9(4): e15304. doi: 10.1016/j.heliyon.2023.e15304

Li C, Xia W, Wang L (2021). The transfer mechanism of pollution industry in China under multi-factor combination model—Based on the perspective of industry, location, and environment. Environ Sci Pollut Res 28(42): 60167-60181. doi: 10.1007/s11356-021-14643-6

Li P, Lin Z, Du H, et al. (2021). Do environmental taxes reduce air pollution? Evidence from fossil-fuel power plants in China. Journal of Environmental Management 295: 113112. doi: 10.1016/j.jenvman.2021.113112

Millsap AA, Hobbs BK, Stansel D (2019). Local Governments and Economic Freedom: A Test of the Leviathan Hypothesis. Public Finance Review 47(3): 493-529. doi: 10.1177/1091142118817909

Narwane VS, Raut RD, Yadav VS, et al. (2021). The role of big data for Supply Chain 4.0 in manufacturing organisations of developing countries. JEIM 34(5): 1452-1480. doi: 10.1108/jeim-11-2020-0463

Noël C, Van Landschoot L, Vanroelen C, Gadeyne S (2022). The Public's Perceptions of Air Pollution. What's in a Name? Environmental Health Insights 16: 117863022211235. doi: 10.1177/11786302221123563

Oderinwale T, van der Weijde AH (2016). Carbon taxation and feed-in tariffs: Evaluating the effect of network and market properties on policy effectiveness. Energy Syst 8(3): 623-642. doi: 10.1007/s12667-016-0219-3

Paine J (2022). Dynamic supply chains with endogenous dispositions. System Dynamics Review 39(1): 32-63. doi: 10.1002/sdr.1725

Puspaningtyas L (2023). YLKI: Indonesia Surplus Listrik. Repbulika.

Qudrat-Ullah H, Seong BS (2010). How to do structural validity of a system dynamics type simulation model: The case of an energy policy model. Energy Policy 38(5): 2216-2224. doi: 10.1016/j.enpol.2009.12.009

Rahadianto NA, Maarif S, Yuliati LN (2019). Analysis of intention to use transjakarta bus. Ind Jour Manag & Prod 10(1): 301. doi: 10.14807/ijmp.v10i1.748

Ramli RR (2023). Emisi Karbon Pembakaran Sampah di Jabodetabek Setara Kebakaran 108.000 Hektar Hutan. Kompas.Com.

Saikawa E, Wu Q, Zhong M, et al. (2020). Garbage Burning in South Asia: How Important Is It to Regional Air Quality? Environ Sci Technol 54(16): 9928-9938. doi: 10.1021/acs.est.0c02830

Sandi MR (2022). Jakarta Provincial Government Proposes Draft Regulation on Restricting Private Vehicles. Sindonews.

Satispi E, Aziz Samudra A (2022). Study of Policy Implementation: Strategy of COVID-19 Plastic Waste Management in Indonesia. JPPA 6(4): 155. doi: 10.11648/j.jppa.20220604.11

Schoenberg W, Hayward J, Eberlein R (2023). Improving Loops that Matter. System Dynamics Review 39(2): 140-151. doi: 10.1002/sdr.1728

Schoenenberger L, Schmid A, Tanase R, et al. (2021). Structural Analysis of System Dynamics Models. Simulation Modelling Practice and Theory 110: 102333. doi: 10.1016/j.simpat.2021.102333

Siddiqua A, Hahladakis JN, Al-Attiya WAKA (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. Environ Sci Pollut Res 29(39): 58514-58536. doi: 10.1007/s11356-022-21578-z

Staadt J (2015). The Cultural Analysis of Soft Systems Methodology and the Configuration Model of Organizational Culture. SAGE Open 5(2): 215824401558978. doi: 10.1177/2158244015589787

Supriana FJR, Siregar ML, Tangkudung ESW, Kusuma A (2020). Evaluation of Odd-Even Vehicle Registration Number Regulation Before and After Expansion of the Rule in Jakarta. In: Proceedings of the 2nd International Symposium on Transportation Studies in Developing Countries (ISTSDC 2019). doi:10.2991/aer.k.200220.032

TEZEL Ö, TİRYAKİ BK, ÖZKUL E, KESEMEN O (2021). A New Goodness-of-Fit Test: Free Chi-Square (FCS). Gazi University Journal of Science 34(3): 879-897. doi: 10.35378/gujs.743444

Umasugi RA (2019). Pemprov DKI: 114 Pabrik di Jakarta Cemari Lingkungan Lewat Cerobong Buangan Gas Sisa. Kompas.Com.

Wang S, Zhou H (2021). High Energy-Consuming Industrial Transfers and Environmental Pollution in China: A Perspective Based on Environmental Regulation. IJERPH 18(22): 11866. doi: 10.3390/ijerph182211866

Warren K (2005). Improving strategic management with the fundamental principles of system dynamics. System Dynamics Review 21(4): 329-350. doi: 10.1002/sdr.325

Wei H, Yao H (2022). Environmental Regulation, Roundabout Production, and Industrial Structure Transformation and Upgrading: Evidence from China. Sustainability 14(7): 3810. doi: 10.3390/su14073810

Williams R, Pettinen R, Ziman P, et al. (2021). Fuel Effects on Regulated and Unregulated Emissions from Two Commercial Euro V and Euro VI Road Transport Vehicles. Sustainability 13(14): 7985. doi: 10.3390/su13147985

Xu J, Jiang Y, Guo X, Jiang L (2021). Environmental Efficiency Assessment of Heavy Pollution Industry by Data Envelopment Analysis and Malmquist Index Analysis: Empirical Evidence from China. IJERPH 18(11): 5761. doi: 10.3390/ijerph18115761

Zhao M, Sun T (2022). Dynamic spatial spillover effect of new energy vehicle industry policies on carbon emission of transportation sector in China. Energy Policy 165: 112991. doi: 10.1016/j.enpol.2022.112991

Zhong M, Saikawa E, Avramov A, et al. (2019). Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): Emissions of particulate matter and sulfur dioxide from vehicles and brick kilns and their impacts on air quality in the Kathmandu Valley, Nepal. Atmos Chem Phys 19(12): 8209-8228. doi: 10.5194/acp-19-8209-2019