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A network model for the short-term prediction of the evolution of cocaine consumption in Spain

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Abstract

Cocaine consumption is a social problem with acute consequences and its dependency can be regarded as a health concern of social transmission. This fact leads us to develop the idea that its transmission dynamics can be studied using type-epidemiological mathematical models. Under this point of view, in this paper we propose a network model to study the short-term evolution of the cocaine consumer subpopulations. The model parameters are obtained from data source and from an analogue continuous model. Sensitivity of the model parameters is studied. The parameters are associated with prevention and treatment policies and the sensitivity study gives us information about which parameters have more incidence on the future evolution of consumers. Results and discussion are also presented.

Key words: cocaine consumption, network modeling, short-term predictions, confidence intervals.

1. Introduction

Cocaine consumption is growing at a worrying rate in developed and developing countries [1, 2]. In Spain it is becoming a serious problem not only from an individual health point of view but also from the public socioeconomic one [3, 4]. We note that cocaine consumption is increasing (see Table 1).

Thus it is in the interest of public health to study the dynamics of cocaine consumption. In this article, we analyze the evolution of people with habitual cocaine consumption in Spain and simulate some health policy proposals and

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Table 1: Evolution of the proportion of Non-consumers, Occasional consumers, Regular Consumers and Habitual Consumers subpopulations for different years. The data have been obtained from the Drug National Observatory Reports [3, 4].

<table>
<thead>
<tr>
<th>Percentages/years</th>
<th>1995</th>
<th>1997</th>
<th>1999</th>
<th>2001</th>
<th>2003</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Non-consumer</td>
<td>0.944</td>
<td>0.948</td>
<td>0.948</td>
<td>0.911</td>
<td>0.903</td>
<td>0.884</td>
</tr>
<tr>
<td>% Occasional consumers</td>
<td>0.034</td>
<td>0.032</td>
<td>0.031</td>
<td>0.049</td>
<td>0.059</td>
<td>0.070</td>
</tr>
<tr>
<td>% Regular consumers</td>
<td>0.018</td>
<td>0.015</td>
<td>0.015</td>
<td>0.026</td>
<td>0.027</td>
<td>0.030</td>
</tr>
<tr>
<td>% Habitual consumers</td>
<td>0.004</td>
<td>0.005</td>
<td>0.006</td>
<td>0.014</td>
<td>0.011</td>
<td>0.016</td>
</tr>
</tbody>
</table>

their effect in reducing this population. Spanish Government strategy on drug abuse appears in the Plan Nacional sobre Drogas (Drugs National Plan) [3, 5], issued by the Spanish Health Ministry. The objectives mentioned in this document are:

1. The prevention of drug consumption, pointing out the health concerns produced by their consumption, delaying the age of the first contact with drugs, education programs and legal fight against drugs dealing.
2. To improve quantitative and qualitative research, implement new treatments, evaluate current therapy programs and training to increase professional competence of the people who work with drug abusers.

In this paper, we take cocaine consumption as a socially transmitted epidemic disease. We treat cocaine consumption as a disease that spreads through social peer pressure or social contact. These social contacts have an influence on the probability of transmission of cocaine consumption. The main idea behind this conception is that cocaine consumption can spread from one person to another. In recent times, health behaviors (smoking, drinking or unhealth nutritional habits) have been considered as social epidemics [6, 7]. These facts lead us to propose an epidemiological-type model to study the evolution of this consumption where the health policies proposed by the Plan Nacional sobre Drogas will be considered. These types of continuous mathematical models already have been used in the study of other drug addictions, such as alcohol, tobacco, ecstasy or heroin addiction [8, 9, 10, 11].

The spread of epidemic diseases has been traditionally simulated by means of systems of differential equations [12, 13, 14]. Differential equations are a powerful and well-known mathematical tool for studying the dynamics of any system and, consequently, it is not surprising that it has dominated the research in epidemiology for many years. The SIR model has been widely studied [14, 15] but, although it is a good approximation in some cases, it is clear that it cannot be the final word in the epidemiology of any real disease because, for instance, the continuous approach cannot, by its own nature, distinguish among individuals and, consequently, the effect of age, sex, previous infections and any other parameters influencing the propagation of the epidemic under study.

Due to this facts, in this paper we consider a complete network model for the spread of cocaine consumption in Spain, based on the continuous model proposed in [16], in order to predict the consumption trends in the next few
years. This is a first step in which we want to reproduce similar results as in the continuous model, in order to take it as a starting point to develop, in the future, more complex network models where we can easily monitor the age or situation of any individual and implement precise strategies at a given age or in some target populations or seasons or special situations of interest, what may be difficult or impossible in continuous models.

One important and useful feature of the continuous models is that they are more reliable concerning the application of optimizing techniques. Consequently, we recall the continuous model proposed in [16] where parameters have been fitted with data of Table 1 in order to apply it to the evolution of a complete network model for Spain.

The paper is organized as follows. In Section 2 the classical continuous compartmental mathematical model developed in [16] is recalled. Section 3 is devoted to the details of the stochastic network model. Simulations and predictions of the model are discussed in Section 4. Model sensitivity is presented in Section 5. The paper ends with some discussions and conclusions in Section 6.

2. The continuous mathematical model

In this section we summarize the main results obtained in [16]. In order to build the mathematical model, the 15–64 years old Spanish population is divided into four subpopulations: $N(t)$: Non-consumers, individuals that have never consumed cocaine. $C_o(t)$: Occasional consumers, individuals that have consumed sometimes in their life. $C_r(t)$: Regular consumers, individuals that have consumed in the last year. $C_b(t)$: Habitual consumers, individuals that have consumed in the last month. These subpopulations are defined by the Spanish Health Ministry. This classification is frequently used in the surveys of the Spanish Health Ministry [3, 4, 17].

Furthermore, we consider the following assumptions:

1. Let us assume homogeneous population mixing, i.e., each individual can contact with any other individual [14].
2. The transitions between the different subpopulations are determined as follows:
   (a) Let us consider that the newly recruited 15 years old individuals become members of the $N(t)$ subpopulation, i.e., we consider that they never consumed cocaine before.
   (b) Once an individual begins cocaine consumption he/she becomes an occasional consumer, $C_o(t)$. If this person increases cocaine consumption he/she may become a regular consumer, $C_r(t)$. If this individual continues with his/her consumption he/she may become a habitual consumer, $C_b(t)$.
   (c) An individual of subpopulation $C_b(t)$ becomes a member of subpopulation $N(t)$, non-consumer subpopulation, if he/she decides to give up cocaine consumption and go into therapy.
An individual in \( N(t) \) transits to \( C_o(t) \) because people in \( C_o(t), C_r(t) \) or \( C_b(t) \) transmit cocaine consumption habit by social contact at rate \( \beta \). Therefore, this is a nonlinear term modeled by \( \beta N(t)(C_o(t) + C_r(t) + C_b(t)) \). The remainder transits are governed by terms proportional to the sizes of the subpopulations:

i. \( \gamma C_o(t) \) to transit from \( C_o(t) \) to \( C_r(t) \),
ii. \( \sigma C_r(t) \) to transit from \( C_r(t) \) to \( C_b(t) \),
iii. \( \epsilon C_b(t) \) to transit from \( C_b(t) \) to \( N(t) \).

Under the above assumptions, a dynamic cocaine consumption model for Spanish population is given by the following nonlinear system of ordinary differential equations, whose diagram is depicted in Figure 1:

\[
\begin{align*}
N'(t) &= \mu P(t) - d N(t) - \beta \frac{N(t)(C_o(t) + C_r(t) + C_b(t))}{P(t)} + \epsilon C_b(t), \\
C_o'(t) &= \beta \frac{N(t)(C_o(t) + C_r(t) + C_b(t))}{P(t)} - d C_o(t) - \gamma C_o(t), \\
C_r'(t) &= \gamma C_o(t) - d C_r(t) - \sigma C_r(t), \\
C_b'(t) &= \sigma C_r(t) - d C_b(t) - \epsilon C_b(t), \\
P(t) &= N(t) + C_o(t) + C_r(t) + C_b(t).
\end{align*}
\]

Figure 1: Flow diagram of the mathematical model (1)-(5) for the dynamics of cocaine consumption in Spain. The boxes represent the subpopulations and the arrows represent the transitions between the subpopulations. Arrows are labeled by the parameters of the model where the parameters of the model are:

- \( \mu = 0.01 \text{ years}^{-1} \) is the average Spanish birth rate between years 1995-2007 [18].
- \( d = 0.008388 \text{ years}^{-1} \) is the average Spanish death rate between years 1995-2007 [18].
- \( d_c = 0.01636 \text{ years}^{-1} \) is the augmented death rate due to drug consumption. In Spain, approximately 6.8% of mortality is due to drugs consumption [17].
• $\epsilon = 0.0000456$ years$^{-1}$. From official data [17] 4.25% of habitual consumers begin a therapy program every year. Furthermore, using data from Table 1 corresponding to National Drug Observatory Reports [17], the average proportion of population with habitual consumption is 0.93%. Moreover, the conclusion specified in [17, 19, 20] that a habitual consumer takes about nine years before going to therapy. Therefore, the percentage of habitual consumers in therapy per year is 0.00439%. To be precise, $0.0093 \times 0.0425 \times 1/9 = 0.0000439$. Additionally, [20, 21, 22, 23, 24, 25, 26] they conclude that around 52% of the individuals on therapy recover with an average of six months. Then, we obtained $\epsilon = 0.0000439 \times 0.52 \times 1/0.5 = 0.0000456$, i.e.,

$$\epsilon = \epsilon_1 \times \epsilon_2 \times \epsilon_3 \times \epsilon_4 \times \epsilon_5 =
0.0093 \times 0.0425 \times 1/9 \times 0.52 \times 1/0.5 = 0.0000456. \quad (6)$$

• $\beta = 0.09614$, transmission rate due to social pressure to consume cocaine.

• $\gamma = 0.0596$, rate at which an occasional consumer transits to the regular consumption subpopulation.

• $\sigma = 0.0579$, rate at which a regular consumer transits to the habitual consumption subpopulation.

• The initial conditions of the model are taken for year 1995 ($t = 0$), $N(t = 0) = 0.944$, $C_o(t = 0) = 0.034$, $C_r(t = 0) = 0.018$ and $C_b(t = 0) = 0.004$.

3. The social network model for cocaine consumption

Let us discuss the implementation of a social network model (graph in which individuals are nodes and relationship types are ties) for the cocaine consumption. We consider the following assumptions:

• We consider that every person occupies a node of a network of relations among individuals. These individuals (nodes) could be in any of the four states: non-consumer, occasional consumer, regular consumer or habitual consumer.

• We consider a complete graph (all the nodes are connected), i.e., every person is potentially connected with any other person. Therefore, each cocaine consumer can transmit the habit to consume cocaine to any other individual (it is the easiest way to translate continuous models into networks).

• The network starts with $N$ people (that will vary along the time) at $t_0 = January, 1995$. The initial conditions are: 94.4% of the nodes have the state of non-consumer, 3.4% of nodes have the state of occasional consumers, 1.8% of nodes have the state of regular consumers and 0.4% have the state of habitual consumer.
• Time steps are set to one month. We study the cocaine incidence rate month by month.

The evolution rules are as follows:

• The new 15-years-old individuals enter in the system as non-consumers following a Poisson distribution of mean $\lambda = \mu N/12 = 0.01 N$ people/month. Poisson distribution has been chosen because is the natural discretization of the underlying exponential distribution in the continuous model which mean is $\mu$. Thus, for every time step, we compute a pseudorandom number $0 \leq s \leq 1$ and we find the minimum natural number $i$ such that

$$\sum_{k=0}^{i-1} \frac{e^{-\lambda \lambda k^k}}{k!} > s.$$ 

Then, we introduce in this month $i$ new 15-years-old non-consumers. Hence, in this way, with the Poisson distribution, we introduce randomness in the recruitment.

• Every time step and for every non-consumer, we calculate a pseudorandom number. If it is smaller than $d/12 = 0.008388/12 = 0.000699$ month$^{-1}$, the non-consumer dies and it is removed from the system. Similarly for occasional, regular and habitual consumers with probability $d_c/12 = 0.01676/12 = 0.001363$ month$^{-1}$.

• Every time step we draw a pseudorandom number for every occasional consumer, if this number is smaller than the transition rate per month $\gamma/12 = 0.0596/12 = 0.004967$ month$^{-1}$ we change its state from the occasional consumer to regular consumer.

• Analogously, every time step, for every regular consumer and for every habitual consumer, we perform the stochastic transition from regular to habitual consumer and from habitual to non-consumer with probabilities

$$\sigma/12 = 0.0579/12 = 0.004825 \text{ month}^{-1},$$

$$\epsilon/12 = 0.0000456/12 = 0.0000038 \text{ month}^{-1},$$

respectively.

• The social spreading of the cocaine consumption is simulated by a mean-field procedure. The probability for a non-consumer individual to become occasional consumer at a given time step is:

$$P(\text{non-consumer} \rightarrow \text{occasional consumer}) = 1 - (1 - \beta^* C_o(t) + C_r(t) + C_b(t))$$

where $\beta^*$ is the probability for a non-consumer individual to become in social contact with a consumer individual times the probability for the consumption habit to be transmitted in this contact. $C_o(t) + C_r(t) + C_b(t)$ are all the cocaine consumers at time step $t$. The correspondence with the rate in the continuous model is $\beta^* = \beta/N = 0.09614/N$. 

6
The mean-field approach has been successfully applied in other network models [27] and it yields good results in comparison with the correct, but very computational intensive, procedure of visiting every pair of consumer and non-consumer sites to determine the propagation of the consumption habit at the next time step. The required condition to this simplifying procedure to be valid is that $\beta^* << 1$.

4. Simulations and predictions

The procedure to simulate the evolution of cocaine consumption in Spain described in the above section depends on the generation of several pseudorandom numbers that determine the transit of the state of the nodes. A single simulation may lead to an extreme situation therefore, in order to avoid these undesirable situations, it is recommendable to do several simulations (realizations) and calculate the mean of the obtained results. Thus, the "mean" simulation is not biased by some extreme realizations. For the simulations in this paper, after some empirical tests balancing results and computation time, we decided to do 4 realizations.

In Figure 2 we present the mean model predictions in the next few years for the starting population $N = 10000$ and 4 realizations. Points represent data from Table 1.

![Figure 2](image-url)

**Figure 2:** Numerical simulations of the network model with starting population $N = 10000$ and 4 realizations. The left graphic include the four subpopulations, non-consumers, occasional, regular and habitual consumers. The right graphic only appear the consumer subpopulations. $t = 0$ corresponds to December of year 1995 and $t = 216$ to December of year 2013. Points are data from Table 1. Moreover, the predictions for the next few years until December of 2013 are included. Note the increasing trend of cocaine consumption in Spain.

We noted a decreasing trend in non-consumer subpopulation. Also, there is an increasing trend in the occasional, regular and habitual consumers subpopulation. If there are no changes in current cocaine consumption policies in the next few years, the model predicts that 80.25%, 11.66%, 4.98% and 3.09% of 15 – 64 years old individuals in Spain will be, by December of year 2015, non-consumer, occasional consumer, regular consumer and habitual consumer respectively.

This prediction may seem very alarming but the survey of 2007 recently published gives the following data for the considered subpopulations: Non-consumers = 87.4%; Occasional consumers = 8%; Regular consumers = 3%
and Habitual consumers = 1.6% these being very similar to the ones predicted by the proposed model, 86.77%, 8.04%, 3.29% and 1.88%. A possible explanation of this increase would be that, even thought there is an intensive effort put into anti-drugs campaigns, this is accompanied by legal permissibility to consumers (they are viewed as victims) and to small dealers.

5. Sensitivity analysis

We performed several simulations varying the parameters of the model in order to find out what the influence of the changes on the final solution is (cocaine consumption). We carry out these variations (sensitivity analysis) to analyse the strategies of Spanish Government against drug abuse.

The five health policies simulated here related to the ones mentioned in the introduction (recall from expression (6) that parameter $\epsilon$ is computed as a product), are:

1. Variation on the time that a habitual consumer takes before going into therapy. It involves a variation in parameter $\epsilon_3$ to be precise in $\epsilon_1$. This parameter $\epsilon$ is associated with the implementation of new treatments, evaluation of current therapy programs, training plans to increase professional competence of the people who work with drug consumers, etc.
2. Variation on the percentage of habitual consumers in therapy. It also involves a variation in parameter $\epsilon$, to be precise in $\epsilon_2$.
3. Variation on the success rate of therapy programs. It involves a variation in parameter $\epsilon$, to be precise in $\epsilon_4$.
4. Variation on the duration of therapy programs. It involves a variation in parameter $\epsilon$, to be precise in $\epsilon_5$.
5. Variation on the transition rate from non-consumers to occasional consumers. It involves a variation of parameter $\beta$. This parameter is associated with prevention policies.

In order to perform the sensitivity analysis, let us use the technique called Latin Hypercube Sampling (LHS) to vary parameter values in the proposed model. Latin Hypercube Sampling, a type of stratified Monte Carlo sampling, is a sophisticated and efficient method for achieving equitable sampling of all input parameters simultaneously [28, 29]. Each parameter of the model can be defined as having an appropriate probability density function associated with it. It is usual to use the uniform distribution centred at deterministic parameters estimators in absence of data to inform on the distribution for a given parameter [30, 31]. Then, the model can be simulated by sampling a single value from each parameter distribution. Many samples should be taken and many simulations should be run, producing variable output values.

To vary $\epsilon_2$, $\epsilon_3$, $\epsilon_4$ and $\beta$, we assume that all of them follow a uniform probability distribution with support on the intervals $[0, 0.085]$, $[0.06, 0.2]$, $[0.32, 0.72]$, $[0, 4]$ and $[0, 0.19]$ respectively. The intervals for $\epsilon_2$ and $\beta$ are chosen assuming that the value of the parameter may have a perturbation not greater
than 100%. The interval for $\epsilon_5$ (time of treatment) is chosen assuming a perturbation not greater than 100% to consider all of the treatments studied in Dutra study [20]. The interval for $\epsilon_4$ (success rate of therapy programs) is chosen taking into account all of the programs analyzed in studies [20, 21, 22, 23, 24, 25, 26]. The interval for $\epsilon_3$ (years of cocaine consumption before therapy) is chosen assuming the years of cocaine use before therapy presented in Dutra study [20], that is, 5 – 15 years.

LHS was used to generate 5000 different values of the parameters $\epsilon_2$, $\epsilon_3$, $\epsilon_4$, $\epsilon_5$ and $\beta$ (input). Then we used these samples to run 5000 evaluations of the model. The results of these evaluations allow us to determine the 90% confidence interval, the mean value of the 5000 realizations and the model consumption predictions. The values of the non perturbed parameters are the ones described in Section 2. The obtained predictions (percentage of habitual consumers) for December of year 2011 and December of year 2015 after the variation of the parameters are:

1. Variation of the habitual consumers in therapy, i.e., $\epsilon_2 \in [0, 0.085]$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>90% confidence interval</th>
<th>Mean 5000 realizations</th>
<th>Model estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2011</td>
<td>[2.527%, 2.796%]</td>
<td>2.643%</td>
<td>2.619%</td>
</tr>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2015</td>
<td>[2.965%, 3.222%]</td>
<td>3.065%</td>
<td>3.095%</td>
</tr>
</tbody>
</table>

2. Variation of the time before going into therapy, i.e., $\epsilon_3 \in [0.06, 0.2]$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>90% confidence interval</th>
<th>Mean 5000 realizations</th>
<th>Model estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2011</td>
<td>[2.527%, 2.799%]</td>
<td>2.641%</td>
<td>2.619%</td>
</tr>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2015</td>
<td>[2.958%, 3.228%]</td>
<td>3.092%</td>
<td>3.095%</td>
</tr>
</tbody>
</table>

3. Variation of the rate of success of therapy programs, i.e., $\epsilon_4 \in [0.32, 0.72]$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>90% confidence interval</th>
<th>Mean 5000 realizations</th>
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</tr>
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<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2011</td>
<td>[2.529%, 2.761%]</td>
<td>2.642%</td>
<td>2.619%</td>
</tr>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2015</td>
<td>[2.960%, 3.236%]</td>
<td>3.093%</td>
<td>3.095%</td>
</tr>
</tbody>
</table>

4. Variation of the duration of therapy programs, i.e., $\epsilon_5 \in [0, 4]$. 

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>% of $C_\mathcal{H}(t)$ at Dec 2011</td>
<td>[2.529%, 2.789%]</td>
<td>2.644%</td>
<td>2.619%</td>
</tr>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2015</td>
<td>[2.967%, 3.227%]</td>
<td>3.095%</td>
<td>3.095%</td>
</tr>
</tbody>
</table>

5. Variation of the transition rate to occasional consumers, i.e., $\beta \in [0, 0.19]$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>90% confidence interval</th>
<th>Mean 5000 realizations</th>
<th>Model estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2011</td>
<td>[1.921%, 4.107%]</td>
<td>2.767%</td>
<td>2.619%</td>
</tr>
<tr>
<td>% of $C_\mathcal{H}(t)$ at Dec 2015</td>
<td>[1.941%, 4.247%]</td>
<td>3.291%</td>
<td>3.095%</td>
</tr>
</tbody>
</table>

6. Variation of $\epsilon_2$, $\epsilon_3$, $\epsilon_4$, $\epsilon_5$ and $\beta$ (all together), i.e., $\epsilon_2 \in [0, 0.085]$, $\epsilon_3 \in [0.06, 0.2]$, $\epsilon_4 \in [0.32, 0.72]$, $\epsilon_5 \in [0, 4]$ and $\beta \in [0, 0.19]$. 

<table>
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<td>% of $C_\mathcal{H}(t)$ at Dec 2015</td>
<td>[1.941%, 4.247%]</td>
<td>3.291%</td>
<td>3.095%</td>
</tr>
</tbody>
</table>
The perturbation of parameter $\beta$ leads to larger variations in output than the rest of perturbed parameters. This fact allows us to say that prevention policies (the ones related to parameter $\beta$) may have a noticeable effect in the reduction of drug consumption. Alternatively, if prevention policies are disregarded, drugs consumption will increase.

6. Conclusions

In this paper, we propose a network epidemiological mathematical model applied to cocaine consumption in Spain. This model considers the habit of cocaine consumption as a communicable disease that is spread by social transmission. The Spanish population is divided into subpopulations of interest where certain parameters determine the transitions among these subpopulations. Furthermore, these parameters are associated with health policies of the Spanish Health Ministry.

After the simulation of different health policy proposals of the Spanish Health Ministry, we can conclude that prevention policies seem to be the best effective strategy to reduce the population of regular and habitual consumers. We note that taking into account random perturbations on $\beta$, the 90% confidence interval prediction presents the most important variability, i.e., modifications in prevention programs (variations of $\beta$) are the best option to modify consumption (confidence interval). In the other cases the variations on the parameters do not produce so noticeable variations on the confidence intervals (cocaine consumption prediction).

Also, it is shown how this type of mathematical models can be an useful tool to experiment with health policy proposals. Using such mathematical approach, we are able to simulate different situations and analyze the effect of changes in health policies on the dynamics of drug consumption.

References


