A Pollution Control Problem for the Aluminum Production in Eastern Siberia: Differential Game Approach*

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Abstract In this paper, we apply a dynamic game-theoretic model and analyze the problem of pollution control in Eastern Siberia region of Russia. When carrying out the analysis we use real numerical values of parameters. It is shown that cooperation between the major pollutants can be beneficial not only for the nature but also for the respective companies.

1 Introduction

Air pollution is a major environmental problem that affects everyone in the civilized world. Emissions from large industrial enterprises have a great adverse impact on the environment and the people's quality of life.

A detailed review of the scientific literature published in 1990–2015 on the topic of climate and environmental changes can be found in [4]. Air pollution is closely linked to climate change. Therefore, one of the most important issues in ecologic management concerns the reduction of the pollutant emission into the atmosphere.

Game theory offers a powerful tool for modeling and analyzing situations where multiple players pursue different but not necessarily opposite goals. In particular, it is well suited for analyzing the ecological management problems in which players

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(countries, plants) produce some goods while bearing costs due to the emitted pol-

tion [5, 6, 11, 12, 13, 15]. It should be noted that most results on pollution control
turn out to be of more theoretical nature because it is difficult to obtain realistic
numerical values of the model parameters.

In contrast to the mentioned approach we consider local situations that can be
modeled with more precision. Furthermore, we hope that the obtained results can be
of use when planning local policies aimed at decreasing pollution load in particular
regions. Recently, there has been a paper devoted to the pollution control problem
of the city Bratsk from the Irkutsk region of the Russian Federation based on data for
2011. [16]. Our contribution extends the model presented in the mentioned paper,
moreover, the ecological situation is considered for the largest alum enterprises
of Eastern Siberia located in Krasnoyarsk, Bratsk, and Shelekhov that the largest
plants which produce about 70% of aluminum in Russia has been built. In the model
we include an absorption which is considered for different weather conditions. It
is known that the ecological situation aggravates in the wintertime on account of
the frequent temperature inversions, weak winds, and fog [1, 2, 3]. The problem of
pollution control is formulated with a differential game framework and is considered
based on data for 2016 [24, 25].

The paper is structured as follows. In section 2, the description of the differential
game model is presented. In section 2.1, a non-cooperative solution is found, the
Nash equilibrium is considered as an optimality principal. Section 2.2 deals with
cooperative differential game. The numerical example of pollution control for the
aluminum production in Eastern Siberia is presented in the section 3.

2 A Game-Theoretic Model

Consider a game-theoretic model of pollution control based on the models [5, 8].
It is assumed that on the territory of a given region there are n stationary sources
of air pollution involved in the game. Each player has an industrial production site.
Let the production of each unit is proportional to its pollution \( u_i \). Thus, the strategy
of a player is to choose the amount of pollution emitted to the atmosphere. We
assume that the n sources ”contribute” to the same stock of pollution. Denote the
stock of accumulated net emissions by \( x(t) \). The dynamics of the stock is given by
the following equation with initial condition:

\[
\dot{x}(t) = \sum_{i=1}^{n} u_i(t) - \delta x(t), \quad t \in [t_0, T], \quad x(t_0) = x_0,
\]

where \( \delta \) denotes the environment’s self-cleaning capacity. Each player i controls its
emission \( u_i \in [0, b_i] \), \( b_i > 0 \), \( i = 1, \ldots, n \). The solution will be considered in the class of
open-loop strategies \( u_i(t) \).

The net revenue of player i at time instant t is given by quadratic functional
form: \( R_i(u_i(t)) = u_i(t) \left( b_i - \frac{1}{2} u_i(t) \right), \quad t \in [t_0, T], \) where \( b_i > 0 \). Each player i bears
It can be noted that then optimal control for player \( i \) has no switching points.

\[
K_i(x_0, T - t_0, u_1, u_2, \ldots, u_n) = \int_{t_0}^T (R_i(u_i) - d_i x(s)) ds. \tag{2}
\]

### 2.1 Nash Equilibrium

We choose the Nash equilibrium as the principle of optimality in non-cooperative game. To find the optimal emissions \( u_{1}^{NE}, \ldots, u_{n}^{NE} \) for players 1, \ldots, \( n \), we apply Pontrygin’s maximum principle. The Hamiltonian for this problem is as follows:

\[
H_i(x_0, T - t_0, u, \psi) = u_i(t) \left( b_i - \frac{1}{2} u_i(t)^2 \right) - d_i x(t) + \psi_i \left( \sum_{i=1}^{n} u_i(t) - \delta x(t) \right). \tag{3}
\]

From the first-order optimality condition we get the following formulas for optimal controls:

\[
u_{i}^{NE}(t) = b_i - \frac{d_i}{\delta} + \frac{d_i}{\delta} e^{\delta(i-T)}, \quad i = 1, \ldots, n.
\tag{4}
\]

Here we assume that for the environment’s self-cleaning capacity \( \delta \) the following inequalities hold: \( \delta \geq \frac{d_i}{b_i}, i = 1, \ldots, n \). This condition ensures that \( u_i \in [0, b_i], i = 1, \ldots, n \).

Let \( b_N = \sum_{i=1}^{n} b_i, d_N = \sum_{i=1}^{n} d_i \). Then the optimal trajectory is:

\[
x^{NE}(t) = C_1 e^{\delta t} + \frac{d_N}{2 \delta^2} e^{\delta(t-T)} + b_N \frac{d_N}{\delta} - \frac{d_N}{\delta^2}, \tag{5}
\]

where \( C_1 = e^{\delta t} x_0 - \frac{b_N}{\delta} + \frac{d_N}{\delta^2} e^{\delta(t-0)} \).

But in the case when for some \( i \) \( \delta < \frac{d_i}{b_i} \), it may happen that optimal control \( u_i^{NE} \) for player \( i \) leaves the compact \([0; b_i]\). Let \( \tilde{t}_i = T + \frac{1}{\delta} ln(1 - \frac{b_i \delta}{d_i}) \). If \( \delta < \frac{d_i}{b_i} \) and \( \tilde{t}_i > t_0 \) then optimal control for player \( i \) has a following form:

\[
u_{i}^{NE}(t) = \begin{cases} 
0, & \text{for } t_0 \leq t \leq \tilde{t}_i; \\
b_i - \frac{d_i}{\delta} + \frac{d_i}{\delta^2} e^{\delta(t-0)} & \text{for } \tilde{t}_i \leq t \leq T.
\end{cases}
\tag{6}
\]

It can be noted that \( T + \frac{1}{\delta} ln(1 - \frac{b_i \delta}{d_i}) \geq T - \frac{b_i \delta}{d_i} \) for all \( \delta > 0 \). It means if \( T \leq t_0 + \frac{b_i \delta}{d_i} \), then optimal controls have no switching points.
2.2 Cooperative Solution

Consider now the cooperative case of the game. Assume the players agreed to co-operate and their goal is to achieve the joint optimum. The joint payoff is:

$$\sum_{i=1}^{n} K_i (x_0, T - t_0, u_1, u_2, \ldots, u_n) = \int_{t_0}^{T} \left( \sum_{i=1}^{n} R_i (u_i) - d_N x(s) \right) ds. \quad (7)$$

Similarly to non-cooperative case we apply Pontrygin’s maximum principle and obtain:

$$u^*_i(t) = b_i - \frac{d_N}{\delta} + \frac{d_N}{\delta} e^{\delta(t-T)}, \quad i = 1, \ldots, n. \quad (8)$$

Here we assume that for the environment’s self-cleaning capacity $\delta$ the following inequalities hold: $\delta \geq \frac{d}{b_i}, \quad i = 1, \ldots, n$. This condition ensures that $u^*_i \in [0, b_i], \quad i = 1, \ldots, n$. Then the optimal cooperative trajectory is:

$$x^*(t) = C_2 e^{-\delta t} + \frac{nd_N}{\delta^2} e^{\delta(t-T)} + \frac{b_N}{\delta} - \frac{nd_N}{\delta^2}, \quad (9)$$

where $C_2 = e^{\delta t_0} (x_0 - \frac{b_N}{\delta} + \frac{d_N}{\delta} + \frac{d_N}{\delta^2} e^{\delta(t_0-T)}).

Notice that the open loop Nash equilibrium yields more pollution than the optimal strategies in the cooperative game: $\sum_{i=1}^{n} u^*_i(T) = \sum_{i=1}^{n} u^{NE}_i(T)$, and for all $t \in [t_0; T)$:

$$\sum_{i=1}^{n} u^*_i(t) - \sum_{i=1}^{n} u^{NE}_i(t) = \frac{d_N (n-1)}{\delta} (e^{\delta(t-T)} - 1) < 0.$$

Also consider the situation, when for player $i$ the inequality $\delta < \frac{d}{b_i}$ holds. In this case $u^*_i(t)$ becomes negative when $t < \tilde{t}_i$, where $\tilde{t}_i = T + \frac{1}{\delta} \ln(1 - b_i \frac{d}{\delta})$. So, if $\delta < \frac{d}{b_i}$ and $\tilde{t}_i > t_0$, then optimal control for player $i$ has a following form:

$$u^*_i(t) = \begin{cases} 0, & \text{for } t_0 \leq t \leq \tilde{t}_i; \\ b_i - \frac{d_N}{\delta} + \frac{d_N}{\delta} e^{\delta(t-T)}, & \text{for } \tilde{t}_i \leq t \leq T. \end{cases} \quad (10)$$

It can be noted that $T + \frac{1}{\delta} \ln(1 - b_i \frac{d}{\delta}) \geq T - \frac{b_i}{d_N}$ for all $\delta > 0$. It means if $T \leq t_0 + \frac{b_i}{d_N}$, then optimal cooperative control of player $i$ has no switching points.

3 A Pollution Control Problem in Eastern Siberia

Non-ferrous metallurgy is one of the most developed industries in Eastern Siberia. Large aluminum smelters such as Krasnoyarsk, Bratsk and Irkutsk Aluminum Plants are located in this region. All of the above-mentioned factories belong to the United
Company RUSAL, which is one of the world’s major producers of aluminium. In the model under consideration, the problem of reducing emissions from smelters during adverse weather conditions can be solved by changing the parameter \( \delta \) denoted the environment’s self-cleaning capacity.

We consider the 3-players differential game, where players are the specified companies. To calculate the required model parameters \( b_i \), \( d_i \), we use the data about the sources of air pollution for year 2016. Let the coefficient \( b_i \geq 0 \) equals to a ratio of operating profit of company \( (P_i) \) to its amount of air emissions \( (V_i) \). Furthermore, \( d_i \geq 0 \) determines the amount of fine for air pollution depending on the total pollution. To determine the fines, we used the data about companies payments for air pollution in the year 2016. Let \( L_i \) be the payment for air pollution of the company \( i \), then:

\[
 b_i = \frac{P_i}{V_i}, \quad d_i = \frac{L_i}{V_1 + V_2 + V_3}.
\]

Table 1 includes the data corresponding to 2016 on the operating profit of each company, its air pollution and payments for air pollution. The operating profit of Krasnoyarsk Aluminum Smelter could be found in [19]. [18] gives us the joint operating profit of Bratsk and Irkutsk Aluminum Smelters, which is equal to 4210,43 million rubles. We estimated the profit of each company in proportion to the volume of aluminum produced by these companies in 2016. According to [20], Bratsk Aluminum Smelter produced 1005500 tons of aluminum and Irkutsk Aluminum Smelter – 415400 tons in 2016. So, the operating profit of the two plants accounts for 2979,51 million rubles and 1230,92 million rubles respectively. The payment for air pollution of Krasnoyarsk Aluminum Smelter amounted to \( L_1 = 87723,95 \) thousands rubles in 2016. According to [23] the payment for air pollution of the company Irkutsk Aluminum Smelter accounted for \( L_2 = 18830 \) thousands rubles in the same year. Environmental impact fee including waste disposal fee of Bratsk Aluminum Smelter is equals to 65278 in 2016 [23]. According to [22] the payment for air pollution of Bratsk Aluminum Smelter is approximately 90 percent of its total environmental impact fee. So, we estimated its payment for air pollution at \( L_2 = 0.9 \cdot 65278 = 58780 \) thousands rubles. Using formulas (11) we get the respective coefficients of the model \( b_i \), \( d_i \) (Table 1).

| Company                  | \( P_i \) (mln. rubles) | \( V_i \) (tons) | \( L_i \) (ths. rubles) | \( b_i \)            | \( d_i \)        |
|--------------------------|-------------------------|------------------|------------------------|----------------------|-----------------|
| Krasnoyarsk Aluminum Smelter | 3412,23                | 57800            | 87723,95               | 59035,12             | 525,06          |
| Bratsk Aluminum Smelter  | 2979,51                 | 83578,707        | 58780,2                | 35649,15             | 351,64          |
| Irkutsk Aluminum Smelter | 1230,92                 | 25694,1          | 18830                  | 47906,72             | 112,71          |

Table 2 represents the non-cooperative solutions obtained for some numerical parameters \( (t_0 = 0, \ T = 0,4) \). We consider two cases of meteorological conditions, more precisely, value \( \delta = 0,02 \) corresponds to adverse weather conditions, for instance, in winter months and \( \delta = 0,2 \) to normal weather conditions. The inequalities
According to [9] players from coalition $S$ payoffs and its differences with sum of payoffs in Nash equilibrium are also given in the Table 4. The joint cooperative controls of players have no switching points (we use (4), (8) to compute the optimal strategies). Table 3 contains the optimal cooperative strategies.

**Table 2** Nash equilibrium strategies. Payoffs of companies in Nash equilibrium

| Company | $u^\text{NE}_{i}, \delta = 0.02$ | $u^\text{NE}_{i}, \delta = 0.2$ |
|---------|---------------------------------|---------------------------------|
| KrAS    | 32782.12 + 26253e^{-0.02x-0.008} | 56409.82 + 26253.3e^{0.2x-0.08} |
| BrAS    | 18067.15 + 17582e^{-0.02x-0.008} | 33890.95 + 17582.2e^{0.2x-0.08} |
| IrAS    | 42271.22 + 5635.5e^{-0.02x-0.008} | 47343.17 + 5635.5e^{0.2x-0.08} |

$k_i(x_0, T - t_0, u^\text{NE}), \delta = 0.02, k_i(x_0, T - t_0, u^\text{NE}), \delta = 0.2$

| Company | $u^*, \delta = 0.02$ | $u^*, \delta = 0.2$ |
|---------|-----------------|-----------------|
| KrAS    | 9564.62 + 49470,5e^{-0.02x-0.008} | 54088.07 + 49470.5e^{0.2x-0.08} |
| BrAS    | -13821.35 + 49470,5e^{-0.02x-0.008} | 30702.1 + 49470.5e^{0.2x-0.08} |
| IrAS    | -1563.78 + 49470,5e^{-0.02x-0.008} | 42959.67 + 49470.5e^{0.2x-0.08} |

If we compare cooperative and non-cooperative emissions of players from Table 2 and 3 it is easy to show that the optimal cooperative emissions are less. Table 4 shows differences between total air pollution in cooperative and non-cooperative cases and differences between the accumulated emissions. The joint cooperative payoffs and its differences with sum of payoffs in Nash equilibrium are also given in the Table 4.

**Table 4** Differences between total air pollution in cooperative and non-cooperative case and differences between the accumulated emissions. Joint cooperative payoff

| $\delta$ | $\delta$ | $\sum_{i=1}^{n} u^\text{NE}_i(t) - \sum_{i=1}^{n} u^*_i(t)$ | $x^\text{NE}(T) - x^*(T)$ | $\sum_{i=1}^{n} k_i(x_0, T - t_0, u^*_i)$ | $\sum_{i=1}^{n} k_i(u^*) - \sum_{i=1}^{n} k_i(u^\text{NE})$ |
|---------|---------|---------------------------------|-----------------|---------------------------------|-----------------|
| $\delta = 0.02$ | 98941(1 - e^{-0.02x-0.008}) | 157,044 | 1398986922 - 394,18x0 | 14748,7 |
| $\delta = 0.2$ | 9894(1 - e^{-0.2x-0.05}) | 146,2124 | 1399250309 - 380,35x0 | 13979,5 |

Consider the Shapley value as a cooperative solution. To calculate it we use a non-standard method of construction a characteristic function proposed in [9]. According to [9] players from coalition $S$ use (obtained earlier) strategies $u^*_i$ from the optimal profile $u^*$ and the players from $N \setminus S$ use (obtained earlier) strategies $u^\text{NE}_{N \setminus S}$ from the Nash equilibrium strategies:
of the absorption parameter in Eastern Siberia. In doing so, we considered the real data for 2016-2018 years obtained from statistical and accounting reports. It can be noted that for small values of the absorption parameter $\delta$, when unfavorable weather conditions occur, players are more motivated for cooperation. We also observe a greater decrease of accumulated emissions under cooperation during adverse weather conditions. This shows that the model, which takes into account a self-cleaning ability of the atmosphere, allows more effective influence on companies to reduce emissions during adverse weather conditions.

In this paper, we applied game theory to analyze the problem of pollution control in Eastern Siberia. In doing so, we considered the real data for 2016-2018 years obtained from statistical and accounting reports. It can be noted that for small values of the absorption parameter $\delta$, when unfavorable weather conditions occur, players are more motivated for cooperation. We also observe a greater decrease of accumulated emissions under cooperation during adverse weather conditions. This shows that the model, which takes into account a self-cleaning ability of the atmosphere, allows more effective influence on companies to reduce emissions during adverse weather conditions.

**Conclusion**

Table 5 contains the characteristic function for our example. The Shapley values are presented in Table 6. It is also interesting to see how much each firm benefits from cooperation as compared to a non-cooperative case. Table 6 shows this difference. We can observe that it is profitable to the companies to stick to the cooperative agreement, however to different extent.

**Table 5 Characteristic function**

| $\delta = 0.02$ | $\delta = 0.2$ |
|------------------|------------------|
| $V^\eta(\{1\}, x_0, T - t_0)$ | 691061320.2 - 209.19, 691201653.2 - 201, 84x0 |
| $V^\eta(\{2\}, x_0, T - t_0)$ | 250173553 - 140, 09x0 250267647.2 - 135, 18x0 |
| $V^\eta(\{3\}, x_0, T - t_0)$ | 457722552.2 - 44, 9x0 4577753050 - 43, 33x0 |
| $V^\eta(\{1, 2\}, x_0, T - t_0)$ | 941245436.6 - 349, 28x0 941479313.4 - 337, 02x0 |
| $V^\eta(\{1, 3\}, x_0, T - t_0)$ | 1148794743 - 254, 09x0 1148965007 - 245, 17x0 |
| $V^\eta(\{2, 3\}, x_0, T - t_0)$ | 707904167 - 184, 99x0 708028338 - 178, 5x0 |

**Table 6 Shapley value. Difference between the Shapley value and the Nash equilibrium**

| Company | $Sh_i(x_0, T - t_0)$ | $Sh_i(x_0, T - t_0)$ | $Sh_i - K_i(\alpha^{NE})$ | $Sh_i - K_i(\alpha^{NE})$ |
|---------|------------------|------------------|------------------|------------------|
| $\delta = 0.02$ | $\delta = 0.2$ | $\delta = 0.02$ | $\delta = 0.2$ |
| KrAS | 691072037.4 - 209, 19x0 691211811.9 - 201, 84x0 | 8431.6 | 7991.9 |
| BrAS | 250182865.8 - 140, 09x0 250267647.5 - 135, 18x0 | 5000.2 | 4739.5 |
| IrAS | 457732018.6 - 44, 9x0 457762022.7 - 43, 33x0 | 1316.7 | 1248.2 |

The results show that cooperation is beneficial for all smelters. It should be noted that the higher value of the fine $d_i$, the more profitable the company is to cooperate. In our example Krasnoyarsk Aluminum Smelter is most motivated for cooperation.
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