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Risk Factors and Predictive Modelling of Homicide–Suicide in the Southeastern Serbia: Evidence of a Multiplicative Effect and Public Health Implications

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Abstract:

Background and Objectives: Homicide-suicide is the most extreme outcome of close interpersonal relationships, in public health terms. Although the influence of alcohol, mental disorders and psychoactive substances has often been considered, their combined quantitative effect has not been sufficiently investigated. *Materials and Methods:* This study aims to quantitatively examine and model the impact of these risk factors on homicide-suicide in Southeastern Serbia in the period 2000-2022 based on aggregated annual data of 86 cases. Simple linear regression was used to analyse time trends, while Poisson regression with a log-link function was used to assess the impact of risk factors. *Results:* The results show that mental disorders represent the most significant risk factor, with a statistically highly significant positive effect ($\beta=0.1985$; $p<0.001$), which corresponds to an increase in the expected number of homicide-suicides by approximately 22.0% per unit increase in the factor. Chronic alcoholism has a positive effect ($\beta = 0.2590$; $p = 0.053$), with borderline statistical significance and an estimated increase of about 29.6%; acute alcoholism has a weak and statistically insignificant effect ($\beta = 0.0498$; $p = 0.593$), with an increase of about 5.1%; and psychoactive substances show a negative and statistically insignificant effect ($\beta=-0.2136$; $p=0.718$), which corresponds to a decrease of approximately 19.2%, but without reliable interpretative significance. *Conclusions:* The model indicates a multiplicative effect between mental disorders and chronic alcoholism. The results show that mental disorders present the dominant risk factor, while alcoholism takes a significant role. The model indicates a multiplicative effect between these risk factors, and the homicide-suicide probability significantly increases with their combination. Statistically significant differences were observed in relation to the place of residence and the choice of execution method, especially in connection with the use of firearms. The developed regression framework quantifies the statistical significance of individual risk factors, providing the predictions of the expected number of homicide-suicides under different input conditions. The integration of statistical modelling with public health interpretation of results provides a basis for developing targeted, evidence-based preventive strategies, indicating the need to strengthen mental health services and reduce alcohol abuse as key preventive measures.

Keywords: homicide-suicide, risk factors, alcoholism, mental disorders, psychoactive substances, Simple Linear Regression, Poisson regression, public health, forensic epidemiology.

1. INTRODUCTION

The World Health Organisation recognises violence in close interpersonal relationships as a significant public health problem, which has long-term consequences for the physical and mental health of individuals. In the large heterogeneous homicide group, special attention is given to a homicide followed by suicide, in the literature known as homicide-suicide (H-S), which, as a separate entity, represents the suicide of the perpetrator after killing one or more people [1-3].

In this context, homicide-suicides represent an extreme outcome of continued exposure to risk factors, such as mental disorders, psychoactive substances and alcohol abuse. Analysing the impact of these risk factors provides significant insights for developing more effective preventive strategies from a public health perspective [3,4].

Homicide-suicides are violent deaths involving two or more interconnected individuals, with their relationship being key to understanding the motives of the occurrence and the circumstances. These murders most often occur in the context of close interpersonal relationships, such as partner and family relationships, and are often associated with jealousy, breakup, family conflicts and mental disorders. Within partner relationships, homicide-suicides involve violence between persons in an intimate relationship, including partners, ex-partners, and spouses. Within family relationships, the most common include parent-child and brother-sister relationships. Homicide-suicides are often significantly influenced by alcohol, mental disorders and psychoactive substances [3-7].

Alcohol plays an important role in homicide-suicides because it reduces inhibitions, increases impulsivity, impairs the ability to realistically assess the situation and increases aggressiveness, which facilitates the transition from conflict to violence. In many cases of partner murder, one or both actors are under the influence of alcohol at the time of the crime. Previous research further confirms the strong association between alcohol consumption and violent crimes, especially murders, with alcohol often present in both actors and contributing to the escalation of conflict with a fatal outcome [8-11].

Mental disorders, especially depression, psychotic disorders and personality disorders, can contribute to distorted reasoning, a sense of hopelessness and pathological jealousy, which increases the risk of violent outcomes and suicidal behaviour, especially in cases of homicide-suicide. However, it is important to emphasise that most people with mental disorders are not violent, but the risk increases when additional factors are present, such as alcohol, conflict, and the availability of weapons [3,7,11-18].

Abuse of psychoactive substances such as sedatives and opioids, stimulants and other drugs further increases aggression and irritability, paranoia and anxiety, and emotional instability, which may contribute to the increase in the number of homicide-suicides [3,7,11,19-21].

Mental disorders, psychoactive substances and alcohol abuse are well-established public health issues that are closely associated with suicidal behaviour and an increased risk of adverse outcomes, including violence and homicide–suicide. Thus, alcohol, mental disorders and psychoactive substances are not independent causes of homicide-suicides, but they significantly

increase the violent outcome probability, especially in the context of close interpersonal relationships. The highest risk arises when these factors co-occur with preexisting conflicts and dysfunctional relationships and communication between actors. These factors are risk factors that, in certain circumstances, can contribute to the escalation of violence, but they do not act deterministically [17,18,22-29].

Background

The aim of this paper is to quantitatively examine and model the influence of alcohol consumption, mental disorders and psychoactive substances consumption on homicide-suicides in Southeastern Serbia (Republic of Serbia) in the period from 2000 to 2022.

One of the first quantitative studies of homicide-suicides in the Republic of Serbia by analysing the influence of mental disorders, acute and chronic consumption of alcohol and psychoactive substances, using regression models for counting occurrences, is presented in this paper. Unlike existing research, which is predominantly based on descriptive analyses or qualitative approaches, this paper uses formal statistical modelling that enables a precise assessment of the relative importance of individual risk factors. Although there are numerous studies examining the influence of alcohol, psychoactive substances and mental disorders in homicide-suicides, quantitatively modelling their joint influence on homicide-suicides using regression models is very rare, especially in the context of a single country. Thus, there are studies that examine risk factors for homicide-suicides using statistical models, but a small number of studies use an integrated approach that simultaneously includes several key factors and models their joint impact on the number of occurrences using Poisson regression [5,6,15,22-45].

This paper focuses on combining time trend analysis with a regression model, enabling simultaneous observation of the dynamics of risk factors over time and their quantitative impact on the number of homicide-suicides. In addition, the application of 3D models provides visualisation of non-linear and multiplicative relationships between these factors. In this way, multiplicative effects that are not visible in standard analyses are identified. Empirical verification of the absence of overdispersion showed that the applied model in this case reduces to Poisson regression, providing additional validity and interpretative clarity for the results.

Thus, this research combines statistical modelling with public health interpretation, providing a framework for evidence-based prevention strategies and presenting one of the first quantitative analyses of homicide–suicide in the Republic of Serbia, thereby contributing valuable region-specific insights to the international literature. In addition, the study contributes to the field of forensic epidemiology through the integration of forensic autopsy data with quantitative public health modelling.

2. METHODOLOGY

This research covered the period from 2000 to 2022, during which 15,438 autopsies were performed at the Institute of Forensic Medicine in Niš. Based on expertise and the autopsy protocols, in the observed period, 86 cases of homicide-suicides were registered out of a total number of 529 murders. As part of the autopsies performed, as a standard procedure, toxicological analysis of the corpses' material for the presence of alcohol and psychoactive substances of the perpetrator and the victims was performed at the Institute of Forensic Medicine in Niš, while data on chronic alcoholism and mental disorders were obtained from the medical history of the autopsied persons. All analysed cases originate from the territory of Southeast Serbia, which has a population of 1,406,050 inhabitants. The autopsy protocols were supplemented with other sources, including expert opinions from court and prosecutorial cases, as well as relevant hetero-anamnestic

data. Scientific research conducted on cadaveric material (autopsy protocols) was approved by the Ethics Committee Decision of the Faculty of Medicine, University of Niš, number 12-11238/2-3, dated 12.10.2022. To ensure data confidentiality, all personal and identifying information about participants in this study was removed from the database. After the analysis, the data were stored in the archives of the Institute of Forensic Medicine in Niš - the teaching and scientific database of the Faculty of Medicine, University of Niš [5].

In order to quantitatively examine the impact of alcohol, mental disorders and psychoactive substances on homicide-suicides, a regression models for the number of occurrences were applied. Poisson regression was chosen as the most suitable statistical model for analysis in this research, given that the dependent variable represents the number of homicide-suicides per year, that is, discrete count-type data. The Poisson model is particularly suitable for the analysis of rare and stochastic events that occur in a certain time unit, which in this case is a year. Also, the application of a logarithmic relationship between variables enables the interpretation of the effects of risk factors in a multiplicative way, which is of particular importance for considering their combined action. The analyzed data, based on forensic autopsies and accompanying medical documentation, ensures a high level of reliability in the identification of risk factors, whereby the application of the Poisson model enables the quantification of the impact of precisely verified forensic findings on the frequency of homicide-suicides. Before applying the model, negative binomial regression was also considered as an extension of the Poisson model in conditions of overdispersion. However, the dispersion parameter assessment did not indicate its presence, thus confirming the adequacy of the Poisson regression. Taking into account that the analysed data refer to the annual number of homicide-suicides in the period from 2000 to 2022, as well as to the annual representation of the observed risk factors, a negative binomial regression model was initially considered, which is suitable for the analysis of discrete data and enables modelling of overdispersion. However, the estimated dispersion parameter was negligibly small, indicating the absence of overdispersion in the data. Therefore, Poisson regression with a log-link function was applied as the appropriate model [46-48].

Assuming that

$$Y_t \sim \text{Poisson}(\lambda_t) \tag{1}$$

the mathematical form of the model is given by the expression:

$$\log(\lambda_t) = \beta_0 + \beta_1 A_t + \beta_2 H_t + \beta_3 P_t + \beta_4 D_t \tag{2}$$

or

$$\lambda_t = \exp(\beta_0 + \beta_1 A_t + \beta_2 H_t + \beta_3 P_t + \beta_4 D_t) \tag{3}$$

where $t$is the year of observation, Y_t is the annual number of homicide–suicides in year t, and λ_t is the expected number of homicide–suicides per year. The predictor A_t represents the annual number of homicide–suicide cases in year $t$with evidence of acute alcohol intoxication, whereas H_t represents the annual number of cases related to chronic alcoholism. The predictor P_t represents the annual number of homicide–suicide cases involving documented mental disorders, whereas D_t represents the annual number of cases involving toxicological evidence of psychoactive substance use. Accordingly, a one-unit increase in a predictor corresponds to an increase of one case associated with the respective risk factor, reflecting a higher prevalence of that factor in a given year. Since these risk factors may co-occur within the same case, the predictors were not treated as mutually exclusive.

The regression coefficients β_i, where $i=0,1,2,3,4$, were determined using the Maximum Likelihood Method, which estimates parameter values that maximize the probability of the observed data within a defined model. This approach allows for finding optimal coefficient values that best describe the relationship between the independent variables and the number of homicide-suicides. The parameters were estimated using numerical optimisation methods. Positive coefficient values β_i indicate an increase in the expected number of homicide-suicides, while negative values indicate a decrease.

Besides, Simple Linear Regression, given by the equation: $y(x) = k \cdot x + n$, generally, is also used to find annual trends in risk factors (mental disorders, acute and chronic alcohol consumption, and psychoactive substances) associated with homicide-suicides in Southeast Serbia.

The analysis of perpetrator characteristics in homicide-suicide incidents and the relationship between perpetrator and victim was also performed using contingency tables, with associations between variables examined using the chi-square test of independence.

3. RESULTS AND DISCUSSION

In recent years, the global homicide-suicide rate has ranged from a low of 0.05 per 100,000 population per year in England and Wales, and the Netherlands, to a high of 0.38 per 100,000 in the Toyama region of Japan. Compared with England and Wales, the United States has a relatively high homicide-suicide rate. Recent reports indicate that the homicide-suicide rate ranges from 0.27 per year in Kentucky to 0.38 per 100,000 population per year in central Virginia. In Australia and New Zealand, the murder-suicide rate ranges from 0.07 to 0.11 [3,5,13,28,49-53]. In the period 2000-2022, 529 murders occurred in the territory of Southeast Serbia, of which 86 were homicide-suicides. According to this, the homicide-suicide rate was 0.26 per 100,000 persons per year [5].

The results of the analysis of the influence of alcohol, psychoactive substances and mental disorders in homicide-suicides are given in this section.

An overview of the analysed risk factors (acute and chronic alcoholism, psychoactive substances and mental disorders as independent variables) for homicide-suicides in the period 2000–2022 is given in Table 1.

Table. 1. An overview of the analysed risk factors (acute and chronic alcoholism, psychoactive substances and mental disorders as independent variables) for homicide-suicides in the period 2000–2022

Independent variables	Total	Participation in the total number of homicides-suicide (%)	Note
Total number of homicide-suicides (N)	86	100.0	Dependent variable
Acute alcoholism (A)	16	18.6	Weak growth over time
Chronic alcoholism (H)	12	14.0	No pronounced linear trend
Mental disorders (P)	31	36.0	The most common factor
Psychoactive substances (D)	1	1.2	An extremely rare occurrence

The mental disorders are the most prevalent risk factor in the total sample of 36.0%, followed by acute and chronic alcoholism (18.6% and 14.0%, respectively), while psychoactive substances were registered in only one case (1.2%). This distribution indicates that mental problems play a dominant role among the observed factors, as can be seen in Table 1.

3.1. Analysis of risk factor trends using simple linear regression

A graphic of annual trends in risk factors (mental disorders, acute and chronic alcohol consumption, and psychoactive substance consumption) associated with homicide-suicides in Southeast Serbia is given in Figure 1.

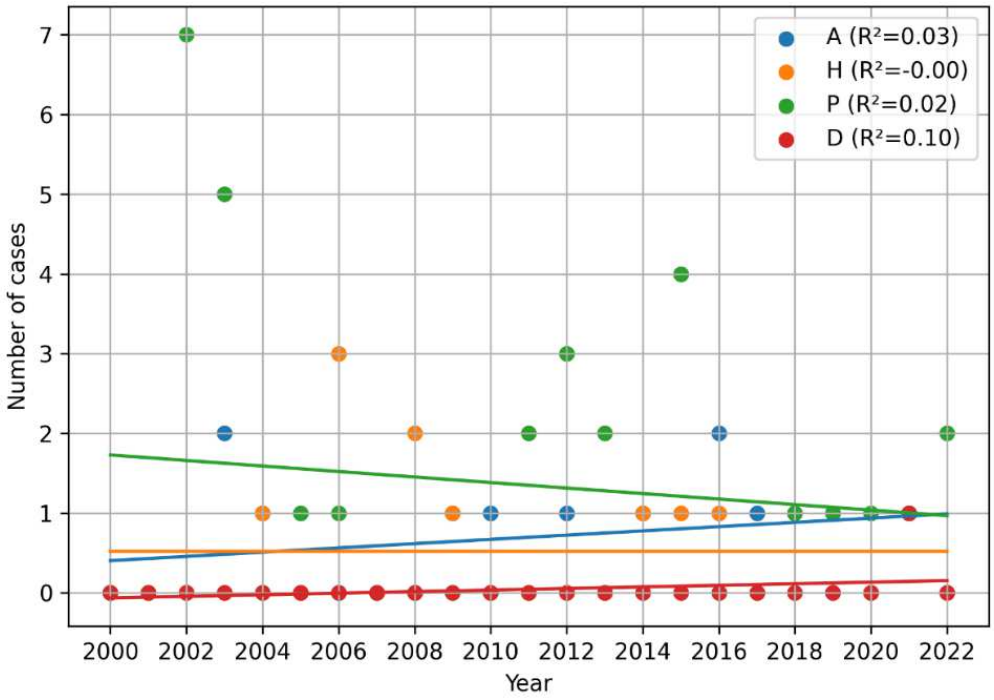


Figure 1. A graphic of annual trends in risk factors (acute and chronic alcohol consumption, mental disorders and psychoactive substance consumption) associated with homicide-suicides in Southeast Serbia.

Figure 1 shows trend lines obtained by applying simple linear regression, wich illustrate changes in the representation of risk factors (acute and chronic alcohol consumption, mental disorders and psychoactive substances consumption) over time. This analysis has a descriptive character and is used to visualise trends.

Acute alcoholism (*A, blue line and dots*) shows moderate growth over time, with occasional oscillations and isolated values of higher intensity, which indicates the increased presence of this factor in later years of observation. Using simple linear regression, the trend of acute alcoholism A(t) was obtained and is described by a linear function: $A(t) = 0.026798 \cdot t - 52.9575$, where t represents the year of observation. Trend analysis shows a slight increase in the observed factor

A(t) over time, which is confirmed by the positive slope coefficient (k = 0.0267), with the value of this factor increasing by approximately 0.027 units per year. Since the intensity of changes is low, this indicates a relatively stable representation of this factor over the observed period. Therefore, this analysis indicates a slight increase in acute alcoholism over the years, but despite the positive trend, the relatively low slope value indicates that the changes over time are of limited magnitude.

Chronic alcoholism (*H, orange line and dots*) remains relatively stable throughout the entire period, with minor fluctuations and no pronounced trend of growth or decline. Using simple linear regression, the trend of chronic alcoholism, H(t), was obtained and is described by the linear function: $H(t) = 1.19703 \cdot 10^{-15} \cdot t + 0.521739$, where t represents the year of observation. Linear regression analysis shows no significant trend in chronic alcoholism over time, as confirmed by the extremely small slope coefficient ($k \approx 0$). Thus, the obtained slope coefficient of the order of magnitude 10^{-15} practically indicates the absence of a linear relationship between time and the observed factor. The obtained results indicate a stable representation of chronic alcoholism during the observed period, without a pronounced increasing or decreasing trend.

Mental disorders (*P, green line and dots*) show the greatest variability and the highest representation among the other factors, with pronounced peaks in certain years (e.g., the beginning of the 2000s), followed by a slight decrease. The trend in perpetrator mental disorders, P(t), obtained by the linear regression function $P(t) = -0.034585 \cdot t + 70.8982$, shows a slightly decreasing trend in the observed factor P(t) over time, as indicated by the negative slope coefficient ($k = -0.0346$). However, the intensity of the change is low, suggesting a gradual, limited decrease over the observed period.

Psychoactive substances (*D, red line and dots*) are minimally represented throughout the entire period, with almost negligible values and a slight increase only in the final years. Linear regression analysis, given by the function: $D(t) = 0.00988142 \cdot t - 19.8281$, indicates a slight increase in the observed factor D(t) over time, which is confirmed by the positive slope coefficient (k = 0.0099) and indicates a slight increase in the abuse of psychoactive substances by the perpetrator, with the value of this factor increasing by approximately 0.01 units per year. However, the intensity of the changes is very low, indicating a gradual, almost stable movement of this factor during the observed period.

Thus, the trend lines further suggest that mental disorders play a dominant role among the analysed factors, while alcohol, especially in acute form, shows increasing importance. Taken as a whole, Figure 1 indicates the heterogeneity and temporal variability of risk factors, with a clear dominance of mental disorders relative to the other analysed variables. It should be noted that, throughout the fitting of linear trends, calendar years (2000–2022) were used as the time variable. Due to the large values of the time variable, the obtained slope coefficients (k) are numerically small, while the free terms (n) can have large absolute values. This does not affect the correctness of this model, but only its record and explainability. When the slope coefficient is approximately equal to zero, it is concluded that there is no pronounced linear trend over time.

In addition, the coefficients of determination (R^2), indicating the extent to which the linear regression model explains the variability in the observed factors over time, are marked and shown in Figure 1. In this case, low R^2 values show the absence of a significant linear trend in the observed risk factors over time, indicating that their changes are not systematically related to the year of observation.

3.2. Analysis of risk factor effects using Poisson regression

As shown in Section 3.1, no stable temporal pattern was observed. Accordingly, in Section 3.2, a regression model was applied to estimate the expected number of homicide-suicides based on the overall dataset, rather than focusing on year-specific expected values (λ_t).

Thus, by applying Poisson regression to the analysed data for the observed period of 23 years, Eq. (2) takes the form:

$$\log(\lambda_t) = 0.8049 + 0.0498\mathrm{A}_t + 0.2590\mathrm{H}_t + 0.1985\mathrm{P}_t - 0.2136\mathrm{D}_t \quad (4)$$

while the exponential transformation of the log-linear model, given by Eq. (4), yields the expression for the expected number of homicide-suicides:

$$\lambda_t = \exp(0.8049 + 0.0498A_t + 0.2590H_t + 0.1985P_t - 0.2136D_t) \quad (5)$$

The exponential form of the model, given by Eq. (5), shows that risk factors have a multiplicative effect on the expected number of homicide-suicides.

Percentage effects of regression coefficients in a Poisson regression model are given in Table 2.

Table 2. Percentage effects of regression coefficients in a Poisson regression model

Variable	**Regression coefficients (β_i)**	**Standard error**	**Statistical significance (*p-value*)**	**% change [exp(β) − 1]**
Constant	0.8049	0.1914	<0.001	—
Acute alcoholism (A)	0.0498	0.0933	0.593	+5.1%
Chronic alcoholism (H)	0.2590	0.1336	0.053	+29.6%
Mental disorders (P)	0.1985	0.0516	<0.001	+22.0%
Psychoactive substances (D)	−0.2136	0.5921	0.718	−19.2%

Table 2 shows that:

- *Acute alcoholism* shows a positive, but statistically insignificant effect in the model (β_1 = 0.0498; p = 0.593). The positive coefficient indicates that an increase in this factor leads to a slight increase in the expected number of homicide-suicides, where it is estimated that an increase of one-unit increases the expected number of homicide-suicides by approximately 5.1%. However, due to the lack of statistical significance, this effect cannot be considered reliable, indicating that acute alcoholism has a limited and unstable influence.
- *Chronic alcoholism* shows a positive effect with the largest estimated percentage increase among the observed risk factors in the model (β_2 = 0.2590; p = 0.053). The positive coefficient indicates that an increase in this factor is associated with an increase in the expected number of homicide–suicides, with a one-unit increase corresponding to an approximate 29.6% rise in the expected number of events. Although the statistical

significance is borderline, this result suggests that chronic alcoholism may represent a relevant risk factor with a positive association.

- *Mental disorders* are the model's most statistically significant risk factor ($\beta_3 = 0.1985$; $p < 0.001$). The positive effect indicates that an increase in this factor leads to an increase in the expected number of homicide-suicides, with a one-unit increase estimated to increase the expected number of homicide-suicides by approximately 22%. This finding confirms the central role of mental problems in the explanation of dyadic homicides.
- *Psychoactive substance abuse* shows a negative, but statistically insignificant effect in the model ($\beta_4 = -0.2136$; $p = 0.718$). The negative coefficient suggests a decrease in the expected number of homicide-suicides by approximately 19.2% per unit increase in this factor. However, due to the very low prevalence of this factor and the high p-value, this result cannot be considered reliable and should not be interpreted as a real protective effect.

Overall, Table 2 indicates that risk factors have a multiplicative effect on the number of homicide-suicides, whereby mental disorders and chronic alcoholism are the most important in explaining the variation in the number of occurrences, while other factors have a weak or unreliable influence. In other words, the increase in mental disorders and chronic alcoholism increases the expected number of occurrences, while the effects of acute alcoholism and psychoactive substances are weaker and statistically insignificant.

Besides, the standard errors of the estimated coefficients (β_i) indicate the reliability of their estimates. Smaller values of the standard error indicate more stable and precise estimates, while larger values indicate greater variability and less reliability. In this model, mental disorders have the smallest standard error, which confirms the stability of their influence, while psychoactive substances have the largest standard error, which indicates the unreliability of the estimate due to the small number of cases.

It should be noted that in the applied regression model, it is not a requirement that the predictors be mutually independent, but that there is no pronounced collinearity between them. Given that risk factors can occur simultaneously within the same case, their effects are observed in the model simultaneously, while due to the logarithmic relationship between the variables, their influence is manifested in a multiplicative manner. Thus, the combined effect of the factors may lead to a greater increase in the expected number of homicide-suicides than would be expected from their individual effects.

Model performance was evaluated using mean absolute error (MAE) and root mean square error (RMSE). The obtained values (MAE = 1.31; RMSE = 1.76) indicate that the model satisfactorily approximates the observed data, with relatively small deviations considering the low number of cases per year. Analysis of residuals, including Pearson's and deviance residuals, did not show a systematic pattern or extreme deviations, indicating an adequate fit of the model to the observed data.

In order to visualise the effect of the most significant factors, a 3D model was constructed in which the expected number of homicide-suicides depends on the number of cases of mental disorders and chronic and acute alcoholism, and is shown in Figure 2.

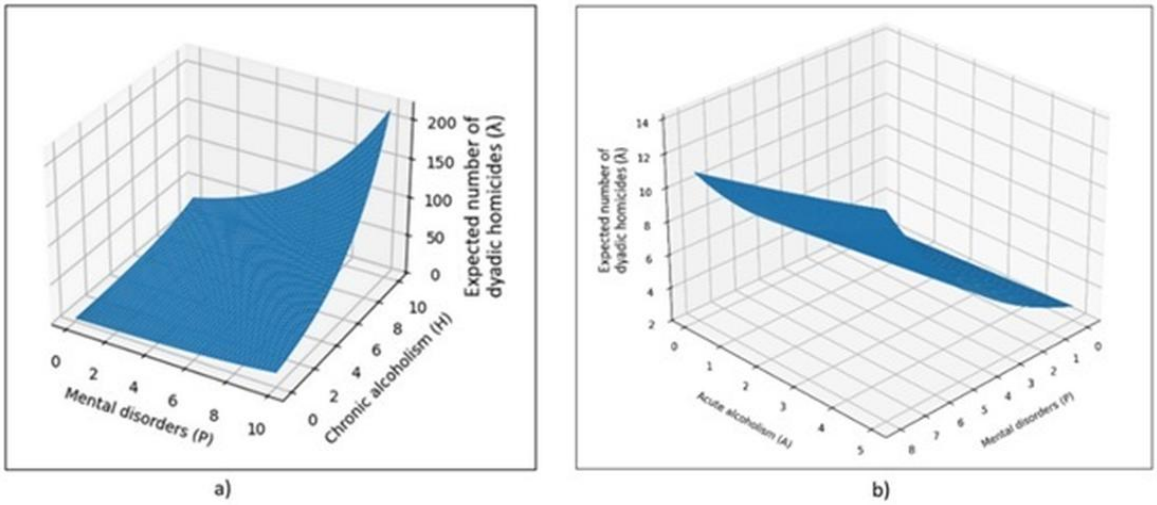


Figure 2. 3D representations of the expected number of homicide-suicides as a function of mental disorders (P) and: (a)chronic alcoholism and (b) acute alcoholism (A), showing their common multiplicative effect.

Figure 2 shows that the surface indicates an increase in the expected number of homicide-suicides with both factors.

The 3D representation additionally illustrates the results of the regression model, suggesting a pronounced joint effect of mental disorders and chronic alcoholism on the expected number of homicide-suicides (Figure 2a). The observed surface shows that the expected number of homicide-suicides does not increase linearly but rather exponentially with increases in these two factors (H and P). As the expected number of homicide-suicides increases, additional increases in these factors produce a larger absolute effect, indicating an escalating trend. When both factors are present simultaneously, there is a marked increase in the expected number of occurrences, indicating a multiplicative joint effect. These results suggest that the combination of mental disorders and chronic alcoholism may have a stronger joint influence than each factor individually. The multiplicative character of this model further shows that these risk factors' effects do not add up; rather, they multiply. The joint multiplicative effect suggests that the combination of these risk factors may play an important role in the occurrence of homicide-suicides. Thus, the model's exponential nature indicates that increases in these risk factors may lead to an accelerated rise in the expected number of homicide-suicides.

In the case of the 3D model of the expected number of homicide-suicides depending on the number of cases of mental disorders (P) and acute alcoholism (A), the surface of the model shows an increasing trend, where an increase in both factors leads to an increase in the expected number of homicide-suicides (Figure 2b). However, the surface slope is more evident along the axis of mental disorders than along the axis of acute alcoholism, which indicates that mental disorders have a stronger influence on the expected number of homicide-suicides compared to acute alcoholism. The shape of the surface reflects the exponential nature of the model, where the expected number of occurrences increases non-linearly, i.e. rapidly with the growth of the risk factor. However, compared to chronic alcoholism, the effect of acute alcoholism is weaker, which is in accordance with the results of the regression analysis that indicate its statistically insignificant influence.

Comparative 3D analysis of alcoholism (acute and chronic) and mental disorders in homicide-suicides is shown in Figure 3.

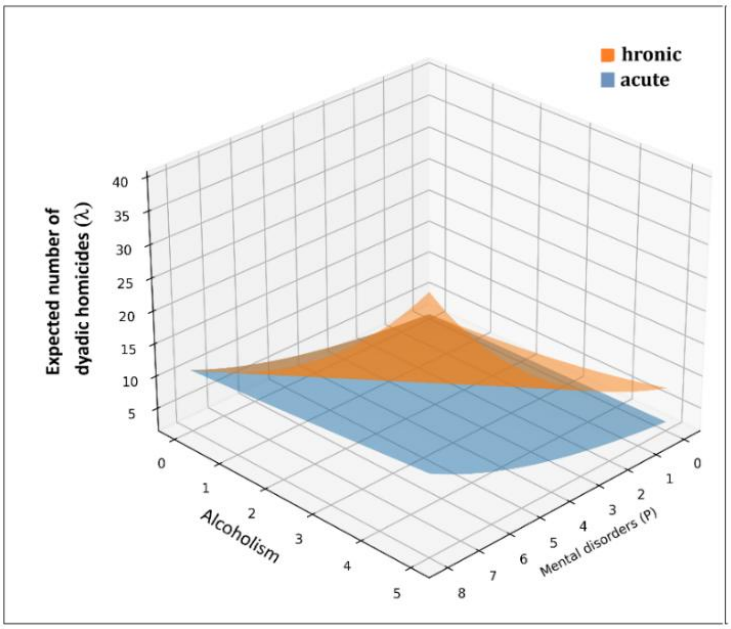


Figure 3. Comparative 3D analysis of alcoholism (acute and chronic) and mental disorders in homicide-suicides.

A comparative analysis of Figure 3 suggests that mental disorders appear to be the dominant factor in both cases, while the difference between chronic and acute alcoholism is reflected in the intensity of their contribution. Chronic alcoholism acts as a long-term and structural risk factor with a stronger positive association, while acute alcoholism has a more situational and weaker role. Thus, this presentation suggests that mental disorders are a dominant factor in the explanation of homicide-suicides, while acute alcoholism has a limited and less pronounced contribution.

It should be noted that, in addition to the assessment of the statistical significance of risk factors on the number of homicide-suicides, the regression model (Poisson regression) applied in this paper also allows the prediction of the expected number of homicide-suicides based on changes in input parameters. The analysis of residuals and evaluation of model performance indicated a satisfactory agreement between observed and predicted values, which further confirms its applicability for modeling homicide-suicides in the observed period. In this way, the model could have practical applications, as it allows the simulation of different scenarios and the assessment of the potential effects of preventive measures. In addition, the quantitative modelling presented in this paper provides an effective approach to understanding homicide-suicides and also indicates the need for further research with larger data sets and additional variables to enable a more precise view of cause-and-effect relationships and to improve prevention strategies. Despite limitations in sample size, the model shows stable parameter estimates and consistent results, which further confirm its applicability for analysing these types of data.

In the public health and violence prevention terms, these results indicate that interventions focused exclusively on one factor may be insufficient, and that an integrated approach that simultaneously includes mental health and the problem of chronic alcohol abuse is necessary.

3.3. Homicide-suicide incidents analysis

The distribution of perpetrator characteristics and methods by risk factors (acute and chronic alcoholism, mental disorders, and psychoactive substance abuse) is shown in Table 3.

Table 3. The distribution of perpetrator characteristics and methods by risk factors (acute and chronic alcoholism, mental disorders, and psychoactive substance abuse) (N, %)[1]

Characteristic	Category	Acute alcohol (N=16)	Chronic alcoholism (N=12)	Mental disorders (N=31)	PAS (N=1)
Sex	Male	15 (93.8%)	8 (66.7%)	21 (67.7%)	1 (100.0%)
	Female	1 (6.2%)	4 (33.3%)	10 (32.3%)	0 (0.0%)
Residence	Urban	6 (37.5%)	2 (16.7%)	23 (74.2%)	0 (0.0%)
	Rural	10 (62.5%)	10 (83.3%)	8 (25.8%)	1 (100.0%)
Education	No education	2 (12.5%)	3 (25.0%)	3 (9.7%)	0 (0.0%)
	Elementary school	7 (43.8%)	6 (50.0%)	8 (25.8%)	0 (0.0%)
	High school	6 (37.5%)	2 (16.7%)	13 (41.9%)	1 (100.0%)
	College	0 (0.0%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
	University	1 (6.2%)	1 (8.3%)	6 (19.4%)	0 (0.0%)
Method of suicide	Hanging	5 (31.2%)	3 (25.0%)	10 (32.3%)	0 (0.0%)
	knife-stabbing	0 (0.0%)	0 (0.0%)	2 (6.5%)	0 (0.0%)
	Axe	0 (0.0%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
	Poisoning	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (100.0%)
	Firearm	9 (56.2%)	8 (66.7%)	15 (48.4%)	0 (0.0%)
	Cutting (throat)	1 (6.2%)	1 (8.3%)	1 (3.2%)	0 (0.0%)
	Jump from height	0 (0.0%)	0 (0.0%)	2 (6.5%)	0 (0.0%)
	Train impact	1 (6.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Method of homicide	Blunt force trauma	1 (6.2%)	1 (8.3%)	2 (6.5%)	0 (0.0%)
	Asphyxia	2 (12.5%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
	knife-stabbing	2 (12.5%)	2 (16.7%)	5 (16.1%)	0 (0.0%)
	Poisoning	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (100.0%)
	Firearm	9 (56.2%)	0 (0.0%)	21 (67.7%)	0 (0.0%)
	Burning	1 (6.2%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
	Cutting (throat)	1 (6.2%)	1 (8.3%)	1 (3.2%)	0 (0.0%)
	Fall from height	0 (0.0%)	0 (0.0%)	1 (3.2%)	0 (0.0%)

[1] Data in Table 3. are presented as absolute numbers and percentages (N, %).

Based on Table 3, it is shown that:

Acute alcohol abuse is present in 16 cases and shows certain patterns in terms of sociodemographic characteristics and methods of execution. Women are represented in a much smaller percentage (6.2%), while male perpetrators are extremely dominant (93.8%). In terms of residence, the majority of cases (62.5%) are related to rural areas, compared to urban areas (37.5%). In terms of the education of the perpetrators, the most common perpetrators are those with elementary and high school education (43.8% and 37.5%, respectively), while shooting (56.3%) is the most common method of suicide, followed by hanging (31.3%), while other methods are sporadic. A similar pattern is observed for the method of murder, where the use of firearms dominates (56.3%). These results indicate that acute intoxication may play the role of a situational factor that, in combination with the availability of firearms, contributes to the escalation of violence.

In *chronic alcoholism*, it has been shown that men make up the majority, while women are represented in a higher percentage than in acute consumption (66.7% and 33.3%, respectively). Most of these cases (83.3%) are associated with rural areas, which indicates a strong link between this factor and specific socioeconomic conditions. In terms of education, elementary school (50.0%) and lower levels of education dominate, while higher levels are minimally represented. The most common method of suicide is shooting (66.7%), while other forms are much rarer. There is also diversity in the method of murder, but without a pronounced dominance of one method, as in mental disorders. These results indicate that chronic alcoholism acts as a long-term risk factor associated with social and economic conditions, especially in rural areas.

In this research, *mental disorders* are the most prevalent factor (31 cases) and show the most pronounced patterns. Men account for 67.7% of cases, while women account for 32.3%. Unlike alcoholism, mental disorders are significantly more common in urban areas (74.2%), compared to rural areas (25.8%). In terms of education, high school (41.9%) and elementary school education (41.9% and 25.8%, respectively) dominate, but a higher participation was also observed among those with higher education than among the other observed risk groups. In terms of the method of suicide, the most common is shooting (48.4%), followed by hanging (32.3%), while other forms are less common. It is important to note that shooting is the dominant method of murder (67.7%). These results confirm the central role of mental disorders in the occurrence of homicide-suicide, with a clear connection to urban areas and the use of firearms.

As *psychoactive substance abuse* was identified in only one case, which represents 1.7% of the total sample, this case refers to a male perpetrator from a rural environment with secondary education. The method of suicide was poisoning, while the method of murder also included poisoning. Due to the extremely small number of cases, it is not possible to draw reliable conclusions about the influence of this factor. However, the results indicate that psychoactive substances may be present in specific circumstances, but their significance in this sample remains limited.

A Heatmap of the distribution of homicide and suicide methods in relation to risk factors is given in Figure 4.

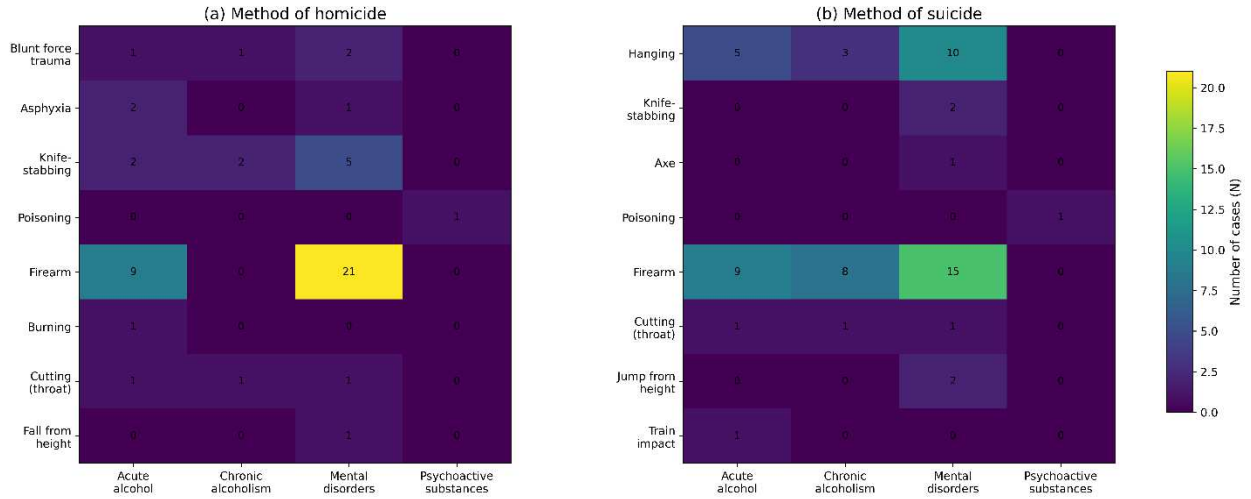


Figure 4. A Heatmap of the distribution of homicide and suicide methods in relation to risk factors.

Figure 4 shows the clear dominance of firearms as a method of execution of both homicide and suicide, especially in cases related to mental disorders. Mental disorders are the most significant risk factor with the widest range of methods represented, which indicates their key role in the occurrence of highly lethal outcomes. In contrast, acute alcohol consumption shows an association with impulsive and highly lethal methods, especially with the use of firearms, which indicates its role as a situational trigger in the escalation of violent behaviour. Chronic alcoholism shows a specific and somewhat more diffuse pattern compared to acute alcoholism, but with clear tendencies towards the representation of highly lethal methods. In cases of homicide chronic alcoholism is most often associated with knife-stabbing and the use of firearms, while in suicides, it is predominantly associated with hanging and the use of firearms. Accordingly, chronic alcoholism does not act only as an immediate trigger, but as a long-term risk factor that influences the formation of more potentially dangerous patterns of behaviour. In the case of suicides, in addition to firearms, hanging also plays an important role, especially in cases related to mental disorders and chronic alcoholism, which indicates the combined influence of psychiatric and behavioural factors. Psychoactive substances are represented in a very small number of cases, so no reliable conclusions about behavioural patterns can be made for this factor.

To examine the connection between the perpetrator's characteristics and risk factors, the Chi-square (χ^2) test of independence was applied to assess whether the distribution of individual characteristics differs depending on the presence of a given risk factor. A statistically significant association was found for the place of residence ($\chi^2 = 14.54$, df = 3, $p = 0.002$), the method of suicide ($\chi^2 = 68.55$, df = 21, $p < 0.001$) and the method of murder ($\chi^2 = 66.85$, df = 21, $p < 0.001$), while for gender ($p = 0.199$) and level of education ($p = 0.679$) no statistically significant association was found. It should be noted that due to the small expected numbers in some categories, the results should be interpreted with caution.

The distribution of homicide–suicide cases according to the relationship between perpetrator and victim and associated risk factors (N, %) is shown in Table 4.

Table 4. Distribution of homicide–suicide cases according to the perpetrator relationship to victim and associated risk factors (N, %)[2]

Perpetrator relationship to victim	Acute alcoholism (N=16)	Chronic alcoholism (N=12)	Mental disorders (N=31)	Psychoactive substances (N=1)
Stranger	0 (0.0%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
Child	1 (6.2%)	1 (8.3%)	4 (12.9%)	0 (0.0%)
Parent	0 (0.0%)	2 (16.7%)	3 (9.7%)	1 (100.0%)
Spouse	6 (37.5%)	3 (25.0%)	4 (12.9%)	0 (0.0%)
Other intimate partner	2 (12.5%)	1 (8.3%)	3 (9.7%)	0 (0.0%)
Ex-spouse/intimate partner	0 (0.0%)	2 (16.7%)	0 (0.0%)	0 (0.0%)
Acquaintance / neighbor	2 (12.5%)	2 (16.7%)	2 (6.5%)	0 (0.0%)
Stepparent	0 (0.0%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
Relative	2 (12.5%)	0 (0.0%)	2 (6.5%)	0 (0.0%)
In-law relationship	1 (6.2%)	1 (8.3%)	4 (12.9%)	0 (0.0%)
Divorcing partner	2 (12.5%)	0 (0.0%)	1 (3.2%)	0 (0.0%)
Colleague	0 (0.0%)	0 (0.0%)	5 (16.1%)	0 (0.0%)
Victim's partner/ex-partner	0 (0.0%)	0 (0.0%)	1 (3.2%)	0 (0.0%)

Table 4 shows that partner relationships, especially spouses, are most represented in cases related to acute alcohol consumption (37.5%) and chronic alcoholism (25.0%), which indicates the importance of conflicts within intimate relationships as a key context for the escalation of violence. The role of acute alcohol consumption is particularly pronounced in partner relationships, but also in a wider range of social interactions, including relationships with acquaintances and relatives. This pattern suggests that acute alcoholism acts as an immediate trigger that reduces inhibitions, increases impulsivity and contributes to the sudden escalation of the conflict into a violent outcome. The existence of this factor shows that in situations of partner separation (12.5%), it further indicates its role in emotionally intense and unstable relationships. Unlike, chronic alcoholism has a different but equally significant pattern. Its presence in cases where a parent kills a child (16.7%), as well as in relationships with ex-partners (16.7%) and acquaintances (16.7%), indicates a long-term disruption of interpersonal relationships. Unlike acute alcohol, which acts situationally, chronic alcoholism can be seen as a factor that gradually destabilises family and social ties, creating conditions for the accumulation of conflicts and increasing the risk of violent outcomes. Mental disorders stand out as the most prevalent factor across different types of relationships. Their significant representation in cases of colleagues (16.1%), as well as in family relationships (child killed a parent - 12.9%; in-laws - 12.9%; spouses - 12.9%), indicates a wide range of situations in which this factor can operate. This distribution suggests that mental disorders affect the wider social environment, including professional and institutional contexts and are present in almost all categories of relationships. It is consistent with previous analyses that indicate the association of psychopathological conditions with an increased risk of violent behaviour, especially in combination with other factors, such as alcohol or social stressors. Family

[2] Data in Table 4. are presented as absolute numbers and percentages (N, %).

relationships, including parent-child and child-parent relationships, also show a significant presence, especially in combination with mental disorders and chronic alcoholism. An interesting finding is the presence of cases without a previous relationship between the perpetrator and the victim, although in a very small percentage (3.2% in the case of mental disorders). These data point to the existence of situations in which violence is not conditioned by an interpersonal relationship, but may be related to individual psychopathological or situational factors. Psychoactive substances are represented in a minimal number of cases, with one recorded case in the category of parent killed child (100%). Due to the extremely small sample, it is not possible to draw reliable conclusions about their role, but this finding indicates the need for additional research on this factor.

Due to the multidimensional structure of the contingency Table 4, the chi-square (χ^2) test of independence was applied, while the application of the Fisher test was limited by the size of the table. The results showed that the relationship between the perpetrator-victim relationship and risk factors is not statistically significant ($\chi^2 = 35.88$, df = 36, p = 0.474). Although certain distributional differences were observed, the statistically significant absence indicates that these patterns must be interpreted with caution, as they may be due to a limited sample and low frequencies in certain categories.

A Heatmap of the distribution of relationship types in relation to risk factors is given in Figure 5.

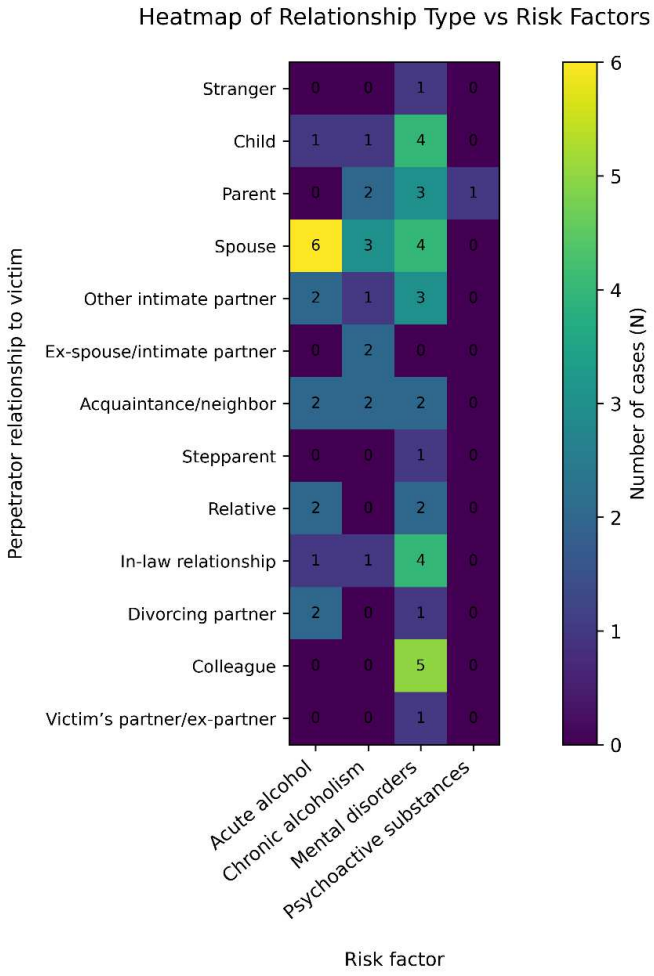


Figure 5. A Heatmap of the distribution of relationship type in relation to risk factors.

Figure 5 shows that partner relationships, especially marriage, are the most represented in cases related to acute alcohol consumption. Acute alcohol abuse affects as an immediate trigger in emotionally intense situations, while chronic alcoholism shows a more even distribution across different relationships, suggesting its long-term impact on the destabilisation of interpersonal relationships. Mental disorders show a wide distribution across different types of relationships, including family, partner and professional relationships. In particular, the presence of mental disorders in cases of colleague murders, as well as in family relationships, is highlighted, which indicates the wider social context in which this factor operates. Psychoactive substances are represented in a very small number of cases, which is manifested in the picture by the weak color intensity, and based on the available data, no reliable conclusions can be drawn about their role.

The results of the analysis of perpetrator characteristics in homicide-suicide incidents indicate the need for a comprehensive and integrated public health approach in the prevention of violent behavior with fatal outcomes, with a special focus on mental health, alcohol abuse and control of access to means of execution. Considering the dominant role of mental disorders, it is necessary to improve the availability of psychiatric and psychological services, especially in primary health care; introduce systematic screening for depression, suicidal ideation and violent behavior; develop early identification programs for at-risk individuals and strengthen community-based mental health services. Given the importance of acute and chronic alcoholism, it indicates the need to develop national programs for the prevention of alcohol abuse; improve the availability of addiction treatment; more intensively implement educational campaigns about the risks of alcohol and introduce alcoholism screening in primary health care with a special focus on rural areas where chronic alcoholism is more pronounced Bearing in mind that there is a dominance of the use of firearms in the analyzed type of violence, it is necessary to tighten controls on the possession of weapons; introduce regular psychiatric evaluations for gun owners; develop a system for confiscating weapons in risky situations and improve records and supervision over the possession of weapons. In Serbia, there are legal frameworks regarding firearms, but stricter enforcement is needed. In terms of partner and family relationships, it is necessary to develop programs for the prevention of domestic violence; improve cooperation between the health system, police and centres for social work; introduce risk assessment in cases of partner conflicts and strengthen victim protection mechanisms. Regarding Serbia, it is necessary to further improve the implementation of the Law on Prevention of Domestic Violence. In addition, the results indicate differences in urban and rural areas, so in urban areas it is necessary to focus on mental health, while in rural areas the focus is on alcoholism and social factors. In terms of education, it is necessary to train health workers more intensively to recognize risk patterns, educate the population about the risks of violence and suicide, and intensively implement campaigns to reduce the stigma of mental disorders Therefore, effective prevention requires the cooperation of the health system, social services, the police and the judiciary, that is, the strengthening of coordination between institutions is crucial for suppressing violent behaviors that lead to fatal outcomes and homicide-suicides.

4. LIMITATIONS

One of the main study limitations is the limited availability of data on victims and perpetrators of homicide-suicides, which is largely due to the fact that both actors in the critical incident have a fatal outcome. Although the analysed data were based on forensic autopsy findings, medical documentation, toxicological analyses, and indirect information obtained during investigative and judicial proceedings, some cases may have remained partially undocumented due

to the limited availability of relevant information. Nevertheless, the use of multiple forensic and medico-legal data sources ensured a relatively high degree of reliability of the analysed data. In addition, the actual number of cases of homicide-suicides in the territory of southeastern Serbia during the observed period is likely not fully covered, given that in some cases the investigating authorities did not request a forensic autopsy, especially when both the victim and the perpetrator died at the scene. Consequently, the possibility of a certain degree of underestimation of the total number of cases cannot be excluded. Due to the observational and aggregated nature of the data, causal relationships between risk factors and homicide-suicides cannot be definitively established.

Besides, there are certain study limitations related to the relatively small sample size and the aggregated nature of the data. The analysis is based on annual values, which may obscure individual-level variability and limit the precision of the effect estimates. In addition, the low frequency of cases related to psychoactive substances reduces the reliability of conclusions related to this factor. Accordingly, future studies should include larger samples, individual-level data and additional relevant variables, as well as more complex statistical models, in order to improve the reliability and precision of assessing the influence of risk factors on homicide-suicides.

5. CONCLUSION

Homicide-suicides in Serbia represent a complex phenomenon associated with the combined influence of several risk factors. The analysis of time trends did not show the existence of a stable time pattern for the observed factors, while Poisson regression showed that certain factors have a significant influence on the number of homicide-suicides. Furthermore, the effects of risk factors are not only additive but multiplicative, which suggests that their simultaneous presence is associated with an increase in the expected number of homicide-suicides. Although the analysis of the perpetrator-victim relationship did not show a statistically significant association with the analyzed risk factors, the observed patterns indicate the importance of intimate and family relationships as a key context for the occurrence of these events. Statistically significant differences in the choice of methods of execution of murder and suicide additionally confirm the importance of social and environmental factors in the occurrence of homicide-suicides. Overall, the results of this study indicate the need for an integrated public health approach aimed at improving mental health care, reducing alcohol abuse, developing violence prevention strategies, and enhancing the early identification of individuals at increased risk of fatal violent behaviour.

Abbreviations

The following abbreviations are used in this manuscript:

H-S: homicide-suicide

N: total number of homicide-suicides

A: acute alcoholism

H: chronic alcoholism

P: mental disorders

D: psychoactive substances

β_i: the regression coefficients.

Ethics approval and consent to participate

Ethical approval was obtained following the ICH Harmonized Tripartite Guideline for Good Clinical Practice, Guidelines and Recommendations for European Ethics Committees, and Operational Guidelines for Ethics Committees that Review Biomedical Research, on which the work of the institutional board of the Ethics Committee of the Faculty of Medicine, University of Niš, Serbia (No. 12-11238/2-3, approved on 12 October 2022) is based. All procedures performed in this study involving human participants and human data were conducted in accordance with the ethical standards of the institutional research committee and with the Declaration of Helsinki and its later amendments. The Ethics Committee waived consent to participate due to the anonymous nature of the data and the absence of identifying information. The Committee approved both the research and the subsequent publication of the obtained results.

Consent for publication

Clinical trial number: Not applicable.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Authors′ Contributions

Conceptualization was performed by S.T. and D.D.T.; methodology by S.T and D.D.T.; formal analysis by S.T. and D.D.T.; validation by D.D.T, T.K. and S.J.; investigation by S.T., D.D.T. and A.A.; data curation by S.T. and D.D.T.; Resources, S.T., A.A. and I.S.; data collection by S.T., A.A. and I.S.; writing—original draft preparation by S.T. and D.D.T.; writing, review and editing by T.K. and S.J. All authors have read and agreed to the published version of the manuscript.

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