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Multivariate analysis applied to a test procedure for determining gun propelling charge weight Part II. Partial least squares analysis

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Abstract

The aim of this study was to find out why several 155 mm gun propelling charge lots produced according to the conventional test procedure for determining gun propelling charge weight had failed to meet the acceptance requirements. Multivariate analysis was applied as an alternative approach to the conventional analysis method to a data set consisting of results connected to 68 test firing occasions. In this paper the results of partial least squares (PLS) modeling applied to the data set are reported. Based on this study the main defects in the conventional analysis method could be identified, the propelling charge lots with safety risks could be traced and the consequences of the change in the procedure parameter could be evaluated.

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1. Introduction

A conventional gun is essentially a heat engine in which the chemical energy of the propellant is transformed into the kinetic energy of the projectile [1]. Nitrocellulose based gun propellants are most commonly used as main propellants in gun propelling charges. The internal ballistic cycle includes all the phenomena taking place during the barrel phases of firing.

In long range firings an essential aim is the maximum muzzle energy. Longer range and greater accuracy are constant objectives when new ammunition is developed. Thus the gun propelling charge has to be determined very precisely in order to ensure precise muzzle velocity value and small muzzle velocity dispersion. According to the firing tables for the 155 mm round combination to be studied, the effect of 1 m/s muzzle velocity deviation on firing distance at range 17.5 km is about 27 m, and correspondingly at range 27.5 km about 47 m. Thus, in the field firing situation wide and uncontrolled discrepancies in the muzzle velocity values between propelling charge lots can have a substantial impact on hit probability.

Unexpected difference in muzzle velocity level has several times been found between the analyzed results of the two test firings (charge establishment and uniformity tests) carried out for each main propellant lot. The gun propelling charge lots produced according to the test procedure for determining gun propelling charge weight used by the Finnish Defence Forces (FDF) had also too often failed to meet the acceptance requirements. The data set consisted of the test firing results for 68 propellant lots of the test procedure for determining gun propelling charge weight of 155 mm full charge, base-bleed ammunition. In the first part of this study [2] principal component analysis (PCA) was applied in order to make a preliminary analysis of the data set.

A mathematical model typically refers to a deterministic and often causal mathematical relationship between the systematic parts of measured variables. The deviations between systematic parts and the data (the residuals) are often explicitly shown in this mathematical relationship [3]. For example, the conventional method used in the initial analysis of the results to be discussed in this paper may well not provide adequate accuracy...
of the correction factors used or take into consideration unexpected changes in procedure parameters. The latter possibility already materialized as a change of the barrel forcing cone construction and in the use of several projectile types [2].

The partial least squares (PLS) method is a modern statistical method combining features from principal component analysis and multivariate regression analysis [4–8]. The PLS method is a representative of the chemometric approach aiming at modeling covariance in data structures as presented by the authentic individual measurements [9]. Thus PLS provides an independent check on the validity of mathematical models. The PLS method has been applied in pattern recognition, classification and discrimination, process monitoring and quality control, modeling and optimization of processes, statistical experiment design, chemical structure–(re)activity modeling of chemicals and multivariate calibration in analytical chemistry. PLS has also earlier been used for process and quality monitoring. However no example of applying PLS in connection to gun propelling charge establishment was found in the literature.

The idea of this study was to repeat the analysis of the data set using an alternative approach to the conventional method of analysis. Using PLS modeling data sets connected to 67 test firings could be studied simultaneously, instead of separate analysis of each test firing carried out with a conventional method of analysis. The aims of this study were to gain further information of possible defects in the procedure studied and to evaluate the usability of the propelling charge lots produced.

2. Experimental

2.1. Test procedure for determining charge weight and the data set

The round studied consisted of the 155 mm full charge with inert projectile and base-bleed unit. The main components of the charge are first a primer igniter of granular porous nitrocellulose propellant, second a primer igniter of tubular porous nitrocellulose propellant and the main propellant of multitubular single base propellant in cloth bags. The propelling charge is ignited with a breech percussion primer. A base-bleed unit is a metal cylindrical body equipped with a propelling charge mounted on the base of the projectile. The base-bleed unit can extend the range of the projectile by as much as 30% [10].

A description of the measurement of variables, data sets and the FDF test procedure has been given in [2]. A schematic presentation of the measuring system is shown in Fig. 1. The variables to be modeled are the temperature of the propelling charge (T_r), the weight of the main propellant (m_r), the relative vivacity of the propellant lot (B_r), the moisture content of the main propellant (H_r), the projectile weight (m_p), the barrel wear (L), the muzzle velocity of the projectile (V_0), the peak chamber pressure by piezo-electric measurement (P_h) and the peak chamber pressure by crusher measurement (P_cr).

The main purpose of charge establishment is to determine the weight of the main propellant that will fulfill the defined muzzle velocity requirement within the maximum permissible peak chamber pressures. In addition, it is also ensured that the main propellant lot meets the ballistic requirements given for standard deviations in peak chamber pressure. The maximum permissible peak chamber pressures for each gun, projectile and charge type to be approved for war materiel have to be specified according to defined standards [11] in order to manage the risk of gun and/or ammunition breakage during firing.

The purpose of the uniformity tests is to ensure that the propelling charges produced based on charge establishment fulfill the specified muzzle velocity requirement, and to ensure that the requirements for standard deviations in muzzle velocity and peak chamber pressure and for maximum permissible peak chamber pressures are fulfilled.

In the charge establishment and the uniformity tests technically similar measurements are carried out. In an analytical sense these firings differ, because for each propellant lot three different test charge weights are used in charge establishment, but in the uniformity tests only one charge weight is used.

The initial data set included uncorrected data connected to 2842 rounds fired by a 155 mm test gun on 67 test firing occasions 1999–2003. The number of propellant lots was 68. The data set was formed by collecting data from the test firing database of the FDF and from the propellant procurement documents. Data design has been described in [2]. For each charge establishment or uniformity test there was only one projectile type and one gun barrel. Likewise for all series fired, for each propellant lot, there was only one relative vivacity (B_r) and moisture content (H_r), for each test charge size one main propellant weight (m_r) and for each serial one charge temperature (T_r).

In light of the analysis of the initial data set with 13 variables, some observations were eliminated and the data set was divided on the basis of the barrel forcing cone construction used in the test firings into two parts referred to as cone 1 (1098 observations) and cone 2 (1744 observations).
cone 2 (1611 observations) [2]. The characteristics of the nine variables in cones 1 and 2 data sets to be modeled in this study are presented in Table 1.

The results of each test firing included in the data set were analyzed by the conventional method of analysis. The objective of this method is to present results as fired in a standard environment, with a standard gun and a standard round, i.e. to obtain comparable results from one test firing occasion to another, from one gun to another and from one round to another. The method is based on the correction of results with the differences from the standard values defined for certain variables. The variables to be corrected are muzzle velocity \((V_o)\) and piezo-electric and crusher peak pressures \((P_h, P_{e})\). The gun and round specific standard values and correction factors are defined for temperature of propelling charge \((T_i)\), moisture content of main propellant \((H_r)\), projectile weight \((m_a)\) and barrel wear \((L)\). The temperature factors, i.e. change in muzzle velocity and peak chamber pressures per 10 °C change in temperature of propelling charge [12], are calculated for each propellant lot based on the charge establishment firing results. A propellant lot specific correction factor of weight of main propellant is defined in each charge establishment. The two last mentioned correction factors are thus more up-to-date than the permanent correction factors of \(H_r, m_a\) and \(L\).

Comparative ballistics refers to the firing of a series of calibration rounds consisting of 155 mm projectiles and propelling charges taken from specific lots in each test firing [13,14]. The results of comparative ballistics rounds fired can be used in propelling charge determination and in the evaluation of the muzzle velocity and peak pressure level differences from one test firing occasion to another. Comparative ballistics have not yet been introduced in the FDF, but have been applied in some cone 1 firings and in almost all cone 2 firings. The results of comparative ballistics were not included in the data set, because different main propellant type was used in the calibration round propelling charge lot.

2.2. Methodology

In the PLS method a linear multivariate model is used in order to describe the explanatory variable matrix \(X\) and the response variable matrix \(Y\). The PLS model can be considered as consisting of outer relations (\(X\) and \(Y\) blocks individually) and an inner relation (linking both blocks). The result can be graphically visualized as score and loading plots [5–8]. The use of PLS as a quality control tool is based on the diagnostics of deviating observations [8]. The estimation of response variable \(y\) values using PLS can be accomplished with Eq. (1).

\[
y_{im} = \sum_h q_{ih} \sum_k w_{ik} x_{ik} + f_{im}
\]

Parameter \(q_{ih}\) indicates \(h\)th latent variable of PLS component (LV) for the \(m\)th \(Y\) weight. The relation between \(X\) weight \(w\) and transformed \(w^*\) is \(w^* = w(p'^*w)^{-1}\), where \(p\) is the \(X\) loading. Residuals of response matrix \(Y\) are denoted by \(f\) and \(x_{ik}\) indicates \(k\)th \(X\) variable for \(i\)th round.

3. Results and discussion

3.1. PLS models

The functions from the Multi-Block Toolbox for Matlab [15] were applied to the construction and cross validation of PLS models. In PLS model construction the properties of the nonlinear iterative partial least squares algorithm (NIPALS) were used [5]. Before the composition of PLS models the data set was pre-treated. The data set was mean-centered, because the interpretation of PLS diagnostics is easier if the data are quite symmetrically distributed. As can be seen in Table 1 there were substantially different numerical ranges in variable values. Hence the scaling of the data set was also necessary in order to let each variable have the same prior importance in the PLS modeling. The scaling was carried out by the division of mean-centered values by the standard deviations of the initial variable values.

The PLS estimations to be discussed in this paper were carried out by PLS models 1 and 2 built for cone 1 data (1098 observations) and cone 2 data (1611 observations). The explanatory variables for model 1 were temperature of propelling charge \((T_i)\), relative vivacity of propellant lot \((B_p)\), moisture content of main propellant \((H_r)\), projectile weight \((m_a)\), barrel wear \((L)\) and muzzle velocity \((V_o)\) and for model 2 \(T_r\), weight of main propellant \((m_i)\),

### Table 1

Means, standard deviations, ranges and interquartile ranges of the variables in the data set for cones 1 and 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cone 1</th>
<th>Cone 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature of propelling charge, (T_i/°C)</td>
<td>1.07 22.0</td>
<td>2.76 26.4</td>
</tr>
<tr>
<td>Weight of main propellant, (m_a/g)</td>
<td>11,532 368</td>
<td>11,763 257</td>
</tr>
<tr>
<td>Relative vivacity of propellant lot, (B_p/%)</td>
<td>101.3 3.7</td>
<td>99.0 2.2</td>
</tr>
<tr>
<td>Moisture content of main propellant, (H_r/%)</td>
<td>0.72 0.025</td>
<td>0.73 0.023</td>
</tr>
<tr>
<td>Projectile weight, (m_a/g)</td>
<td>43,450 85.2</td>
<td>43,690 45.4</td>
</tr>
<tr>
<td>Barrell wear, (L/mm)</td>
<td>949.6 2.08</td>
<td>950.8 1.20</td>
</tr>
<tr>
<td>Muzzle velocity of the projectile, (V_o/m^2)</td>
<td>798.4 12.6</td>
<td>797.1 11.2</td>
</tr>
<tr>
<td>Peak chamber pressure, piezo-electric</td>
<td>324.9 25.1</td>
<td>317.4 20.5</td>
</tr>
<tr>
<td>measurement, (P_{h}/MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak chamber pressure, crusher measurement,</td>
<td>293.9 25.1</td>
<td>286.4 15.9</td>
</tr>
<tr>
<td>(P_{e}/MPa)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The response variable for model 1 was \( m_r \) and for model 2 piezo-electric and crusher peak chamber pressures \( (P_h, P_{cr}) \). The cumulative sums of variance captured by the model from the X block \( (\sum |r^2|X) \) and Y block \( (\sum |r^2|Y) \) are presented in Table 2.

The correct complexity and the predictive ability of the PLS models mentioned in this section were determined by applying a chronological group cross validation [4,5]. For cross validations the data of cone 1 was divided into five groups and the data of cone 2 into seven groups in chronological order. The root mean squared errors from cross validation \( (\text{RMSEP}_{CV}) \) and the predictive abilities of the models from cross validation \( (Q^2_{CV}) \) with optimal number of LVs for models 1 and 2 are also presented in Table 2.

The scatter diagrams for response variables weight of main propellant \( (m_r) \) and piezo-electric and crusher peak pressures \( (P_h, P_{cr}) \) for cones 1 and 2 are presented in Fig. 2. In the estimation of \( m_r, P_h \) and \( P_{cr} \) the same numbers of LVs as mentioned in Table 2 were used.

As can be seen from the lines in Fig. 2, the difference of the estimates from the observed values was positive at the lower end and negative at the upper end in all cases presented. Thus, the validity ranges of the models are limited to the range of the values of each variable in the data set (Table 1). The variation in the peak chamber pressures measured by the crusher method was found to be higher if compared to the piezo-electric method, which is in accordance with the uncertainty of these pressure measurement methods [16].

At first the PLS models based on explanatory variables \( T_r, m_r, B_r, H_r, m_s \) and barrel wear \( (L) \) and response variables \( V_0, P_h \) and \( P_{cr} \) were constructed. The PLS model for cone 1 data had the following model statistics: \( \text{RMSEP}_{CV}(V_0)=6.66 \text{ m/s} \) and \( Q^2_{CV}(V_0)=80.6\% \) (6 LVs), \( \text{RMSEP}_{CV}(P_h)=16.1 \text{ MPa} \) and \( Q^2_{CV}(P_h)=64.3\% \) (4 LVs), \( \text{RMSEP}_{CV}(P_{cr})=13.1 \text{ MPa} \) and \( Q^2_{CV}(P_{cr})=61.2\% \) (4 LVs). These models were rejected because improved predictive abilities were achieved for PLS models 1 and 2, as can be seen in Table 2.

In the modeling of models 1 and 2 only nine of the thirteen variables in the initial data set were used. The variables number of rounds fired \( (L_{sn}) \), loading distance \( (L_{lat}) \), recoil length \( (S_r) \) and retardation \( (k) \) have no role in the conventional determination of charge weight. In addition to variable barrel wear \( (L) \) variables number of rounds fired \( (L_{sn}) \) and loading distance \( (L_{lat}) \) also describe gun barrel wear. A model with \( L_{sn} \) and \( L_{lat} \) added to explanatory variables of model 1 and with response variable \( m_r \) was constructed for cone 1 data. This model with 5 LVs gave the following model statistics: \( \sum R^2 Y=78.2\% \), \( \sum R^2 X=90.0\% \), \( \text{RMSEP}_{CV}=133.6 \text{ g} \) and \( Q^2_{CV}=87.7\% \). As can be seen in Table 2, variables \( L_{sn} \) and \( L_{lat} \) did not substantially improve the PLS model. Because it was difficult to fit together all three variables describing barrel wear in the application of PLS models, \( L_{sn} \) and \( L_{lat} \) were left out of the explanatory variables of models 1 and 2. Variables of recoil length \( (S_r) \) and retardation \( (k) \) were excluded because they did not provide useful information for the model applications in this study.

Several PLS diagnostic methods were applied to examine deviations in the data set and the importance and correlations of the variables. For example, the variables causing most of the outliers seen in Fig. 2 could be traced by visual analysis of residuals and loading diagrams for the three first LVs. In certain test firings too low piezo pressures were obtained because of technical measuring problems and several too low crusher pressures were also included in the data sets. A review of every single finding is beyond the scope of this paper, but it was found that with PLS diagnostics comprehensive and illustrative information of the procedure and results studied could be obtained. PLS diagnostics could be applied in quality control of the procedure studied.

### Table 2

| Model number | \( \sum |r^2|X \) % | \( \sum |r^2|Y \) % | \( Y \) | \( \text{RMSEP}_{CV} \) | \( Q^2_{CV} \) % | \( \text{RMSEP}_{CV} \) | \( Q^2_{CV} \) % |
|--------------|---------------------|---------------------|------|------------------|----------------|------------------|------------------|
| Cone 1       | Cone 2              | Cone 1              | Cone 2| Cone 1           | Cone 2         | Cone 1           | Cone 2           |
| 1            | 80.7                | 89.5                | 70.5  | 81.7             | \( m_r \)      | 133.7 g         | 87.7             | 118.0 g          | 78.9             |
|               | 5                   | 5                   | 4     | 4                | \( P_h \)      | 7.73 MPa         | 91.7             | 6.01 MPa          | 91.3             |
| 2            | 87.9                | 90.4                | 88.2  | 90.4             | \( P_{cr} \)   | 8.67 MPa         | 83.0             | 5.74 MPa          | 87.0             |
|               | 6                   | 6                   | 6     | 6                |               |                 |                  |                  |
following. An average relative vivacity propellant lot of \( H_r = 100.1\% \) was used. By application 1.2 the weights of the main propellant \( m_r(\text{cone 1}) = 11,507 \) g and \( m_r(\text{cone 2}) = 11,617 \) g were estimated. Then the values of one variable \( T_r, H_r, m_r, L \) and finally \( m_r \) at a time were raised one by one within the validity range of the model and the effect on the muzzle velocity value was evaluated using application 1.3 for cones 1 and 2. The variables in addition to the variable examined and \( m_r \) had their standard values. The correlations between variables have been presented in [2]. The negative correlation between the relative vivacity of propellant lot and propellant weight was taken into consideration in the selection of variable values.

The most important results of evaluations of correction factor reliability was that correction for barrel wear should have been greater than in the conventional analysis of the results. The correction factor for barrel wear used in the conventional analysis for both cones was \(-0.4 \text{ ms}^{-1} \text{ mm}^{-1}\) and with PLS models the factors evaluated for cones 1 and 2 were \(-1.8 \text{ ms}^{-1} \text{ mm}^{-1}\) and \(-2.4 \text{ ms}^{-1} \text{ mm}^{-1}\). For the time being the most reliable estimates of correction factors for barrel wear were presented in [2].

Fig. 2. Observed values vs. estimates of response variables \( m_r \) (model 1), \( P_h \), and \( P_{cr} \) (model 2), and the fitted lines with their slopes (S) and the identity lines (––) for cones 1 and 2.
Table 3
Applications of the PLS models and input variable values to be used

<table>
<thead>
<tr>
<th>Model</th>
<th>Application</th>
<th>Input variable values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1 Evaluation of reliability of correction factors for muzzle velocity (V_r) used in the initial data analysis. 1.2 Simulation of charge establishment. The weight of main propellant (m_r) of a defined propellant lot needed to fulfill the muzzle velocity requirement is estimated. 1.3 Simulation of the uniformity tests. Iteration of the muzzle velocity (V_r) using model 1.</td>
<td>One explanatory variable value at a time is changed within the validity range of the model(^a). Standard variable values(^b) except the determined value of relative vivacity ((B_r)) for the propellant lot. Standard variable values(^b) except for the propellant lot the determined value of relative vivacity ((B_r)) and weight of main propellant (m_r) from charge establishment (analyzed of test firing results or estimated by application 1.2). One explanatory variable value at a time is changed within the validity range of the model(^a). Muzzle velocity value temperature corrected to 20 °C(^c). Same variable values as used for application 1.2 except determined weight of main propellant ((m_r)) (analysis of test firing results or estimated by application 1.2) and muzzle velocity value temperature corrected to 20 °C(^c).</td>
</tr>
<tr>
<td>2</td>
<td>2.1 Approximation of reliability of correction factors for piezo-electric and crusher peak pressures ((P_h, P_{cr})) used in the initial data analysis. 2.2 Estimation of piezo-electric and crusher peak chamber pressure values ((P_h, P_{cr})).</td>
<td>The standard value of the temperature of propelling charge ((T_r)) for piezo-electric and cruiser peak pressures ((P_h, P_{cr})) is 20 °C instead of 0 °C for muzzle velocity ((V_r)). Before the estimations with model 2 the (V_r) values were temperature corrected to 20 °C using temperature correction factors determined for each propellant lot in connection with the analysis of charge establishment results.</td>
</tr>
</tbody>
</table>

\(^{a}\) The negative correlation between the relative vivacity of propellant lot and propellant weight has to be taken into consideration when selecting variable values.

\(^{b}\) The standard variable values used in estimations were as follows: \(T_r(0)\) = 0 °C, \(T_r(P_h, P_{cr})\) = 20 °C, \(H_r\) = 0.7%, \(m_r\) (cone 1) = 43,400 g, \(m_r\) (cone 2) = 43,700 g, \(L(cone\ 1)\) = 946.3 mm and \(L(cone\ 2)\) = 949.7 mm; the requirement for \(V_r\) in standard conditions is 800 ± 5 ms\(^{-1}\).

\(^{c}\) The standard value of the temperature of propelling charge \((T_r)\) for the propellant lot.

It was found that only rough approximations for correction factors could be obtained with applications 1.1 and 2.1. This was, however, assumed given the low correlations between some of the variables. Test firings using the experiments designed have to be carried out in the definition of accurate correction factors for the moisture content of main propellant \((H_r)\) and projectile weight \((m_r)\). Propellant lot specific correction factors for temperature of the propellant charge \((T_r)\) and weight of main propellant \((m_r)\) can, however, be defined accurately enough after each charge establishment test firing.

3.2.3. Effect of difference in cone construction

As noted in the first part of this study [2], the use of two different barrel forcing cone constructions in the test firings studied was detected. Thus instead of one, two different standard values of barrel wear should have been used in conventional data analysis. The effect of the barrel cone construction change on the weights of main propellants \((m_r)\) in charge establishment, on the muzzle velocities \((V_r)\) and on the peak chamber pressures \((P_h, P_{cr})\) in uniformity tests was estimated. Applications 1.2, 1.3 and 2.2 presented in Table 3 were used in these estimations for cones 1 and 2 and carried out for 68 propellant lots included in the initial data set.

The differences between estimates for cone 2 and 1 \(m_r, V_r, P_h\) and \(P_{cr}\) values were calculated. The means of these differences (MD) and their 95% confidence intervals are presented in Table 4. It can be concluded from the MDs shown in Table 4 that using barrel forcing cone constructions 2 higher propellant weights were determined and in the uniformity tests lower muzzle velocities and peak pressures were obtained than using cone 1.

In addition to the use of too low a barrel wear correction factor, the difference in the barrel forcing cone construction was found to be the other main reason for the deviation in the muzzle velocity result level in the initial uniformity tests results.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Application (Table 3)</th>
<th>MD</th>
<th>Confidence Interval of MD (95%, (n=68))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_r/g)</td>
<td>1.2</td>
<td>118</td>
<td>107–130</td>
</tr>
<tr>
<td>(V_r/\text{ms}^{-1})</td>
<td>1.3</td>
<td>–7.5</td>
<td>–8.0 to –7.1</td>
</tr>
<tr>
<td>(P_h/\text{MPa})</td>
<td>2.2</td>
<td>–15.0</td>
<td>–16.9 to –13.1</td>
</tr>
<tr>
<td>(P_{cr}/\text{MPa})</td>
<td>2.2</td>
<td>–14.7</td>
<td>–16.0 to –13.5</td>
</tr>
</tbody>
</table>
cone 1 than cone 2 firings. Because too low a correction factor for barrel wear was also used, too large a weight of main propellant was determined for several propellant lots to be fired from cone 1 barrels. Fortunately the changeover to use cone 2 barrels mitigated this effect. Because of the use of less worn barrels, not many oversized charges could be found in the cone 2 uniformity tests results.

Secondly the muzzle velocities of the charge lots produced were estimated and compared with the muzzle velocity requirement. The weights of main propellant realized in the uniformity tests were used as input values using application 1.3. The expected deviations of muzzle velocity values from the muzzle velocity requirement were then evaluated for charge lots produced from 68 propellant lots. The data of repeated conventional analysis could also be utilized in this evaluation. As an outcome the user of the gun propelling charges studied could be provided with propellant lot specific expected muzzle deviations in cases where the muzzle velocity requirement was not fulfilled. The FDF will be able to monitor the expected deviations of muzzle velocity values from the muzzle velocity requirement were then evaluated for charge lots produced from 68 propellant lots. The data of repeated conventional analysis could also be utilized in this evaluation. As an outcome the user of the gun propelling charges studied could be provided with propellant lot specific expected muzzle deviations in cases where the muzzle velocity requirement was not fulfilled. The FDF will be able to monitor the expected deviations of muzzle velocity values from the muzzle velocity requirement were then evaluated for charge lots produced from 68 propellant lots. The data of repeated conventional analysis could also be utilized in this evaluation. As an outcome the user of the gun propelling charges studied could be provided with propellant lot specific expected muzzle deviations in cases where the muzzle velocity requirement was not fulfilled. The FDF will be able to monitor

The consequence of an oversized propelling charge produced from a high relative vivacity main propellant entails a risk of exceeding the defined maximum permissible peak pressure for the charge type studied. The third objective was to find the risky charge lots possibly produced. Peak chamber pressures of the uniformity tests were estimated using application 2.2. The main propellant weights for each propellant lot realized in the uniformity tests were used as input values. It was found that risky charges had been produced from three high relative vivacity propellant lots. After their high pressure levels had been confirmed in a test firing, all these risky charges were designated to be used for test purposes only.

4. Conclusions

Despite the limitations in the construction of the historical 155 mm data set consisting of the results of test firings for 67 propellant lots, PCA [2] and PLS could be successfully used as alternative methods of data analysis. The main reasons for the deviations in the muzzle velocity result level in the initial uniformity tests results were the too small correction for barrel wear in the conventional analysis and the change of the barrel forcing cone construction not detected using the conventional method of analysis.

Using the PLS models developed, the need to replace some of the calibration factors used in conventional analysis could be demonstrated, but further testing was needed for specification of the factors. These standard values and calibration factors were subsequently updated and firing of comparative ballistics at each test firing has been introduced. The importance of in-depth definition of standard values and calibration factors has been emphasized in new gun propelling charge design projects.

PLS modeling was found to be a useful method to trace the propelling charges not expected to meet the muzzle velocity requirement or having a safety risk of exceeding the maximum permissible peak pressure. The results obtained with PLS modeling were taken into consideration in the usability assessment of the gun propelling charge lots studied.

Appendix A. Supplementary data


References