A Comprehensive system dynamics model for air pollution management in metropolitans

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Abstract

In this paper, a system dynamics model is presented in which the effect of particulate matters (PM) emitted from fixed and mobile resources on air quality of metropolitans is analyzed from economic, environmental and social perspectives. Tehran metropolitan city is investigated as a case study and the model is calibrated through 22-year data during 2001-2023. Finally, a managerial dashboard is proposed for policymakers to see the effect of the proposed scenarios for air pollution reduction in the next years.

Keywords: Fixed sources, Mobile sources, Environmental factors, Economic and Social Consequences.

1. Introduction

One of the most challenging issues that policymakers currently face and will continue to grapple with more intensely in the near future, is air pollution. This problem has irreparable consequences across various areas, particularly impacting health systems. The major source of pollution comes from industrialization and population growth (Oakes, 2022). Global statistics reveal that numerous countries are struggling to deal with this issue. In 2022, Iran's rank was 21st amongst the most polluted nations worldwide, with a concentration of 32.5 μg/m³—more than six times the World Health Organization's guidelines. A comparative analysis of relevant data over different years underscores the worrying upward trend in the country during the last five years. Apart from its direct impact on health and mortality, pollution has also led to the closure of schools, offices, and businesses, as well as migration. Moreover, it has significantly diminished the quality of life and adversely affected mental and emotional well-being.

In various studies, the problem of air pollution in cities is studied using system dynamics. At the central point of these models, the production of pollution is mentioned, which naturally includes the sources of emission of stationary and mobile pollutants. System dynamics modeling is one of the best tools to model feedback loops and cause-and-effect relationships between variables. For instance, Vafa-Arani et al. (2014) proposed an SD model for the air pollution of Tehran and proposed some efficient policies to reduce air pollution as short and long-term plans. The subsystems considered were transportation and industrial subsystems. Rusiawana et al. (2015) presented a system dynamics model for Jakarta as a case study based on relations between CO2 emission and economic growth. They proposed some policies based

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on the use of renewable energies. Rabiei Hosseinabad and Moraga (2017) proposed a system dynamics model to evaluate applicable policies to mitigate air pollution in Mexico City. Jia (2021) applied an integrated algorithm comprising system dynamics, entropy weight method, and gray system theory to model pollution caused by vehicle emissions. Shahsavari-Pour et al. (2022) presented a system dynamics model, including air pollution sources and consequences of air pollution in Tehran. Finally, Samudra et al. (2024) investigated the contribution of the resources of air pollution in Jakarta, including power plants, industry, and landfill, using a system dynamics model.

In this paper, a comprehensive and dynamic model for the problem of air pollution is proposed through the system dynamics methodology. The main subsystems considered include stationary sources, mobile sources, the consequences of pollution, and environmental self-purification. The case study focuses on Tehran City in Iran. In subsequent sections, the proposed comprehensive pollution model developed using the system dynamics methodology is presented.

2. System dynamics model

The proposed casual model was firstly constructed based on several reports from the literature about the air pollution of metropolitan. Then, the model was validated through several discussion sessions with experts from energy sector, health ministry, traffic and municipality, and also the related academic disciplines experts from universities. Following this session, the causal loop diagrams was revised and the boundary of the system was determined.

The proposed system dynamics model for air pollution consists of 4 sub-systems:

- First subsystem relates to fixed resources of air pollution, which includes the pollution resulted from gas consumption of domestic and business consumers, industries and powerplants, the pollution resulted from waste incineration and alternative fuel (gas oil or fuel oil) in case of natural gas shortage in powerplants and industries. Main drivers of this subsystem are population growth and energy sector capabilities.
- Second subsystem refers to mobile resources consisting of combustion and non-combustion emissions exited from vehicles (cars, taxies, buses, trucks and motorcycles). It connects to the traffic congestion of city, because more congestion means more fuel consumption. The other main driver of this subsystem is the travel distance in the city. The more travel distance, the more combustion and non-combustion emissions.
- Third subsystem refers to pollution absorption factors (such as plants, rain and wind), environmental factors that intensify pollution (e.g. thermal island, inversion, the city form and haze) which most of them are not controllable and will be strengthen by water crisis and drought periods.
- Fourth subsystem models the consequences of air pollution including Economic, Social and Environmental consequences.

Figure 1 illustrates the subsystems' diagram of the proposed model.

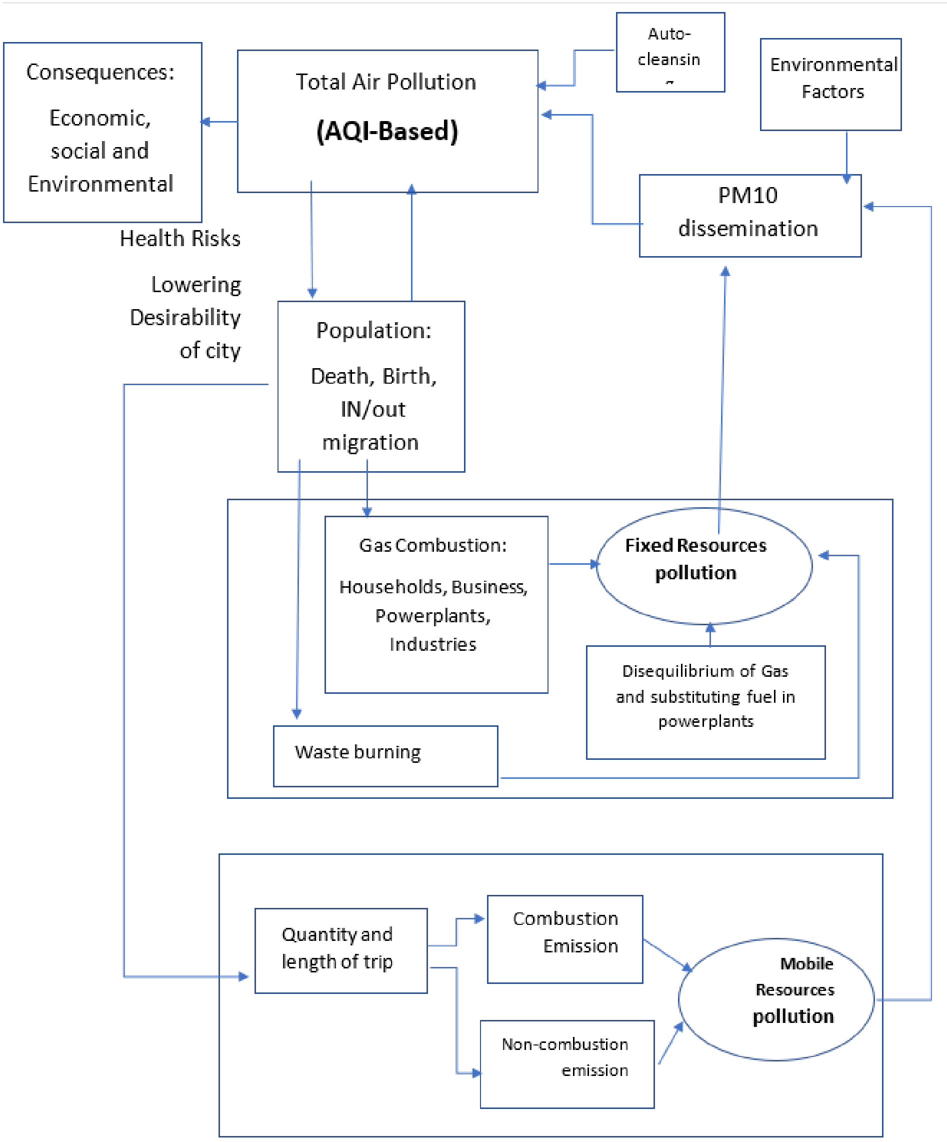


Figure 1. Subsystems' diagram of the proposed model

3. Simulation Results

The proposed model was run using air pollution data extracted from different sources such as Emission inventory of air pollutants, World Bank reports, Pollution atlas of the country's power plants, Energy balance sheet, Statistical center of Iran, Tehran's air quality control company, Iran's ministry of health, just to name a few.

Main objective of the dynamic model is to simulate the total PM2.5 pollutions emitted from stationary and mobile resources. Figure 2 illustrates the simulation mode versus the reference mode based on data collected during years 2001-2023. As can be seen, the simulation mode conforms well with the reference mode. For more analysis, Theil 'statistics is used. The value of Theil index equals to 0.0574, which its smallness and closeness to zero indicate the good behavior of the simulation model.

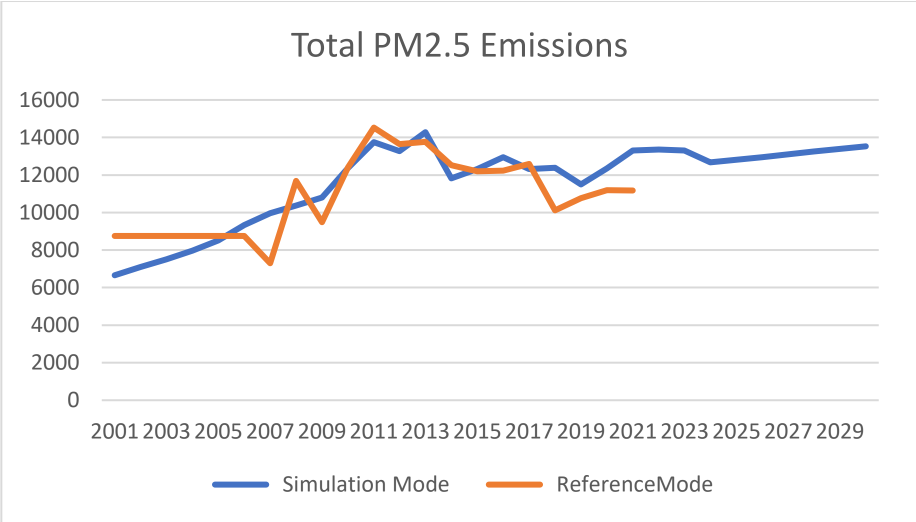


Figure 2. Simulation mode vs. Reference mode of PM2.5 emissions based on Tehran's data

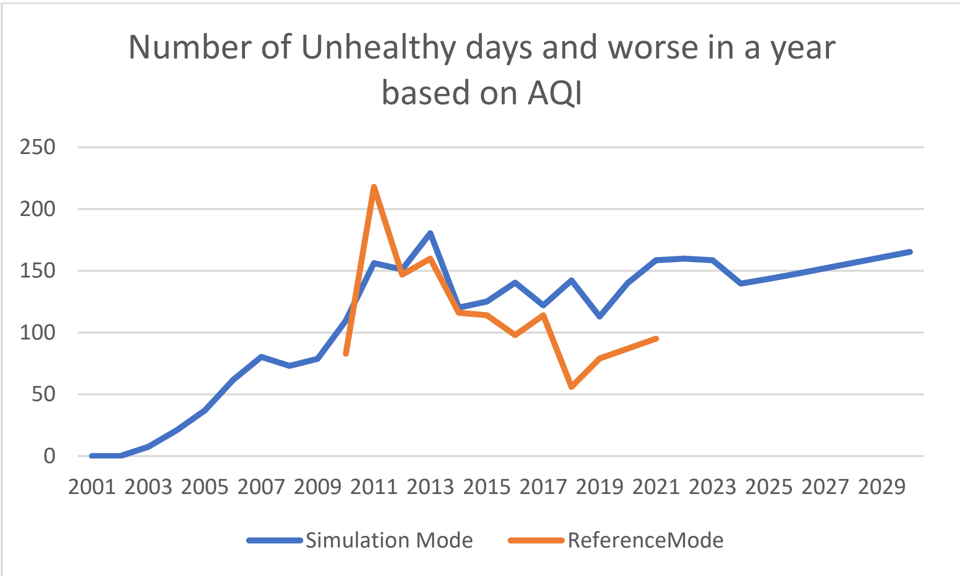


Figure 3. Simulation mode vs. Reference mode of number of unhealthy days and worse

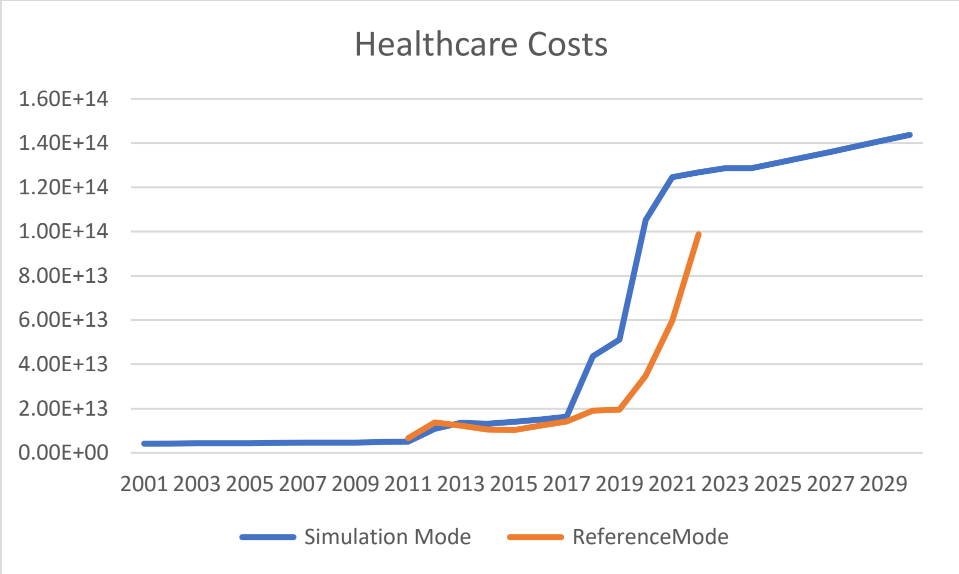


Figure 4. Simulation mode vs. Reference mode of healthcare costs based on Tehran's data

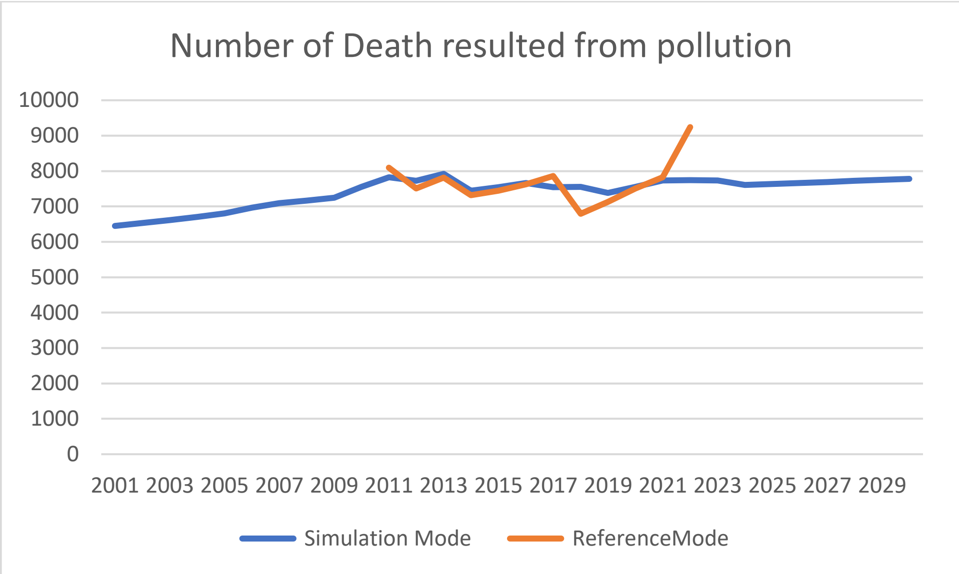


Figure 5. Simulation mode vs. Reference mode of death number resulted from pollution

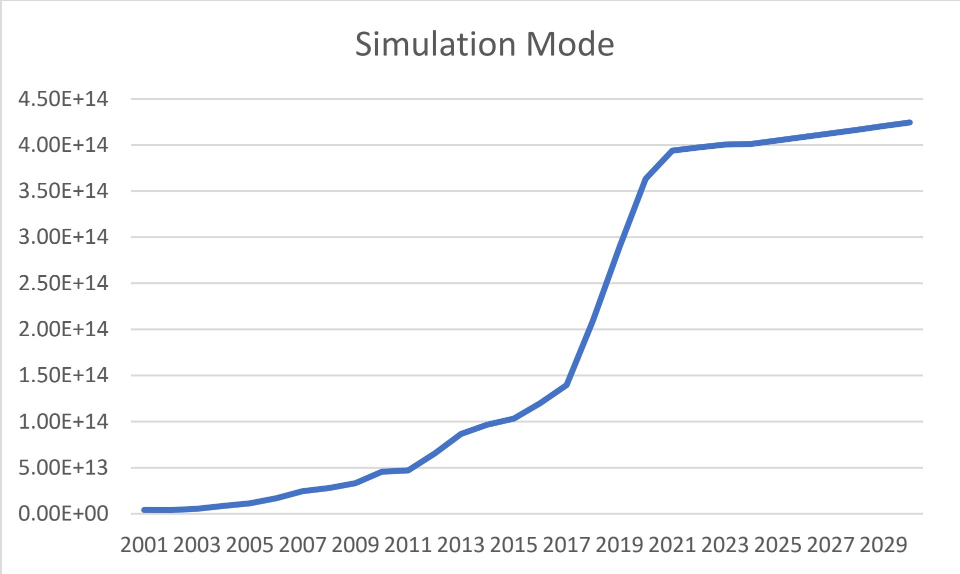


Figure 6. Simulation mode of Economic Costs

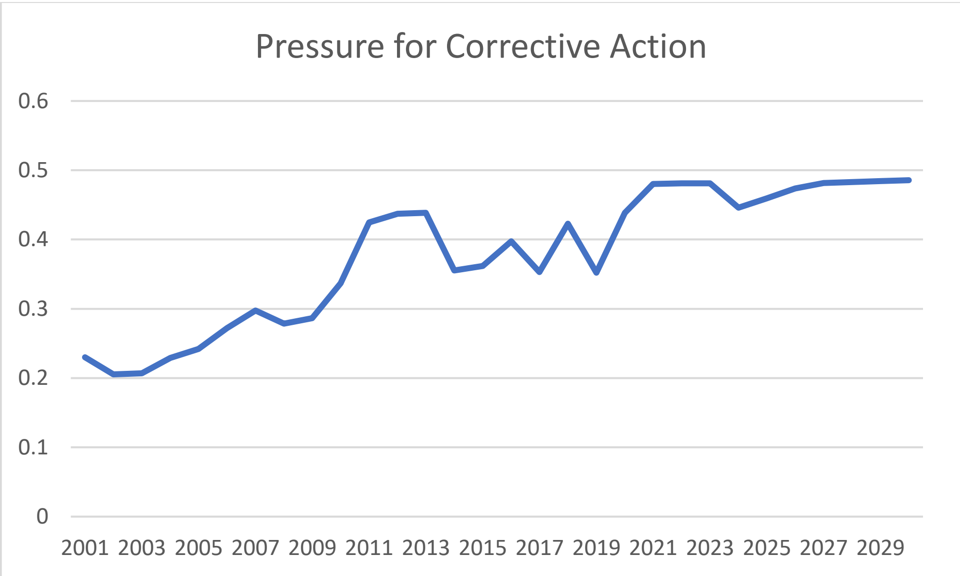


Figure 7. Simulation mode of pressure for pollution reduction

4. Policy making by the proposed dynamic model

The policy-making approach with the help of system dynamics modeling provides the possibility of evaluating the results of decisions and actions on the entire system before implementation. The policies proposed in this study can be divided into three groups: policies related to fixed resources, policies related to mobile resources, and policies related to environmental factors.

4.1 Policy making for stationary resources

As mentioned, emissions from stationary resources come from gas and alternative fuel usages as well as waste incineration. The increase in gas consumption causes gas imbalance and forces power plants to use alternative fuel (gas oil or fuel oil) and causes more pollutions in the air. The basic solution to reduce the use of alternative fuels by power plants can be the improvement of power plants and the development of combined cycle power plants or renewable power plants and the use of clean fuels such as biogas.

On the other hand, with the consumption of gas by power plants to produce electricity, depending on the efficiency of the power plants, suspended particles are released in the air. The use of pollutant filters can be a solution to reduce air pollution. Considering that more than 80% of the country's electricity production is dependent on natural gas, diversifying the energy portfolio for electricity production can be a solution to reduce the use of alternative fuels due to gas imbalance. Gas imbalance occurs due to the lack of gas, and one of the solutions to reduce domestic gas consumption can be insulation of buildings, renovating engine houses, and applying incentives or penalties for gas consumption. The simulation results before and after implementing the proposed policies for the subsystem related to stationary resources, in terms of percentage change in the emission of PM2.5 pollutant, are given in Table 1. Negative values mean reduction in the considered criterion.

- The policy of improving power plants increases the efficiency of power plants and as a result reduces gas consumption as well as alternative fuel consumption by power plants and reduces the resulted pollution.
- With the policy of using filters by power plants and industries, both the pollution resulted from the consumption of gas and alternative fuel by industries and power plants will be reduced.
- With the policy of granting facilities for the renovation of engine houses and insulation of buildings and its effect on reducing the per capita gas consumption by commercial and domestic sectors, the pollution caused by the gas allocated to the commercial and domestic sectors will be reduced. Consequently, stationary resource pollution and total pollution are reduced.
- The policy of promoting industrial technology will reduce the gas consumption by industries and as a result the pollution emitted from.

Table 1. Simulation results related to the policies implemented to the stationary resource subsystem

Pressure for Corrective Action	Economic Cost	Fixed resource emissions	Total PM2.5 pollutions	Effect type	Fixed resource policy
-0.0006	-0.0003	-0.0020	-0.0007	Average Percent Deviation from the base scenario	Improvement of power plants and development of Combined Cycle and Renewable power plants
-0.00024	-0.03 (Thousand Billion IRR)	-9.1 (Ton)	-9.4 (Ton)	Average Deviation Value from the base scenario	
-0.0074	-0.0087	-0.02331	-0.00892	Average Percent Deviation from the base scenario	Use of Pollution Filters
-0.00224	-2 (Thousand Billion IRR)	-92.35 (Ton)	-92.35 (Ton)	Average Deviation Value from the base scenario	
-0.0535	-0.0256	-0.1636	-0.0564	Average Percent Deviation from the base scenario	Renovation of Engine houses and Insulation of buildings
-0.02198	-3 (Thousand Billion IRR)	-742.9 (Ton)	-766.4 (Ton)	Average Deviation Value from the base scenario	
-0.0004	-0.0002	-0.0013	-0.0004	Average Percent Deviation from the base scenario	Upgrading Industrial Technology
-0.00015	-0.018 (Thousand Billion IRR)	-5.6 (Ton)	-5.8 (Ton)	Average Deviation Value from the base scenario	

As an instance, simulation results by implementing the policy of using purifying filters in industries and power plants, show that the 20% effect of using purification filters on average will reduce 0.9% of total pollution and 2.3% of stationary resource pollution in the following years. The details of the results are given in Table 2.

Table 2. Simulation results before and after using purifying filters

Policy of using purifying Filter				Total stationary source pollution (without Filters)	Total PM2.5 pollutions (without Filters)	Year
Percent change	Total stationary source pollution (with using Filters)	Percent change	Total PM2.5 pollutions (with using Filters			
-0.04606	-0.04606	-0.04606	6546.92	2432.82	6658.97	2001
-0.04278	-0.04278	-0.04278	6989.07	2670.76	7103.43	2002
-0.03914	-0.03914	-0.03914	7399.76	2893.55	7513.22	2003
-0.03509	-0.03509	-0.03509	7861.76	3099.83	7970.83	2004
-0.03167	-0.03167	-0.03167	8406.68	3308.39	8511.85	2005
-0.02876	-0.02876	-0.02876	9238.6	3518.9	9340.31	2006
-0.0275	-0.0275	-0.0275	9867.1	3629.11	9967.51	2007
-0.02569	-0.02569	-0.02569	10278.9	3727.52	10375.4	2008
-0.0241	-0.0241	-0.0241	10714.7	3829.76	10807.8	2009
-0.02394	-0.02394	-0.02394	12273.1	3961.74	12368.9	2010
-0.02367	-0.02367	-0.02367	13660.5	4080.1	13758.1	2011
-0.01885	-0.01885	-0.01885	13191.9	4203.08	13272.3	2012
-0.01895	-0.01895	-0.01895	14196.4	4435.36	14281.8	2013
-0.01799	-0.01799	-0.01799	11743.3	4644.88	11828.2	2014
-0.01737	-0.01737	-0.01737	12234.1	4863.99	12320.2	2015
-0.01597	-0.01597	-0.01597	12868.7	5057.41	12951.1	2016
-0.01552	-0.01552	-0.01552	12233.6	5191.32	12316	2017
-0.01502	-0.01502	-0.01502	12311.9	5323.09	12393.7	2018
-0.01454	-0.01454	-0.01454	11416.3	5454.98	11497.7	2019
-0.01407	-0.01407	-0.01407	12277.6	5587.21	12358.4	2020
-0.01364	-0.01364	-0.01364	13231.4	5719.38	13311.8	2021
-0.01316	-0.01316	-0.01316	13275.6	5875.14	13355.4	2022
-0.0127	-0.0127	-0.0127	13232.7	6031.06	13311.9	2023
-0.02331		-0.00892	میانگین			

As can be seen in Figures 8 and 9, the use of purifying filter reduces the total pollution caused by allocated gas and alternative fuel.

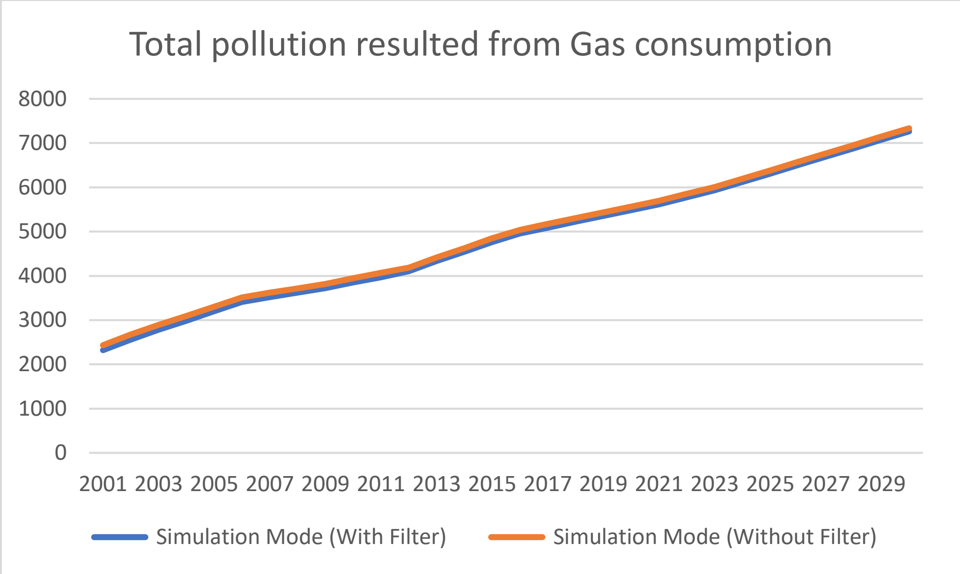


Figure 8. Total pollution resulted from Gas consumption before and after using purifying filters

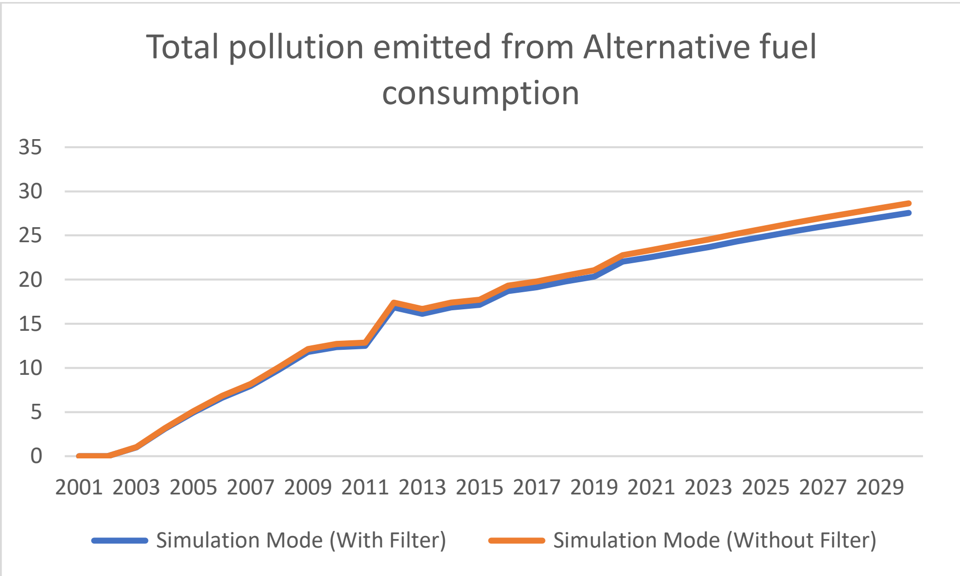


Figure 9. Total pollution resulted from alternative fuel consumption before and after using purifying filters

4.2 Policy making for mobile resources

The simulation results of policies related to the subsystem of mobile resources are given in Table 3. The following findings are obtained:

- The policy of promoting technical inspection of vehicles reduces the combustion emissions of all types of vehicles and as a result the total pollution of mobile sources as well as the total PM2.5 emissions.

- Through the policy of offline services and reducing the travel distance, both combustion and non-combustion emissions, and as a result, the total pollution of mobile resources and total PM2.5 emissions will be decreased. As mentioned, the non-combustion emission is caused by the wear of the pads and it decreases with the decrease of the travel distance. Making services offline and using e-government services and reducing the dispersion of service centers can be a solution to reduce the emission of suspended particles caused by the non-combustible emission of vehicles. On the other hand, as the number of trips decreases, combustion emissions also decrease.
- The policy of improving the level of technology of vehicles has an effect on the combustion emission coefficient of vehicles and causes a reduction in combustion emissions and as a result reduces the pollution of mobile resources and total PM2.5 emissions.
- The policy of electrification of vehicles reduces combustion emissions and thus reduces the pollution of mobile resources and total PM2.5 emissions. But it does not affect the non-combustion emissions of vehicles.

Table 3. Simulation results of policies related to the subsystem of mobile resources

Corrective Action pressure	Economic cost	Mobile resource emissions	Total PM2.5 pollutions	Effect type	Mobile resource policy
-0.11644	-0.05673	-0.19114	-0.13355	Average Percent Deviation from the base scenario	Improvement of technical examination
-0.05077	-7.4 (Thousand Billion IRR)	-1900.04 (Ton)	-1900.04 (Ton)	Average Deviation Value from the base scenario	
-0.12406	-0.06078	-0.2	-0.13978	Average Percent Deviation from the base scenario	Offline service
-0.05423	-8.2 (Thousand Billion IRR)	-1986 (Ton)	-1987.05 (Ton)	Average Deviation Value from the base scenario	
-0.11644	-0.05673	-0.19114	-0.13355	Average Percent Deviation from the base scenario	Improving the technology level of vehicles
-0.05077	-7.4 (Thousand Billion IRR)	-1900.04 (Ton)	-1900.04 (Ton)	Average Deviation Value from the base scenario	
-0.00688	-0.00565	-0.04631	-0.03467	Average Percent Deviation from the base scenario	Electric public vehicle
-0.0034	-2.3 (Thousand Billion IRR)	-546.007 (Ton)	-544.461 (Ton)	Average Deviation Value from the base scenario	

As an example, Figure 10 schematically shows the effect of offline services in reducing total pollution and pollution emitted from mobile resources before and after using offline services. As can be seen, after the simulation, the blue line is below the red line, which shows the reduction of air pollution caused by PM2.5 pollutant.

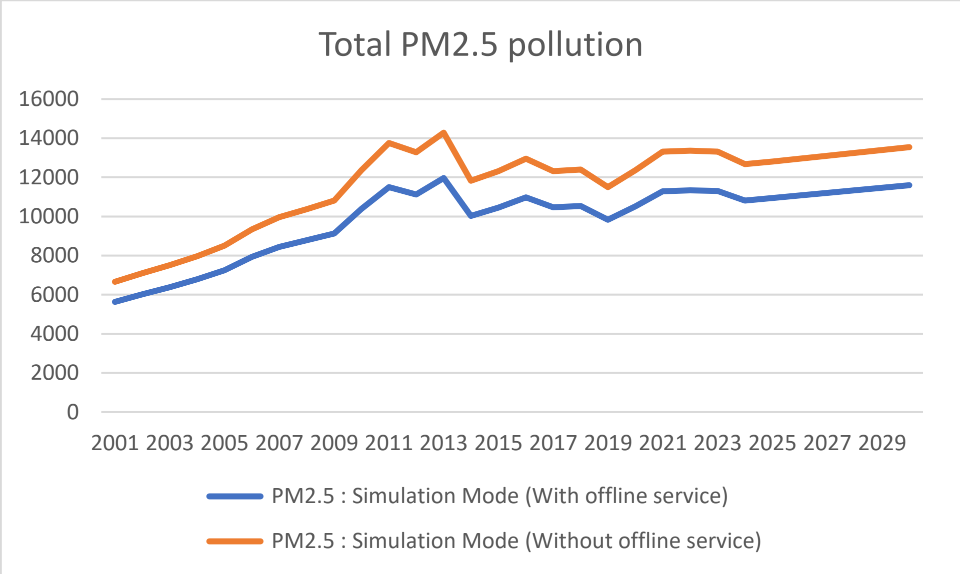


Figure 10. Total PM2.5 pollution before and after using offline services

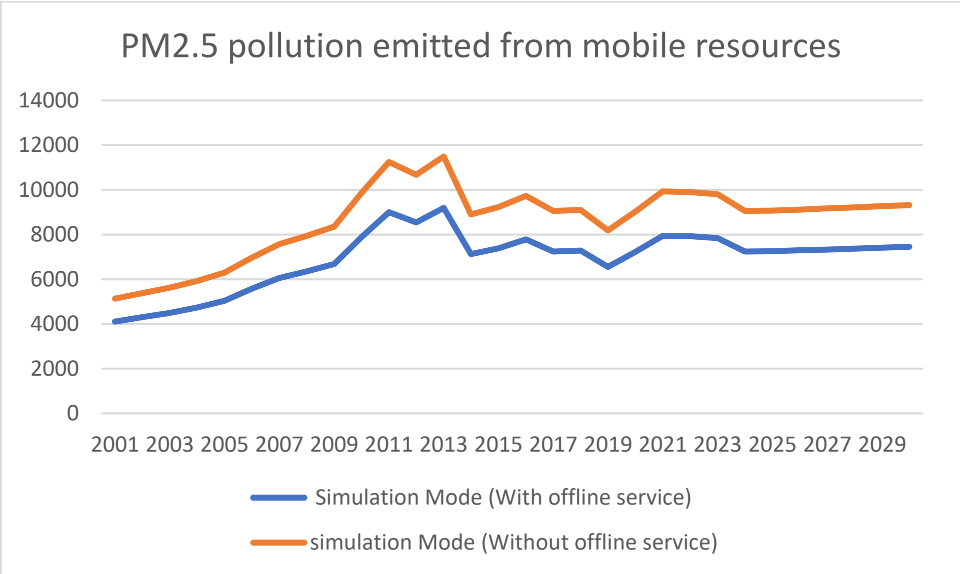


Figure 11. Total pollution emitted from mobile resources before and after using offline services

4.3 Policy making for environmental factors

In the proposed model, by the process of natural decomposition of pollutants (by green space and rain) and transfer of air pollution (by wind), a certain amount of air pollution is removed from the system in each time period of simulation. Therefore, policies to expand urban green spaces can be considered as a key strategy in reducing the air pollution. In the basic model, the amount of increase in basic vegetation equals 3%. With a 20% increase in the base vegetation, the amount of pollution reduction is shown in Figure 12.

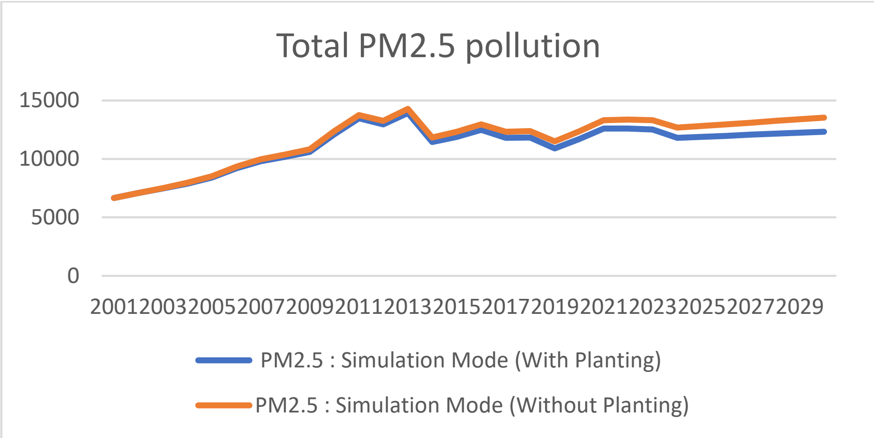


Figure 12. Total PM2.5 pollutions before and after planting

The results of the simulation of policies related to the subsystem of environmental factors are given in Table 4. By implementing the policy of planting vegetation and improving the urban form, the capacity of the environment to absorb or reduce pollution increases and as a result, the total pollution decreases.

Table 4. Simulation results of policies related to the subsystem of environmental factors

Economic cost	Corrective Action pressure	Environment capacity to reduce pollution	Total PM2.5 pollutions	Effect type	Environmental related policy
-0.06594	-0.02514	0.224551	-0.09188	Average Percent Deviation from the base scenario	Planting vegetation
-0.03147	-8.9 (Thousand Billion IRR)	1411.194	-1411.19	Average Deviation Value from the base scenario	
-0.00022	-0.00016	0.001001	-0.00035	Average Percent Deviation from the base scenario	Improvement of urban form
-8.2E-05	-0.015 (Thousand Billion IRR)	4.89098	-4.89098	Average Deviation Value from the base scenario	

5. Conclusion

With population growth and industrialization, air pollution has become one of the serious and important problems in metropolitans, which, in addition to economic costs, accompanies with irreparable social and environmental consequences. In other words, air pollution reduces workforce productivity and in severe cases causes industries and service centers to become shut down, and also has many side effects for the health of humans, animals, and the environment, and reduces the desirability of the city for life.

The purpose of this study was to model the emission of the particulate matter pollutant (PM2.5 due to its correlation and significant contribution in creating unhealthy days for sensitive groups) and evaluate different scenarios to reduce this pollutant in the air of city. In order to make decisions for policy makers to solve the problem of air pollution, by using the methodology of systems dynamics, the dynamic factors affecting the emission of PM2.5 in the air of Tehran were identified and the causal-loop relationships between them were formulated. Then, with the implementation of the model (using the annual average of the twenty-two-year data between years 2001 and 2023) and construction of a management dashboard, the results of the implementation of the proposed policies to reduce the emission of PM2.5 were simulated. Finally, effective policies and strategies have been presented to reduce air pollution, which can be effective in reducing air pollution in the coming years.

References

1- https://www.iqair.com/world-most-polluted-countries

2- Steve Oakes(2020), Insights on Air Pollution Using a System Dynamics Approach, Journal of Accounting & Marketing, 11:2.

3- Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., & Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. Transportation Research Part D: Transport and Environment, 31, 21-36.

4- Rusiawan, W., Tjiptoherijanto, P., Suganda, E., & Darmajanti, L. (2015). System dynamics modeling for urban economic growth and CO2 emission: a case study of Jakarta, Indonesia. Procedia Environmental Sciences, 28, 330-340.

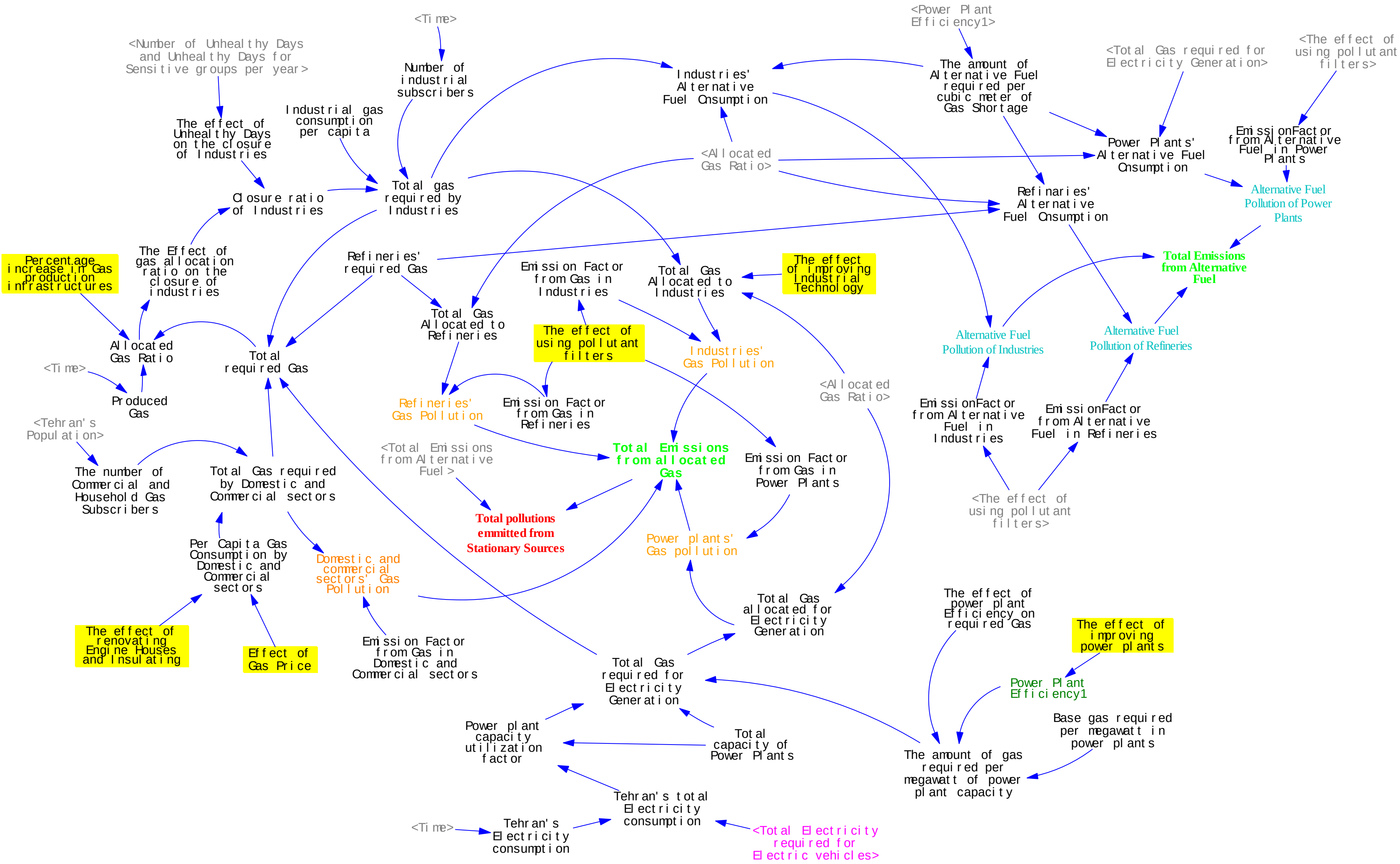
5-Moraga, R., & Hosseinabad, E. R. (2017). A system dynamics approach in air pollution mitigation of metropolitan areas with sustainable development perspective: a case study of Mexico City. Journal of Applied Environmental and Biological Sciences, 7(12), 164-174.

6- Jia, S. (2021). Effect of combined strategy on mitigating air pollution in China. Clean technologies and environmental policy, 23, 1027-1043.

7- Shahsavari-Pour, N., Bahador, S., Heydari, A., & Fekih, A. (2022). Analyzing Tehran's Air Pollution Using System Dynamics Approach. Sustainability, 14(3), 1181.

8- Samudra, A. A., Hertasning, B., & Amiro, L. (2024). Policy for handling air pollution in Jakarta: Study using System Dynamics Simulation Models. *Journal of Infrastructure, Policy and Development*, *8*(2).

Appendix 1: Subsystem of Stationary air pollution resources



Appendix 2: Subsystem of Bus emissions