DOCTORAL THESIS

THE INFLUENCE OF FIREARMS AND AMMUNITION PROPERTIES ON THE EFFECTIVENESS OF AUTOMATED BALLISTIC CORRELATIONS

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Brasilia, 26 NOVEMBER 2020
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A thesis submitted in partial fulfilment of the requirements of University of Brasilia for the degree of Doctor in Mechanical Sciences.

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CATALOG SHEET

Dt DOS SANTOS, LEHI SUDY
THE INFLUENCE OF FIREARMS AND AMMUNITION PROPERTIES ON THE EFFECTIVENESS OF AUTOMATED BALLISTIC CORRELATIONS / LEHI SUDY DOS SANTOS; orientador Palloma Vieira Muterlle; co-orientador Cosme Roberto Moreira da Silva. -- Brasília, 2020.
303 p.

Tese (Doutorado - Doutorado em Ciências Mecânicas) -- Universidade de Brasília, 2020.

1. ciência dos materiais. 2. ciências forenses. 3. identificação de arma de fogo. 4. comparação automatizada. 5 eficácia de correlações. I. Muterlle, Palloma Vieira, orient. II. da Silva, Cosme Roberto Moreira, co-orient. III. Título.

BIBLIOGRAPHIC REFERENCE

Dos Santos, L. S. THE INFLUENCE OF FIREARMS AND AMMUNITION PROPERTIES ON THE EFFECTIVENESS OF AUTOMATED BALLISTIC CORRELATIONS. Tese (Doutorado em Ciências Mecânicas) - Departamento de Engenharia Mecânica, Universidade de Brasília, Brasil, 303p. 2020.

ASSIGNMENT OF RIGHTS

AUTHOR'S NAME: Lehi Sudy dos Santos.

TITLE: THE INFLUENCE OF FIREARMS AND AMMUNITION PROPERTIES ON THE EFFECTIVENESS OF AUTOMATED BALLISTIC CORRELATIONS.

DEGREE: Doctorate YEAR: 2020

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To Vanessa and Pietro, loves of my life.

Lehi Sudy dos Santos

ACKNOWLEDGMENT

In the course of this extensive research, I had the honor to interact with many professors, researchers, and practitioners, from whom I learned so much. I recognize that without their contribution this work could not be completed, and because of that, I express my gratitude to:

- ✓ *Palloma Vieira Muterlle and Cosme Roberto Moreira da Silva, Professors at University of Brasilia, for accepting the research and for the unconditional and invaluable support;*
- ✓ *Rachel Bolton-King, Associate Professor at Staffordshire University, for making possible my visiting Ph.D. period in the United Kingdom, and for after that being continuously available and encouraging;*
- ✓ *Anatoli Leontiev, in name of whom I appreciate Pappilon systems for the availability of the Arsenal® system;*
- ✓ *Michael Derenovskiy and Michael Schrodel, in name of whom I thank you Scannbi Technology Europe GmbH company for Evofinder® new software versions and for always being available to discuss results;*
- ✓ *Alain Beauchamp, Augusto San Cristobal, and Jose MacDonald in name of whom I appreciate the Ultra Electronics Forensic Technology personel, that never spared efforts to give me access to the IBIS® system, and to discuss the results;*
- ✓ *Andre Meinecke, Andre Montanini, Eduardo Sato, and Magali Brito, forensic experts that have taught me so much and help me in many aspects of the research;*
- ✓ *Greiciane Alves and Mariana Esper, co-workers that did an incredible contribution in many tiresome tasks, that were likewise crucial for the completion of this research.*
- ✓ *To many colleagues that had somehow contributed and made this research possible, especially the ones that work with me daily, and the ones that while serving in many positions in the Federal Police of Brasil had officially or informally expressed support to this research;*
- ✓ *To many other I cannot name but somehow help me more they can even realize and to whom I can not properly retribute.*

At this opportunity I also express my deepest gratitude to my wife Vanessa, and my son Pietro, for believing in me, and loving me, many times letting aside their own needs and projects, to make this research viable. I hope they excuse me for so many hours away from their pleasant company in order to complete this work.

Lehi Sudy dos Santos

"(...) in science there are no authorities; at most, there are experts." —

Carl Sagan

RESUMO

Esta pesquisa investiga propriedades físicas, mecânicas e geométricas de armas de fogo e munições, para determinar quais são os fatores que mais influênciam a eficácia de correlações balísticas automatizadas, que são realizadas por sistemas que correlacionam deformações plásticas impressas nos componentes de munição durante o processo de disparo.

Para possibilitar este estudo 1684 componentes de munição, disparados com diferentes tipos de munição de revólveres .38SPL, e pistolas 9x19mm e .40S&W, foram digitalizados nos sistemas de identificação balística Arsenal®, Evofinder®, e IBIS®. Um critério de eficácia, baseado na acurácia das listas de resultado disponibilizadas pelos sistemas, foi utilizado para medir o grau de influência de parâmetros das armas e das munições na eficácia das correlações automatizadas.

Um decaimento exponencial foi encontrado para a eficácia como função do tamanho do banco de dados em diversos calibres e sistemas. Devido aos valores e características do decaimento observado a influência do crescimento do banco de dados mostrou-se menos crítica do que anteriormente considerada. Análise de variança (ANOVA) suporta influência significativa da dureza dos projéteis, uma maior diferença na dureza entre os projéteis comparados resultando em 0.16, 0.18 e 0.13 menor eficácia nos sistemas Arsenal®, Evofinder®, e IBIS®. Composição e tipo de projétil, tipo de cano, fabricante da arma, calibre, número de padrões cadastrados, e tipos de correlações realizadas em cada sistema foram fatores adicionais com influência relevante na eficácia das correlações com projéteis. ANOVA revelou variação estatisticamente significativa também da energia de disparo nas correlações de estojos por marca de culatra, resultando em média 0.04, 0.006, e 0.09 decréscimo na eficácia de cada sistemas. Já por pino percutor, não houve evidência contra a hipótese nula, com exceção do sistema IBIS®, com variação de 0.12 na eficácia em função da energia de disparo. Adicionalmente, uma relação entre a velocidade do projétil, e consequentemente da energia de disparo, foi estabelecida com a massa e composição do propelente, a massa do projétil, o tipo e comprimento do cano, e o arrasto ao que o projétil é submetido dentro do cano. Outros fatores com influência relevante na correlação com estojos foram o tipo de estojo, calibre, número de padrões cadastrados, tipos de correlações realizadas, profundidade da marca de percussão, e presença da marca de bigorna.

Uma comparação de eficácia pelo fabricante da arma revelou que a unicidade e reprodutibilidade das marcas geradas não são os únicos fatores para uma correta correlação tanto com projéteis quanto com estojos, uma vez que se obteve diferenças de desempenho significativas entre os sistemas avaliados. Ou seja, os fatores que influenciam a deformação plástica afetarão a eficácia da correlação, mas as possibilidades de identificação correta também dependem da precisão e da capacidade dos algoritmos empregados.

Os resultados permitiram a identificação de diferenças em desempenho e fatores de influência que podem ser utilizados para refinar os sistemas, bem como para o estabelecimento de protocolos de operação dos sistemas por calibre, visando desta forma aumentar a probabilidade de identificação da arma fonte.

Palavras-chave: ciência dos materiais, ciências forenses, identificação de arma de fogo, comparação automatizada, eficácia de correlações.

ABSTRACT

This research investigates the physical, mechanical and geometric properties of firearms and ammunition, to determine which are the factors that most influence the effectiveness of automated ballistic correlations, which are performed by systems that correlate plastic deformations printed on the ammunition components during firing.

To enable this study, 1684 ammunition components, fired with different types of ammunition from .38SPL revolvers, and 9x19mm and .40S&W pistols, were digitized in the Arsenal®, Evofinder®, and IBIS® ballistic identification systems. An effectiveness criterion, based on the accuracy of the result lists made available by the systems, was used to measure the degree of influence of firearms and ammunition properties on the effectiveness of automated correlations.

An exponential decay was found for effectiveness as a function of the database size in various calibers and systems. Due to the values and characteristics of the observed decay, the influence of the database growth proved to be less critical than previously considered. Variance analysis (ANOVA) supports significant influence of bullet hardness, a greater difference in hardness between the compared bullets resulting in 0.16, 0.18 and 0.13 decrement in the effectiveness of Arsenal®, Evofinder®, and IBIS®. Bullet composition and type, barrel type, firearm manufacturer, caliber, number of registered test-fires, and types of correlations performed in each system were additional factors with a meaningful influence on the effectiveness of the bullet correlations. ANOVA also revealed a statistically significant impact of the discharge energy in the cartridge case correlations by breech face, resulting in average 0.04, 0.006, and 0.09 decrease in effectiveness of each system. For the firing pin correlations, there was no evidence against the null hypothesis, with the exception of the IBIS® system, with a variation of 0.12 in effectiveness as a function of the discharge energy. In addition, a relationship between the velocity of the bullet, and consequently the discharge energy, was established with the mass and composition of the propellant, the mass of the bullet, the type and length of the barrel, and the drag to which the bullet is subjected within the barrel. Other factors with a relevant influence on the cartridge case correlations were the type of cartridge case, caliber, number of registered test-fires, types of correlations performed, depth of the firing pin mark, and presence of the anvil mark.

A comparison of effectiveness by the firearm manufacturer revealed that the uniqueness and reproducibility of the marks generated are not the only factor for a correct correlation with both bullet and cartridge cases, since significant performance differences were found between the systems assessed. That is, the factors that influence plastic deformation will affect the correlation effectiveness, but the possibilities of correct identification also depend on the accuracy and capabilities of the employed algorithms.

The results allowed the identification of differences in performance and parameters of influence that can be used to refine the systems, as well as for the establishment of operation protocols of the systems by caliber, aiming in this way to increase the likelihood of identification of the source firearm.

Keywords: material science, forensic science, firearm identification, automated comparison, correlation effectiveness.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

Latin Symbols

a	Parameters to be determined by fitting the curve of equation 3.1 to the results
Al	Aluminum
A_N	Angular (or numerical) aperture
b	Parameters to be determined by fitting the curve of equation 3.1 to the results
Ba	Barium
c	Parameters to be determined by fitting the curve of equation 3.1 to the results
C	Carbon
c_m	Charge mass (propellant mass)
Cu	Copper
d’	Diameter of the barrel bore
d	Diameter of the of the permanent cavity in the hardness test
D	Diameter of the indenter for hardness test
D	Distance between the orthogonal projection of a 2D score on the matches best fitting line and a fixed point on this line
D_A	Airy disk diameter
dt	Time variation
dV	Velocity variation
F	Focal length
F	Loading force
F	Resultant force upon the projectile
F’	Force at the base of the projectile
g	Gram
gr	Grain
h	Height of the permanent cavity in the hardness test
h0	All mean effectiveness criterions are statistically indistinguishable
h1	At least one of the mean effectiveness criterion are statistically different from the others
H	Hydrogen
i	Database size
I	Image radiance intensity
I_d	Image distance

k	Parameter of equation 3.7
k'	Parameter of equation 3.11
k_d	Diffusion coefficient (of light)
l	Chamber length
L	Barrel length
m_g	Mass of the gas generated by the combustion of the propellant
m_p	Mass of the projectile
$m_{p'}$	Superior mass of projectile that takes into account the resistance toward its movement
M	Magnification of the lens system
n	Position of a hit in the result list
n	Normal of a surface patch
n_i	Refractive index of the medium
N	Nitrogen
O	Oxygen
O_d	Object distance
p_b	Breech face pressure
p_s	Pressure at the base of the projectile
Pb	Lead
Pe	Probability of error
P(n)	Cumulative probability of a hit at position *n*
r	Resolution
R	Specific gas constant
w	Chamber width
S	Sulfur
s	Vector that defines lighting direction
Sb	Antimony
t	Time
T_o	Adiabatic flame temperature
V	Velocity
Zn	Zinc

Greek Symbols

α	The acceptance angle of the aperture
π	Mathematical constant pi (Archimedes' constant)
ε_b	Ballistic efficiency
Γ_0	Effectiveness criterion proposed by Rahm
Γ_1	Effectiveness criterion proposed by Santos and Muterlle
λ	Radiation wavelength
µm	Micrometer = 10^{-6} meters
θ	Illumination direction
ρ	Albedo (measure of the diffuse reflection of a surface)
γ	Scale parameter in Lorentz distribution
γ_0	Ratio of specific heats of the gas

Acronyms

ABIS	Automated Ballistic Identification System
ABNT	Brazilian Technical Standards Association
AFTE	Association of Firearm and Tool Mark Examiners
ANSI	American National Standards Institute
APM	Advanced Process Monitor
ATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
ATR	Attenuated total reflectance
ATR-FTIR	Attenuated total reflectance-Fourier transform infrared
BMC	Bullet material composition
BF	Breech Face
BFOA	Breech face mark orientation angle
BIS	Ballistic Identification System
BKA	Federal Criminal Police Office of Germany
BRDF	Bidirectional reflectance distribution function
BSD	Backscattered Electron Detector
BUL	Bullet
CBC	*Companhia Brasileira de Cartuchos*
CIP	*Commission internationale permanente pour l'épreuve des armes à feu portatives* (Permanent International Commission for the Proof of Small Arms)

ºC	Degree Celsius
CC	Cartridge case
CCD	Charged-coupled device sensor
CCF	Cross-correlation function
CMS	Consecutively Matching Striations
COV	Conventionally rifled barrel
CUP	Copper Units of Pressure
DAS	Evofinder® Data Acquisition Stations
dp_{cc}	Firing pint mark depth of the cartridge case
dp_r	Firing pin depth of the reference
ΔBKE	Difference in bullet kinetic energy
$\Delta BFOA$	Difference of the breech face orientation angle
ΔHBW	Difference in Brinell hardness
ΔRdp	Differences in relative firing pin mark depth
EDS	Energy Dispersive X-Ray Spectroscopy
EL	Elongation
ETD	Everhart-Thornley Secondary Electrons Detector
EWS	Evofinder® Expert Workstations
FBI	Federal Bureau of Investigation
FBSP	*Fórum Brasileiro de Segurança Pública* (Brazilian Public Security Yearbook)
FCC	Face-centered cubic
FPD	Vector difference between the firing pin marks' center
FMJ	Full Metal Jacket
FMJ-F	Full Metal Jacket Flat
FMR	False match rate
FN	Fabriqué Nationale
FNR	False negative rate
FP	Firing Pin
FPMC	firing pin marks' center
FT-IR	Fourier-transform infrared
GDP	Gross domestic product
GEA	Groove Engraved Area

HBW	Brinell hardness value obtained with a tungsten carbide tip
HP	Hollow-Point
IBIS®	Integrated Ballistic Identification System
IM	Intra-material
IM-N	Inter-material noiseless
IM-N1	Inter-material noise1
IM-N2	Inter-material noise2
in	Inch
IPEA	*Instituto de Pesquisa Econômica Aplicada* (Institute of Applied Economic Research)
JHP	Jacketed Hollow Point
KE	Kinetic energy
kgf	Kilogram-force
KM	Known match
KNM	Known non-match
ksi	kilopound per square inch = 103 psi
LEA	Land Engraved Area
LR	Likelihood ratio
LRN	Lead round nose
MA	Magtech Ammunition
MB	Megabyte
min	Minute
mm	millimeters
MPa	Mega Pascal = 10^6 Pascal
MS	Match score
MSmin	Minimum match score
NIBIN	National Integrated Ballistic Information Network
NMS	Non-match score
NMSmax	Maximum non-match score
PE	Propellant potential energy
POL	Polygonal rifling
PS	PAPPILON Systems
psi	Pound per square inch

QB	Questioned bullet
QC	Questioned cartridge case
RBD	Registered ballistic database
RBID	Reference Ballistic Image Database
Rdp	Firing pin mark relative depth
RMS	Root Mean Squared
ROI	Region of interest
SJHP	Semi-Jacketed Hollow Point
SAAMI	Sporting Arms and Ammunition Manufacturers' Institute
SAS	Evofinder® Specimen Analysis System
SEM	Scanning Electron Microscopy
SD	Standard Deviation
STEGC	Scannbi Technology Europe GmbH company
S&W	Smith and Wesson
TFB	Test-fired bullet
TFC	Test-fired cartridge case
UNB	University of Brasilia
UEFT	Ultra Electronics Forensic Technology Inc
USA	United States of America
WDS	Wavelength-Dispersive X-Ray detector
wt%	Weight Percent
5L	Five grooves left-handed twisted rifling
5R	Five grooves right-handed twisted rifling
6L	Six grooves left-handed twisted rifling
6R	Six grooves right-handed twisted rifling
9x19mm	Nine per nineteen millimeters
.357 Mag	Three five seven Magnum
.38SPL	Thirty-eight Special
.40S&W	Forty Smith and Wesson
+P	Greater power of cartridge
+P+	Power of cartridge even greater

1 INTRODUCTION

This chapter briefly presents the research approach, contextualizing and defining the problem, the project objectives, and its originality.

1.1 THEME APPROACH

This research project addresses a problem that has two motivating aspects. Firstly, from the point of view of the Brazilian's social welfare, this is a matter of great significance, given the current high indices of firearm-related homicides in Brazil and the low-resolution rate for this type of crime (section 1.1.1). Also, to scientifically understand which firearm and ammunition features influence the likelihood of accurate correlations in ballistic identification systems (BIS) (section 1.1.2).

1.1.1 Social justification for the study

According to records of the Mortality Information System of the Brazilian Ministry of Health "in 2017 there were 65,602 homicides in Brazil, which is equivalent to a rate of approximately 31.6 deaths for every hundred thousand inhabitants" (IPEA; FBSP, 2019, p. 5, our translation), the largest number ever recorded. Previous records also indicate that the percentage of homicides classified as firearm-related crime increased from 36.8% in 1984 to 71.7% in 2014 (Waiselfisz, 2013). The impact of this problem on the life of Brazilians results in huge costs for the Government and its civilians, compromising everyone's quality of life.

A numerical value for the cost of violence in Brazil was prepared by the *Anuário Brasileiro de Segurança Pública* (Brazilian Public Security Yearbook) (FBSP, 2017), which considering intangible homicide costs spent on public and private sector, and on health and prison systems, estimated it at R$ 372 billion *Reais*[1], each year; i.e. around 6% (six percent) of Brazil GDP (gross domestic product). A value that can be highly underestimated when considering the inaccuracy of data made public on this subject.

Further analysis on the last decade's data reveals that the situation is worsening, as observed for instance with the evolution of the number of homicide and its rate per 100.000

[1] Aproximately $ 70 billion American dolars (Exchange rate in 14/08/2020: $1,00 = R$5,37).

people, plotted in Figure 1. The seriousness of the issue demands that governing authorities and all sectors of society tackle this situation.

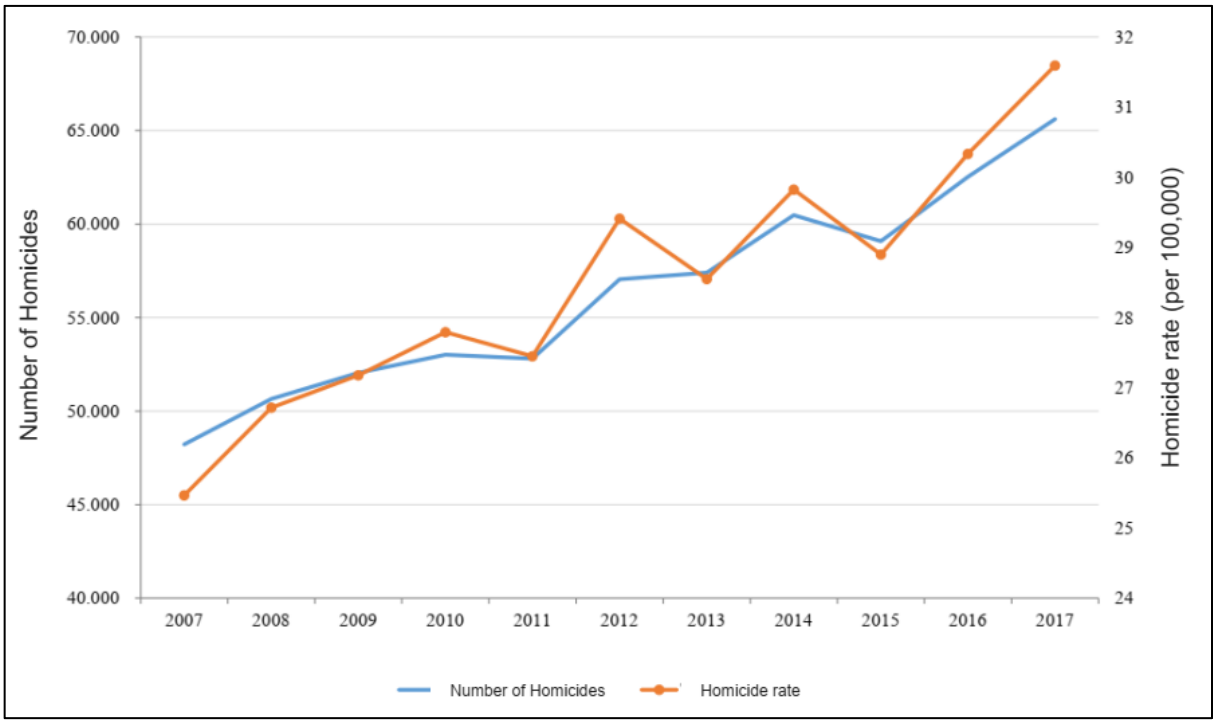


Figure 1 – Number and rate of homicides in Brazil (2007-2017) (Source: Adapted from IPEA; FBSP, 2019, p. 5).

Additional data shows that a total of 112,718 firearms were seized by police forces in 2016 (FBSP, 2017). This number is relevant because one of the most effective forensic tasks to elucidate, link and investigate these crimes is through ballistic comparison, correlating test-fires of seized firearms against the fired ammunition components (bullet or cartridge case) collected as evidence from crime scenes or deceased persons.

Although this type of examination can be performed in forensic institutes in Brazil, particularly in ballistic laboratories, the traditional method allows the manual ballistic comparison only when a suspected relationship between the firearm and the crime is already assumed. This limitation can be one of the factors for the very low-resolution rate of this type of crime. In a previous report, after an in-depth analysis of available official data, Waiselfisz (2013) stated that ease of access to firearms, the culture of violence and the feeling of impunity are three main factors that contributed to this serious problem.

The same mentioned report cites studies indicating that the homicide solution rate in Brazil is between 5% to 8% (five to eight percent), in contrast to 90% (ninety percent) of homicides solved in some developed countries (Waiselfisz, 2013).

No doubt this is an issue that needs to be tackled from many angles, including stakeholders perspectives (Leshner et al., 2013). From a scientific perspective, establishing parameters for the implementation of a ballistics identification network may contribute to an increment in the resolution of firearm-related crimes, reducing homicide rates and the sense of impunity, which therefore acts as the main social justification for this study.

1.1.2 Influence factors in automated ballistic correlations

Despite the undeniable relevance of the theme to the Brazilians welfare, the implementation of a ballistics identification network is a complex issue and the technical and technological challenges for its correct application also justify the present study.

As mentioned, an important task for forensic experts responsible for analyzing the material evidence of firearm-related crime is to identify the firearm used. To do that, the marks imprinted on ammunition components when the firearm is discharged are compared (Warlow, 2005).

The correlation between fired ammunition components is possible in most cases due to the high internal pressure generated during the deflagration of the propellant. This leads to plastic deformation when the cartridge case violently strikes parts of the firearm, receiving imparted marks from the surface of these harder surfaces. Common marks on cartridge cases for comparison include those imparted by the breech face, firing pin, ejector, and extractor, if present. Pressure also propels the bullet through the barrel, generating a contact in which the side of the bullet, more ductile than the barrel internal surface, is dug and striated (Rabello, 1995).

The comparison of these striae (parallel lines) and other tiny marks of two fired ammunition components, performed under a comparison optical macroscope, allows an expert to decide if they were fired by the same firearm. Although it is a technique successfully used in countless criminal cases since the 1920s, it has some relevant limitations.

The first limitations are technical, as meaningful differences in the ammunition may affect the reproducibility of marks even in ammunition components fired from the same firearm.

For bullet comparisons, some firearm and ammunition produce consistently reproducible marks, while others vary from shot to shot (Bachrach, 2006). The type and the material composition of the bullet being a factor of meaningful influence (Bachrach, 2000; apud Gerules et al., 2013; Heard, 2008). For cartridge cases, there is general knowledge among the firearm identification practitioners that the alternation of the revolver chamber, cartridge case manufacturer, primer cup composition, difference in pressure generated by the ammunition, or even the way the gun is gripped, can influence the marks on discharged cartridge cases and consequently on the ballistic comparison. Although chamber alternation or gun grip can be regarded as myths, which at the time of this research were not properly investigated, or no one has quantified the degree of its influence in ballistic comparisons, others, as cartridge case manufacturer or primer cup composition, had been proved as influential in possibilities of correct identification or exclusion (De Kinder et al., 2004; Addinall et al., 2019).

Because of these and other factors, one of the premisses for matching a firearm to a fired ammunition component is to perform traditional comparison microscopy of samples with features as similar as possible. That is, for the comparison to be successful it is expected that during shooting the same physical conditions which led to the production of the microscopic marks must be reproduced. For this to be guaranteed a priori, the most similar possible ammunition must be selected.

In spite of these technical restraints, the use of ballistic comparison to solve criminal cases dates back more than a century. This approach has also been accepted in judiciary systems of most countries of the world, and has been scrutinized and proved scientifically reliable in many studies (Nichols, 2007; Hamby et al., 2009; Hamby et al., 2016).

Other limitations of traditional (manual) ballistic comparison is the time spent on the microscope, and the need of an investigative or intelligence lead pointing to a suspicious firearm in order for the comparison to be requested, particularly because there is at present no reference database in Brazil. To tackle these constraints, more technological, forensic laboratories around the world have implemented ballistic identification systems (BIS), which record fired bullet and cartridge case images, and automatically correlate them, allowing the comparison beyond human capabilities and greatly expanding the possibilities of the identification of firearms used in a crime (Gagliardi, 2014).

The prosecutors, investigators, and forensic experts are the stakeholders that may have their work leverage for this kind of technology. Digitalized images of the ammunition components are entered into the systems and correlated against other cases or registered firearms in search of hits. A hit is a match between two samples, indicating that two cases were performed with the same firearm, or identifying that a seized firearm was utilized in a crime. Hits obtained using these systems have been critical to solving many firearm-related crimes.

In terms of technology there are almost three decades of studies (Heard, 2008), but "the challenges in this field are diverse and clarify why a definitive solution for adopting a system and creating a database of all firearms has not yet been obtained" (Santos, 2015, p. 54, our translation).

As well described by Sakarya et al. (2008), "[in] forensic science, automated firearms identification is an important and yet unsolved problem" (Sakarya, 2008, p. 209).

In the early stages of the development of BIS, De Kinder (2002) pointed out that should be taken into account that the quality and the quantity of the data would impact the efficiency of the databases. Kopel and Burnett (2003) also noted that the selection of ammunition to test-fire the seized firearm would impact the quality and applicability of these BIS. Other challenges to theme were identified by Thomas and Leary (2010), among which, correlation algorithms have to operate between data with a lot of noise, so far there is low effectiveness in automated correlations, the acquisition process is not appropriately standardized, and there is a lack of interoperability between different technologies. As will be seen, many of these issues 'have not yet been put to rigorous and formal experimental test' (Bolton-King, 2012).

De Kinder et al. (2004) and De Ceuster and Dujardin (2015) studies, which were limited to cartridge cases, showed that ballistic identification systems had their correlation effectiveness decreased significantly when operating with ammunition from different manufacturers, compared to effectiveness with ammunition of the same brand.

In this regard, Addinall et al. (2019) concluded that the primer cup material influenced the topography of the firing pin, and therefore the correlation possibilities. Because this difference in hardness led to physical differences in the topography of the impressions, they opined that filters may not be sufficient to remove the differences observed. In facing this important result, they emphasized the necessity of expanding the research to encompass other geometrical and physical variables of cartridge cases:

> […] There are several variables that have not been considered in this study which could be affecting correlation results, including material thickness, primer cup angle, and weight and composition of propellant. Therefore, this study should be expanded to include all variables to determine how significant each variable is with regards to correlation efficacy (Addinall et al., 2019, p. 150).

Regarding bullets, studies have found that the effectiveness of ballistic identification systems correlating copper jacketed bullets are significantly higher than correlating lead bullets (Brinck, 2008; apud Gerules et al., 2013; Santos, 2015).

The use of the firearm can also affect marks with individual characteristics and therefore comparisons of ammunition components fired with great elapse of time between them can significantly decrease the chance of a correct correlation (Kopel; Burnett, 2003; Gerules et al., 2013).

Another critical challenge when designing a ballistic database is regarding its size, as its increase in time, more noise can be added, and therefore is critical to assure that the algorithm employed is still efficient in pointing out significant similarities and discarding inevitable random resemblances. Many studies support the conclusion that the increase of the database can meaningfully erode system effectiveness (Kopel; Burnett, 2003; Cork et al., 2008; De Ceuster; Dujardin, 2015; Santos; Muterlle, 2015).

At this point must be clarified that these mentioned parameters of influence point to the necessity of establishing best practices and protocols, and nevertheless, there are other studies, despite these challenges, which emphasized the worthly of using such solutions to help the process of linking fired ammunition components to the firearm that they came from.

Recently, an assessment of Evofinder® BIS effectiveness obtained a 100% successful identification for bullets and cartridge cases fired from 1000 Norinco pistols, concluding that the system can effectively distinguish the known matches (KM) from the known non-matches (KNM). Because the study was limited to one firearm model and one type of ammunition, the authors highlighted that "more models of firearms should be added (…) and studies with other ammunitions should be conducted" (Yuesong et al., 2019, p. 1343).

Rahm (2012) published an important paper on the effectiveness of the Evofinder® sytem, evaluating its performance with cartridge cases and bullets, and proposing a quantitative effectiveness criterion that allows comparing the performance of two systems or of a system operating under different conditions, such as different calibers, ammunition types or operator qualifications.

Santos and Muterlle (2015) refined the BIS effectiveness determination method proposed by Rahm (2012) and applied it to study effectiveness of the Evofinder® BIS regarding many types of .38SPL (thirty-eight Special) bullets. Among other findings, the study measured how Brinell hardness directly influences the system effectiveness with .38SPL bullets. The same study pointed out but did not conclude, that there are possible influences of the hardness of 9x19mm (nine per nineteen millimetres) bullets as well as the possible influence of the type of gun barrel on the effectiveness of the system (Santos, 2015).

The replication of that experiment by students with no previous experience in firearm identification has shown that part of the imaging process of the system can easily be managed by technical personnel, not necessarily qualified firearm identification experts. Only marking the bullet images for automated correlation has been found sensitive to expert qualifications (Ibid.).

De Kinder (2002) suggests that to establish a ballistic database the following should be standardized: number of test-fires, data to be stored, type of firearms to be registered, and insertion and comparison routine. The study by Santos and Muterlle (2015) presented important results in this regard and this research project aims to expand the research on the subject.

Finally, systems from different manufacturers do not communicate to each other (Wilson et al., 2010), making it relevant to study the characteristics of each system and to verify the existence or not of one that has higher effectiveness, or that presents any physical or operative desirable feature.

Very few initiatives have tried to compare different systems. Drugfire and Integrated Ballistics Identification System (IBIS®) Heritage™ had been briefly compared by Geradts et al. (2001).

De Kinder and associates carried out, in 2004, a research on IBIS® Heritage™ Technology, which was partially replicated in a 2015 study of De Ceuster and Dujardin, this time conducted on Evofinder® 5.4 System Version. Although they both have used the same reference database and the finds of the research pointed out many advances in the technologies, the more than 10 (ten) years passed between systems versions can hardly be accepted as a comparative result, being more an assessment of the evolution in the concept of a Reference Ballistic Image Database (RBID). This idea was emphasized in the preliminary remarks of the later research:

> The reader has to be aware that both systems are very different. They are developed in a different era, make use of other computer infrastructure and correlate different input. It could be objected that a comparison does not make sense for these reasons. **It is the goal of the article, however, to evaluate the concept of the RBID and not to compare the systems that were used** (De Ceuster; Dujardin, 2015, p. 83, emphasis added).

1.2 RESEARCH AIM AND OBJECTIVES

As summarized in the brief literature review above (Section 1.1) it has been widely reported that automated ballistic identification has been hampered by the variability displayed by firearms and ammunition in the market. Also, it was noted there are few studies measuring the variability degree of these features and the effect of them on the effectiveness of ballistic identification systems.

The majority of the investigations concentrated on the effectiveness of BIS with cartridge cases, but none assessed the cartridge case composition, energy of discharge or the geometrical features of impressed marks, such as firing pin mark' center and depth, anvil mark presence or absence on the bottom of the firing pin mark, or the breech face orientation. Additionally, and most importantly for this research, none investigated the impact of these factors of the effectiveness of BIS.

Of the few initiatives assessing BIS effectiveness with bullets, limited previous studies assessed the influence of bullet material, firearm barrel type, and bullet hardness on the influence of BIS effectiveness.

This research aims to provide answers to some of these technical and technological questions, especially those related to the types of firearms and ammunition most commonly employed in firearm-related crime in Brazil. That is why the research will be conductued employing the CBC (*Companhia Brasileira de Cartuchos*) ammunition only. Addicionaly, this research is the first time an effectiveness assessment is replicated in three greatly worldwide distributed BIS, Arsenal®[,2], Evofinder®[,3], and IBIS®[,4] (Gerard et al., 2017). This unique proposition of this study will allow comparing the performance of these systems with the same samples and to evaluate whether or not the properties that substantially affect the firearm identification is specific to one particular system or all of them.

Therefore, the primary aim of this research is to answer which factors most influence automated ballistic correlations and to measure its degree of influence. To answer this question, this research will focus on reaching these specific objectives:

1. Determine for the most used .38SPL, 9x19mm, and .40S&W (forty Smith and Wesson) ammunitions of CBC brand, cartridge case material, bullet material composition and hardness, propellant mass and composition;
2. Assess the details of the firearms, including manufacturer, bullet velocity, and barrel type;
3. Determine the following geometrical features of impressed marks on fired cartridge cases: firing pin mark's center and depth, anvil mark presence or absence on the bottom of the firing pin mark, and breech face orientation;

[2] http://www.papillon.ru/eng/14/ [Acessed 28/3/2019].
[3] http://evofinder.com/installations/ [Acessed 28/3/2019].
[4] http://www.ultra-forensictechnology.com/about#ibin [Acessed 28/3/2019].

4. Develop a program to compute effectiveness of the BIS Arsenal®, Evodinder®, and IBIS®, and apply it to asses the effectiveness of the systems regarding the properties mentioned in objectives 1 to 3 above, comparing the 3 (three) systems operating with the same samples;
5. Identify for each of the 3 (three) assessed systems, the parameters of influence that should be standardized in order to enhance the system probability of a hit, specifically assessing systems regarding database size, ammunition selected for test-firing, number of test-fires, and best set of correlators to be evaluated in order to find a match.

1.3 RESEARCH QUESTION

From the reviewed literature (Section 1.1.2), it is well-established that firearm, bullet, and cartridge case properties may affect the impressed marks on fired ammunition components. This raises the question to what degree do these properties vary and how do they influence BIS effectiveness? Therefore, the primary research question is which firearm and ammunition properties most influence BIS effectiveness?

1.4 ORIGINAL CONTRIBUTION TO KNOWLEDGE

The performance of a BIS is underpinned by the knowledge of how firearms impart marks and ammunition components. As the main goal of this research is to assess the influence of firearm and ammunition properties on BIS effectiveness, the results have the potential to enhance the performance of BIS in at least two applications.

Firstly, a deeper understanding of the variabilities observed in fired ammunition component individualization marks may lead to the improvement of the image acquisition process and correlation algorithms. Due to the replication of the experiment in three calibers and three systems, the properties found meaningful influencing any particular 'BIS+calibre' effectiveness, if properly addressed for system developers, have the potential to increase the discriminatory capability of the systems to correctly rank ammunition components fired from the same firearm.

Also, the enhanced knowledge developed on influence factors in BIS can be used by stakeholders responsible for incorporating them into crime gun investigation protocols; standardizing procedures of insertion and search would increase the likelihood of finding hits.

Ultimately, it will be the first time the effectiveness of these systems will be assessed within the same period of time, with firearms and ammunition most commonly related to crimes in Brazil, which are firearms on calibers .38SPL, 9x19mm and .40S&W and ammunition from CBC brand. Therefore, the results obtained have the potential to add much information on the understanding of ballistic identification systems effectiveness, and because of the straightforward application of the data to Brazil's peculiarities, it may be useful for the establishment of the best protocols in order to implement a national ballistic identification network.

1.5 STRUCTURE OF THE THESIS

This thesis is divided into 7 (seven) numbered chapters, including a reference list, 4 (four) appendixes, and 4 (four) attachments.

Chapter 1 has introduced the proposed theme giving an overview of the problem and the motivating aspects for this study. It is presented as a summarized review of the main publications in the field of ballistic comparison and BIS factors of influence, and also regarding the observed gaps in the knowledge that justify the research question, research aim, objectives, and the expected original contribution to knowledge.

Chapter 2 discusses the main concepts involved in the context of this thesis, such as a brief explanation of the operation of firearms and ammunition, the characterization methods for determination of ammunition components properties, the process of imparting marks during firing, the factors that influence reproducibility or alteration of these marks, the principles that allow the identification of the firearm employed to fire an ammunition component, the initiatives, designs, and state of the art of ballistic identification systems, and the effectiveness' assessment of these systems.

Chapters 3 to 6 describe the methods and procedures employed in the experiment and its replication in three systems and three calibers. The interpretation of the results for each discussed part is detailed. The precautions to guarantee independence and reliability of the data and the consequent validity of the conclusions are well explained. The limitations and scope in what the drawn conclusions are thought valid are considered in the discussions of each investigated factor of influence, suggesting steps for additional research or for more robust interpretation.

Chapters 7 summarize the main conclusions of the research, the suggested further investigation for a more in-depth understanding of the subject.

2 BACKGROUND

This chapter covers a review of the operation of firearms and ammunition, the ballistic comparison, the initiatives, designs, and state of the art of ballistic identification systems, the effectiveness studies of them, as well the mechanical and physical characterization of the research objects.

2.1 FIREARMS AND AMMUNITION

A gun can be “loosely defined as a one-stroke internal combustion engine. In this case, the projectile is the piston and the propellant is the air-fuel mixture” (Carlucci; Jacobson, 2007, p. 20). This generic definition encompasses ‘true gun’, howitzer, mortar or recoilless rifle, with propellant playing the role of the fuel necessary for the work, which consists in the transformation of the ammunition chemical energy into projectile kinetic energy. This study will focus on specific types of ‘true gun’ manufactured for sales, named revolvers, and pistols, that will be called 'firearms' or simply 'gun', this way avoiding confusing with other gun types or with homemade ones. In law terms, in Brazil firearms are currently defined by the Presidential decree 10.030 of November 30th, 2019[5], which defines it as a gun that fires projectiles employing the force generated by the gases resulted from the propellant combustion.

To study the firearm operation, let us define a firearm as a gun that fires **projectiles** (bullets in the context of this research) of mass m_p, using the energy from the expansion of the gas, of mass m_g, generated by the combustion of solid **propellant**. To work effectively, a firearm needs a **barrel** with length *L* and bore diameter *d’*, whereby the projectile will be accelerated, a combustion **chamber**, with specified length and diameter *l* and *w*, employed to accommodate the **cartridge case** that originally comprised of the **bullet**, **propellant**, and **primer**, and an **ignition system** to start the discharging process (Figure 2) (Ibid.).

Cartridge case, primer, propellant, combustion chamber, barrel, and bullet will be used to explain the firearm variable features and the importance of them to firearm identification. This does not intend to be an extensive explanation of firearm classifications and operations, rather focus on the necessary concepts to understand this research project.

[5] http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2019/decreto/D10030.htm [Accessed 1/12/2020].

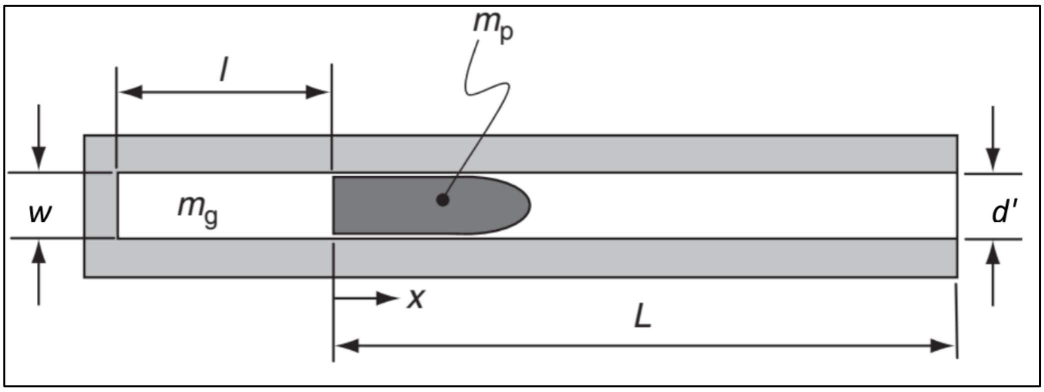


Figure 2 – Illustration of a firearm system (Source: Adapted from Carlucci; Jacobson, 2007, p. 26).

2.1.1 Cartridge case and caliber

The first important component to understand modern firearms and ammunition is the cartridge case, which is used to hold all other ammunition components (see Figure 3). Firearm design, including nominal caliber and firing mechanism, is dictated by the cartridge case that it is intended to fire (Bolton-King, 2012). That is why material, shape and dimensions of the cartridge case are so relevant, being essential to proper firearm operation and to prevent the rearward escape of propellant gases from the chamber during firing (B-GL-306-006, 1992).

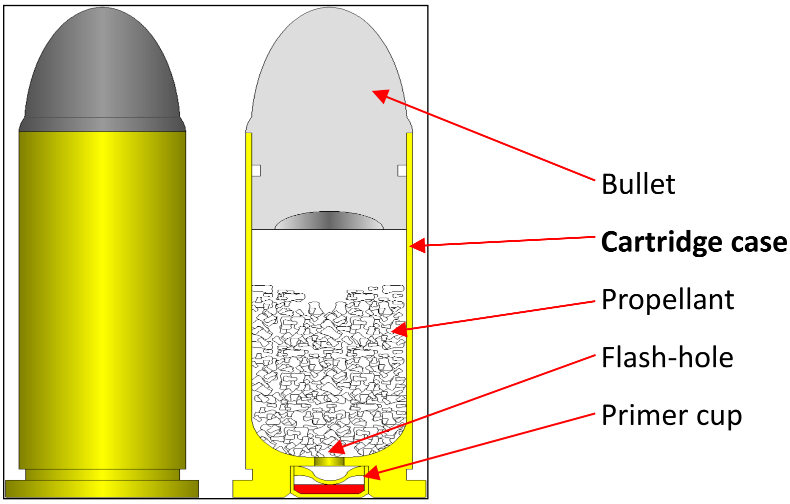
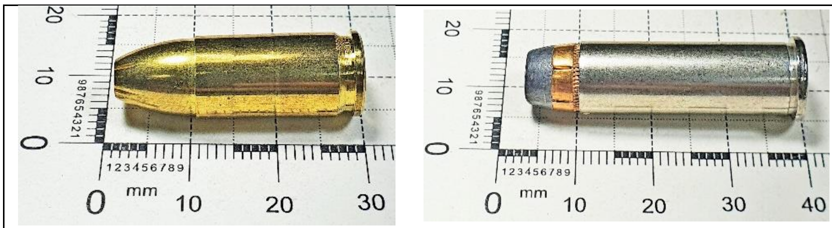


Figure 3 – Illustration of a central fire ammunition cartridge (Source: Adapted by the author from an unidentified source - Santos, 2015, p. 31).

As often occurs in many technological subjects, the understanding of material properties was the forerunner for the development of more precise and powerful ammunition (Callister, 2007). Cartridge case needs to be able to support high pressures during firing and its shape is designed to properly interact with firearm mechanisms, such as the chamber, extractor, and ejector.

Cartridge cases are made from a wide variety of metals, for example brass, steel, and aluminum, and in some firearms, such as shotguns, even polymeric materials are employed (B-GL-306-006, 1992). For this study, 15 (fifteen) types of cartridges (further described in Table 4, Table 10, and Table 11) were used, but their material composition and shape are fundamentally classified into the 2 (two) categories depicted in Figure 4.



a) **b)**

Figure 4 – Two types of cartridge employed in this research: **a)** 9x19mm rimless brass, and **b)** .38SPL rimmed nickel-plated.

The main constituent of these cartridge cases is brass, an alloy generally 70 wt% Cu (weight percent copper) and 30 wt% Zn (zinc) (Tochetto, 1999). The literature and manufacture data are not always as precise on the composition of the ammunition components. Therefore, in instances where the composition was not destinct, it was determined through Energy Dispersive X-Ray Spectroscopy (EDS) in conjunction with Scanning Electron Microscopy (refer to section 4.1.5).

The cartridge case in Figure 4b is nickel-plated, which means it has a thin Nickel layer responsible for its silver or metallic gray color tone. Scratching this thin layer reveals the same brass compound material (refer to Figure 5).

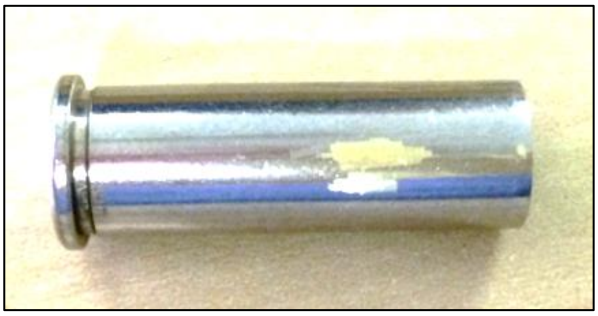


Figure 5 – Scratched cartridge case b) in Figure 4, revealing brass internal material (Source: Oliveira Júnior, 2015, p. 23).

As can be seen in the copper-zinc phase diagram of Figure 6, for concentrations up to 35 wt% Zn , the α phase is stable at normal temperatues. This phase has an FCC (face-centered cubic) structure, and is ductile, soft and easily cold worked. In order to enhance its mechanical properties, even after cold working, is common to anneal brass for cartridge case application. Table 1 (refer to p. 47) presents some mechanical properties of annealed cold-worked brass (Callister, 2007).

Annealing is a heat treatment in which the material is heated to a temperature above that needed for recrystallization and then cooled in a manner that will alter its mechanical properties as desired. Some consequences of the annealing process is the release of internal stresses and an increase in ductility and toughness (Ibid.). As can be seen in Table 2 (refer to p. 47), brass presents relatively high ductility in comparison to other annealed metal alloys. This desirable characteristic, while still not compromising too much of yield and tensile strength, are attractive features that concur for its selection for cartridge cases, especially considering the expansion, chamber sealing, contraction, and extraction, which it must fulfill during firing (B-GL-306-006, 1992).

The use of zinc as a substitutional impurity makes brass not propense to corrosion, becoming a reliable container for propellant and primer storage. Its high ductility allows the cartridge case expansion to seal the chamber while gas pressure is still rising at the beginning of propellant deflagration. On the other hand it needs to be pliable enough to recover to a diameter less than the internal diameter of the chamber once the pressure drops, therefore it is heat-treated in order to have a hardness gradient along its length, being softer on the mouth (extremity that grasps the bullet) and harder on the base (also known as the head). The high degree of toughness and acceptable tensile strength ensure that it does not easily fracture when a crack is present or fails even under high stress gradients. (B-GL-306-006, 1992; Callister, 2007).

In terms of shape, the cartridge cases shown in Figure 4 present slightly tapered walls and two configurations on its bases. The cartridge case in Figure 4b presents a flange or rim, that is larger than the rest of the cartridge, and is so named rimmed. On the other hand cartridge case in Figure 4a also features a rim, but because this flange has almost the same diameter as the case body, it is named rimless (Jenzen-Jones; Schroeder, 2018).

Rimmed cartridge cases are commonly employed in revolvers and the wider rim is utilized to accommodate the cartridge in one of the chambers (holes in the revolving cylinder) facilitating its manual extraction after firing. Rimless ones are customarily designed for semi-automatic firearms, like pistols, with the region between the cartridge base and the rim providing a groove for the extractor to engage, allowing an automatic extraction of the empty cartridge case after fired, completing a firearm cycle.

The cartridge dimensions are defined by the nominal caliber; a designation of type of ammunition and of firearm, which must coincide or be compatible, for the firing take place. When nominal caliber refers to a number it generally specifies the maximum diameter of the bullet and the smallest inner diameter of the firearm barrel bore. Sometimes it also includes the cartridge case length or other particular designation.

The nomial caliber of firearms and ammunition employed in this study are:

- **.38SPL:** 0.38" (thirty-eight hundredths of an inch) for approximate internal diameter of the firearm barrel bore and external diameter of the bullet, and SPL (Special) for delimiting further cartridge case dimensions and gun chamber specifications;
- **9x19mm:** 9mm (nine millimeters) for approximate internal diameter of the internal surface of the barrel (bore) and for external diameter of the bullet, and 19mm (nineteen millimeters) for cartridge case length and consequentely internal chamber dimensions;
- **.40S&W:** 0.40" (forty hundredths of an inch) for approximate internal diameter of the barrel bore and external diameter of the bullet, and S&W (Smith and Wesson) being the well-known USA (United States of America) firearm factory that developed this caliber.

Because the dimensions of the cartridge case and firearm combustion chamber must concur for effective discharge, firearms and ammunition manufacturing bodies and associations publish standards for existing nominal calibers, which include ammunition dimensions and allowed pressure levels, with appropriate tolerances.

In the USA the SAAMI (Sporting Arms and Ammunition Manufacturers' Institute)[6] standardizes the nominal calibers and in Europe the CIP (*Commission internationale permanente pour l'épreuve des armes à feu portatives* – Permanent International Commission for the Proof of Small Arms) [7] plays the same role.

ATTACHMENTS A, B and C on pp. 299 to 301 depict the SAAMI cartridge and chamber drawings for the calibers of this study.

[6] https://saami.org/ [Accessed 21/10/2019].
[7] http://www.cip-bobp.org/ [Accessed 21/10/2019].

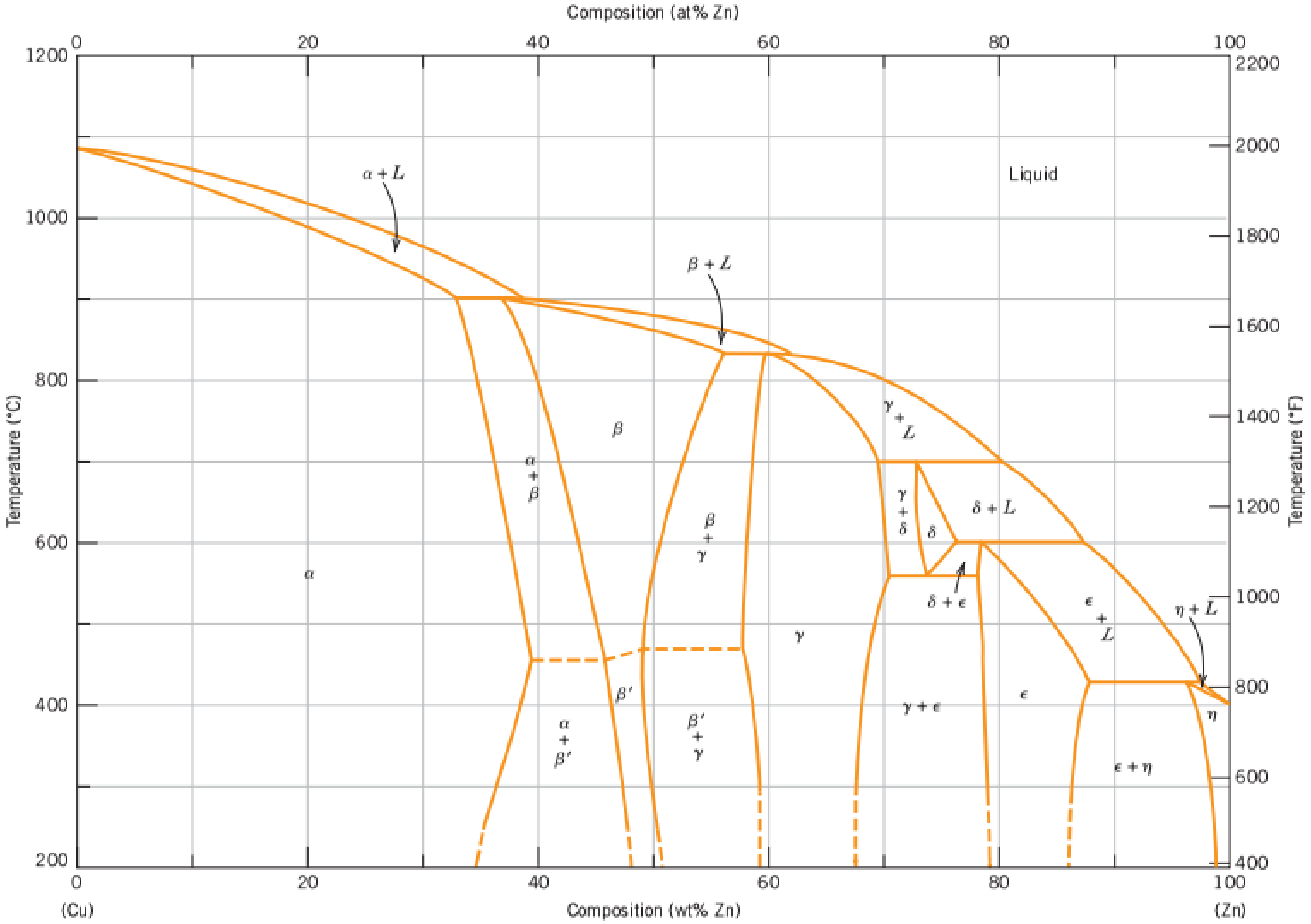


Figure 6 – Copper-zinc phase diagram (source: Callister, 2007, pg. 283).

Table 1 – Composition, mechanical properties, and typical applications for brass.

				Mechanical Properties			
Alloy name	*UNS number*	*Composition (wt%)*	*Condition*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductibily [% EL in 50mm (2in.)]*	*Typical applications*
Cartridge Brass	C26000	30 Zn	Annealed cold-worked	300 (44)	75 (11)	68	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates

(source: Callister, 2007, pg. 374)

Table 2 – Typical mechanical properties of several metals and alloys in an annealed state.

Metal Alloy	***Yield Strength MPa (ksi)***	***Tensile Strength MPa (ksi)***	***Ductility, %EL [in 50 mm (2 in.)]***
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

(source: Callister, 2007, pg. 148)

2.1.2 Primer and ignition process

As shown in Figure 3, at the center of the cartridge base is located the primer cup, a capsule containing an impact-sensitive compound intended do be detonated by the firing pin striker, igniting the firearm firing process. Because of its location, this firing mechanism is named the centerfire system. Just like most modern firearms this is the firing mechanism used by all the firearms in this study, and is considered so important to firearms evolution that it is regarded as "the great milestone in weapon and ammunition development" (Heard, 2008, p. 11).

For the firearms of this study, this ignition system can be briefly described as:

a) in automatically operated pistols, a magazine is introduced into the firearm and a cartridge case is fed from the magazine into the combustion chamber of the firearm;
b) revolvers have a revolving cylinder with several chambers, and one containing a cartridge case needs to be aligned between the barrel and the firing pin aperture for the shooting to take place (Di Maio, 1999);
c) pressuring the firearm trigger releases a striker pin (firing pin) to exert pressure on the primer cup, which as aforementioned contains an impact-sensitive compound;
d) the pressure of the firing pin detonates the primer, generating a flame that communicates with propellant through flash-hole(s) inside the cartridge case;
e) the flame ignites the propellant charge, generating gases and increasing the pressure inside the cartridge case;
f) under pressure the cartridge case expands into the walls of the combustion chamber, sealing it;
g) pressure also decouples the bullet from the cartridge case mouth and accelerates it through the barrel;
h) in automatically operated pistols this process is also accompanied by the action of extractor and ejector pin, responsible for the extraction of the discharged cartridge case, completing a firing cycle.

Primer cups and cartridge cases are generally made of the same material, this way avoiding problem with differential expansion if dissimilar materials were employed (B-GL-306-006, 1992). The two most common type of primer cup employed in modern centerfire firearms is Berdan and Boxer, named after their inventors (Figure 7).

Figure 7 – Berdan (left of each image) and Boxer (right of each image) primed cartridges and cups from RUAG Ammotec manufacture (source: RUAG website[8]).

The Boxer primer, which is the type used in the ammunition within this study, features the **anvil,** a separate stirrup piece against which the explosive mixture is squeezed by the firing-pin, detonating it and generating a spark. Figure 8 depicts a Boxer primer cup showing the explosive mixture (in red), the anvil and the flash-hole.

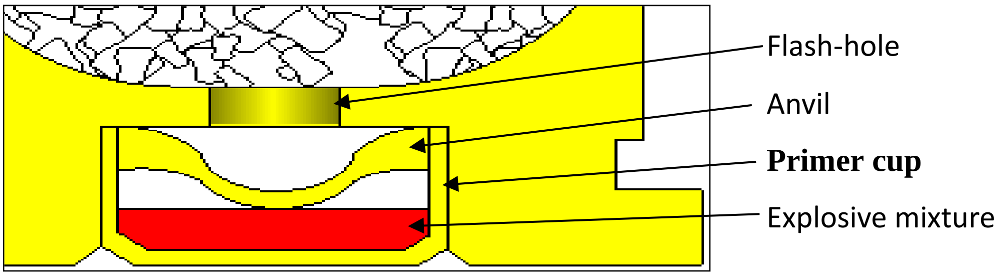


Figure 8 – Illustration of a Boxer primer within a centerfire cartridge.

The first stable compound to be encapsulated in primers was the 1800-synthesized mercury fulminate (Beck et al., 2007), which was applied to CBC ammunition up to 1975. After this, lead styphnate, or Lead 2,4,6-trinitro-m-phenylene dioxide ($C_6HN_3O_8Pb$), an orange reddish-brown explosive that is stable in storage even at high temperatures (Echa, 2011). The current compound also applies barium nitrate and antimony trisulfide, respectively as oxidant and fuel (Schwoeble; Exline, 2000), in addition to other stabilizers such as aluminum powder (Cunico, 2010).

To start the ammunition deflagration, when the firing pin deforms the primer cup, the explosive mixture is compressed against the anvil, breaking lead styphnate crystals (Tochetto, 1999). Lead styphnate breaking releases energy through an exothermic reaction, the exact enthalpy variation depends on the reaction products, generating flames at approximately 2500

[8] https://www.ruag.com/en/products-services/land/ammunition-components-industry/primers/ [Acessed 17/11/2019].

°C (two thousand and five hundred degrees Celsius). These flames reach the propellant through cartridge case flash-holes and have enough energy to ignite the propellant (Rabello, 1995).

2.1.3 Propellant and pressure of discharge

To identify the cartridge's origin, manufactures engrave at the head of the case, alphanumeric informative symbols, known as the headstamp (Jenzen-Jones; Schroeder, 2018). The CBC headstamp presents, besides the caliber and sometimes the ammunition year of production, an engraved 'V' or 'C' mark to guarantee ammunition originality (Figure 9). The symbols '+P' or '+P+' are also stamped to inform the user that this is ammunition with 'greater power' or 'power even greater', ie they were designed to offer energy higher than the conventional ammunition (CBC, 2018).

Assuming the firearm is in good condition and the correct type of ammunition is being employed, the pressure produced in the combustion chamber ultimately determines whether the bullet will reach the muzzle (front end of the barrel) at an acceptable velocity or completely destroy the firearm (Heard, 2008). Because of this, another important standardization for firearms and ammunition is the pressure limits at which they must operate, which is dependant on the propellant amount and composition, and the case density of loading (Whelen, 1947).

Figure 9 – Photomicrographs of CBC cartridge headstamps, showing "V" mark at the primer cup, and inscriptions on .38SPL, .38SPL +P, and .38SPL +P+ cartridges.

Because these propellants are typically organonitrogen compounds, the SEM is inappropriate to analyze its composition, revealing just the presence of carbon (C), oxygen (O), and nitrogen (N), and other elements employed by the primer, regardless of their structure. Instead, Attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy may be employed (refer to section 4.1.5).

For the revolvers and pistols of this research, the deflagration needs to be fairly fast because the barrels are relatively short and therefore it is important that most of the powder is burnt in a short time span. The confined gas pressure rises during powder burning allowing firearm operation, which includes bullet launching and recoil of the cartridge case, breechblock and firearm (Tochetto, 1999). The two SAAMI-recognized centerfire cartridge pressure measurement systems are the copper unit system and the piezoelectric transducer system (ANSI/SAAMI, 2015).

The copper unit system employs a copper crusher cylinder that is compressed by a piston mounted in a hole in the test tube chamber. The pressure developed by the propellant gases acts through the piston bore, allowing the gases to force the piston upward, thereby permanently compressing the copper crusher cylinder. SAAMI has adopted the designation of "Copper Units of Pressure" (CUP) pressure units for this system (Ibid., pg. 8).

On the other hand, the piezoelectric transducer system employs a piezoelectric transducer embedded in the test tube chamber. The pressure developed by the combustion propellant gases exerts force on the transducer on the wall on the side of the cartridge case causing the transducer to deflect and creating a measurable electrical charge. This electrical charge is converted to a pressure reading. SAAMI has adopted pressure units called "pounds per square inch" (psi) for this system, which is currently the most widely adopted (Ibid., p. 8).

Another way to study the influence of pressure of discharge is measuring the bullet velocity. Figure 10 depicts an idealized discharging firearm process. The burning of the propellant leads to an exponential increase in gas pressure in the chamber, and although the pressure measurement methods usually measure the pressure at the breech (p_b), it is the pressure at the base of the projectile (p_s) that is responsible for its movement.

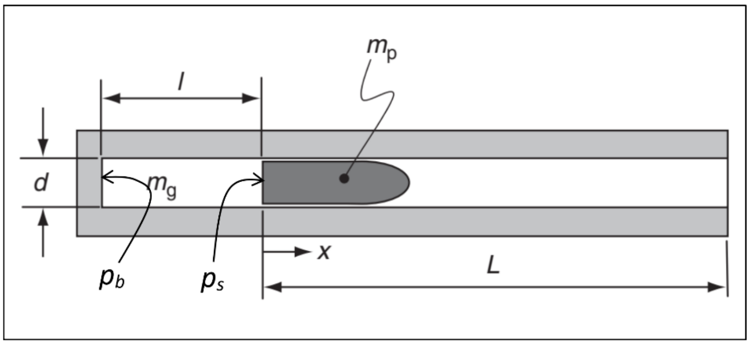


Figure 10 – Firing process in a simplified firearm model (Source: Adapted from Carlucci; Jacobson, 2007, p.26).

Writing Newton's second law for the projectile moviment:

$$F = m_P . \frac{dV}{dt} . \qquad 2.1$$

On the other hand, the pressure at the base of the projectile:

$$p_s = \frac{F'}{\pi . pd^2} , \qquad 2.2$$

While *F'* and *pd* are the force and radius at the base, *F* is the resultant force that acts upon the projectile, which is smaller than *F'* because of opposite and resistive forces, such as friction and air compression in front of the projectile. A way to equate the forces of equations 2.1 and 2.2 is to substitute the projectile mass m_p for a superior mass $m_{p'}$ that takes into account the resistance toward projectile movement, allowing to write:

$$m_{P'} . \frac{dV}{dt} = p_s . \pi . pd^2 . \qquad 2.3$$

Before write in terms of acceleration should be notted that:

$$p_s = p_s(t) , \qquad 2.4$$

$$\frac{dV}{dt} = \frac{\pi . pd^2}{m_{P'}} . p_s(t) . \qquad 2.5$$

The exact behavior of $p_s(t)$ as a function of time *(t)* is beyond the scope of this thesis, and although mass and size of the projectile, mass, shape, and temperature of the propellant, chamber format, and many other factors influence the gas pressure curve, the variations of pressure and velocity depicted in Figure 11 are similar in character to numerous gass pressure firearm diagrams (B-GL-306-006, 1992).

It should be noted that the pressure depicted in Figure 11 are the ones measured by the aforementioned SAAMI accepted methods (refer to p. 51) regarding the breech face pressure. A relationship between the breech face pressure (p_b) and the pressure at the projectile base

(p_s) was established by Carlucci and Jacobson (2007), after some assumptions about the behaviour of the gas pushing the projectile out of the firearm:

$$p_b(\mathrm{t}) = p_s(t).\left(1 + \frac{m_g}{2.m_{p'}}\right). \qquad 2.6$$

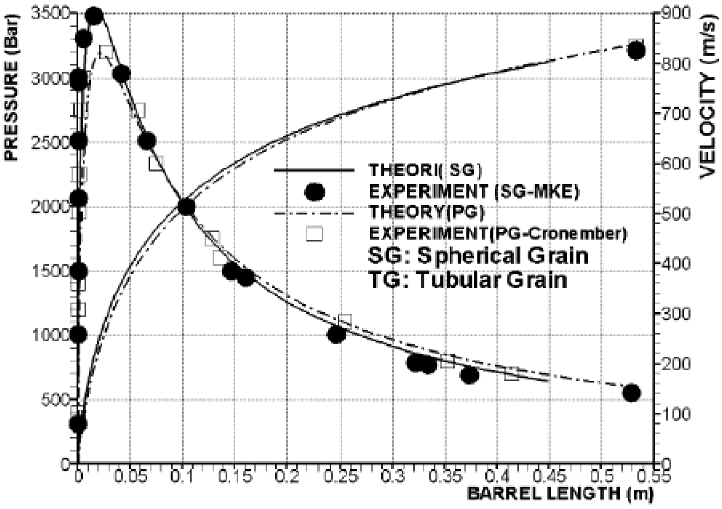


Figure 11 – Theoretical and experimental pressure velocity distribution along the barrel.
(Source: Akçai, 2017)

Substituting 2.6 into 2.5 leads to a projectile equation of motion:

$$\left(m_{P'} + \frac{m_g}{2}\right).\frac{dV}{dt} = \pi.pd^2 .p_b(\mathrm{t}) . \qquad 2.7$$

Besides demonstrating that pressure generated by propellant burning pushes the projectile, equation 2.7 also implies that, in the absence of a means to measure the pressure0020 during the discharging process, recording projectile exit velocity is an alternative way to study the pressure influence on the identification marks.

Another important factor regarding this relationship between pressure and projectile velocity is the ballistic efficiency, ε_b, defined as the ratio of the projectile kinetic energy (KE) as it exits the muzzle to the total propellant potential energy (PE) (Carlucci; Jacobson, 2007):

$$\varepsilon_b = \frac{muzzle\ KE}{propellant\ PE} = \frac{\frac{1}{2}.m_p.V^2}{\left(\frac{R.T_O}{\gamma_O - 1}\right).c_m} . \qquad 2.8$$

In this equation R is the specific gas constant, T_o is the adiabatic flame temperature of the gas, c_m is the charge mass (propellant mass), and γ_0 is the ratio of specific heat of the gas. “The ballistic efficiency of most guns is approximately 0.33” (Ibid., p. 112).

2.1.4 Combustion chamber and firing cycle

The firearm chamber dimensions will be defined by the ammunition that it is designed to fire, and therefore the SAAMI and CIP standardizations include the specifics for the chamber (refer to ATTACHMENTS A, B, and C on pp. 299 to 301).

As shown in Figure 12, for pistols, the chamber is manufactured as an part of the barrel positioned at its rear end. To properly operate, the chamber rear end is open, and when filled with a cartridge, the cartridge case, including primer cup, will be seated against the face of the breech, which for pistols is part of the slide. To allow the forward movement of the firing pin, an aperture is provided in the center of the breech face, and each designed pistol will have a particular ejector and extractor orientation (refer to Figure 13).

Figure 12 – Annotated parts of a disassembled 9x19mm semi-automatic Jericho 941F pistol.

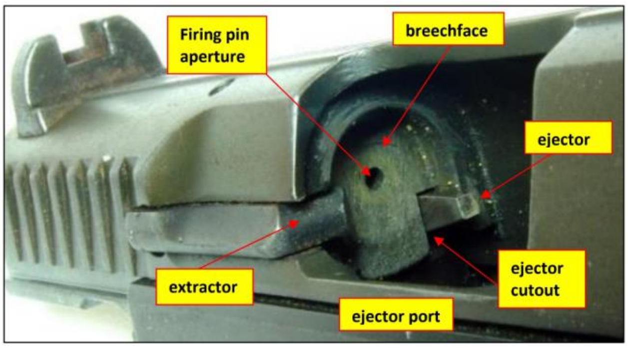
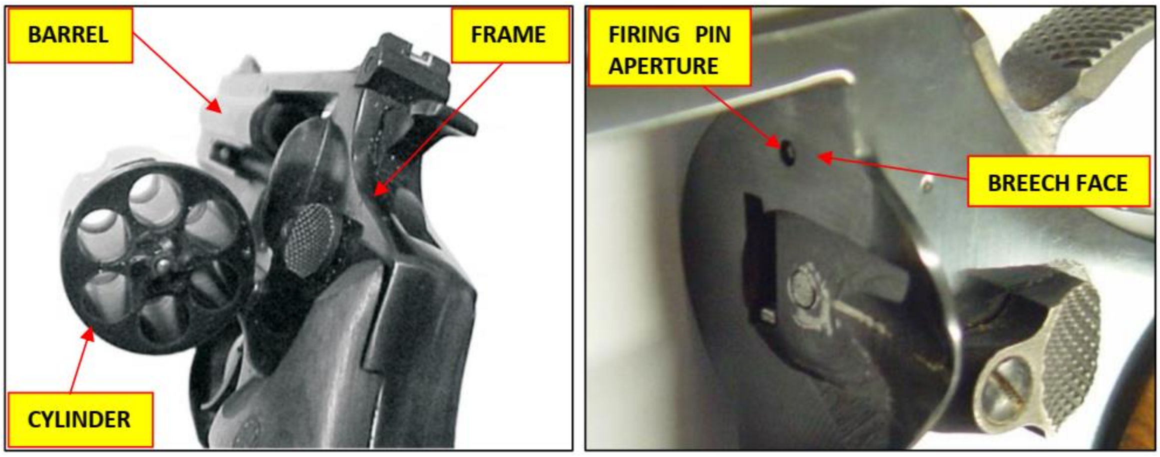


Figure 13 – Pistols importante parts for cycle mechanism and firearm identification.

By conservation of motions law, the bullet's forward movement is accompanied by a cartridge case and slide backward movement, that is partially absorbed by a recoil spring. Because the pressure generated in many pistols is too high during initial deflagration stages, some pistols also have a mechanism to retard cartridge case extraction from the chamber and ejection port opening for ejection - a locking mechanism that keeps the barrel attached to the slide for a brief time. Because the unlocking mechanism is sometimes rotating and others downward sliding, this can cause an observable drag mark on the firing pin impression.

To complete the cycle in semi-automatic firearms, the rearward movement of the slide and the ejection of the cartridge case is followed by a new cartridge feeding from the magazine, introduced between the breech face and chamber rear end. The forward movement of the slide (due to the recoil spring recovery) positions the cartridge inside the chamber for a new discharge.

On the other hand, in revolvers, the chamber is not part of the barrel, and the discharging mechanism is manually operated, which means it does not involve a semi-automatic cycle. To feed the firearm, revolvers have a revolving cylinder, positioned between the breech face and the barrel, containing the chambers. This firing mechanism does not involve extractor or ejector, but still, there is a firing pin aperture, firing pin and chamber (refer to Figure 14).



a) **b)**

Figure 14 – Two different perspectives of a .38SPL Taurus six chambers revolver: **a)** rear view, and **b)** side view through cylinder opening.

The very intense operation of both revolvers and pistols imparts many marks on cartridge cases during feeding, firing, and extraction. Some of these marks will have unique characteristics that are used for firearm identification, and others have features that will be observed in a particular group of firearms.

When designing a firearm, a manufacturer has some limitations regarding the caliber the firearm is intended to fire, but also has some features to determine, such as the firing pin and aperture shape, and the orientation and shape of ejector and extractor. The features observed on fired cartridge cases can be classified by their **class characteristics**. The class characteristics cannot be employed to identify the specific firearm that fired a cartridge case but can reduce the suspect firearm to a particular manufacturer and/or model, or can disregard some firearms from the list of suspects, helping to narrow the population of potential firearm sources (Thompson, 2010).

The firearm parts that impart class characteristics on the fired cartridge case have been through many manufacturing processes, like cutting, drilling, grinding, filing or polishing. During this whole process, the surface of the part is constantly changing, giving a variety of striation marks on its surface. Each of these steps is subjected to many variables, such as the force applied, direction and angle of attack, wearing and blunting of the tool's surface. Each step will have an effect on the microscopic imperfections observed in the part's surface. The process is so random that Heard (2008) expressed this way about the improbability of two parts present same **individual characteristics**:

> Such are the variables involved, that the chance of two firing pin having exactly the same manufacturing stria is so low as to be negligible. It is the combination of these randomly produced patterns of individual stria which enable, with a degree of certainty beyond reasonable doubt, to match a weapon to fired ammunition (Heard, 2008, p. 174).

Figure 15 depicts some of impressions on fired cartridge cases that feature class and individual characteristics potentially useful for firearm identification, including:

- Breech face: as individual characteristics;
- Firing pin: shape as class characteristic and imperfections as individual characteristic;
- Firing pin drag mark: shape as class characteristic and imperfections as individual characteristic;
- Firing pin aperture: as class characteristic;
- Extractor: orientation as class characteristic, and striae as individual characteristic;
- Ejector cutout: shape and orientation as class characteristic;

- Ejector pin; orientation as class characteristic and imperfections as individual characteristic;
- Magazine lips: class or individual characteristic;
- Chamber: class or individual characteristic;
- Ejector port: class or individual characteristic.

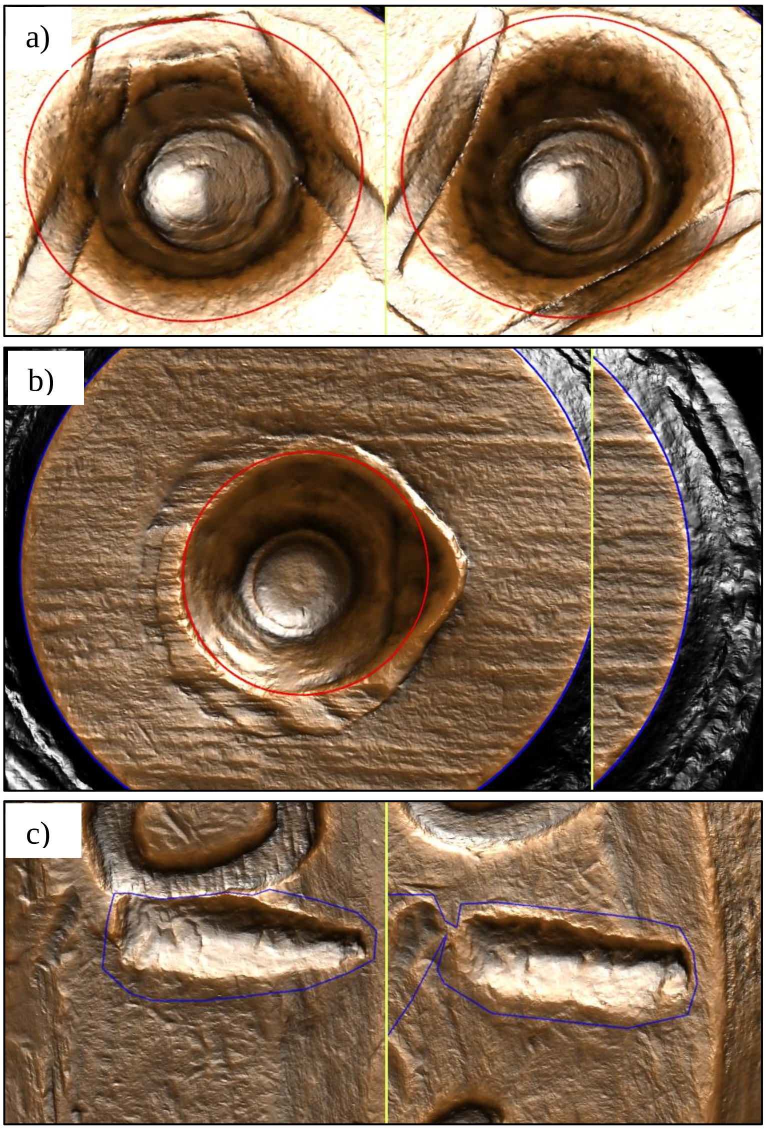


Figure 15 – Comparison of: **a)** firing pin, **b)** breech face, and **c)** ejector marks, in cartridge cases discharged from: **a)** .40S&W PT100AF Taurus pistol, **b)** 9x19mm Hi-Power FN Browning pistol, and **c)** .40S&W MD7 Imbel pistol (IBIS® images).

2.1.5 Barrel

In the firearm production, some pieces are punched out of sheet steel, while others, such as the barrel and the frame, are forged and molded roughly, special presses, starting from blocks of steel previously cut in the convenient dimensions. The other operations are cold-worked, on special machines, using extremely hard steel tools (Rabello, 1995).

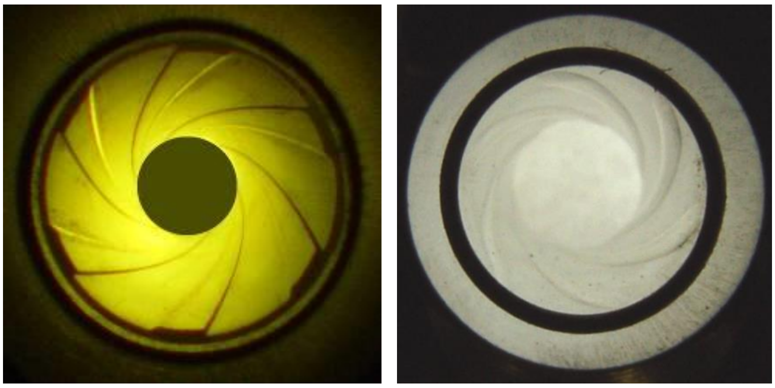
The barrel is an essential part of the firearm to accelerate the bullet. As can be seen in Figure 12 and Figure 14, in pistols the barrel and the chamber are manufactured as a single part, although in revolvers they are separate pieces. The exact stages of barrel production may vary a lot between manufacturers, and many parts of the processes may be regarded as company's secret (Bolton-King, 2012). Nevertheless, some common steps can be outlined as essential for its manufacturing, including, roughly drilling a steel rod, milling to smooth the roughness of spiral scratches acquired during the drilling process, rifling production, and adding final features for barrel operation, like locking surfaces for pistols or screw-thread for revolvers (Heard, 2008).

The inner diameter of the barrel bore will be determined by the external diameter of the bullet intended to fire, defining its caliber. The rifling producing are helical grooves or valleys, cut or forged within the barrel bore, which are designed to impart a rotatory motion or spin to the bullet being fired, enhancing its range, stability, and accuracy, and characterizing the barrel of rifled firearms (Thompson, 2010; Werner et. al 2020).

Historically the grooves had been produced by metal removal processes, such as cutting or scraping the bore inner surface, producing parallel sided grooves with sharp edges, being termed conventional riflings (Bolton-King, 2012). More recently developed methods do no involve metal removal, being based on metal deformation, such as button rifling, mandrel rifling, or cold hammer forging, generating rounded or angular profiles with no sharp edges, termed polygonal rifling (Bolton-King, 2012; Werner et. al 2020).

Between many cutting processes for barrel rifling, like hook cutter, scrape cutter, and broach, gang broach rifling is the most conventionally employed. In this process, the cuts are obtained using a series of 20 to 30 steel discs on a rod, each disc being slightly larger than the predecessor, and are used to progressively cut the inside of the barrel. A broach cutter is used to give the final dimensions to all grooves and lands at once, generating rifling with sharp edges as can be seen in Figure 16a (Heard, 2008).

The rifling produced by metal deformation results in a more refined and higher quality final product. For instance, in the hammering process, the barrel initial bore is cut slightly larger than the final desired caliber. A mandrel, which is a very hard steel plug tapered at both ends, is introduced in the bore, and hammers hydraulically compress the barrel material leading to the bore acquiring a negative of the mandrel features. Assuming the mandrel is of good quality, the barrel is produced with exceptional quality and features rounded edge riflings, as can be seen in Figure 16b (Ibid.).



a) **b)**

Figure 16 – Photographs of the bore of two 9x19mm firearm barrels: **a)** 6L (six left) conventional rifling, and **b)** 6R (six right) polygonal rifling (Source: Jost et al., 2014, p. 14).

There are many geometrical features of rifling that can be employed for firearm classification. Modern firearms can feature rifling made of 1 (one) groove up to 24 (twenty-four), and indeed the number of them looks like it does not influence the stabilizing effect (Heard, 2008). Another feature of the rifling is the twist, or the length of the barrel, in inches, required for the rifling to complete one spiral. Twist is very important for bullet stability, being necessary to calculate it, in order to prevent being too high or too little. Also, the rifling can feature a right-handed twist (clockwise) or left-handed twist (counter-clockwise), and for instance, six right-handed twist grooves will be designated as 6R, while five left-handed twist grooves as 5L (Ibid.).

Figure 17 depicts lands and grooves of a conventional rifled barrel and illustrates other important features: the width of the lands and grooves, the depth of grooves, measure between the top of the land and the bottom of the groove, the pitch, that is the angle of the groove edge obtained from the width and steepness of the groove a which alters over time, and the shoulder, that is the transition area between groove and land (Crawford, 2010).

All these mentioned features are **class characteristics** that are imparted into the bullet during its traveling through the barrel. The barrel lands account for the recesses/grooves observed on the fired bullet and are named Land Engraved Areas (LEA), while the grooves account for the raised geometries/lands of the bullet, named Groove Engraved Areas (GEA) (Ibid.).

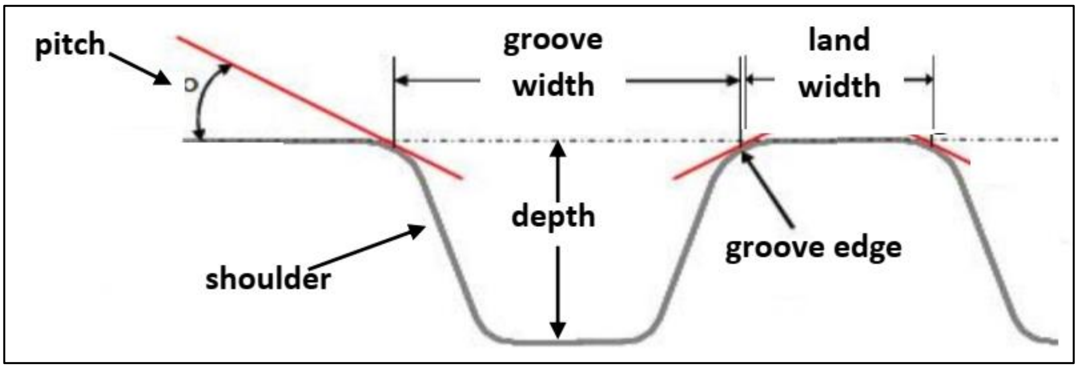


Figure 17 – Illustration of lands and grooves of a rifled barrel – not to scale (Source: Adapted from Crawford, 2010, p. 3).

Gerules et al. (2013) well emphasized the utility of these features:

> The class characteristics, such as the number of lands and grooves, direction of twist, and widths of the lands and grooves, can be used for class identification. That is, they can narrow down a bullet as having been fired by a particular type of firearm and can eliminate the possibility of others (Gerules et al., 2013, p. 238).

Besides these features, the importance of rifling for firearm identification is the micro striae (microscopic scratch or scrape marks) that are imparted on a bullet that is launched through it.

As explained for chamber and other firearm parts involved in cartridge discharge, each barrel and rifling producing is under the influence of many variables, as the force applied, direction and angle of attack, wearing and blunting of the tool's surface, that will affect the microscopic imperfections of the barrel bore surface. Regarding this uniqueness of individual micro striae marks, Heard (2008) stated:

> Whilst all weapons of the same make and model will have the same class characteristics, statistically and empirically, **it can be shown that no two weapons will have exactly the same individual rifling characteristics** (Heard, 2008, p. 171, emphasis added).

Most of the marks left inside rifled barrels are created during drilling, flaring, trimming, and finishing operations. Burrs are also left after the barrel is crowned and the chamber and forcing cone are cut off (Warlow, 2005). In the use of the firearm "original individualizing characteristics are irreversibly destroyed or modified and new characteristics are acquired" (Rabello, 1995, p. 257).

Bachrach (2006) stated that "The barrel manufacture seems to be the dominant factor in the individuality of the bullets fired by it" (Bachrach, 2006, p. 36), and specifically pointed out that "dimensional tolerances of the barrel, the degree to which the interior surface of the barrel is polished during manufacture, and the general quality of the machining all seem to contribute to the overall quality of the barrel" (Ibid., p. 37).

Another type of interesting mark is a skid mark (or slippage mark) imparted on the bullets as it moves from the chamber to the rear of the barrel bore. Because this mark is the first to be engraved it is named 'primary mark', and it is identifiable in fired bullets because they feature different directions in comparison to LEA and GEA mark directions, as they are generated before the bullet is rotated by the riflings (Yuesong et al., 2019).

In turn, the forged barrels will feature less identifiable marks for transferring and comparison than conventionally rifled barrels. "As a consequence, the identification of bullets fired by very high-quality barrels can be very challenging" (Bachrach, 2006, p. 37).

It is worth to mention that because the barrel is an interchangeable part for many firearms, the analyses of a bullet, in search for class and individual characteristics, are potentially useful for barrel identification, which not in all cases means firearm identification, as sometimes the barrel may have been switched between two firearms of the same model.

Figure 18 depicts micro striae matches between side by side comparison of two LEA, that demonstrates that these two bullets were fired through the same barrel.

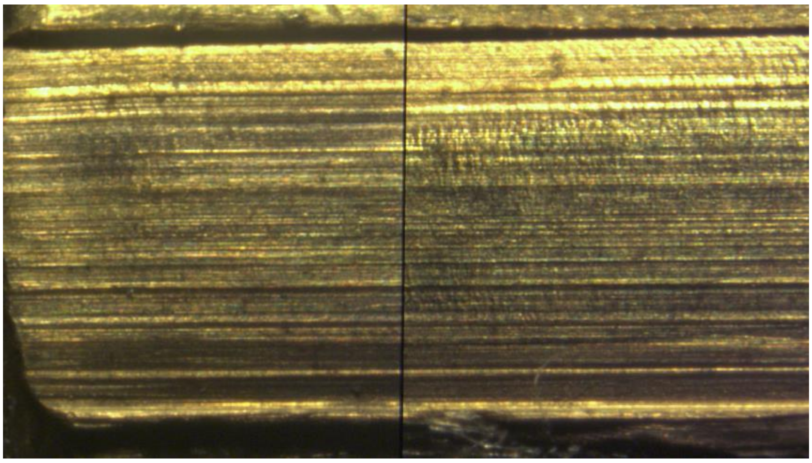


Figure 18 – Photomicrograph of a side-by-side comparison of the impressed marks in two .38SPL bullets' LEA.

2.1.6 Bullet

In section 2.1.3 was demonstrated that "(pressure) and velocity are the milestones which measure the ability of a small arm to do work – to propel the (bullet)" (Whelen, 1947). Bullets may be presented in many forms and compositions. The geometric variation in the bullet's shape is an important parameter regarding the range and accuracy of fire (Aboelkhair;

Yakout, 2013). In turn, the composition is very relevant for the bullet interaction within the barrel and therefore for firearm identification.

In the context of this research, the employed ammunition features 14 (fourteen) bullets types (further described in Table 4 – p. 108, Table 10 – p. 132, and Table 11 – p. 132), that were collected and termed test-fired bullet (TFB) or questioned bullet (QB). These bullets can be categorized in 3 (three) calibers, 6 (six) forms, and 7 (seven) material compositions, as depicted in Figure 19 to Figure 21.

Figure 19 – Instances of bullet calibers.

Figure 20 – Instances of bullet forms.

Figure 21 – Instances of bullet materials.

The first variable of these bullets is the caliber. The real caliber of a bullet is its external diameter, measured in mm (millimeter) or in (inch), which must be slightly larger than the smallest inner diameter of the firearm barrel bore, so the bullet will engage with the rifling lands and grooves and receive an angular momentum while is accelerated down the barrel (Xie et al., 2009).

In terms of forms, it can be observed from left to right in Figure 20, that the first bullet features a dark gray color and round tip (or nose), resembling a half-sphere, and for that is named Lead Round Nose (LRN). The second and third bullets are composed of a lead core totally encased in a copper alloy jacket, one presenting a pointed nose, named Full Metal Jacket (FMJ), and the other with a flat nose, named Full Metal Jacket Flat (FMJ-F). The last three bullets feature a hollow at the tip, designed to expand upon impact with fluid materials, controlling penetration and causing more damage to the target. Because the fourth bullet is only partially covered by a jacket, the fifth totally covered, and the sixth is a solid single piece, they are named respectively Semi-Jacketed Hollow Point (SJHP), Jacketed Hollow Point (JHP), and Hollow-Point (HP) (Magtech, 2016).

The bullet material composition (BMC) is another important variable for firearm identification, and in the scope of this research were determined by the literature or, when data was insufficient, by Energy Dispersive X-Ray Spectroscopy (EDS) in conjunction with Scanning Electron Microscopy (SEM)

The condition of a recovered bullet, if damage or pristine, may difficult to be match to other bullets, because of that the form and composition of bullets are very relevant to firearm identification (Cork et al., 2008). For instance, the expanding bullets (SJHP, JHP, HP) are frequently recovered with a high degree of deformation, resembling a mushroom, or having lost material. This constitutes a challenge for ballistic comparison as the lateral surface and the striae may have been obliterated or are covered. Previous to comparison microscopy or image acquisition, these and other types of damaged bullets need to be processed, trying to recover the original form, or cleaning covered areas, releasing the striae for visualization.

As can be observed from the bullet characterization, they are either solid or jacketed (Stefanopoulos et al., 2014). Lead is the most common solid type, but a solid copper bullet is also regularly found. Because pure lead is too soft, lead is alloyed with small amount of antimony to increase its hardness and facilitate the moulding process. The two processes most common employed to manufacture unjacketed bullets are casting or swaging.

> Plain lead bullets can be manufactured either by casting from molten metal or swaged from lead wire. In swaging, lead wire is cut into the appropriate

> length then cold forged with hydraulic pressure into a die with the correct dimensions and shape of the finished bullet. Nowadays, virtually all commercially manufactured lead bullets are swaged (Heard, 2008, p. 67).

On the other hand jacketed bullets have a lead core covered by some harder metal alloy jacket. Reasons to employ such jacketed bullets include to prevent deposition of lead in barrel’s bore, which has a negative impact on firearm life expectance and accuracy, and to increase the grip of the rifling for high-velocity bullets (Heard, 2008).

The above described bullets are only those relevant to the ammunition employed in this research. A great variety of bullet profiles, materials and construction exist to cater a lot of conceivable circumstances (Ibid.).

Due to differences in material composition and manufacturing process, bullet hardnesses may vary a lot. This is an important ammunition feature which will affect the observable class and individual imparted characteristic marks, as described in section 2.1.5.

The imparting of LEA and micro striae into a fired bullet occurs when its comparatively softer surface passes down the barrel; the minute irregularities in the bore surface leaving longitudinal scores or striations down the length of the bullet. The LEA and micro striae are plastic deformation responses to the force exerted by the bore rifling lands and microscopical irregularities, therefore the comparative hardnesses of the parts in contact are critical (Ibid.).

“Early hardness tests were (…) constructed on the ability of the material to scratch another that was softer” (Callister, 2007, p. 155). More modern techniques were developed in which a small indenter is compressed against the tested sample, the depth and size of the relative indentation, taking into consideration the applied load, is utilized to establish the hardness number.

Due to bullet characteristics, such as conical shape and heterogeneous jacketed surface, the Brinell hardness test was selected, between other modern techniques, to evaluate the bullet hardness of this research (refer to section 4.1.5).

2.2 FIREARM IDENTIFICATION

Many of the concepts discussed on the previous chapter (section 2.1) also apply to a larger discipline, Toolmark Identification; the “tool” being “the harder of two objects where the surface of the harder ‘tool’ produces toolmarks on a softer material” (Thompson, 2010, p. 7). A toolmark, therefore, is any impression, cut, gouge, or abrasion resulting from the contact of one object with a tool (Wheeler; Wilson, 2008). When the tool involved is a firearm, the subdiscipline is firearm identification; the "tool" including, interior of the barrel, chamber, and other parts involved in cartridge case discharge, extraction, and feed, and the softer material role played by bullets or cartridge cases.

Regarding the firearm identification, it was stated that "(there) are more than thirty characteristic markings that can be distinguished to identify a firearm" (Gerules et al., 2013, p. 237). The use of this premise has been successfully applied to solve criminal cases for more than 100 years.

Hamby et al. (2016) mentioned early instances of the use of that premise to solve criminal cases that greatly contributed to the establishment of firearm identification as a field of Forensic Science. Between the famous cases solved by applying these concepts there are:

- the shotting incident investigated by the USA Army's Frankford Arsenal, during riots in Brownsville, Texas, in 1907;
- the case of Nicola Sacco and Bartolomeo Vanzetti, that were convicted of murdering a guard and a paymaster, in Braintree, Massachusetts, USA, in 1920;
- the assassination of the British army officer and Governor-General of the Anglo-Egyptian Sudan, Major-General Sir Lee Oliver Fitzmaurice Stack, in Cairo, Egypt, in 1924;
- the murder of Police Constable George W. Gutteridge, in Essex, United Kingdon, in 1927; and
- the assassination of seven people, in Chicago, USA, in 1929, known as St. Valentine's Day Massacre.

Essential to the development of the discipline in its early stages it was the design of tools to magnify the minute characteristics of the available marks for comparison. In the investigation of the shots in Brownsville, Texas, in 1907, it was recorded the use "of magnified photographs of the firing pin impressions on the cartridge cases" (Heard, 2008, p. 146) allowing the positive identification of the firearms that discharged 33 of 39 examined cartridge cases. The Gutteridge murder case in 1927, probably was solved by the use of a personal comparison microscope, manufactured for himself by Robert Churchill, or by experts "using a simple monocular microscope and photomicrographs" (Ibid.).

Concomitant to these cases some empirical studies were carried out by independent practitioners. In an article published in 1900 Buffalo Medical Journal edition, Dr. A. L. Hall discussed the variability in the rifling types observed in bullets of the same caliber, fired from different makes and types of firearms. In 1912 Victor Still Balthazard photomicrographed LEA and GEA of fired bullets, aiming to identify the firearm source of each bullet:

> Balthazard's work was, however, exceedingly labour intensive, requiring the production of numerous photomicrographs under exactly the same lighting and magnification. These photomicrographs then had to be painstakingly enlarged under identical conditions to produce the photographs which could be compared to the unaided eye (Ibid.).

Balthazard's extensive work led him to conclude it was possible to positively identify the barrel which the bullet was fired through or to exclude others as possible sources. Examining cartridge cases he also concluded that the firing pin, breech face, cartridge extractor, and ejector present unique marks that can be used to identify the firearm that discharged a questioned case. Although it was probably not recognized at the time, the underpinning for the firearm identification discipline was being established (Ibid.).

These early cases and studies led to the refinement and application of more sophisticated magnification tools, that culminated in the establishment of the comparison microscope as the standard tool for ballistic comparison (refer to section 2.2.1). During decades, improvements on this tool included the introduction of binocular eyepieces, application of different sources of light, design of special object mountings and stages, motorized functions, integrated software and cameras, but not much change in the essential idea of the solution for nearly 70 years. In the 1990s, ballistic identification systems (refer to 2.2.5) started to be developed and incorporated into firearm identification protocol, bringing a new set of approaches and possibilities for firearm identification.

2.2.1 Comparison Microscope

The comparison microscope is a traditional and well-established tool to carry out ballistic comparisons. Although probably designed and applied previously for mineral and document analyses, Calvin Goddard attributed its application to firearm identification to Philip Gravelle, in 1925 (Ibid.).

A comparison microscope consists of a bridge mounted on the vertical tubes of two microscopes. On each side, sources of light illuminate the sample, meaning that generated electromagnetic waves interact with the sample's surface and are reflected. If the sample surface is smooth the reflection is specular, like that occur in a mirror, if it is not smooth the light is scattered and reflected, suffering diffuse reflectance (Bell; Morris, 2010). By a series of internal prisms and mirrors, the light rays are directed from two objective lenses to the same field of view (Cork et al., 2008). The resulting image can be visualized in an eyepiece or in the screen of an auxiliary computer, allowing overlapping of the images for each illuminated sample as well as a side-by-side image composition separated by a thin line, which greatly facilitates the process of striae and other individual marks comparison (refer to Figure 22).

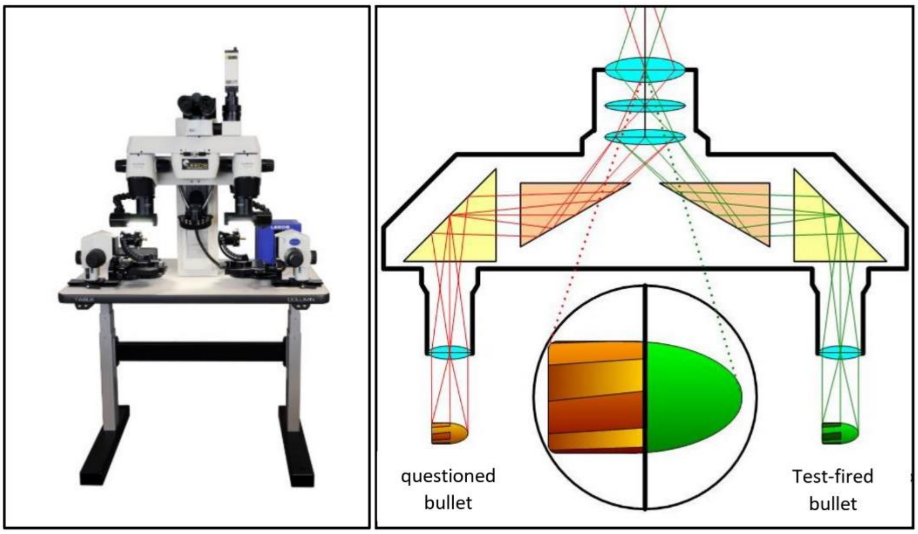


Figure 22 – LEEDS comparsion microscope, and illustration of its optical operation (Source: Adapted from Jost et al., 2014).

In the formation of the image, three aspects are critical, magnification, resolution, and contrast. The first two are very dependant on the components of the microscope, and the last on their adjusts. To observe properly the tiny features of the fired ammunition component marks, they need to be macroscopically magnified, generally 10x to 100x are required. The capability of the microscope to capture the light after its interaction with the sample will determine which fine details it can resolve. The third component for proper visualization is the contrast, and as will be explained further in section 2.2.2, this is one of the critical points in the use of the comparison microscope (Bell; Morris, 2010).

Previous to the comparison, when it is questioned if a firearm were the one that fired an ammunition component, the firearm must be test-fired. Test-firing involves firing a firearm in the direction of a device that allows efficient bullet braking, without deforming it. From each discharge, the bullet and the cartridge case are collected as control samples. The two most common means for collecting test-fired bullets are using a water tank or cotton tube (Figure 23).

a) **b)**

Figure 23 – Devices for collecting test-fired bullet: **a)** water tank, and **b)** cotton tube.

Subsequent to the test-fires, the fired ammunition components are analyzed using the comparison microscope. Special stages are designed to allow the rotation and movement of the samples so that marks can be compared from different angles and on various surfaces. A preliminary assessment should be made by comparing test-fired components, followed by the comparison of the observable features found invariably repeating on the known samples, to the feature's spot on the unknown sample. Both class and individual characteristics must be compared (Wheeler; Wilson, 2008).

For ballistic comparison, the possible range of conclusions, established by AFTE[9], are[10]:

1. IDENTIFICATION: Agreement of a combination of individual characteristics and all discernible class characteristics where the extent of agreement exceeds that which can occur in the comparison of toolmarks made by different tools and is consistent with the agreement demonstrated by toolmarks known to have been produced by the same tool.
2. INCONCLUSIVE:
   A. Some agreement of individual characteristics and all discernible class characteristics, but insufficient for an identification.
   B. Agreement of all discernible class characteristics without agreement or disagreement of individual characteristics due to an absence, insufficiency, or lack of reproducibility.
   C. Agreement of all discernible class characteristics and disagreement of individual characteristics, but insufficient for an elimination.

[9] "The Association of Firearm and Tool Mark Examiners (AFTE) is the international professional organization for practitioners of Firearm and/or Toolmark Identification and has been dedicated to the exchange of information, methods and best practices, and the furtherance of research since its creation in 1969". https://afte.org/about-us/what-is-afte [Accessed 21/10/2019].

[10] https://afte.org/about-us/what-is-afte/afte-range-of-conclusions [Accessed 21/10/2019].

3. ELIMINATION: Significant disagreement of discernible class characteristics and/or individual characteristics.
4. UNSUITABLE: Unsuitable for examination

The comparison is conducted by the examiner identifying patterns on each sample, “employing a combination of their cognitive ability to recognize agreement between pattern that in their “minds eye” constitutes an identification or “match” between a questioned pattern or (…) patterns produced from known tools” (Moran, 2002, p. 227).

“Pattern matching — aided by the dual, side-by-side inspection made possible by the comparison microscope — has been the historical norm since the field of firearms identification emerged into prominence in the 1930s” (Cork et al., 2008, p. 65).

Riva and Champod (2014) recorded that “the examiner evaluates and weights the similarities and the differences observed between sets of markings seen on the cartridge cases”, allowing to assess “whether or not a questioned cartridge case (typically recovered from a crime scene) had been fired by a given firearm (typically a firearm seized following the inquiry)” (Riva; Champod, 2014, p. 637). They also noticed that, although founded on scientific principles, it is commonly agreed that the identification process is subjective and dependent on the training and experience of the examiner (AFTE Theory of Identification and Range of Conclusions, apud Cork et al., 2008; Riva; Champod, 2014). Similar to that, when describing the traditional procedure for firearm identification, Bachrach recorded that in “reaching (his/her) conclusions, the firearms examiner relies mostly on his/her training and judgment, making current matching procedures mostly subjective” (Bachrach, 2006, p. 2).

2.2.2 Traditional Ballistic Comparison Limitations

The subjective approach to establish conclusions using traditional ballistic comparison is one of the limitations of this examination, and reasons for its criticism, especially by defence attorneys (Schwartz, 2005; Nichols, 2007). Other practical problems arise in examinations, sometimes precluding an identification or elimination. Some challenges are due to the use of optical devices, including the difficulty in obtaining good image contrast and the dependence on lighting conditions, and others are intrinsic to firearm identification subjectivity, as variability observed in marks within a set of components from the same source, alteration of marks during firearm use, and absence of marks on damage bullets or in the ones fired through high-quality barrels.

The terms employed to describe comparison microscopy and pattern recognition in the context of firearm identification, include “sufficient agreement”, “pattern that in their ‘minds eye’ constitutes an identification”, and “evaluates and weights the similarities and the differences”, demonstrate the subjectiveness involved. As recorded by Cork et al. (2008):

> Ultimately, as firearms identification is currently practiced, an examiner’s assement of the quality and quantity of resulting toolmarks and the decision of what does or does not constitute a match comes down to a subjective determination based on intuition and experience (Cork et al., 2008, p. 55).

The variability observed within samples discharged from the same firearm is one of the main drivers to transform ballistic comparison into a more objective approach. As recorded by Heard:

> Factors such as the hardness of the materials, pressures produced, build-up of fouling and general debris mean that the striations found on fired bullets and cartridge cases will inevitably exhibit variations from shot to shot. It is thus an impossibility for two bullets or cartridge cases fired from the same weapon to have absolute concordance in their stria (Heard, 2008, p. 190-191).

On the other hand, just by chance, bullets and cartridge cases from different firearms will have some accidental agreement in some set of striae or in the shape of some marks (Kopel ; Burnett, 2003; Cork et al., 2008). As stated by Heard:

> Conversely, in bullets and cartridge cases fired from different weapons, there will always, due to the sheer numbers of stria present, be some degree of accidental agreement. There is no dispute that out of the thousands of lines present in any one comparison, a number must, by pure chance alone, show agreement (Heard, 2008, p. 190).

Although the comparison using optical devices is an easy and manageable method, in any microscope the contrast dictates how well shapes can be differentiated from its background and surface topographies (depth) can be perceived. Therefore, correct illumination is essential to achieve optimum contrast (Bell; Morris, 2010). So the two vertical tubes of the comparison microscope need to present the same optics, set of lens, prisms, and mirrors, as equally set up and adjusted as possible. Even in good quality microscopes with two sides well set up, the appearance of the marks can look different depending on the lighting condition (Banno et al., 2004). Intensity and type of light, location, and direction of it, as well as inclination, sample orientation and natural variation in surface topography, are some factors that may alter the way the marks appear for comparison (De Ceuster et al., 2012). Gerules et al. noted that “marks left on bullets or cartridge cases can appear completely different depending on lighting angle, intensity, and color” (Gerules et al., 2013, p. 241).

Another challenge is regarding the change in rifling characteristics brought about through firearm usage. Bonfanti and De Kinder (1999a) reviewed the research on this subject and concluded that wear of the bore replaces original toolmark striae with new ones, the number of shots for this to occur depends on the bullet material composition and the conditions of maintenance of the firearm. Small debris and unburned propellant left in the bore, quality of the barrel production, and bullet material are some of the factors that can influence the natural wear of the barrel bore by bullet acceleration down through it.

Hall (1980) noted that as a product of gunpowder combustion, crystalline deposits are build-up in the barrel, leading to changes within barrels after firing (Hall, 1980, apud Bolton-King, 2012).

This alteration of the marks with firearm use is one of the reasons to regard firearm identification different from the identification of people through fingerprints and DNA examination, which are perennial marks (Kopel; Burnett, 2003).

To minimize the odds that striae alteration could contribute to a wrong conclusion, Jost et al. recommended that the samples for traditional ballistic comparison must fulfil the requirement of contemporaneity, which is, a “test-fire must be collected in the shortest time after the questioned bullet or cartridge case has been produced” (Jost et al., 2014, p. 70).

Another practical issue is that high-quality barrel bore finishing makes it harder to examine the marks, generating few or no marks with individual characteristics for evaluation, requiring more sensitive instrumentation, and often leading to an inconclusive result (Bachrach, 2006, apud Gerules et al., 2013). Particularly, polygonal barrel bores, like the ones produced during the hammering process explained in section 2.1.5, and observed in part of 9x19mm pistols of this study (refer to Table 34), is regarded as a challenge for a conclusive result on this type of examination.

Other limitations responsible from time to time to inconclusive results are damaged bullets, which had their individual and/or class marks obliterated or altered on impact, comparison of components with very different material compositions, or lack of a suspicious firearm to proceed with the comparison (Jost et al., 2014).

Because of that, the ballistic comparison is not a trivial identification process, i.e, it is not only an image comparison. It is necessary to consider many factors during the comparison and to establish some criteria that allow positive identification of two components from the same source. The ideal would be a threshold between observable agreement and disagreement to justify an identification beyond any reasonable doubt.

2.2.3 Line Counting

This qualitative rather than quantitative approach of ballistic comparison is seen by many as difficult to describe or convince the judge or jury (Chu et al., 2013). Therefore, the search for a more objective and quantitative criterion began in the 1950s, with the development of a tool named the striagraph and with a pioneer research conducted by Biasotti (Cork et al., 2008).

The striagraph was a optical-mechanical device designed by John E. David from Oakland Police Department, California, USA, in about 1958, which was based on the same principle of very sensitive and accurate surface analyzers used by many industrial fields. Although very precise and sensitive, and quite complex in construction, it is very simple in operation. A rigid rod, ended in a very light and sensitive stylus with about 4 μm (micrometers) in diameter, is put in contact with the bullet or barrel bore surface. By rotating them the striagraph records the minimal irregularities of the striated surface, especially the peak and valley variations. The objective lens and articulated arms allow amplification of the altimetric accidents of the surface up to 400x. Beyond facilitating the striae comparison, the profile was recorded in photosensitive sheets, having the potential to be a very useful tool to convince the judge or jury (Rabello, 1995). “Though the striagraph never advanced beyond the research stage, it was a precursor to the use of imaging and profilometry techniques for firearms identification” (Cork et al., 2008, p. 62).

In 1959 Biasotti carried out a study comparing the existence of coincident marks between bullets fired from a set of .38SPL Smith and Wesson firearms (Biasotti, 1959, apud Grzybowski et al., 2003).

When cataloguing the striae on each bullet and comparing them to others, Biasotti “noted that same-gun bullets yielded a greater number of corresponding marks than different-gun bullets” (Cork et al., 2008, p. 65). He observed that bullets from the same source can match 36 to 38% of the striae in lead bullets and just 21 to 24% in jacketed bullets. From different-guns, the matches were found between 15 to 20%. However, he observed, that these percentages of matching and no match lines were not so distinct as initially expected. Therefore he cautioned that a simple percentage matching line could be misleading if consecutiveness was not regarded (Cork et al., 2008).

When including consecutiveness in the assessment it was found something more conclusive. In the study, it was not possible to find more than four consecutive matches in 720 (seven hundred and twenty) analyzed known non-match (KNM), establishing the first criterion for identification, the consecutive match striations (CMS) stated as:

> The most significant point of the data collected is the fact that 3 consecutive matching lines for lead bullets and 4 consecutive matching lines for metal-cased bullets appears to be the dividing line between data for same and different guns; and therefore, these critical series form the base line upon which the data for bullets from the same gun can be differentiated from the data for different guns (Biasotti, 1959, apud Grzybowski et al., 2003, p. 18).

When the original CMS criterion was proposed, it lacked solid statistical analysis, relying on empirical and manual experiments (Chu et al., 2013). Trying to expand the study to include more comparisons, more recently, Biasotti and Murdock (1997 and 2002, apud Grzybowski et al., 2003 and apud Cork et al., 2008) expanded the study and established a "conservative quantitative criteria for identification":

> (1) In three-dimensional toolmarks when at least two differente groups of at least three consecutive matching striae appear in the same relative position, or one group of six consecutive matching striae are in agreement in an evidence toolmark compared to a test toolmark.
> (2) In two-dimensional toolmarks when at least two groups of ate least five consecutive matching striae appear in the same relative position, or one group of eight consecutive matching striae are in agreement in an evidence toolmark compared to a test toolmark. For these criteria to apply, however, the possibility of subclass characteristics must be ruled out (Cork et al., 2008, p. 66).

It should be noted that these criteria differentiate between 2D and 3D marks. The 3D marks feature observable depth, while in 2D they are ignorable, like in very thin striae. This was appealing for the implementation of algorithms based on line counting applied to CMS methods (Ibid.). No doubt this is an advance on the pattern matching approach that characterized the discipline in its initial steps, but still can be seen embedded in subjectiveness steps, like the necessity of differentiating between 2D and 3D marks, and by the match or non-match between two relative striae will not always be an obvious decision.

At this regard, Nichols is of the opinion that the CMS approach started a fray at the firearm identification, "pitting the old school tradition of 'pattern matching' versus the new school of 'line-counters'" (Nichols, 2003, p. 299, apud Cork et al., 2008, p. 65). On the contrary, Grzybowski et al. (2003) defended that CMS approach is "(however) (…) not a "different" technique, merely an extension", stating that:

> When one examines a pattern, there are several elements that are part of the process of recognizing that a pattern truly exists. Whether or not the features

> of a striated toolmark are actually quantified or simply compared and deemed to be corresponding, several of these elements are quantifiable. It is enough to state that CMS is not a new technique, nor in conflict with the traditional pattern matching that has characterized the discipline from the earliest of times. It is simply an extension, a manner of describing the pattern that is believed to be more concise, more easily understood, and allows for its use by others (Grzybowski et al., 2003, p. 7).

2.2.4 Uniqueness and Reproducibility

Having pointed out some challenges to firearm identification, that from time to time give reason for criticism in an attempt to diminish its value as forensic evidence, it is important to stress that firearm identification has been demonstrated an accurate discipline by many studies and that it is based on well-established principles of uniqueness and reproducibility of the marks produced by firearms.

Uniqueness is the already mentioned statement (p. 61 and p. 57) that “statistically and empirically, it can be shown that no two weapons will have exactly the same individual rifling characteristics” or that such “are the variables involved, that the chance of two firing pin having exactly the same manufacturing stria is so low as to be negligible” (Heard, 2008, pp. 171 and 174).

To prove that, it would be necessary to compare all the existing firearms, which is obviously impossible, or alternatively to find just two firearms that present the same individual characteristic marks. Despite that, to demonstrate the validity of this principle, many studies have been conducted assessing marks of different firearms. Extensive “research has been conducted and published by forensic firearm and toolmark examiners during the past 100+ years to support this theory (Hamby et al., 2009).

Particularly challenging for firearm identification is to compare firearms that are consecutively manufactured. The action of the same tool, sequentially applied upon firearms pieces, may, in theory, produce similar marks, or features subclass marks, which are coincident marks in a particular group of firearms, generally because of some change on the tool surface, this way making the identification process more difficult. The consecutively manufactured is not an easy characteristic to include in research because of the factory line production process of different parts, with the firearm parts being assembled at the end line, with no regard for the sequence of production. One alternative has been to conduct research with some sequentially manufactured firearm parts, that were taken out from its line of production, like barrels or slides. Another challenge for these studies is the frequently small number of firearms and parts available for comparison. Aware of these two limitations, it should be point out that had been carried out many studies, and the unanimous conclusive results of these empirical tests continue to support the uniqueness of the marks, always resulting in high degree of hit in the comparisons (refer to Cork et al., 2008, pp. 70-72).

A very interesting instance of these studies, which shows the accuracy of this examination, indirectly proving the uniqueness of the mark, was carried out in ten years and involved the participation of 507 (five hundred and seven) firearm identification experts. For the study 10 (ten) new consecutively rifled pistol barrels were used, removed in sequence from the assembly line of a manufacturer. The barrels were assembled to the same pistol and test-fired and questioned bullets were collected from each barrel, encoded, packed and sent to ballistics laboratories in 20 (twenty) Countries, being asked to compare the questioned against the test-fires in order to identify which barrel each questioned component came from. Of the 7,605 ballistic comparisons performed, there were 5 (five) inconclusive results, 3 (three) bullets were considered in a laboratory to be "in no condition for confrontation" and in the remaining 7,597 exams, there was a correct combination between questioned bullets and test-fires. No false positive was reported. This would not be possible if these 10 (ten) sequentially manufacture firearm barrels did not feature uniqueness in their individual characteristics marks. The authors concluded:

> This study shows that there are identifiable features on the surfaces of bullets that can link them to the barrel that fired them. Although one would expect bullets fired from consecutively rifled barrels to display subclass characteristics, the issue of subclass characteristics was not an issue for the 502 individuals who participated in this research project. **Based on the results of this research, having fired bullets in good condition and properly trained firearm and toolmark examiners, the identification process has an extremely low estimated error rate**. (Hamby et al., 2009, p. 107, emphasis added).

Another important principle, that was indirectly demonstrated valid on this last mentioned research, is the reproducibility of the marks. Not only the marks need to have uniqueness, but this would be useless if these marks would change from shot to shot or would not be consistently impressed on the fired ammunition components.

Bonfati and De Kinder (1999b) review the literature related to firearm wear on the marks left for identification and concluded that:

> no substantial change in characteristics left by the breech face of the weapon can be discerned' over repeated firings; firing pin impression and extractor marks are subject to 'slight variations,' while 'in one study the ejector marks were seen to vary more strongly'. Bullets, by comparison, showed more dramatic effects due to wear. 'Changes consist of disappearing fine and coarse striation lines,' with the fine

> striations being more variable over time than the coarser. (Bonfanti and De Kinder, 1999b, pp. 319, 312; apud Cork et al., 2008, p. 73).

Cork et al. (2008) cite others studies on the subject that demonstrated that changes of the marks due firearm wear is undeniable, the degree of changes depend on the type of mark, firearm, and bullet, but identification is still possible even after many shots, sometimes after thousands of them. Corroborating this conclusion, a comparison of cartridge cases discharged from five Turkish pistols, fired from 1000 to 5000 times, the first fired cartridge case being compared to consecutive 250th fired ones, concluded that the capacity of the practitioners to match the cartridge cases were not affected by some changes in the individual characteristics observed between the first and the subsequent cartridge cases fired in each pistol (Saribey et al., 2009).

2.2.5 Ballistic Identification Systems

Although the underpinning of firearm identification has not changed significantly over the last century, improvements in the technology and understanding of the factors influencing it, and specially leverage by computer science transformation globally, allowed the next great leap in this field of Forensic Science; the development of Ballistic Identification Systems.

Early discussions on the computerization of firearm identification appear in the records of the nineteenth annual training seminar of AFTE, in 1988. Keith L. Monson, presented an abstract entitled “Computer Correlation of Cartridge Cases Using Breech Face Marks”. The goal of the research was “to develop a computer-based system to objectively and quantitatively express the degree of similarity of any two fired cartridge cases” (Monson, 1988, p. 1). It was suggested, that after image acquisition of two fired ammunition components, the employment of a modified cross-correlation algorithm to compare the overlapped images, generating a numerical value that represents the similarity. Rotation and translation of the two images in search of the maximum numerical value of the cross-correlation function allowed ranking them by similarity. Three decades later, all the implemented and well-established computer-based ballistic identification systems, including the three assessed in this research, employ the concepts discussed in that pioneering abstract, namely; image acquisition (refer to 2.2.6), extraction of ballistic signature, allowing the use of customized algorithms for numerical comparison (refer to 2.2.7), and ranking by similarities (refer to 2.2.8).

Just one year after that abstract, the need for computer assistance for firearm identification was felt by the examiners in the Washington D.C, USA region. The intensification of anti-drug policies overwhelmed the forensic laboratories in the area with a large amount of firearms and fired ammunition for examination. The goal was to relate the new incoming cases to previous ones examined. Initially, large bullet and cartridge case photographs were used, which eventually converged to the adoption of image digitalization and computer-assisted comparisons. At that time, the Federal Bureau of Investigation (FBI) decided to sponsor studies on the digitization of images by initiating the Drugfire system. Although probably the first ballistic identification system, which eventually was replaced by IBIS® technology, Drugfire developed quickly to became capable of imaging the sample, extracting the ballistic signature, automatically correlating the samples, operating within a network between laboratories, and providing a rank of similarities for expert evaluation (Hamby; Thorpe, 1999; Heard, 2008).

At about the same time, more precisely in 1992, ATF (Bureau of Alcohol, Tobacco, Firearms and Explosives) started to use the Integrated Ballistics Identification System (IBIS®), another equipment for imaging the fired ammunition components and computer-assisted automated correlation. In time, IBIS® was adopted as the standard technology for ballistic identification system in the USA, becoming the platform for the National Integrated Ballistics Identification Network (NIBIN), a USA nation-wide network that makes it possible for comparisons of fired ammunition components processed and digitalized in different laboratories (Hamby; Thorpe, 1999).

The limitations of the ballistic comparison optical exam, and the time-consuming process for comparing many ammunition elements, contributed to the design and implementation of many ballistic identification systems around the world, such as Arsenal® Papillon, Condor, and Evofinder® in Russia, Balistika in Turkey, Cible in France, Fireball in Australia, and Lepus in Brazil (Heard, 2008; Santos, 2015), or more recently, Alias[11] in United Kingdom, BalScan[12] in Czech Republic, and Cadre[13] in USA.

Many of these systems have been incorporated into the routines of ballistic laboratories around the world, like the worldwide distributed Arsenal®, Evofinder®, and IBIS® (refer to 4.2 for a description of distribution and operation of these systems).

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[11] http://pyramidaltechnologies.com/services-1/ [Accessed 01/03/2020].
[12] https://www.forensic.cz/en/products/balscan [Accessed 01/03/2020].
[13] https://www.cadreforensics.com/ [Accessed 01/03/2020].

Figure 24 – From left to right, photographs of the a) Arsenal®, b) Evofinder®, and c) IBIS® scanners.

In Brazil, the IBIS® system is used by the Bahia Department of Technical Scientific Police, while the Evofinder® system by the Federal District Civil Police, Goiás Technical Police and Minas Gerais Civil Police. The Federal Police, in its National Forensic Institute in Brasilia, uses Evofinder® for the management of criminal cases, and also had developed some assessment on units of Arsenal® and Lepus (Santos, 2015) (refer to Figure 24).

The performance of these systems may be very different from each other, as each one employs different technologies for image acquisition (refer to 2.2.6), and proprietary correlation algorithms that directly impacts on the effectiveness of the solution in ranking true matches (refer to 2.2.7).

Among the challenges for these technologies to work properly, there is the necessity of image acquisition and topography extraction from bullets with approximate cylindrical and sometimes arbitrary shape, requiring specialized surface tracking and controlling motors. (Roberge et al., 2019).

De Ceuster et al. (2012) recognized that ballistic systems are an improvement in the possibility of linking specimens, but similar to the traditional microscopic method, there are some limitations that contribute to a match not being found on automated correlations. The size of the database can be a factor of influence, as the “bigger the database, the more ‘noise’ is added” (De Ceuster et al., 2012, p. 238), the nature of the samples can add challenges for the comparison. For example, the difference in hardness, or the presence of cover layers, such as lacquer on the primer, can affect the transfer of the marks, as well as firearm use, which can wear out its surface, altering the marks (De Ceuster et al., 2012, apud Gerard et al., 2017). They concluded that “(the) combination of these factors together with the capabilities of the correlation algorithms will reflect the true efficiency of an automated system" (De Ceuster et al., 2012, p. 238).

These limitations can be more significant when considering a ballistic database implemented to register new firearms as they come out from the factory, rather than firearms seized from criminals. The concerns include the possibility of very similar marks on new firearms produced by the very same tool, the alteration in the ballistic signature in worn barrels, meaning that first test-fires may not match those fired later, parts replacement, differences in ammunition, reloaded ammunition, and ways to intentionally alter ballistic (Kopel; Burnett, 2003).

2.2.6 Metrology techniques and 3D Imaging

The introduction of 3D surface topography measurement was introduced to solve some limitations of digital imaging systems, but it is necessary that the imaging process of cartridge case heads and bullet surfaces is accurate, reproducible and reliable (Xie et.al, 2009).

The first challenge to accurately characterise the lateral striae of real fired bullets is the curved shape (form) of bullets, which imposes a challenge for image acquisition and for stria observation. Another issue is because bullets may have been deformed in unexpected ways, systems featuring automated Z-stacking acquisition functionalities are required toallow acquisition of well focus images, even for striae laying in different focal planes. (Cominato et.al, 2015). The same functionality is indispensable for acquiring complete firing pin images in focus.

Because of that, and aiming for an "accurate characterization of micrometric and submicrometric features (…), fundamental for assigning the ammunitions to specific firearms" (Valle et al., 2012, p. 289), an indispensable requirement for any ballistic identification system is the capability of to acquire good quality bullet and cartridge case images.

The starting point when selecting a technology to apply for topography measurements, especially in connection to firearm identification, is the sensitivity to minute differences in surface height (vertical resolution) and the capability to differentiate superficial marks (lateral resolution) (De Groot, 2017), therefore magnification and resolution (or resolving power) are important aspects of these technologies.

Magnification

One important part of any optical measurement tool is the objective lens, designed to collect the light reflected by the object surface and sometimes to focus the light from the source on the sample (Leach, 2011). Although the modern lens is an arrangement of several optical elements, Figure 25 depicts the objective lens operation for the formation of real inverted images and is useful for the introduction of some important definitions.

The focal length (f) of the lens determines where the rays coming from an object at a distance, O_d, from the lens, will converge, forming an image at a plane at a distance, I_d, from the lens. The magnification of the lens system (M) is given by:

$$M = \frac{O_d}{I_d}. \quad (2.9)$$

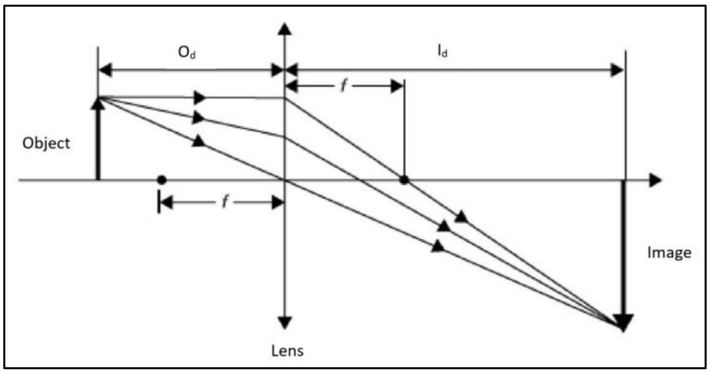


Figure 25 – Image and object related to a simple lens.

The relationship between f and the distances O_d and I_d is given by:

$$\frac{1}{f} = \frac{1}{O_d} + \frac{1}{I_d}. \quad (2.10)$$

In compound microscopes, such as the comparison microscope used for ballistic comparison (refer to 2.2.1), the final magnification is given by the product of the magnifications of the objective lens and of the eyepieces. In systems with an absence of eyepieces, this product is calculated including the magnification of the lens that focuses the image onto a detector (Leach, 2011).

In the context of the image acquisition of ammunition elements, Bolton-King et al. (2010) observed the necessity of imaging steep slopes of the samples, such as the transition areas from LEA to GEA and the internal sides of firing pin impressions. The largest slope angle of a surface that can be imaged is determined by the angular (or numerical) aperture (A_N) of an objective, given by:

$$A_N = n_i . \sin \alpha. \qquad 2.11$$

Here n_i is the refractive index of the medium between the surface and the objective and α is the acceptance angle of the aperture, meaning that this angle will determine the largest slope on the surface that may have reflected light captured by the objective lens, as depicted on the idealized cone of reflection observed at Figure 26 (Ibid.).

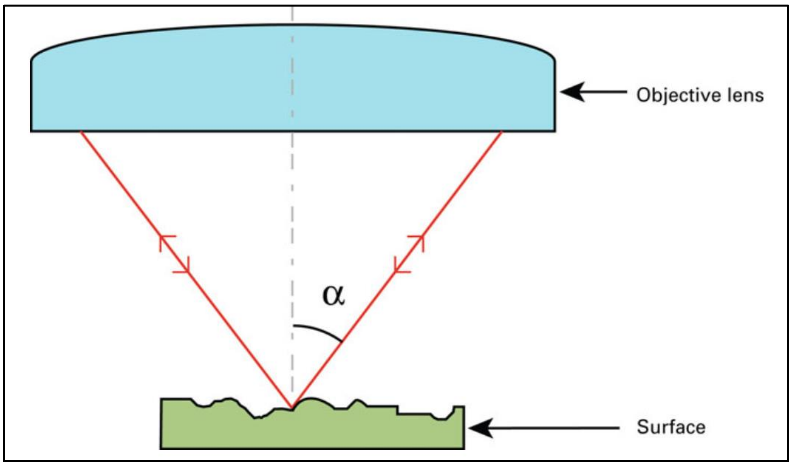


Figure 26 – Cone of reflection determining the angular aperture (A_N) of a microscope objective lens (Source: Leach, 2011, p. 19).

Another relevance of the angular aperture is its influence on the ability of the microscope to capture light after it is reflected by small parts of the illuminated specimen. The larger the cone of light captured by the microscope, the smaller the features in the specimen that can be resolved. The cone is dependant on the diameter of the front lens of the objective and the distance of the specimen from the lens (Bell; Morris, 2010).

Working distance, between the sample and objective front lens, does not only influence the microscope's ability to resolve fine details but also it is an important requirement to prevent accidental collision of samples and objective lens and to allow imaging deep firing pin impressions (Bolton-King, 2010). Other important aspects of the operation of optical measurement tools are optical spot size, the field of view, depth of field, and depth of focus (Leach, 2011).

Resolution

It was aforementioned the importance of the angular aperture of the objective lens in an optical system and its influence on the optical resolution, which is "the ability of the system to differentiate small particles or structures" (Bell; Morris, 2010, p. 20). The resolution can be also defined as "the smallest distance between two points on a sample that can still be distinguished as two separate entities" (Wheeler; Wilson, 2008, p. 16).

It is common to separate this ability in terms of a plan and a perpendicular direction to it. The former is the lateral or spatial resolution, which "determines the minimum distance between two lateral features on a surface that can be distinguished" (Leach, 2011, p. 19), and the latter is the vertical resolution, although a questioned term, it is referred to the smallest surface height that the system can detect, measured in a normal direction to the surface where the lateral resolution was defined (De Groot, 2017).

The resolution can have two limitations in any optical system; one is physical and other technological. When the light passes through the circular aperture of an objective lens, it suffers diffraction, characterized by constructive and destructive interferences of the subsequent wave-fronts leading to the formation of a bright center region, the Airy disk, followed by a series of concentric rings, the Airy pattern (refer to Figure 27).

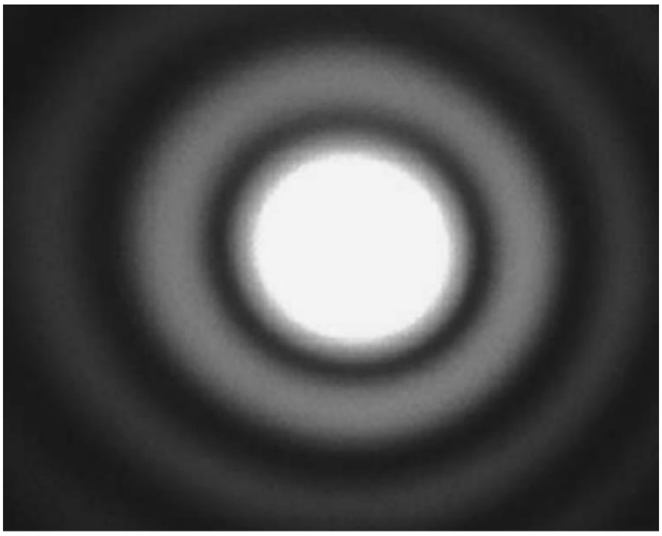


Figure 27 – Image of an Airy disk and Airy pattern (Source: Bell; Morris, 2010, p. 20).

Given radiation with wavelength, λ, the diameter of the Airy disk (D_A) is approximately calculated by equation 2.12 (Bell; Morris, 2010):

$$D_A = \frac{1.22\,\lambda}{A_N}. \quad 2.12$$

If the Airy Disks of two parts of the sample are not sufficiently separated it is said that they cannot be resolved. A criterion to define a limit for the resolution (r) is, therefore, obtained assuming that two parts can be resolved when the center of the Airy Disk of one part falls in the minimum between the Airy disk and the first subsequent ring (Rayleigh Criterion), given by equation 2.13 (Ibid.):

$$r = \frac{0.61\,\lambda}{A_N}. \quad 2.13$$

Equation 2.13 shows that the resolution (r) is limited by the ratio λ / A_N , i.e., for the same radiation, the larger the aperture of the objective lens the finer the details of the sample that can be resolved. It is important to note that this is a minimum value for the resolution, dictated by physical parameters, and in actual equipment, other factors, such as optical imperfections, which can result in chromatic, spherical or comatic aberrations, or when part of the light is not captured due to reflection on steep edges, may deteriorate the final resolution (Leach, 2011).

The other limitation for the resolution of any optical system is related to the pixel size of the sensor utilized to record the image. If the space between pixels is larger than the minimum resolution (r) it is this feature that will determine the resolution (Ibid.).

Importance of magnification and resolution to ballistic identification systems

Bolton-King et al. (2010), while studying different 3D scientific principles applied to firearm identification, defined some preferable criteria to be met in order to determine if the technology is suitable for this pupose, including desirable resolutions:

> The criteria included the capability to obtain lateral and vertical resolutions of at least 1 µm and 0.1 µm respectively with good lateral resolutions at low power magnification, have acceptable working distances, acquire data within a reasonable period of time and have the potential to image steep sample slopes (Bolton-King et al., 2012, p. 30).

Regarding the lateral resolution, they also noted that "'excessive' lateral resolution could lead to the inclusion of highly variable, potentially misleading striae in the comparison, such as obtained when imaging in 2D with objectives higher than 80x" (Ibid., p. 29). Another problem related to resolution is the size of the generated data file, as the inclusion of too much dispensable information can result in too big of a file for storage, affecting database performance and capacity.

The vertical resolution is also very important as it delimits the minimal depth characteristics that the equipment is able to assess. Regarding that, Bachrach (2006) conducted an evaluation of the barrel interior surface finishings, selected from some firearm manufacturers, measuring the value and repeatability of the roughness on LEA of bullets fired through them.

The empirical procedures included obtaining, for each pair of bullets correlated, a *similarity measure* to each LEA-to-LEA compared. Averaging the *similarity measures* allowed them to compute an *orientation similarity measure*. For instance, when comparing two bullets, each with six LEA, there are six *orientation similarity measures,* corresponding to each possible orientation for comparison, starting with set 1 (LEA1 x LEA1, LEA2 x LEA2, …, LEA6 X LEA6), set 2 (LEA1 x LEA2, LEA2 x LEA3, .., LEA6 x LEA1), up to set 6 (LEA1 X LEA6, …, LEA6 x LEA5). For bullets originating from the same firearm, the sets of best and second-best *orientation similarity measures* by barrel brand were used to obtain two distributions. The best *orientation similarity measure* was assumed to be the relative orientation at which the two bullets were aligned, and it was used to draw the 'matching distribution', while the second-best *orientation similarity measure* was assumed as a good approximation of the 'non-matching distribution' regarding each barrel brand.

Figure 28 shows an idealized instance of these two distributions, the green line depicting a threshold selected to minimize the false-positive and of false-negative probabilities of error. One of the statistical approaches to evaluate the statistical difference between sets of data was the empirical probability of error (Pe), which was established as the distance between the two distributions, this value is "inversely proportional to the empirically computed probability of error" (Bachrach, 2006, p. 16). This was one of the statistical approaches used in that research to test the "effect of a variety of factors such as barrel manufacturing quality, bullet brand, barrel wear, number of control bullets" (Ibid., p. 2) on accurate bullet-to-firearm identification.

For the two types of ammunition used in the study, Figure 29 depicts the empirical Pe of classification as a function of the median RMS (Root Mean Squared) surface roughness of the bullets fired through each barrel brand.

One of the apparent and important conclusions was that "the barrel manufacturer is the most dominant factor in both the individuality and classification performance of the bullets fired by it" (Ibid., p. 6). While Ruger, Beretta, and Smith & Wesson "could be identified with very low probability of error", Taurus and Browning "could be identified, but with somewhat larger probabilities of error", finally for Hi-Point, Bryco or SIG Sauer, "the ability of the system to identify bullets fired (…) was very limited" (Ibid.).

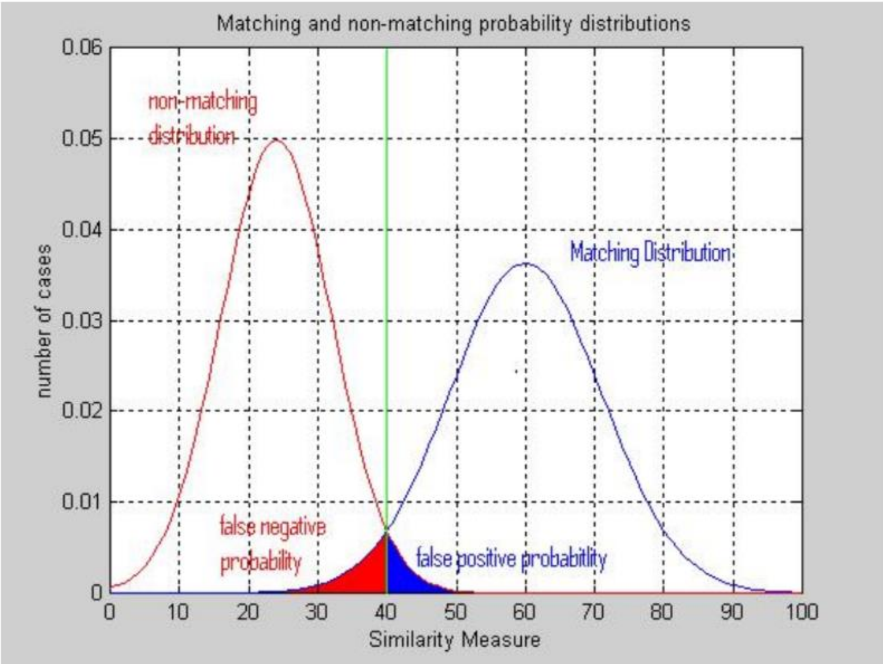


Figure 28 – Empirical Estimation of Probability of Orientation Error (Source: Bachrach, 2006, p. 17).

Although Ruger features a more significant roughness, its associated empirical probability of error was lower than for Hi-Point, which with low roughness, presented a much higher empirical probability of error. The reason for this difference is that it was observed that Ruger barrels show very high repeatability in the roughness, while Hi-Point barrels, despite featuring fired bullets with an intermediate roughness surface, present impressions "hardly repeatable from bullet to bullet" (Ibid. p. 38).

Another factor of influence observed on the results of that research was the type of ammunition. With SIG Sauer barrels being the only exception, all other barrel brands, fired with Winchester ammunition, features lower empirical probability of error than with Remington ammunition, this being consequence of the dimensional tolerances and consistency on ammunition manufacture processes. As similarly noted for barrels, these features "will have a significant effect in the manner in which features are transferred between the barrel and the bullet" (Ibid. p. 40).

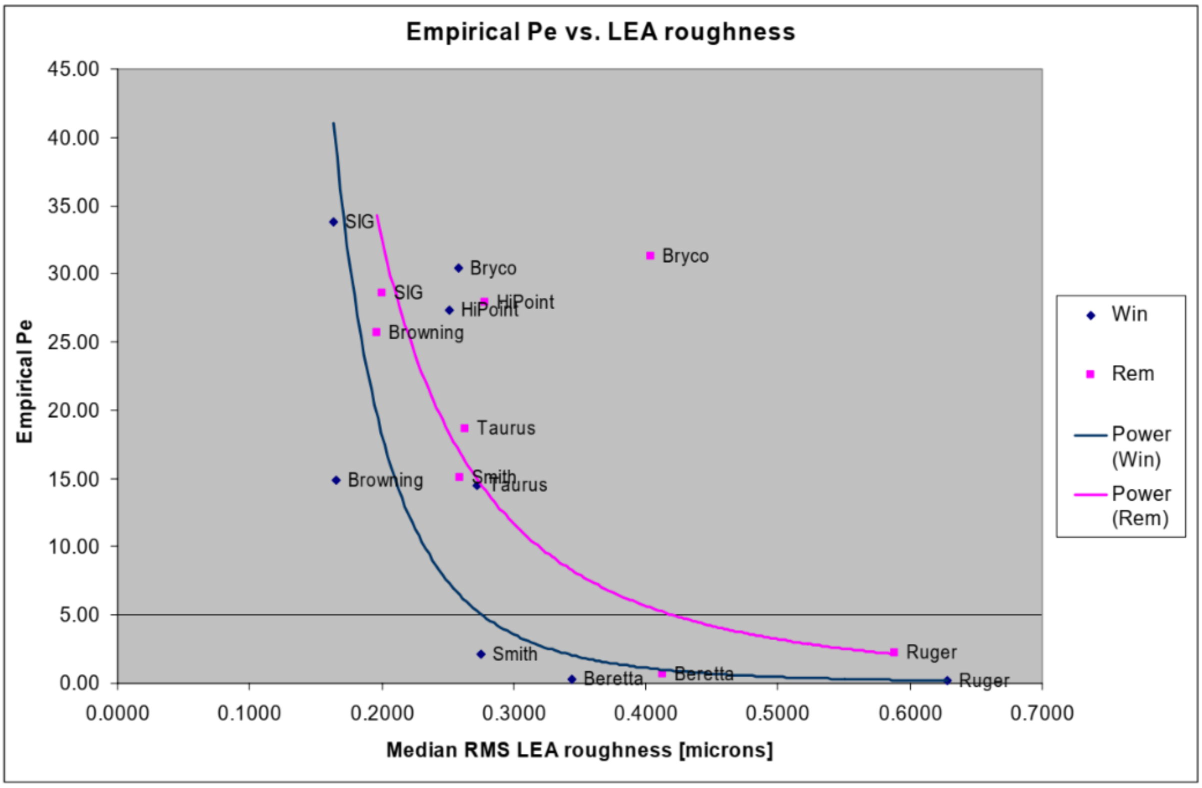


Figure 29 – Relationship between Empirical Probability of Error (Pe) and LEA roughness by Winchester (Win) and Remington (Rem) ammnunition and firearm brand (Source: Bachrach, 2006, p. 39).

The SIG Sauer barrel exception is worthy of further consideration. The land impression cross-section acquired from bullets fired from these barrels showed a very smooth land impression, featuring, with Winchester ammunition, the lowest RMS surface roughness obtained on the experiment, below 0.2 µm (micrometer). The reason for this specific barrel/model/ammunition, that assembled the best qualities for the research, to present the highest probability of error was explained by the researcher due to the questionable capability of the instrumentation to detect features found on that level of roughness:

> Although the specification of the sensor used in this project claims a depth resolution of 0.025 micron, it would seem that the actual resolution of the acquisition platform is on the order of 0.3 – 0.4 microns. This loss of resolution may be due to vibration induced by the motion components during the acquisition process (Ibid. p. 39).

In fact, still analyzing Figure 29, when the roughness is below 0.3 microns there is a very sharp increase in the probability of error, reinforcing the conclusion that the resolution is a very important factor for correct identification.

Banno et al. (2004) presented an algorithm for 3D comparison of fired bullets. The study, carried out using a confocal microscope with 0.02 µm vertical resolution was effective in correctly aligning many overlapping images. If the distance between two regions of the samples were less than a threshold the area was displayed as a dark gray region, otherwise the area was colored light gray. As many comparisons showed extended dark gray regions, they concluded “that determining the threshold as 0.015 mm made clear visualization about matching regions”.

But is this high resolution, 0.02 µm, really necessary in the context of firearm identification? Roberge et al. (2019) (further discussed in section 2.2.7) defend that a lateral resolution of 3.125 µm per pixel provides sufficient information for their proposed objective method of identification.

The image magnification capability of the equipment is another important aspect to consider, as this will allow an expert to check the list of results in searching for hits. This feature is limited not only by the image resolution, but by the software tools, and the dimensions and definition of the screen where images are compared.

For instance, a 27” screen, aspect ratio 16:9, with 2560x1440 pixels, features 598mm in width and therefore square pixels with 0.23x0.23mm lateral dimensions. In that case, an image with 3µm lateral resolution can be magnified, if the software tool is prepared for it, up to 76x (seventy-six times) without pixelation, which is observed whether the image is such a large size that the individual pixels are visible.

Bolton-King et al. (2010) and Vorburger et al. (2016) noted that there are many 3D technologies available to be applied for surface topography acquisitions, boosting the field of firearm identification with competing optical methods, each feature benefits and limitations when applied to the digitalization of ballistic samples.

The technologies that have been reviewed and applied to topographic data acquisition from ballistic samples include Coherence Scanning Interferometry, Confocal Microscopy, Focus Variation, Photometric stereo, Point Laser Profilometers, and Vertical Scanning Interferometer (Bolton-King et al., 2010; Vorburger et al., 2016). Considering the principles utilized to some degree by the ballistic identification systems assessed in this thesis, three of these technologies will be briefly described.

Confocal microscopy

Confocal microscopy, originally described in 1957 by M. Minsky, features a depth discrimination effect by using illumination and detection pinholes. A classical setup of a confocal microscope can be seen in Figure 30 (ASME B46.1-2009, 2010).

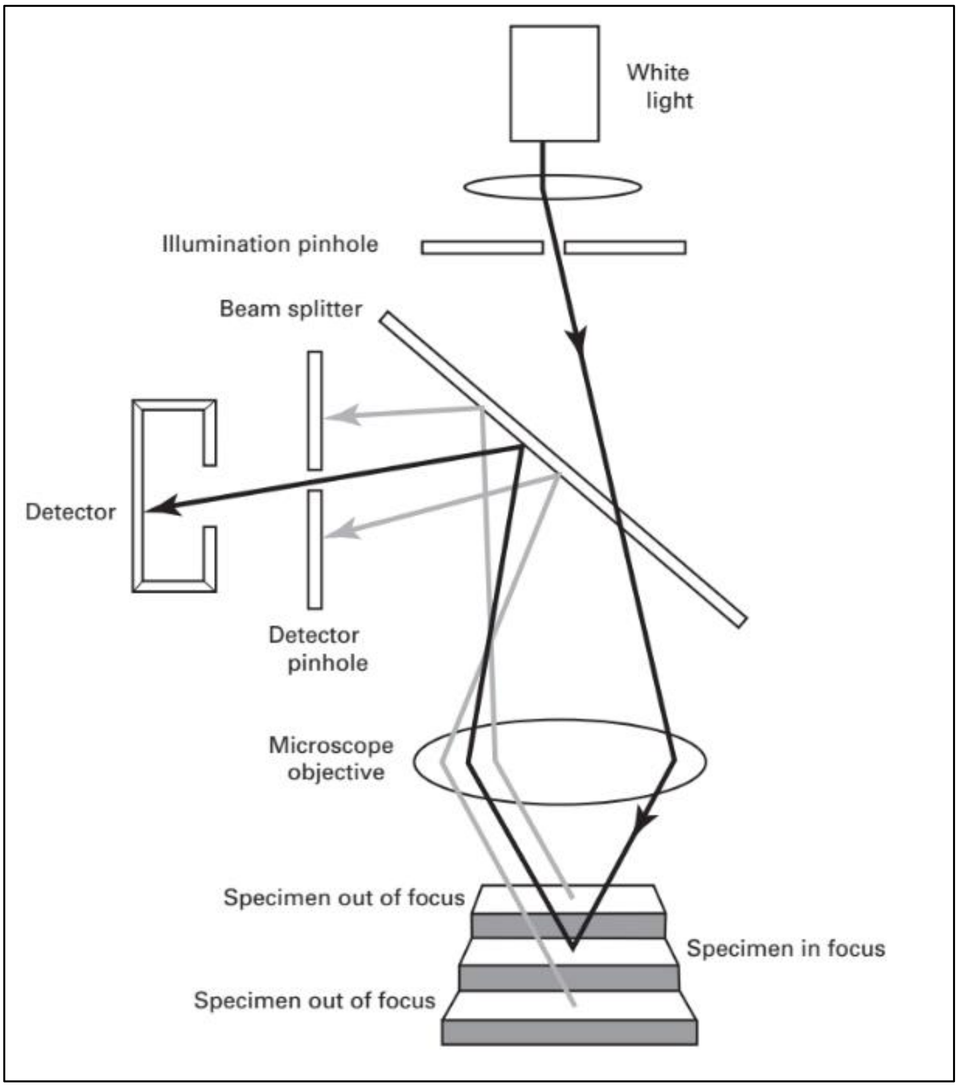


Figure 30 – Schematic Diagram of a Confocal Microscope (Source: ASME B46.1-2009, 2010, p. 92).

The optical path between the light source and the specimen surface is the same length as the path between the specimen and the photo-detector (Figure 30). The incident light passes through the pinhole illumination, beam splitter, and objective lens, being focused near the specimen surface. Light, after being reflected by the specimen surface, is decoupled by the beam splitter and passes through the pinhole detection. Controlling the translation of the distance between the specimen and the objective (z-distance), the intensity of the photodetector signal is affected, as depicted in Figure 31. The intensity of the signal reaches a maximum when the illuminated part of the surface is at the focus point of the objective. If the illuminated part of the specimen is out of focus the reflected light does not pass through the pinhole detector, suppressing the signal on the detector. A correlation between the vertical position of each scanned part and the reflected light intensity at the detector is established. Therefore the vertical scanning of the specimen enables the tool to detect the topography and surface height variations. The vertical and the lateral resolution will improve with the numerical aperture of the microscope, that in turn is dependant on the diameter of the employed front lens and the working distance, reaching up to few nanometers for vertical resolution and in the order of micrometers or less for lateral resolution (ASME B46.1-2009, 2010; Blateyron, 2011; Vorburger et al., 2016).

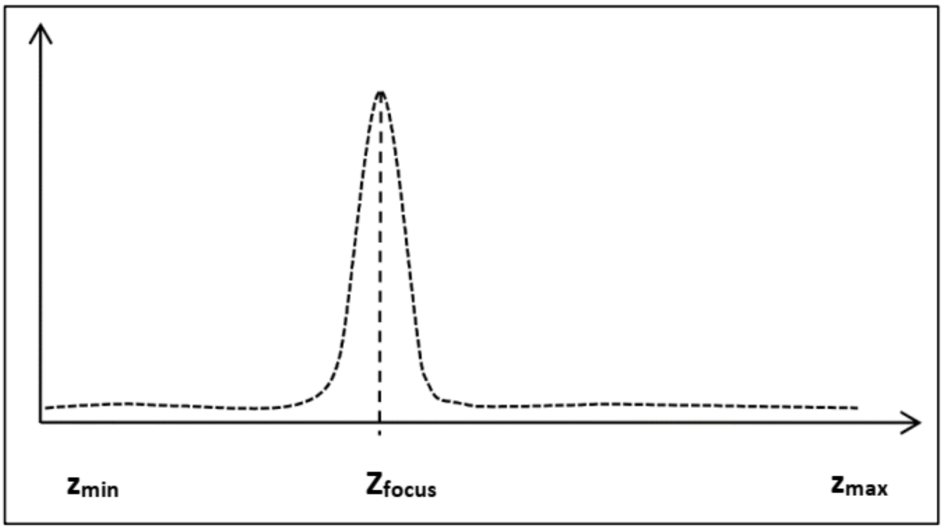


Figure 31 – Intensity curve (vertical axe) registered by the detector during the vertical scan (z-distance) (Source: Blateyron, 2011, p. 73).

Bolton-King et al. (2010) noted that confocal microscopes “can have a high data acquisition speed, with excellent vertical resolution and/or excellent lateral resolution” (p. 29). However, they also observed that although this method is being successfully applied to ballistics imaging within the FTI IBIS® Trax 3D, steep slopes, like the ones found on the LEA to GEA transition areas or in some surface striations, led to gaps on the acquired data, revealing a considerable limitation.

Focus Variation

Although focus variation application to surface texture probing is relatively new, its principle was developed in the mid-1920 by H. von Helmholtz. This technique is capable of measuring roughness and form at the same time by using vertical scanning and optics with limited depths of field, as can be seen in a typical focus variation instrument depicted in Figure 32 (Helmli, 2011; Kapłonek et al., 2016).

Similar to the confocal microscopy technique, focus variation relies on vertically scanning the sample, but its conceptually simpler. It takes advantage of precise optics with small depth of field, and different objective lenses, which means only small parts of the specimen are sharply imaged and measured with different resolutions (Danzl et al., 2011; Vorburger et al., 2016). Figure 32 depicts a typical measurement device based on the focus variation method.

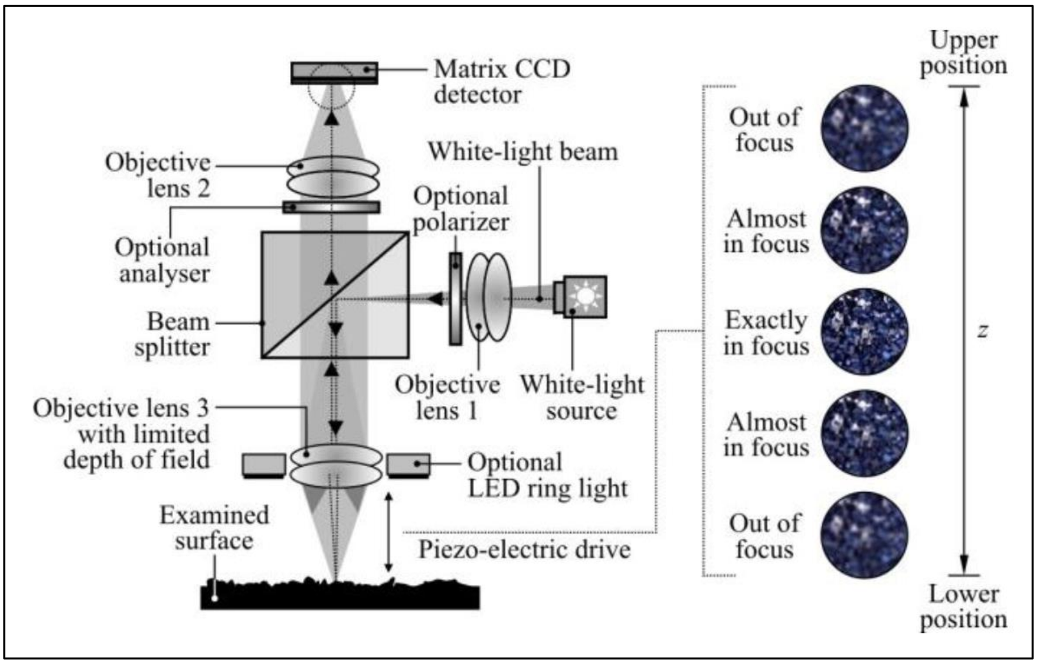


Figure 32 – Schematic Diagram of a typical Focus Varation Instrument (Source: Kapłonek et al., 2016, p. 43).

In this method the beam of light is directed from the source by the objective lens and beam splitter, being projected on a small area of the sample. Due to sample reflectivity properties and the texture within the topography, only part of the reflected light is redirected to the optics of the equipment and recorded on the charged-coupled device (CCD) sensor. The height discrimination of the method is achieved by vertically scanning the surface in relation to the objective lens, locating the best in-focus position of each pixel. One method to measure the focus is to calculate a standard deviation of the grey values of a set of pixels surrounding any one considered (Figure 33).

The relation between the focus measure and the z-distance between the sample and the objective lens generates a curve similar to the intensity curve of the confocal method, though the focus curve width is larger than the intensity curve (Figure 34). The sharpest position is determined by the maximum of the curve, or the highest standard deviation of grey values, meaning that the contrast between the pixel considered and its neighborhood is maximum. Otherwise, a smaller standard deviation of the grey values means low contrast and therefore the image is out of focus. The relationship between the maximum in the focus curve measured and the z-distance of the sample, for each lateral position of the sensor, allows a final 3D image to be generated. The formed image records information of geometric (width, length) and photometric (color, contrast, brightness) features (Helmli, 2011; Kapłonek et al., 2016; Vorburger et al., 2016).

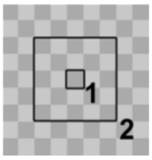
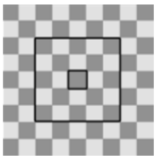
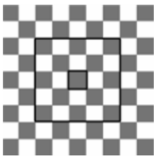
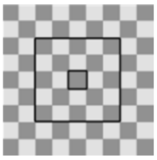
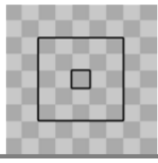
Scan position	Surface image	Standard deviation
Out of focus		10
Almost in focus		20
In focus		50
Almost in focus		20
Out of focus		10

Figure 33 – Standand desviations (focus information) of the grey levels considering a 5x5 pixels neighbourhood area (2) of a pixel (1). (Source: Helmli, 2011, p. 134).

As mentioned, to calculate the focus a contrast is necessary in this method, therefore difficulties arise when there is no material reflectance contrast on the sample, requiring a minimal topography variation so the focus can be found. “To conclude, focus variation technology can be used for form and roughness measurement so long as the samples are not too smooth” (Helmli, 2011, p. 166).

The necessity to consider the response from neighboring pixels compromises vertical and the lateral resolution, resulting in focus variation resolution being more limited than the resolution of other methods, such as confocal microscopy, because “a question arises requiring further research as to whether the straightforward method of focus variation has sufficient resolution for distinguishing the individualized surface characteristics of fired bullets and cartridge cases" (Vorburger et al., 2016, p. 6). Despite this, ScannBI Technology informs on its official webpage that its Evofinder®[14] 3D technology is "based on Focus variation microscopy (…) added by some innovative technologies", resulting in well-recognized quality within its digital images.

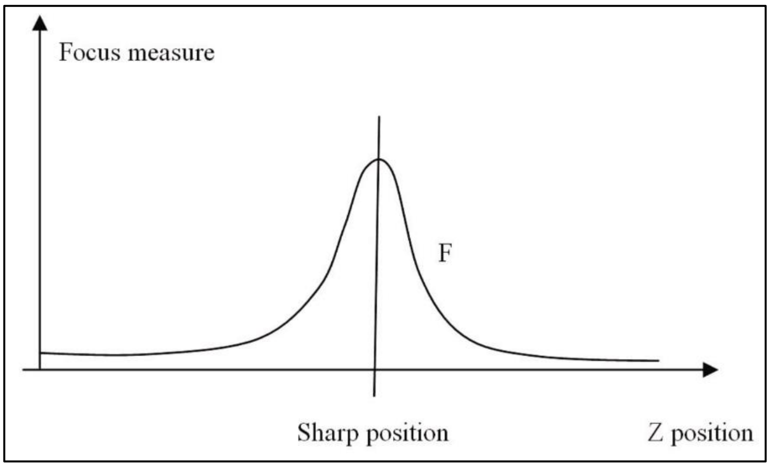


Figure 34 – Focus measure (standand desviation of the grey levels) as the sample is vertically scanned (Z position). (Source: Helmli, 2011, p. 135).

While reviewing focus variation, Bolton-King (2012) also observed at least three advantages of this method applied to ballistic imaging:

- the potential to image steep slopes, facilitating imaging of damaged specimens, of LEA to GEA transition areas, and of firing pin marks;
- higher working distances, without compromising on the required resolution for this kind of application, which is important to prevent a sample's surface hitting the objective lens; and
- lower cost when compared to other technologies.

Photometric stereo

Photometric stereo is a technique, originally introduced by Woodham in 1978, that differs from confocal and focus variation mainly because it keeps the position of the sample constant relative to the optics of the system while varying the direction of the illumination (Woodham, 1978) (refer to Figure 35). Because "it uses the (radiance) intensity values

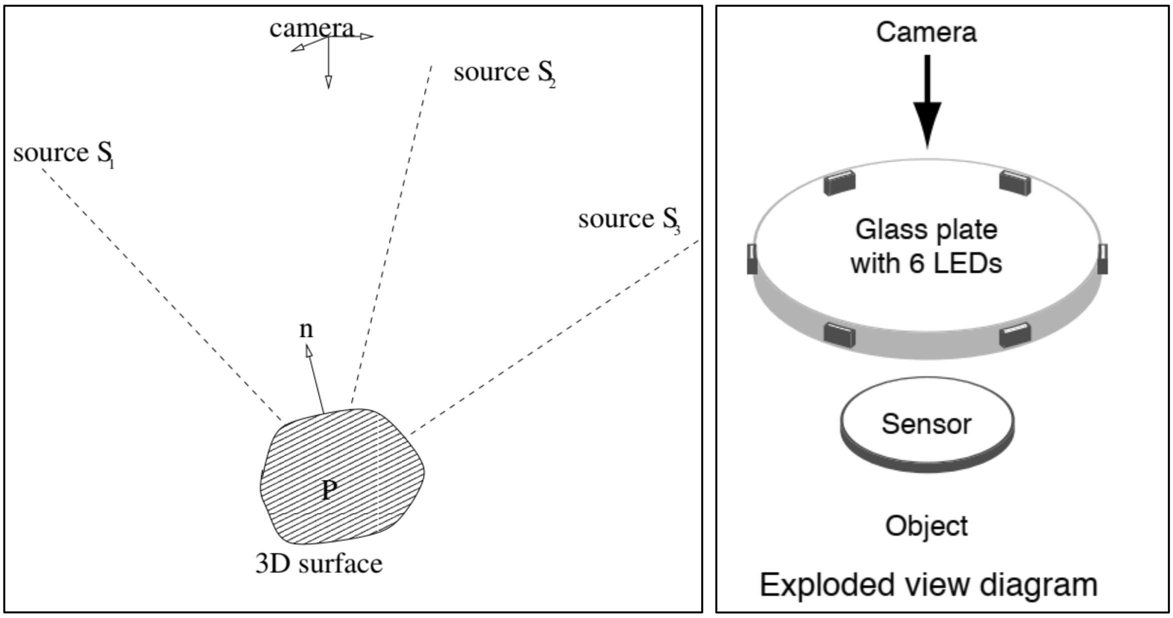
[14] http://evofinder.com/technology/2dd/ [Acessed 2/5/2020].

recorded at a single picture element, in successive views” it is named *photometric* (Ibid., p. 136). Sometimes is also called *shape from shading* as “involves the decoding of shadow patterns on surfaces cast by multiple light sources to produce a surface topography measurement” (Vorburger et al., 2016, p. 7).

Ying Wu (2020) well postulated the problem tackled by photometric stereo as:

> The problem of photometric stereo is quite interesting: if we are given a set of images of the same scene taken under different given lighting sources (the camera and the scene are kept intact), can we recover the 3D (shape) of the scene? (Wu, 2020, p. 8)

The answer to this question is yes, but it is crucial to take into account the importance of surface topography and shape to measure its radiance, as “values depend on properties of radiating sources (i.e., irradiance values on the surface), surface characteristics (i.e., surface reflectance, surface orientation, surface roughness, etc.) and the geometry of the two” (Sakarya et al., 2008, p. 210).



a) **b)**

Figure 35 – a) Principle of photometric stereo setting (Source: Wu, 2020, p. 8), and b) exploded view diagram of lighting configuration appling photometric stereo principle (Source: Johnson; Cole; Raj; Adelson, 2011, p. 4).

Like human eyes, cameras detect objects because they reflect light, and with more reflected light the brighter the image will look (Wu, 2020). Incident rays falling onto a reflecting surface may suffer three types of reflectance: diffuse (Lambertian), specular (as on a mirror), and backscatter reflection (Sakarya et al., 2008).

Each surface patch may have different properties for reflecting light. For each patch a bidirectional reflectance distribution function (BRDF) is defined by the ratio of outgoing radiance and the incident irradiance, i.e, the energy relationship between the incident lights and the reflected lights. The directional integration of the BRDF over a solid angle defines the measure of the diffuse reflection, or Albedo (ρ) (Wu, 2020).

The original photometric stereo method assumes Lambertian surface, meaning that the reflection obeys Lambert cosine law, i.e, the "surface radiance is proportional to the inner product of the surface normal and the unit vector showing the direction of the incident ray" (Sakarya et al., 2008, p. 210).

For Lambertian surfaces, BRDF is independent of outgoing directions (for that they are called ideal diffuse surface), and therefore the image intensity is dependant only of the illumination direction (θ) and surface properties - condensed on the diffusion coefficient (k_d) - and therefore the image intensity (I) can be written as (Wu, 2020):

$$I = k_d \cos\theta = k_d \boldsymbol{s}^T \boldsymbol{n}\,, \qquad 2.14$$

Where $\boldsymbol{n}$ is the normal of a surface patch, and $\boldsymbol{s}$ is the vector that defines lighting direction. If three point light sources are provided, we have a system to solve:

$$I_i = k_d \boldsymbol{s}_i^T \boldsymbol{n}, \quad i = 1, 2, 3. \qquad 2.15$$

Assuming the lighting sources feature the same distance to the sample and have the same intensity, each image pixel related to the same point, has intensity as a function only of lighting direction ($\boldsymbol{s}_i$), allowing to stack I_i up to obtain a vector to each point:

$$\mathbf{I} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = k_d \begin{bmatrix} \boldsymbol{s}_1^T \\ \boldsymbol{s}_2^T \\ \boldsymbol{s}_3^T \end{bmatrix} \boldsymbol{n} = k_d \boldsymbol{S}\boldsymbol{n}. \qquad 2.16$$

Since the light directions from each source are given, and **S** is a 3x3 matrix, is possible to obtain the normalized unit vector ($\boldsymbol{n}$) of the normal of the patch surface under analysis:

$$\boldsymbol{n} = \frac{\mathbf{S}^{-1}\mathbf{I}}{\|\mathbf{S}^{-1}\mathbf{I}\|}. \qquad 2.17$$

Although valid for idealized situations, including point sources, three equally distanced sources with the same irradiance intensity, Lambertian surface, etc., equations 2.14 to 2.17 demonstrate how photometric stereo determines normal for any other surface.

In the exploded view of Figure 35, six surface-mounted LEDs are evenly spaced around the edge of a glass disc. An elastomeric sensor is mounted under the glass disc, providing a medium for the light to propagate by total internal reflection, from the sources, within the disc, to the sample. Light coming from the sources is reflected by each patch of the surface, and the image radiance intensity that reaches the sensor is recorded. This set up provides six lighting conditions for photometric stereo (Johnson et al., 2011). For this case, six reflectance maps are used to represent the relations between image intensity and surface orientation, allowing a system of equations similar to equation 2.16 to be solved for the normals of points of the surface.

The next step is to estimate the 3D surface that best fits the normals that have been figured out (Sakarya et al., 2008).

One of the limitations of photometric stereo is that the surface intensity recorded by the camera is affected by the light rays that suffer interreflections. Liao et al. (2011) addressed this problem and successfully applied different light colors to simulate different surface albedos, improving scene reconstruction by this method.

Another challenge for applying the photometric stereo technique, specifically when imaging ballistic samples, occurs when different sample's surfaces feature different properties of reflecting light. For instance, many types of cartridge case are made of alloys with meaningful specular reflectance components. Since the Lambertian assumption is preferred, types of lights are optimized to diminish specular reflection and very high brightness values are ignored during the process of recording radiance intensity (Sakarya et al., 2008).

Because other metallic surfaces can have a strong specularity and little diffuse reflection, and since these have important industrial applications, the photometric stereo technique has been expanded to be suitable for specularly reflecting surfaces. Different to traditional methods, intended for Lambertian surfaces, the proposed technique does not assume a point source illumination. Instead, extended light sources are used, allowing for the method to also be applied to determine surface orientation from the brightness of specular surfaces (Ikeuchi, 1981).

While reviewing topography measurement techniques applied to ballistic imaging, Vorburger et al. (2016) noted that photometric stereo is more convenient to use and less expensive than other methods, although its resolution is inferior to confocal microscopy and other more expensive methods. The Balistika system and the IBIS® Brasstrax for cartridge case image acquisition of this study are "real-life application of Photometric Stereo" (Sakarya et al., 2008, p. 210).

2.2.7 Ballistic Signature and Correlation Algorithm

Once images are acquired, filtering and correlation algorithms must be applied to allow for an accurate identification. The identification depends on the system's capabilities to identify regions of interest (ROI) and to extract meaningful signatures that will emphasize the similarities in samples from the same source and to disregard random similarities between non-matches. Although the algorithms and correlation parameters to quantify image similarity are proprietary to each system (Vorburger et al., 2016), the aim is the same, "the selection of features within the identifying mark (…) for their apparent uniqueness in an attempt to match both crime scene and test specimens" (Li, 2009, p. 143).

To extract the ballistic signature, limited wavelengths are of interest, depending on the type of mark being assessed. To separate the roughness of interest from waviness with larger wavelengths or from noise with smaller wavelengths, filters with different cutoffs are applied (Vorburger et al., 2016). These filters, like digital Gaussian filters, "are used to separate form error, waviness, and roughness in the data representation of the surface that results from a measurement" (ASME B46.1-2009, 2010, p. 96), meaning that the correlation algorithms operate on resulting profiles that feature roughness containing critical information of the marks for individualization.

Once the filters are applied, algorithms are applied to compare profile signatures. At the beginning of the development of ballistic identification systems Geradts et al. (2001) focused on testing different methods of feature selection and pattern recognition, aiming to optimize image matching of breech face marks and firing pin impressions. In cases were the sample positions and light conditions were ideal, a simple deviation of the subtracted levels generated accurate hit lists. However, rotated and shifted samples showed that brutal force translation and rotation did not solve the problem due to the effect of shadows and highlights, requiring the development of more complex algorithms.

Currently, each technology applies proprietary algorithms. From a commercial point of view it is understandable why companies do not reveal their algorithms, however, this lack of transparency has some drawbacks, such as limitedinteroperability between different systems and preventing objective tests on these algorithms and parameters (Vorburger et al., 2016). Other problems include the uselessness of scores provided by the algorithms for court presentation and error rate estimation. On the other hand, published correlation algorithms and feature parameter recognizing methods, can be easy to understand and used for similarity quantification (Vorburger et al., 2016). Regardless of whether the algorithm is open source or proprietary, one requirement is common, the choice for any particular algorithm and its customization needs to consider the variabilities involved in firearm identification subjectivity.

One instance of why correlation algorithms need to be customized and enhanced is exemplified by the already mentioned study of Bachrach (2006) (refer to p. 83). The results depicted in Figure 29 show that barrel manufacturer and ammunition brand have a notable influence on the individuality of barrels and on the bullet to gun identification. The researcher’s explanation is that both “mechanical characteristics and dimensional tolerances have significant influence in the manner in which features are transferred between the barrel and the bullet” (Ibid., p. 40). This imposes a challenge to comparison algorithms. While in some firearms and ammunitions the marks are consistently transferred to bullets, generally observed on good quality barrel and ammunition, which are manufactured under more restrict dimension tolerances, in others only portions of the features are imparted on each fired bullet, commonly occurring on poor quality barrel or ammunition, where material or dimensions homogeneity can not be guaranteed. Because of that algorithms need to be customized to deal with these different situations.

The cross-correlation function (CCF) is a parameter to quantify the similarity of ballistic samples signatures (Vorburger et al., 2016), CCF was applied to compare topographic images of cartridge cases fired from pistols with consecutively manufactured breech faces by Weller et al. (2012), and for quantifying a score similarity between two bullets, after a system captured five profiles around the circumference of bullets in a study by Bachrach (2002, apud Roberge et al., 2019).

Recently, new parameters have been suggested by Roberge et al. (2019), in conjunction with a method for objective identification, which can be easily used by experts to quantify similarities, to defend and explain results of comparisons as required for legal admissibility, and to estimate error rates or likelihood ratio (LR). They proposed new parameters to obtain scores of compared bullet 3D topographies, defined a linear combination of theses scores and established a method to use the combined score to compute false match rate (FMR), which is the probability that an identified match is actually a non-match, and the

LR, which is the ratio of the probability of being a match to the probability of being a non-match.

The new proposed parameters were a combination of line counting and pattern matching approaches. A line counting score (LCS) was defined as a combination of the normalized number of peaks and valleys that match between two compared profiles, corrected for the influence of consecutiveness, and a pattern matching score (PMS) as a combination of the aforementioned CCF, which is invariant under different vertical scales, with another parameter, the Absolute Normalized Difference, which is not invariant to vertical scales. A 2D space was defined with these two new parameters, providing a visual representation of the method that can facilitate it use for practitioners (refer to Figure 36).

Another concern of their research was to provide statistical distributions built from a bullet population that is larger than the ones often observed in firearm identification studies. Therefore, they applied their method to high-resolution 3D images acquired from bullets fired from 136 (one hundred and thirty-six) conventionally rifled 9x19mm firearms (Roberge et al., 2019).

Figure 36 shows a 2D visual representation of the results from that study.

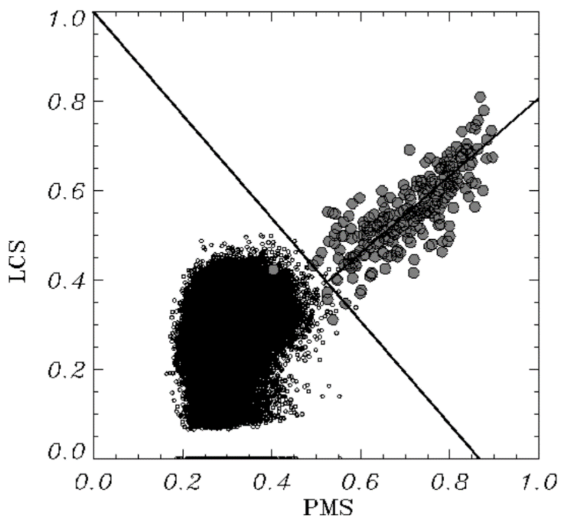


Figure 36 – 2D statistical distributions of the PMS and LCS from Roberge et al. study (Source: Roberge et al., 2019, p. 23).

The gray circles are the 2D scores (PMS, LCS) of 235 visually confirmed matches while the small black circles the 81793 non-match scores. The boundary imposed is a linear decision corresponding to an FMR of 1/10000, and is also observable the line that best fits the match score distribution. Further, the orthogonal projection of a 2D score on the match's best fitting line was performed, allowing to define a distance, D, between the projection and a fixed point on the line. The non-match distribution density of the projected distance D was employed to the computation of the FMR(D), and the match and non-match probability densities of the projected distance D, including an extrapolation for higher scores where non-match distribution data is not available, used to compute the LR(D) (Ibid.).

2.2.8 Ranking by similarities

In Forensic Science instances of known databases are Integrated Automated Fingerprint Identification System (IAFIS) in USA, and the United Kingdon National Criminal Intelligence DNA Database (NDNAD). These databases in principle work similarly to those for firearm identification; the user enters a sample, requests a correlation, and the computer returns the result of a correlation. Because there are well-established empirical testing and scientific understanding that defines a hit or a non-hit in these disciplines, the system informs the user if a hit is found in the NDNAD database, and the same typically applies with IAFIS. In Ballistic databases however, that is not the case (De Ceuster et al., 2012).

De Ceuster and associates note that as the “reproducibility of toolmarks is affected by external factors to a greater extent than DNA and fingerprints”, (Ibid., p. 238), Ballistic Identification Systems provide only lists of results to be checked by the forensic expert.

These systems correlate a number of images beyond human capabilities, generating lists of candidates for possible hits (Heard, 2008; Gagliardi, 2014)). The quality of the images allows the firearm examiner to use the list to compare the samples and decide for an identification or for elimination. The quantity of candidates to be checked vary between laboratories, although in some will be review only up to tenth position (De Ceuster et al., 2012). When a potential match is observed in the result list, the most commonly adopted procedure is to check the class and individual characteristics of multiple regions of interest (ROI) on the physical items of evidence using the comparison microscope to report an identification or to link cases.

Although the use of these systems provides practitioners with more possibilities of what is a match what is a non-match, compared to traditional ballistic comparison (refer to 2.2.2), the final decision still involves “subjective qualitative judgments by examiners and (…) the accuracy of examiners’ assessments is highly dependent on their skill and training” (National Research Council, 2009, p. 153).

2.2.9 Effectiveness assessment in BIS

As demonstrated in previous sections, the ballistic identification systems vary in many aspects, resulting in systems' effectiveness widely depending on its capabilities. For instance, the employed imaging acquisition technology will impact the resolution and quality of the image for automated correlation or manual comparison (refer to 2.2.6) and the comparison algorithm may be more or less effective in distinguishing known matches (KM) from known non-matches (KNM) (refer to 2.2.7), increasing or decreasing the likelihood to find a hit in the initial positions of the result lists (refer to 2.2.8). Because of that is understandable why some studies have tried to assess the effectiveness of these systems (Leloğlu et al., 2000; Tulleners, 2001; De Kinder et al., 2004; Ghani et al., 2010; Rahm, 2012; De Ceuster; Dujardin, 2015; Santos; Muterlle, 2015; Yuesong et al., 2019).

De Kinder et al. (2004) selected cartridge cases from 600 (six hundred) 9x19mm pistols and used the IBIS® Heritage™ system (version 3.4.167) to perform queries with ammunition of the same and different brands. Additionally, by varying the database size involved in the correlations they evaluated how it influenced the accuracy of the result lists.

As a result, 23 out of 32 cartridge cases (71.8%) from the same manufacturer (Remington) were listed by the system within the first 10 (ten) positions of the result lists for breech face and firing pin marks. On the other hand, comparing cartridge cases of different ammunition types resulted in between 6 to 37.5% being ranked from 1 (one) to 10 (ten) in the result lists for breech face or firing pin marks.

They compared and found their results similar to a previous study of 792 (seven hundred and ninety-two) .40S&W pistols, where it was obtained correct samples in the first ten results in 62% (sixty-two percent) of the queries involving cartridge cases fired from the same pistol manufacturer and in 38% (thirty-eight percent) of the correlations with cartridge cases fired from different manufacturers (Tulleners, 2001, apud De Kinder et al., 2004, p. 212).

Another important result in that study is depicted in Figure 37. Increasing the number of samples in the database that are thus involved in the correlations negatively impacts on the ranked position where the correct sample appears in the result lists, unrevealing an important limitation for this type of firearm database. The researchers concluded that this must be due to the appearance of more similar class and individual characteristics in the increasing database, leading to a deterioration of results (De Kinder et al., 2004).

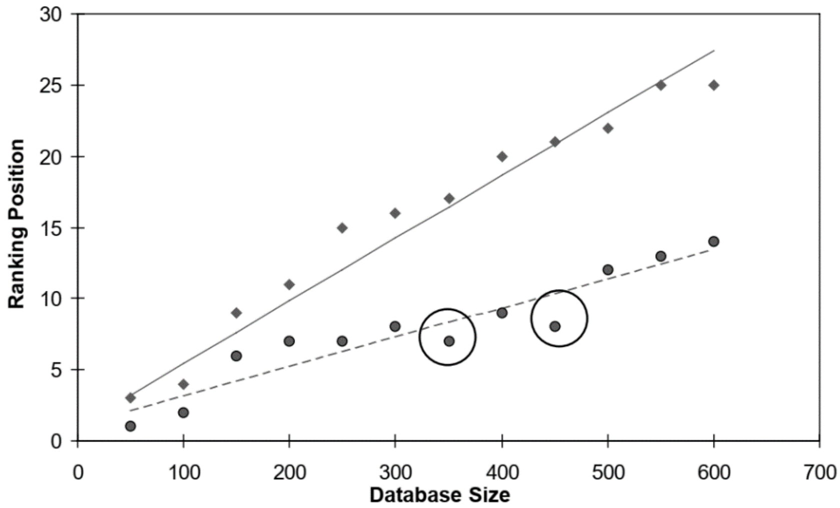


Figure 37 – Best ranking order for either firing pin (circles) and breech face (diamonds) correlations, provided by an RBID of size ranging from 50 to 600 guns (Source: De Kinder et al., 2004, p. 212).

Approximately 10 (ten) years after the De Kinder et al. (2004) study, De Ceuster and Dujardin (2015) used the same set of ammunition to evaluate the effectiveness of another automated comparison system, Evofinder® (software version 5.4). They noted that during the period between the two studies the ballistic imaging systems had experienced drastic improvements, including:

> The state-of-the-art technology offers improvements in image resolution to sub 5 µm, capturing three-dimensional information (topography) of the markings on the object, the semi-automatic selection of the relevant marking areas (specifically for bullets), enhanced correlation efficiencies and improved manipulation possibilities during the on screen comparison process (De Ceuster; Dujardin, 2015, pp. 82-83).

The 2015 study confirmed the linear relationship between database size and the best position of the correct sample in the result lists. Regarding the effectiveness of the system, a significant improvement was observed, demonstrating that the effectiveness of listing the correct sample in the first position on the results nearly doubled, compared to the previous study, when comparisons of different ammunition were involved.

Figure 38 shows the results from their study; the frequency that a match was found on each position of the result lists, and the consequently cumulative percentage (probability) of finding a match. A logarithmic curve was fitted to the data, which enabled a more precise depiction of the effectiveness of finding a match as a function of the position in the result lists.

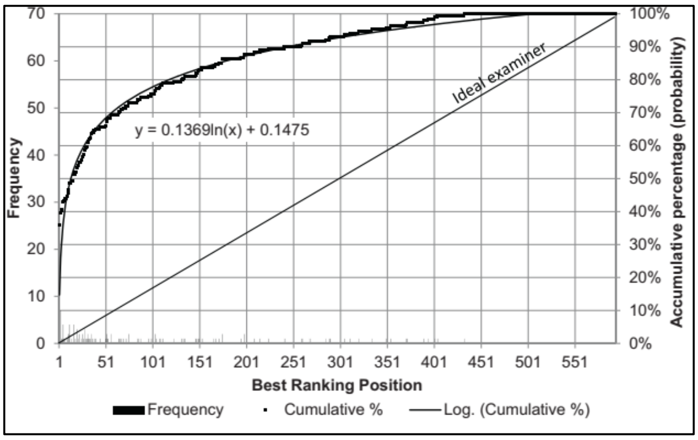


Figure 38 – Probability of finding a match vs ranking position in both the breech and firing pin comparison results as provided by Evofinder® software version 5.4 (Source: De Ceuster; Dujardin, 2015, p. 86).

Despite this notable improvement on effectiveness for these comparisons involving the same database of cartridge cases, the researchers noted:

> The Evofinder® system has demonstrated an important improvement in automated ballistic imaging equipment. No doubt this is also valid for other state-of-the-art equipment that is available on the market nowadays. **Nevertheless the idea of a reference ballistic imaging database remains utopic for now** " (De Ceuster; Dujardin, 2015, p. 82-83, emphasis added).

Evofinder® effectiveness was also assessed in other studies by Rahm (2012) and Santos (2015). These researches are further considered in the next chapter (refer to 3.3.2), but some of their effectiveness results regarding the calibers and databases assessed are summarized in Table 3. Because of differences in effectiveness computations, the database involved and type of ammunition being compared, the results between the two studies are hardly comparable and more appropriately only present system performances at a specified point in time.

Table 3 – Results of Rahm (2012) and Santos (2015) studies.

BUL/CC	Caliber	Rahm		Santos	
		Database size	$\Gamma_0^{(a)}$	Database size	$\Gamma_1^{(b)}$
CC	9x19mm	1075	**0.96**	696	**0.83**
BUL	9x19mm	596	**0.82**	712	**0.75**
BUL	.38SPL; .357Mag	195	**0.83**	223	**0.97**
				1258	**0.51**
CC	.38SPL; .357Mag	-	-	223	**0.95**
		-	-	1053	**0.43**

(a) - Γ_0: effectiveness proposed by Rahm (2012)
(b) – Γ_1: effectiveness proposed by Santos and Mutterle (2015) (refer to 3.2.2 on p. 110).

In a more recent study by Yuesong et al. (2019), 1000 (one thousand) Norinco QSZ-92 pistols were test-fired with three rounds of ammunition each, and the collected ammunition components were registered in an Evofinder® system (software version 6.3.3.9), resulting in a registered ballistic database (RBD) of 2996 bullets and 2999 cartridge cases. The "ranking positions and similarity scores from 1000 bullet (BUL) correlation results and 1000 cartridge case (CC) correlation results" (Ibid., p. 1342), one for each gun, were used to evaluate the established RBD.

In terms of system performance with bullet and cartridge case, one out of two correct test-fires were ranked first in at least one of the correlation lists for primary mark, LEA, or GEA or in one of the correlations for breech face marks or firing pin impressions. Although a very impressive performance, in favor of the effectiveness of the system, the limitation of the study to one firearm model and one type of ammunition, demands that testing should expand the conclusions in favor for a more generic RBID, "more models of firearms should be added (…) and studies with other ammunitions should be conducted" (Ibid., p. 1343). Despite this limitation, the study also provided a good assessment of the validity of using the correlation scores provided by the system to construct the receiver operating characteristic (ROC) curve of the correlation results. Plotting data in this manner enables calculation of the area under the curve (AUC) and to estimate optimal cutoffs, which could be useful for a more objective identification approach.

Figure 39 shows the ROC and AUC for the five correlators assessed on the Yuesong et al. (2019) study. Using the AFTE range of conclusions for a ballistic comparison (refer to 2.2.1), The True Positive Rate axes represent the ratio of true identifications indicated by the system to the total number of identifications involved on the correlations. The False Positive Rate axes represent the ratio of the number of false identifications indicated by the system to the total number of eliminations involved on the correlations. The diagonals depict the lines of no-discrimination and a perfect identification performance can be seen on the LEA ROC curve.

Going further on the study with the Norinco pistols, Dong et al. (2019) analyzed the three types of scores generated by the system from bullet correlations. The 3D plot of Figure 40 is a useful representation of the distribution generated by 1985 KM scores and by 2 982 092 KNM scores. Employing a support vector machine (SVM) method they evaluated the gap between the distributions as a predictor for objective classification.

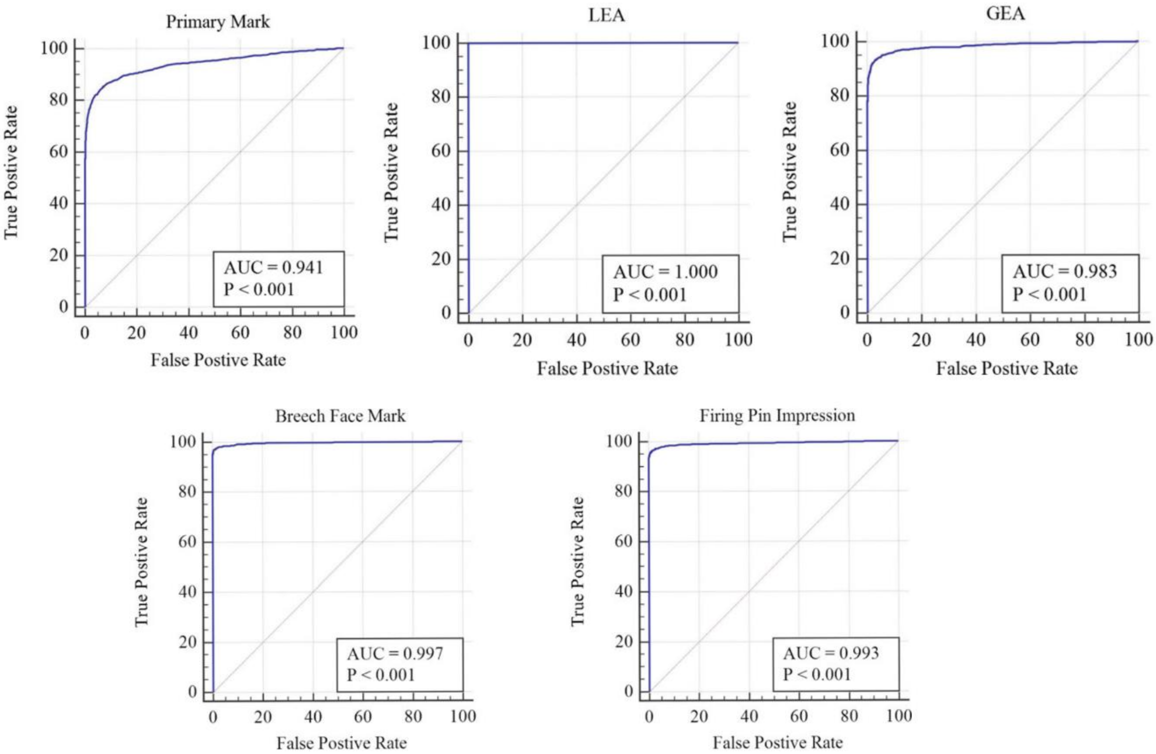


Figure 39 – ROC curves of correlation results based on the similarity scores of five correlators (Source: Yuesong et al., 2019, pp. 1339; 1342).

Knowing that in a ROC curve the sensitivity is the probability of detection (no missing matches) and the specificity is the probability of exclusion (no false match) they concluded that:

> Although the SVM failed to classify (...) two KM scores and six KNM scores into the correct results (…), the accuracy rate was still very high (…). Specifically, the specificity was approximately 99.99% and the sensitivity was approximately 99.90% (DONG et al., 2019, p. 3).

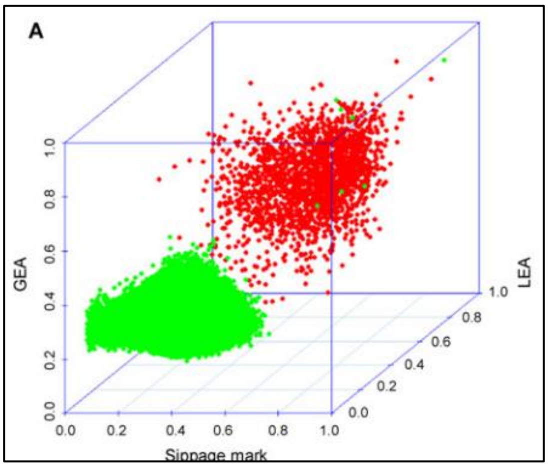


Figure 40 – Scatter plot of KM scores (in red) and KNM scores (in green) for slippage mark, LEA, and GEA, from Evofinder® system correlations (Source: DONG et al., 2019, p. 4).

These last three aforementioned studies were carried out in the same system, but the differences between the involved variables and in results are worthy of note. The best performance was recorded by Yuesong et al. (2019), because that was a more controlled study with only one make and model of pistol within the database. This finding reinforces the idea that as much as the implementation of an RBID is standardized, as precise must be their power discrimination. The Rahm (2012) results look like an intermediate between the other two, and because it was built using a database from the Federal Criminal Police Office of Germany (BKA) real cases, presents a more realistic performance, but still is in favor of the concept of applying ballistic identification systems to solve firearm-related crimes. The worse performance observed on Santos' (2015) study sounds reasonable because a larger variability was intentionally designed within the database and subsequent correlations. Although aiming to understand the influence of ammunition composition on the effectiveness, it is arguable that a scenario like that should be considered on real implementations. Ultimately the comparison of the three studies reinforces that performance will be critically affected if the parameters that influence system effectiveness are not properly addressed.

3 EFFECTIVENESS OF EVOFINDER® ON .38SPL CALIBER

The content of this chapter has largely been published within Journal of Forensic Science as a peer reviewed technical note entitled 'Influence factors on the effectiveness of automated ballistic comparison of bullets and cartridge cases on caliber .38SPL' (Santos; Muterlle 2018) – figures and references were updated.

3.1 INTRODUCTION

The microscopic comparison of bullets and cartridge cases is a powerful exam to link a suspected gun to a crime scene. The correlation is possible due to imperfections of the barrel and other gun parts that mark ammunition components during firing and gun action. These imperfections are primarily produced during the manufacturing of the gun and are totally random in their distribution, shape, and size, allowing to affirm that no two guns, even those consecutively produced, will never have the exact same individual marks (Heard, 2008 and Weller et al., 2012).

Traditionally this kind of comparison uses optical microscopes, but in order to perform comparisons beyond human capability, to properly deal with open cases (Gagliardi, 2014) and aiming a less subjective approach (Riva; Champod, 2014), forensic labs all over the world are implementing electronic solutions. Nowadays many commercial systems are available to implement a ballistic database and to perform automated comparisons. Connect crimes committed with the same gun, or implicate a gun owner as a crime suspect, are the main goals for using these systems.

In the last decade, several papers appeared testing the effectiveness of these systems (Lelog˘lu et al., 2000; Tulleners, 2001; De Kinder et al., 2004; Ghani et al., 2010; Rahm, 2012; De Ceuster; Dujardin, 2015; Santos; Muterlle, 2018; Yuesong et al., 2019). Some of the best contributions of these papers were to show the difference of system's performance regarding ammunition brand and database size, reinforcing the idea that to properly apply this technology, should be established the number of control samples, data to be recorded, and scanning and comparison protocols (De Kinder, 2002).

One of the problems for automated comparison is about selecting the type of ammunition to test-fire seized guns. To decide if two bullets or cartridge cases came from the same gun, one of the important premises is to compare samples of the same material and features (Heard, 2008). Nevertheless, when test-firing guns to search against ballistic evidence from shootings this premise cannot be guaranteed. Furthermore, as bigger the database as difficult for the system to display the correct test-fired in the initial position of correlation results (De Kinder et al., 2004; De Ceuster; Dujardin, 2015).

Recently Santos and Muterlle addressed this problem and studied the influence of bullet material on the Evofinder® effectiveness for comparisons on caliber .38SPL (Santos ; Muterlle, 2015). Giving a step further on this study, the research, developed in a partnership between the National Forensic Institute of the Brazilian Federal Police and the Department of Mechanical Engineering of the University of Brasilia, investigated which other factors influence system effectiveness regarding .38SPL bullets and cartridge cases.

Finally, the study was replicated, with the same steps of imaging the fired ammunition components and performing automated comparisons, which in the first instance were carried out by forensic scientists trained in ballistic comparison, made second time by engineering students of the University of Brasilia. This procedure aimed at investigating if this type of database should be only handled by forensic experts as compared to personnel without any previous training in firearm identification.

3.2 MATERIALS AND METHODS

3.2.1 Automated Comparisons

For this research 16 guns on caliber .38SPL or .357Mag (see Table 33 on APPENDIX B: DETAIL OF FIREARMS EMPLOYED ON THE RESEARCH), all from the same manufacturer and similarly worn, were selected, what allowed a real test for the system as these guns can generate similar marks for comparison (Ghani et al., 2010; Bonfanti and De Kinder, 1999a).

All ammunition used was from CBC brand (The CBC Ammo Group consists of four internationally recognized ammunition brand names: Magtech, CBC, Sellier & Bellot and MEN) (Magtech, 2016), which by far is the most common ammunition brand found in crime scenes and within seized guns in Brazil. Round nose and full metal-jacketed bullets were collected using a water tank, whereas hollow points were obtained using cotton tubes, keeping fired ammunition components in good condition for imaging.

From each gun were collected 14 test-fired bullets (TFB) and 14 test-fired cartridge cases (TFC), 2 from each one of 7 ammunition types detailed in Table 4. After that, were collected more 5 bullets and 4 cartridge cases from each gun. Considering ammunition features, ammunition types 1, 2, 4, 5, and 6 were selected to collect questioned bullets (QB) and types 1, 4, 5, and 6 to collect questioned cartridge cases (QC). The collection of this third ammunition component (per type of ammunition and per gun) aimed to simulate retaining ballistic evidence from shootings to enter into the system. Figure 41 and Figure 42 present images of the selected ammunition components.

These fired ammunition components were imaged by BIS Evofinder® (software version 5.4.0) and were stored in two separate folders, one for the initial two test-fires and the other for questioned. The system technology includes a frame by frame scanning to generate high-resolution images and allows automated comparisons of one exhibit against images of selected folders of the database.

Table 4 – Ammunition types selected to collect test-fired components (TFB and TFC) and questioned exhibits (QB and QC) from .38SPL revolvers.

Ammunition	**Bullet**		**Cartridge case**	
	Mass (gr.)[(c)]	*Symbols*	*Material*	*Symbols*
.38 SPL - Lead Round Nose (LRN)	158	TFB1 and QBI	Brass	TFC1 and QCI
.38 SPL - Semi-Jacketed Hollow Point (SJHP)	158	TFB2 and QBII	Brass	TFC2
.38 SPL +P - Semi-Jacketed Hollow Point (SJHP)	158	TFB3	Nickel-plated	TFC3
.38 SPL +P - Full Metal Jacket Silver Tip (FMJ-ST)	125	TFB4 and QBIV	Nickel-plated	TFC4 and QCIV
.38 SPL +P+ - Jacketed Hollow Point Silver Tip (JHP-ST)	125	TFB5 and QBV	Nickel-plated	TFC5 and QCV
.38 SPL +P+ - Gold Jacketed Hollow Point (G-JHP)	125	TFB6 and QBVI	Brass	TFC6 and QCVI
.38 SPL - Lead Round Nose (LRN)	158	TFB7	Brass	TFC7

(c) - 1 gr (grain) = 0.06479891 g (gram)

TFB1	TFB2	TFB3	TFB4	TFB5	TFB6	TFB7
QBI	QBII	----	QBIV	QBV	QBVI	----

Figure 41 – Types of bullets collected from .38SPL revolvers (2 (two) TFB and 1 (one) QB per type of ammunition and per firearm).

TFC1	TFC 2	TFC 3	TFC 4	TFC 5	TFC 6	TFC 7
QCI	---	---	QCIV	QCV	QCVI	---

Figure 42 – Types of cartridge cases collected from .38SPL revolvers (2 (two) TFC and 1 (one) QC per type of ammunition and per firearm).

Besides setting the correct caliber on the software, the imaging process for cartridge cases does not demand any more action by the operator. On the other hand, after scanning bullet, land engraved areas (LEA), groove engraved areas (GEA), or primary marks of interest should be assigned.

For each automated comparison performed with cartridge cases, the system provides two correlation result lists, one in the decreasing rank of similarity between firing pin marks, and another in decreasing order of similitude between breech face marks. With bullets, the results provided are, also in decreasing sort of likeness, by LEA, GEA or primary mark. A preliminary assessment of the bullets led the study to disregard the 'primary marks' for this assessment.

3.2.2 Effectiveness criterion of BIS

To calculate the effectiveness of the systems in this study it was followed an effectiveness criterion, proposed by Santos and Muterlle (2015), arising from a change on the effectiveness method proposed by Rahm (2012).

Criterion proposed by Rahm

Rahm (2012) conducted an important study of the effectiveness of the Evofinder® system in which it evaluated its performance with cartridge cases and bullets and also proposed a quantitative effectiveness criterion that allows to efficiently compare the performance of two systems or even a system operating under different conditions, such as different calibers, ammunition types or operator qualifications.

The criterion proposed by Rahm is constructed from the result lists that are provided by the system when one sample is selected as reference and correlated against the others on the database. At first, it is verified the best position in the result list that was found a sample of the same firearm as the reference. The number of hits in a given position, divided by the total number of comparisons, establishes a probability of finding a hit at position *n*. The cumulative probability - P(*n*) - defined as the sum of all probabilities up to position *n*, was plotted against position *n*, as shown in Figure 43, obtained by Rahm (2012) from the breech face (BF) and firing pin (FP) correlation results.

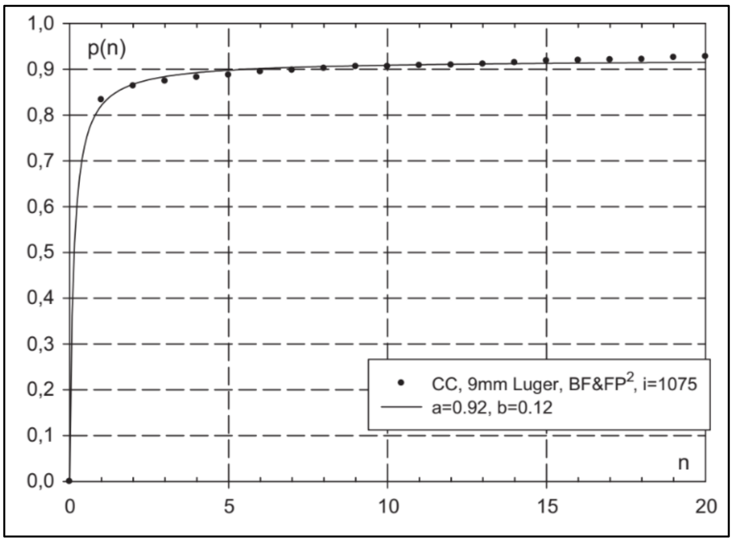


Figure 43 – Probability (P (*n*)) that a hit will be found up to position *n* of the result list (Source: Rahm, 2012, p. 174).

A curve was proposed as most appropriate to fit the data, according to the equation 3.1:

$$\mathrm{P}(n) = \frac{a.n}{n+b} + c.n, \qquad a\ e\ c\ \in [0.1], \text{and}\ n\ \in [0.i]. \tag{3.1}$$

P (n) is the cumulative probability of a hit in position n;
a, b and c are parameters to be determined by fitting the curve to the results; and
i is the size of the database.

The following boundary conditions:

$$\mathrm{P}(i) = 1, \tag{3.2}$$

$$\mathrm{P}(0) = 0. \tag{3.3}$$

Imply that:

$$c = \frac{i.(1-a)+b}{i.(b+i)} \tag{3.4}$$

For effectiveness criterion determination, it was proposed to divide the graph into two areas, as shown in Figure 44.

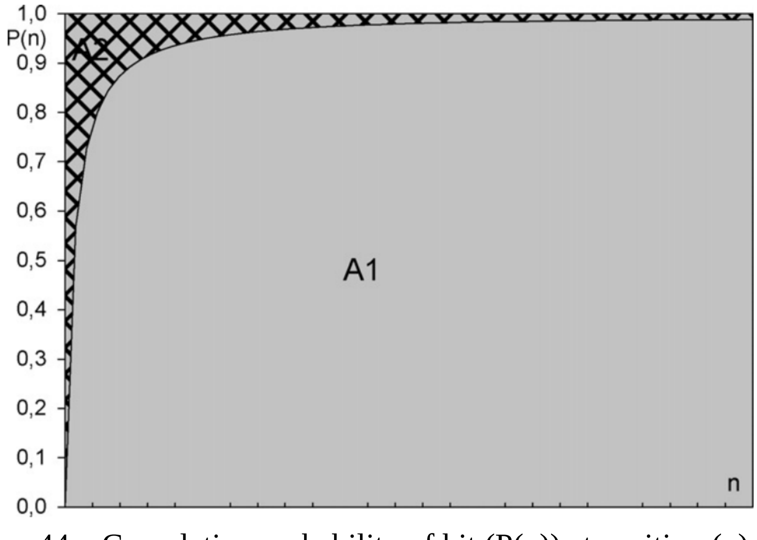


Figure 44 – Cumulative probability of hit (P(n)) at position (n) of the result list (Source: Rahm, 2012, p. 176).

Considering the probability of a hit as a function of the position in the result list (P x n), the effectiveness criterion proposed by Rahm ($\Gamma 0$) was defined as:

$$\Gamma_0 = \frac{A1}{A1+A2} \,. \qquad 3.5$$

$$\Gamma_0 = \frac{\int_0^i P(n)dn}{1.i} \,, \qquad 3.6$$

$$\Gamma_0 = a + \frac{c}{2}.i + \frac{k}{i} \,, \qquad 3.7$$

$$with \qquad k = a.b.(\ln b - \ln(i+b)) \,. \qquad 3.8$$

New criterion proposed by Santos and Muterlle

In the previous research related to this study (Santos, 2015), several cases were observed in which the effectiveness criterion of equation 3.7 overestimated the effectiveness of the system.

The results depicted in Figure 45 represent the actual data obtained from three different 9x19mm bullet setups during the study. Using equation 3.7, the Rahm effectiveness criteria ($\Gamma 0$) for these data are: blue line 0.89; yellow line 0.73; and green line 0.79.

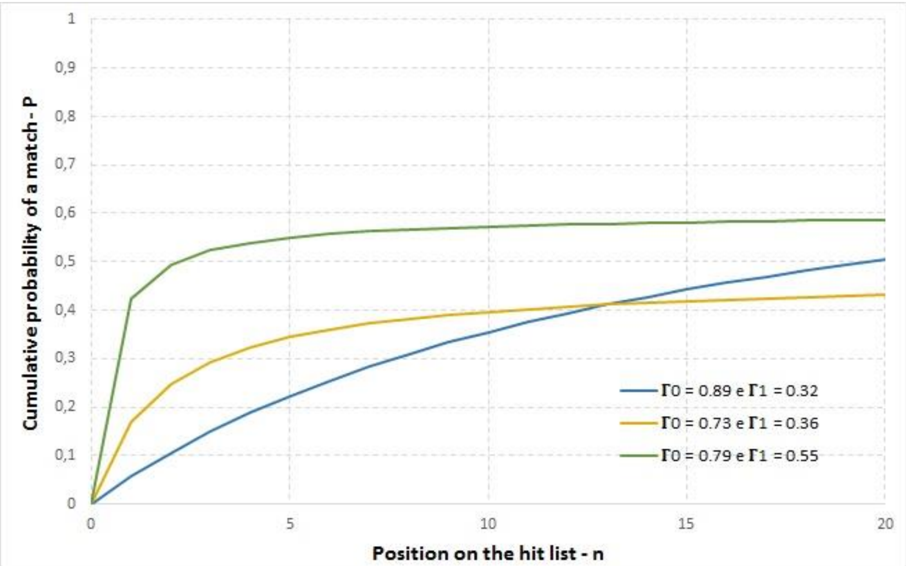


Figure 45 – P x n in three different system settings. The values for the effectiveness criteria by Rahm (Γ_0) and the new effectiveness criteria proposed by Santos and Muterlle (Γ_1) (2015) are displayed (Source: Santos, 2015, p. 92).

To correct this inconsistency, a small change on the effectiveness calculation to measure system performance was proposed by Santos and Muterlle (2015). As the result lists have always been checked up to position 20 (twenty), it is more reasonable to calculate the effectiveness criterion by integrating P(n) from 0 to 20, rather than 0 to i. This new effectiveness criterion (Γ_1) was therefore defined as:

$$\Gamma_1 = \frac{\int_0^{20} P(n)\,dn}{20}\,, \tag{3.9}$$

for $$k' = a.b.(\ln b - \ln(20 + b))\,, \tag{3.10}$$

$$\Gamma_1 = a + 10c + \frac{k\prime}{20}\,. \tag{3.11}$$

Using equation 3.11 the new effectiveness criteria (Γ_1) for the data in Figure 45 are: blue line 0.32; yellow line 0.36; and green line 0.55. These new values more fittingly represent the differences in system performance in these three settings.

3.2.3 Database for comparisons

The experiment was conducted varying the database included in the comparisons in three levels. The aim of this variation was to assess the quality of the test-fires, the possibility to correlate different types of ammunition, and the drop in system performance by increasing the database size.

It is expected that the system can first match two test-fires from the same gun before it can point out the correct gun for a third exhibit collected as evidence. As the test-fired quality is very important to increase the likelihood of a match, preliminary automated comparisons were conducted within the folder of test-fires only. Each test-fired type was collect in pair, therefore was searched one bullet or cartridge case image against the other test-fires and recorded the position of its twin test-fired, namely the test-fired of the same type and from the same gun.

The best-case scenario would be to compare only test-fires of the same type, but as previously mentioned this cannot be guaranteed in criminal cases. The probability exists that a seized gun is test-fired with one type of ammunition and ballistic evidence from shooting is from another type. To test the likelihood of a match with different ammunition types, each questioned bullet or cartridge case was searched against the others test-fires and questioned exhibits, which comprehended 287 cartridges and 303 bullets. The position of all test-fires from the same gun was recorded for evaluation. This was designated as the noiseless complete test.

Finally, the comparisons of this noiseless complete test were repeated at this time including all available images of .38SPL caliber, being designated as the complete test with noise. During this last test, the database size on this caliber slightly varied but most of the time had 1053 cartridge case images and 1258 bullet images. The goal of the noise introduction was to evaluate the drop of the system effectiveness by increasing the database (De Kinder et al., 2004; De Ceuster; Dujardin, 2015).

To analyze the results for the factorial design experiment of noiseless and with noise complete tests were used analysis of variance (ANOVA) (Box et al., 2005). Before doing so, and considering limitations for correct ANOVA application, data were checked for normality, and when it was found sufficient acceptability, assuming constant variance and independence of the data, guaranteed by the way each automated comparison is not related to the other, ANOVA was applied.

ANOVAs were carried out to test the hypothesis *h0* that the mean effectiveness criterion regarding the type of test-fired or type of questioned exhibit, or between two distinct tests, for example, noiseless or with noise test, or contrasting two different user results, were statistically indistinguishable. The alternative hypothesis *h1* is that at least one of the mean is statistically different from the others. The P-value of the ANOVA result indicates the probability that *h0* hypothesis is true. High values of F-Fisher when compare to F-Critical is evidence against the null hypothesis, i.e. *h1* hypothesis must be true for at least one of the means on that level of significance (Ibid.).

3.3 PRELIMINARY RESULTS AND DISCUSSION

3.3.1 Effectiveness regarding bullets

The blue line in Figure 46 shows the general system effectiveness for the initial test with bullets test-fires only. The system effectiveness ($\Gamma 1 = 0.89$) indicates the good quality of the test-fires as also system capability to match them. In fact, in 92 of 112 automated comparisons between test-fires, the system displayed the twin test-fired in the first position in at least one of the two correlation results. In the remaining 20 results only in 6 the twin test-fired was not found until position 20 of the lists.

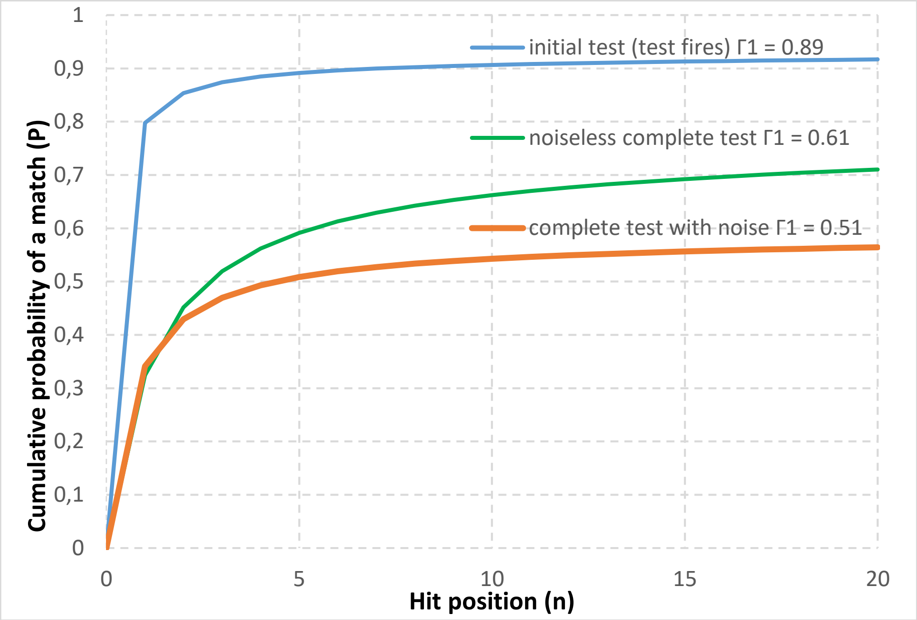


Figure 46 – General system effectiveness in all three set of automated comparisons with bullets.

The system effectiveness by type of test-fired showed in Figure 47 indicates that the most difficult type of test-fired to be matched is TFB 5 (JHP-ST). The wrong results with these test-fired bullets were manually compared, which revealed that one or two of each twin test-fires had few striation marks with enough quality for comparison, showing that these errs are mostly to due lack of individual marks than due system algorithm. Figure 48 shows one instance of this type of difficult match. The low effectiveness with this type of test-fired bullet had influence in the results of noiseless and with noise complete tests, as will be mentioned ahead.

The effects of performing correlations of different types of bullets and of increasing database size can be also visualized in Figure 46. From the initial test to noiseless complete test, the database size kept almost the same, merely increasing from 223 to 303 images, and the drop in system performance from 0.89 to 0.61 can be attributed primarily to the comparisons of different ammunition types. From the noiseless complete test to the complete test with noise, the correlation requests were exactly the same, whereas the database size increased from 303 to 1258 images, and so the observed drop on the effectiveness from 0.61 to 0.51 can be attributed to the database increment.

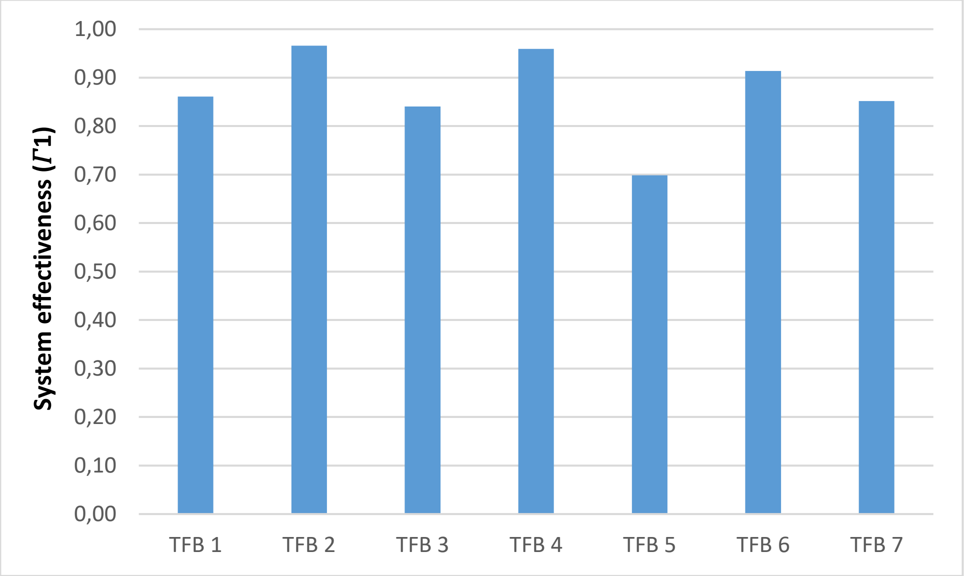


Figure 47 – System effectiveness in the initial test by type of test-fired bullet (TFB).

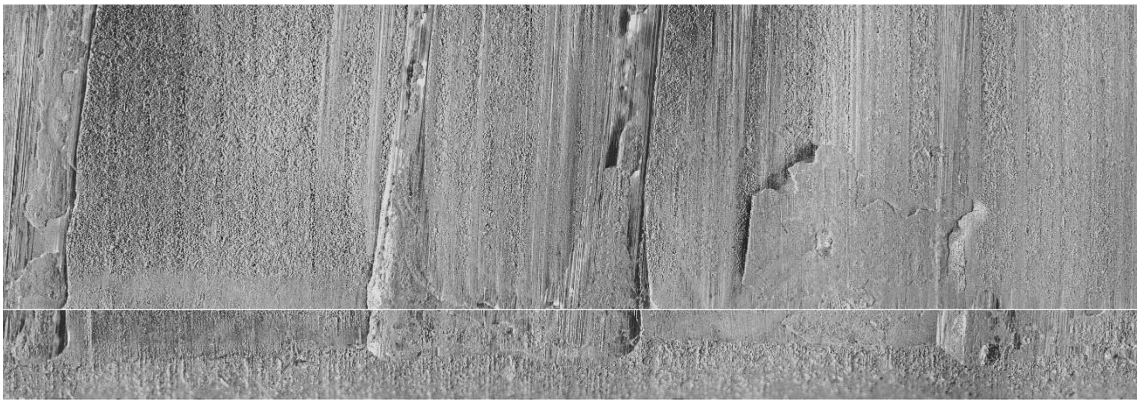


Figure 48 – JHP-SP test-fired bullets with very few striation marks compared to others types of bullets (Evofinder® images).

At this point should be mentioned that the results of the complete test with noise had been analyzed against mechanical properties of bullets, being worthy to repeat the strong relationship found between the system effectiveness and the bullet hardness (refer to Figure 49). Beyond that, successive analyses of variance of these results indicated that when implementing a ballistic database of bullets from .38SPL guns, it is recommended to collect two test-fired bullets with G-JHP or SJHP ammunition and two with LRN bullets from each gun, thus ensuring a higher effectiveness criterion and consequently the best correct gun identification probability (Santos; Muterlle, 2015).

The poor system performance observed in the complete test with noise (refer to Table 6) for LRN and JHP-ST bullets can be better understood by analyzing the results of the initial test. LRN test-fires (TFB1 and TFB 7 of Figure 47) were well matched in the initial test (effectiveness $\Gamma 1$= 0.86 and 0.85 respectively), but their results dropped meaningfully on complete tests ($\Gamma 1$= 0.31 and 0.37 respectively), once more demonstrating how this type of test-fired is inadequate to be correlated against jacketed bullets. For JHP-ST (TFB5) even from the initial test, the matching possibility was not so high ($\Gamma 1$= 0.70), indicating the poor results of complete the test with noise ($\Gamma 1$= 0.46) was primarily due to poor quality of the test-fires.

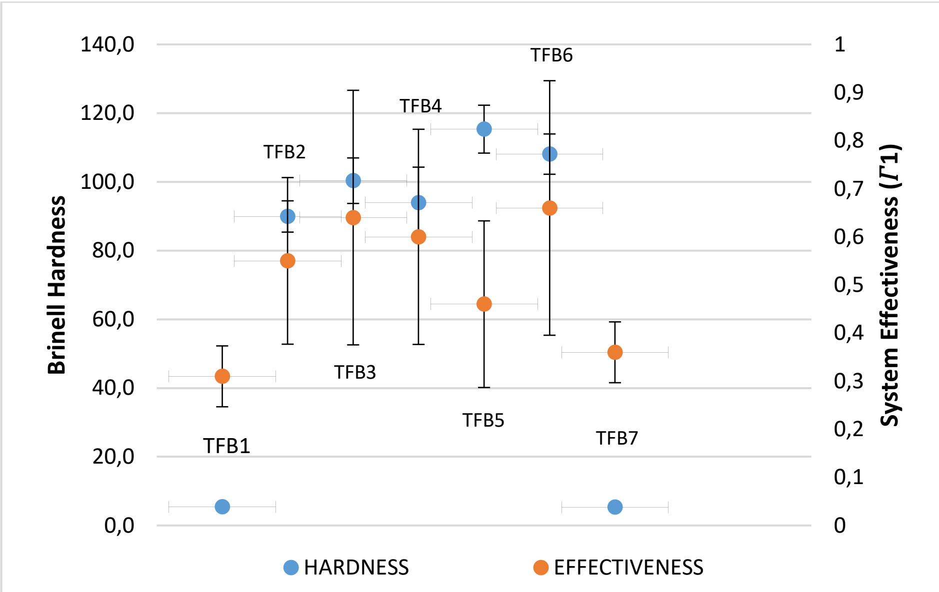


Figure 49 – Mean effectiveness criterion ($\Gamma 1$) and mean Brinell hardness regarding type of test-fired exhibits (TFB1 to TFB7) – (Source: Adapted from Santos; Mutterle, 2015, p. 6).

3.3.2 Effectiveness regarding cartridge cases

Comparing with bullet results, the system effectiveness initial test with cartridge cases (Γ_1 = 0.78), was low, indicating difficulty in match twin test-fired cartridge cases (refer to the blue line in Figure 50). To investigate the reasons for that Figure 51 splits results by firing pin and by breech face for each firearm.

Because firing pin results with gun 8 were very low, its images were manually compared. It was observed that the firing pin marks in images of twin test-fires were not equal in quality, explaining the system difficult in matching test-fires by firing pin in the initial test only for this gun.

The results revealed system difficult for matching by breech face marks twin test-fires from guns 1, 3, 5, 6, 7, 8, 9, 11, 13, 15, and 16 (refer to Figure 51). The manual check of these results showed that in 37 of 55 instances there were good marks for comparisons, and the system difficult in matching them is not justified, possibly representing an algorithm problem.

Three error patterns were identified. Pattern 1 occurs when the two images compared present good breech face parallel marks in the primer cup for matching (see Figure 52-A). In pattern 2, despite the absence of good parallel marks in at least one of the images, they feature individual characteristic marks repeated in both images, which system could use for matching (see Figure 52-B). Moreover, pattern 3 was observed when breech parallel marks exist in both images but were found outside the primer cup perimeter (see Figure 52-C).

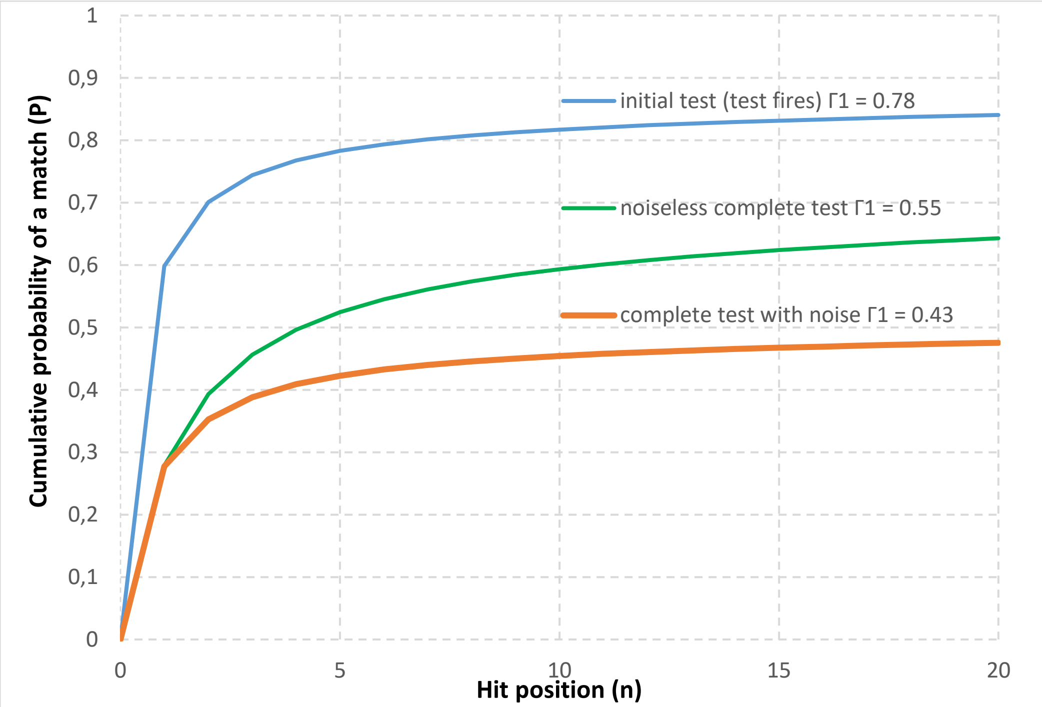


Figure 50 – General system effectiveness in all three set of automated comparisons with cartridge cases.

Although the literature supports the hypothesis that marks left by a breech face can be used to firearm identification (Weller et.al, 2012), in instances of this study in which at least one image had no parallel or individual characteristic mark to allow a match, the wrong result was considered justified, which was observed in 18 of 55 manually comparisons performed to check correlation results mistakes.

The results from noiseless and with noise complete cartridge case tests are compared with the initial test in Figure 50. Meaningful decreament in system effectiveness is observed from the initial to the second and third tests (from 0.78 to 0.55 and to 0.43).

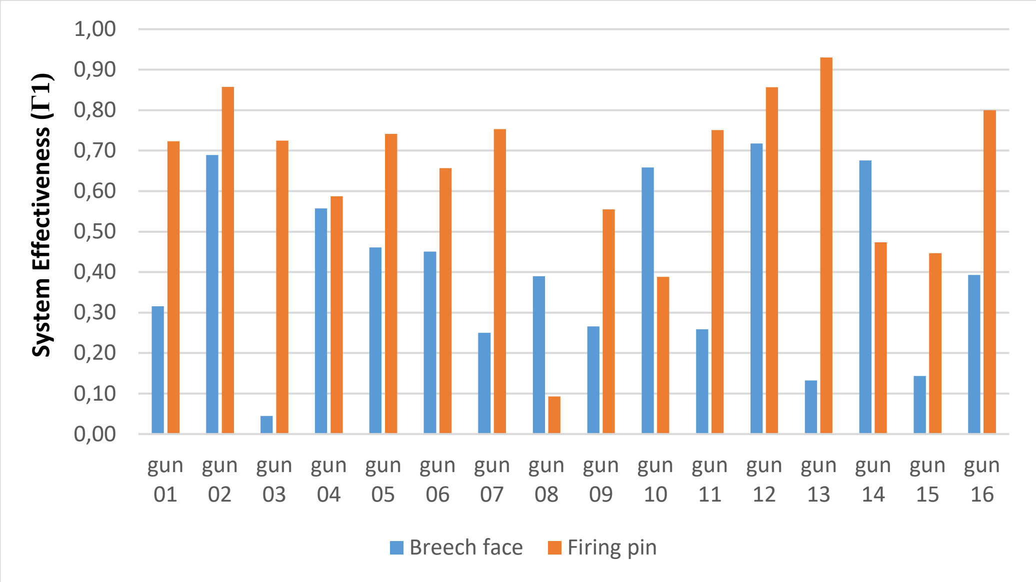


Figure 51 – System effectiveness by breach face and firing pin in the initial test with cartridge cases (test-fires only).

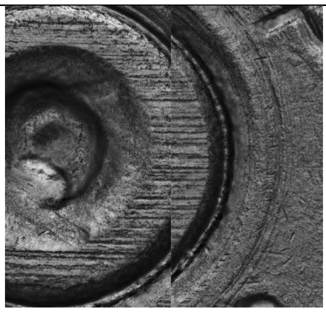
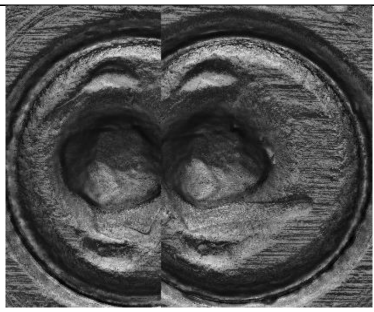
Error Pattern 1	Error Pattern 2	Error Pattern 3
		
(A)	(B)	(C)

Figure 52 – Instances of poor system performance not justified by the existence of parallel or individual characteristic marks (Evofinder® images).

The system's effectivenesses regarding all types of test-fires and types of questioned cartridge cases are displayed in Table 5. All combinations of variables show a decrement in system effectiveness by the introduction of noise. Table 9 provides results of the ANOVA calculation with data from Table 5, and the high comparative value of F-fisher for the type of test confirms the difference in the mean effectiveness from noiseless to with noise complete tests.

Regarding the type of test-fired cartridge case the line 2 of ANOVA1 in Table 9 presents no evidence against the null hypothesis. Therefore for aiming to increase the likelihood of matches, at least by the obtained results, no type of cartridge case could be suggested as best to collect test-fires of .38SPL firearms.

3.3.3 Effectiveness regarding user qualification

To evaluate the user qualification influence on system effectiveness, students of the University of Brasilia replicated the experiment. These students had no previous training in firearms identification and were taught only the essential to scan and stored images of the 592 fired ammunition components of the study. After digitalizing the samples, they marked the LEA and GEA in bullet images and requested again all the automated comparison of bullets and cartridge cases for complete tests with noise.

The goal was to see if the change in users' qualifications would influence meaningfully the system effectiveness. The results for bullets and for cartridge cases are displayed respectively in Table 7 and Table 8, being recorded only the difference in system effectiveness related to previously mentioned results of complete tests with noise.

Even though a negative trend is observed in Table 7, which would at first be indicative of system low effectiveness on the experiment replication by students, the ANOVA2 of these data, displayed in Table 9, presents no evidence against the null hypotheses, i.e. no meaningful difference in system performance regarding user qualification. In spite of this, it was observed that the positive results in Table 7 are most related to LRN bullets, which had worse system effectiveness. For this fact, an additional ANOVA was carried out comparing system effectiveness by the users, but this time withdrawing LRN results. The ANOVA3 in Table 9 assessed this data, presenting a high comparative F-fisher for type of users. Therefore, by removing from analyses LRN results, which had very low effectiveness, better performance of the system when handled by experts was evidenced in comparison to students' performance.

The results and work of students were manually checked to see possible reasons for this low effectiveness and some images were found wrongly marked, specifically in some instances it was confused LEA by GEA and vice versa.

In the replication of cartridge cases complete test with noise, results of Table 8 and the subsequent ANOVA4 in Table 9 show no indication of a significant difference in system effectiveness regarding users' qualifications. In fact, the general system effectiveness in these two tests was quite similar, 0.43 and 0.44, respectively for forensic experts and for students, and this was expected once, except learn to operate the equipment and select the proper caliber, there is no influence of user in the imaging process.

Table 5 – System effectiveness regarding combination of type of test cartridge case (TFC) and type of questioned cartridge case (QC) in noiseless and with noise complete tests.

	TFC1		**TFC2**		**TFC3**		**TFC4**		**TFC5**		**TFC6**		**TFC7**	
	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE
QC1	0.56	0.46	0.29	0.25	0.64	0.45	0.68	0.38	0.55	0.37	0.37	0.30	0.57	0.43
QC4	0.55	0.56	0.71	0.56	0.80	0.70	0.74	0.63	0.74	0.64	0.62	0.50	0.60	0.46
QC5	0.60	0.41	0.64	0.44	0.63	0.54	0.55	0.49	0.55	0.38	0.55	0.38	0.46	0.31
QC6	0.40	0.34	0.38	0.23	0.42	0.33	0.61	0.52	0.43	0.40	0.47	0.36	0.40	0.26

Table 6 – System effectiveness regarding combination of type of test-fired bullet (TFB) and type of questioned bullet (QB) in noiseless and with noise complete tests.

	TFB1		TFB2		TFB3		TFB4		TFB5		TFB6		TFB7	
	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE	NOISELESS	WITH NOISE
QBI	0.30	0.32	0.35	0.30	0.35	0.22	0.52	0.27	0.38	0.16	0.29	0.20	0.50	0.35
QBII	0.66	0.40	0.62	0.61	0.89	0.91	0.80	0.63	0.65	0.51	0.78	0.72	0.47	0.36
QBIV	0.48	0.34	0.66	0.71	0.87	0.74	0.93	0.90	0.70	0.54	0.84	0.80	0.59	0.48
QBV	0.37	0.25	0.60	0.44	0.56	0.65	0.67	0.54	0.67	0.56	0.82	0.70	0.48	0.32
QBVI	0.36	0.25	0.82	0.69	0.82	0.70	0.81	0.68	0.73	0.50	0.95	0.86	0.43	0.33

Table 7 – Difference in system effectiveness of the bullet complete test with noise performed by students in relation to previous complete test with noise by forensic scientists (Table 6).

	TFB1	TFB2	TFB3	TFB4	TFB5	TFB6	TFB7
QBI	0.15	-0.02	0.13	-0.11	-0.10	-0.05	0.10
QBII	-0.13	-0.07	-0.37	-0.17	0.06	0.02	-0.06
QBIV	0.06	-0.06	-0.22	-0.19	-0.19	-0.30	-0.08
QBV	-0.08	-0.06	-0.15	-0.18	-0.16	-0.26	-0.02
QBVI	0.18	-0.16	-0.05	-0.14	-0.04	-0.07	0.14

Table 8 – Difference in system effectiveness of the cartridge case complete test with noise performed by students in relation to previous complete test with noise by forensic scientists (Table 5).

	TFC1	TFC2	TFC3	TFC4	TFC5	TFC6	TFC7
QCI	0.04	0.04	0.06	0.09	0.10	-0.08	0.19
QCIV	-0.12	-0.27	0.07	-0.05	0.01	-0.15	-0.04
QCV	0.01	-0.14	0.01	0.11	0.02	0.05	0.03
QCVI	0.17	0.13	0.00	-0.18	0.07	-0.04	0.17

Table 9 – ANOVA results (significance level 5%).

Data	*Variable Source*	*F-Fisher*	*P-value*	*F-Critical*	*Supported hypothesis*
ANOVA1 (data from Table 5)	**Type of test** *(d)*	13.165	0.00076	4.072	*h1*(e)
	Type of test-fired cartridge	1.763	0.13	2.323	*h0*(f)
ANOVA2 (data from Table 6 and Table 7)	**User**	3.04	0.09	4.01	*h0*
	Type of test-fired bullet	3.14	0.01	2.27	*h1*
ANOVA3 (data from Table 6 and Table 7) *(g)*	**User**	13.84	0.001	4.17	*h1*
	Type of test-fired bullet (no LRN)	3.54	0.02	2.69	*h1*
ANOVA4 (data from Table 5 and Table 8)	**User**	0.10	0.76	4.07	*h0*
	Type of test-fired cartridge	2.94	0.02	2.32	*h1*

(d) – noiseless or with noise complete test
(e) – *h1:* at least one of the mean effectiveness criterion are statistically different from the others
(f) – *h0:* all mean effectiveness criterions are statistically indistinguishable
(g) – data disregarding LRN results

3.4 PRELIMINARY CONCLUSIONS

For the sake of this study, a set of ammunition components collected from .38SPL firearms were entered into the BIS Evofinder®, and automated comparisons in different configurations were performed to investigate influence factors in the system effectiveness.

The initial test comparing only test-fired bullets showed equal quality in marks of test-fires of the same type and from the same gun, and good capability of the system to match them, resulting in system effectiveness 0.89. Only JHP-ST showed an absence of individual characteristic marks, which affected the system's capability to match them in the initial test, and also system effectiveness in the subsequent two tests.

By allowing correlations of bullets of different types, the system effectiveness dropped from 0.89 to 0.61, and it was clear that the LRN bullet is difficult to correlate with other types of bullets. These combined results, and crime characteristics of each site, can be used to establish best practices for collecting test-fires from seized guns.

The system performance in the initial test with bullets, 0.89, demonstrates that BIS, if properly utilized, can be extremely useful to solve firearm-related crimes. Nevertheless, the effectiveness decreasing to 0.61 and 0.51 in the subsequent complete tests, reinforce the conclusion that the state-of-the-art of this technology is not ready for registering all guns (Kopel; Burnett, 2003; Cork et al., 2008; De Ceuster; Dujardin, 2015; Santos; Muterlle, 2015),

The initial test performed with cartridge cases resulted in poor system effectiveness to match them by breech face marks (0.40), even in instances with strong and reproducible individual marks. This fact negatively affected the system performance on cartridge cases noiseless complete test (0.55), and complete test with noise (0.43), letting results relying primarily on firing pin matching possibilities. Possibly because of that, no meaningful difference in system performance was found regarding cartridge case types.

Finally, the experiment replication demonstrated that someone without any previous training in firearm identification can easily operate the system imaging process, being only advisable to review their work in assigning LEA and GEA of interest.

4 ASSESSMENT IN THREE SYSTEMS AND THREE CALIBERS

This chapter explains replications of the experiment on Evofinder®, using their up to date software version, and on Arsenal® and IBIS® systems, the assessment of the ammunition components, as well the expansion of the research to more two calibers.

4.1 EXPANDING THE RESEARCH

Previous chapter results and discussions are related to a specific caliber and a single BIS, and therefore similar conclusions may not be observed with other calibres and correlation algorithms. Thus, replications of the experiment in Chapter 3 using other systems, databases, and calibers were suggested as a further step to more deeply understand the factors affecting system performance and effectiveness.

The same steps described in section 3.2 of the previous chapter were replicated and results obtained from three worldwide adopted systems, Arsenal® (software version 4.1.6), Evofinder® (software version 6.4.1), and IBIS® (software versions 3.0 for BUL and 3.2 for CC) for direct comparison. Additionally, the experiment was expanded to include firearms and ammunition not only on .38SPL caliber but also on 9x19mm and .40S&W calibers.

4.1.1 Rationale for selecting the assessed calibers

Figure 53 shows the number of bullets and cartridge cases from real criminal cases, that have been registered into the IBIS® system employed for approximately ten years in Salvador, Bahia, Brazil, by the Forensic Ballistic Section of the General Institute of Technical Scientific Police.

From a total of 27,467 registered bullets, approximately 58% correspond to the .38SPL caliber family (.38SPL and .357 Mag). Of the remaining, two other calibers present a significant proportion of the total records; 9mm family (9x19mm and .380Auto) at 23%, and the .40S&W caliber at 15%. With a total of 5,076 cartridge cases, the most abundant caliber is 9mm family (9x19mm and .380Auto) with 65% of registered ones, followed by .40S&W caliber, with 22% of all records. This data are the main reason to include these three caliber on this research.

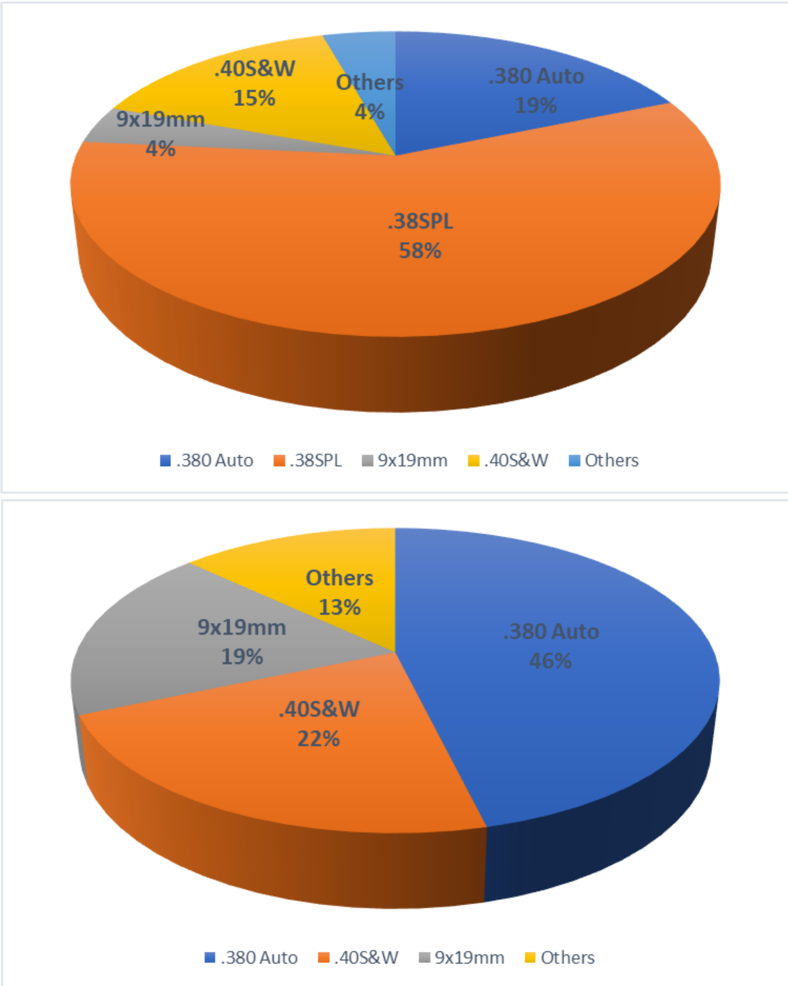


Figure 53 – Number of bullet (top) and cartridge case (bottom) images registered in IBIS® System in Salvador, Bahia, Brazil (Source: System Report provided by Forensic Ballistic Section).

4.1.2 Selected firearms

Some studies assessed the effectiveness of ballistic comparison by creating a reference database from gun parts consecutively or sequentially manufactured (Bachrach, 2006; Hamby et al., 2009; Song et al., 2018). Such an approach tries to demonstrate, regardless of the fairly similar marks observed on barrels or slides manufactured one after another using the same tools, the capability of differentiation even in these more difficult cases.

Although this is a defensible approach, a situation more similar to the physical realities observed in day-to-day comparisons performed in Forensic Laboratories involves a variety of firearm brands, and therefore the firearms selection for this study considered that, encompassing a variety of firearms "to span the spectrum of weapons commonly found in crime scenes" (Bachrach, 2006, p. 2) (refer to Figure 54).

Figure 54 – Instances of firearms involved in the research, featuring .38SPL Taurus revolver, 9x19mm Smith and Wesson pistol, and .40S&W Taurus pistol.

Table 33 to Table 35 of APPENDIX B: DETAIL OF FIREARMS EMPLOYED ON THE RESEARCH (refer to p. 283) detail the 65 (sixty-five) firearms used in this study, recording if they came from the Police academy, where they had been used for training during some years and then put aside; if they were borrowed from police officers, to whom they have been hand over brand new and therefore are less used, or if they are seized firearms, in case that their history is unknown. The firearm of the research are:

- **16 (sixteen) .38SPL revolvers** – 11 (eleven) Taurus brand and 5 (five) Rossi; analysis of the barrels revealed that all have a conventional rifling profile (refer to 2.1.5 and Figure 16a), 9 (nine) featuring 6R rifled barrel, and 7 (seven) featuring 5R rifled barrel;
- **28 (twenty-eight) 9x19mm semi-automatic pistols –** 11 (eleven) Taurus brand, 2 (two) Jerico, 1 (one) FN (Fabriqué Nationale), 1 (one) Norinco, 1 (one) Smith & Wesson, and 12 (twelve) Glock; regarding the rifling profile, the two Jerico and the twelve Glock have 6R polygonal rifling barrels, while the other fourteen feature 6R conventional rifling barrels;

- **21 (twenty-one) .40S&W semi-automatic pistols –** all but one barrel (gun 12 on caliber .40S&W) have a 6R conventional rifling, the exception featuring a 6L (six left) conventional rifling (refer to Table 35 on p. 286).

4.1.3 Ammunition employed

To collect bullets and cartridge cases for this study, shots were fired into a cotton box (a PVC tube filled with cotton waste and cotton) or a water tank (Figure 23), resulting in 1,684 (one thousand six hundred and eighty-four) fired ammunition components.

For this research the adopted nomenclature was:

- test-fired bullet (TFB) or test-fired cartridge case (TFC): bullet or cartridge case collected from a firearm, that represents the test-fired ammunition component obtained from a seized firearm that is examined in a laboratory;
- questioned bullet (QB) or questioned cartridge case (QC): bullet or cartridge case collected from a firearm that, in terms of this study, simulates the fired ammunition component retained as evidence from a crime scene or from a deceased person.

Table 4 (refer to p. 108) features the type of ammunition selected for test firing the .38SPL revolvers and to collect questioned bullet or cartridge case from these firearms, resulting in 304 (three hundred and four) bullets and 288 (two hundred and eighty-eight) cartridge cases in this caliber.

It should be noted that the .38SPL TFB1 and TFB7 have the same material composition (refer to Table 13 on p. 137), but were collected to verify if, from the collection of TFB1 (which was the first shot) to the collection of TFB7 (which was the last one), there is meaningful difference in the striation marks observed. Still referring to .38SPL caliber, TFB2 and TFB3 feature the same type of bullet, the difference between them is cartridge case material composition and load; TFB2 being assembled in a brass cartridge case with conventional load and TFB3 using a nickel-plated cartridge case with +P propellant (refer Figure 41 and Figure 42 in p. 109). Therefore, in a crime scene would be impossible to differentiate TFB 7 from TFB1, and TFB3 from TFB2, and therefore, as shown in Figure 41 (refer to p. 109), TFB3 and TFB7 were not included in the questioned bullets.

The same approach was utilized to define which ammunition would be selected to collect questioned .38SPL cartridge cases. It can be seen, that TFC2 and TFC7 would be indistinguishable in a crime scene from TFC1 (although the TFC1 and TFC2 bullets are differents), and TFC3 is indistinguishable from TFC4. Therefore, TFC2, TFC3, and TFC7 were not included in the questioned cartridge cases (refer to Figure 42 on p. 109).

From each 9x19mm pistol, test-fired and questioned bullets and cartridge cases were collected according to the ammunition described in Table 10 (refer to Figure 55 and Figure 56). These shots resulted in 336 (three hundred and thirty-six) bullets and 336 (three hundred and thirty-six) cartridge cases in the 9x19mm caliber.

TFB1	TFB2	TFB3	TFB4
QBI	QBII	QBIII	QBIV

Figure 55 – Types of bullets collected from 9x19mm pistols (2 (two) TFB and 1 (one) QB per type of ammunition and per firearm).

TFC1	TFC2	TFC3	TFC4
QCI	QCII	QCIII	QCIV

Figure 56 – Types of cartridge cases collected from 9x19mm pistols (2 (two) TFC and 1 (one) QC per type of ammunition and per firearm).

From each .40S&W pistol, the collecting of test-fired and questioned bullets and cartridge cases employed the ammunition described in Table 11 (refer to Figure 57 and Figure 58). Due to changes in the Copper Bullet CBC ammunition, 10 (ten) .40S&W pistols were test-fired with ammunition assembled in nickel-plated cartridge case with bullet featuring BMC 6 (refer to Table 13 on p. 137), while the last 11 (eleven) .40S&W pistols were test-fired with ammunition assembled in brass cartridge case with bullet featuring BMC 7. These shots resulted in 210 (two hundred and ten) bullets and 210 (two hundred and ten) cartridge cases in the .40S&W caliber.

It is noteworthy that the QBIV and QCIV .40S&W bullets and cartridge cases are from Federal brand ammunition. This is the only non-CBC brand ammunition employed in the study. They were not included as test-firing because the laboratories in Brazil hardly will select this ammunition for test-firing, nevertheless, their ammunition components can be found in a crime scene, and therefore they were included as a variation in the questioned types on this caliber.

TFB1	TFB2	TFB3	Not collected as test-fired
QBI	QBII	QBIII	QBIV

Figure 57 – Types of bullets collected from .40S&W pistols (2 (two) TFB and 1 (one) QB per type of ammunition and per firearm).

TFC1	TFC2	TFC3	Not collected as test-fired
QCI	QCII	QCIII	QCIV

Figure 58 – Types of cartridge cases collected from .40S&W pistols (2 (two) TFC and 1 (one) QC per type of ammunition and per firearm).

Table 10 – Ammunition types selected to collect test-fired components (TFB and TFC) and questioned (QB and QC) from 9x19mm pistols.

Ammunition	**Brand**	**Bullet**		**Cartridge case**	
		Mass (g.)	*Symbols*	*Material*	*Symbols*
9x19mm Full Metal Jacket (FMJ)	CBC	124	TFB1 and QBI	Brass	TFC1 and QC1
9x19mm Jacketed Hollow Point (JHP)	CBC	115	TFB2 and QBII	Brass	TFC2 and QC2
9mm +P+ Gold Jacketed Hollow Point (G-JHP)	CBC	115	TFB3 and QBIII	Brass	TFC3 and QC3
9x19mm COPPER Jacketed Hollow Point (C-JHP)	CBC	92,6	TFB4 and QBIV	Nickel-plated	TFC4 and QC4

Table 11 – Ammunition types selected to collect test-fired components (TFB and TFC) and questioned (QB and QC) from .40S&W pistols.

Ammunition	**Brand**	**Bullet**		**Cartridge case**	
		Mass (g.)	*Symbols*	*Material*	*Symbols*
.40S&W Full Metal Jacket Flat (FMJ-F)	CBC	180	TFB1 and QBI	Brass	TFC1 and QC1
.40S&W Gold Jacketed Hollow Point (G-JHP)	CBC	155	TFB2 and QBII	Brass	TFC2 and QC2
.40S&W COPPER Jacketed Hollow Point (C-JHP)	CBC	130	TFB3 and QBIII / TB3* and QBIII*	Nickel-plated / Brass [(h)]	TFC3 and QC3
.40S&W Federal Jacketed Hollow Point (F-JHP)	Federal	165	QBIV	Nickel-plated	QC4

[(h)]Due to changes in CBC Copper Bullet .40S&W ammunition, ammunition for firing guns 01 to 10 featured nickel-plated CC and guns 11 to 21 brass CC.

Another important clarification is that because for each type of ammunition were collected 2 (two) TFB and 2 (two) TFC, they were termed, for instance, TFB3.1 and TFB3.2, meaning respectively the first and the second test-fired collected with bullet type 3, or TFC4.1 and TFC4.2, for the first and second test-fired collected with cartridge case type 4. On the other hand, as questioned samples, it was collected just one for each type of ammunition.

4.1.4 Data collection

To expand the research encompassing the aforementioned firearms and ammunition, the following steps were followed:

- Use of ammunition collected for Santos' research (2015), comprising:
  - 304 (three hundred and four) .38SPL bullets;
  - 288 (two hundred eighty-eight) .38SPL cartridge cases;
  - 192 (one hundred and ninety-two) 9x19mm bullets;
  - 192 (one hundred and ninety-two) 9x19mm cartridge cases;
- Enlargement of the 9x19mm pistols sample, totaling 28 (twenty-eight) firearms in this caliber, 14 (fourteen) with conventional rifling barrels and 14 (fourteen) with polygonal rifling barrels;
- Test firing the 9x19mm pistols, employing the 4 (four) ammunition types, resulting in 8 (eight) test-fired bullets and 8 (eight) test-fired cartridge cases per firearm (refer to Table 10);
- Collection of questioned bullets and cartridge cases from the 9x19mm pistols, using 4 (four) types of ammunition in this caliber per firearm (refer to Figure 55 and Figure 56);
- Selection of 21 (twenty one) .40S&W pistols;
- Test firing the .40S&W pistols, employing 3 (three) ammunition types, totaling 6 (six) test-fired bullets and 6 (six) test-fired cartridge cases per firearm (refer to Table 11);
- Collection of questioned bullets and cartridge cases from the .40S&W pistols, using 4 (four) types of ammunition in this caliber per firearm (refer to Figure 57 and Figure 58);
- Acquire digital images of the 1,684 fired ammunition components in Arsenal®, Evofinder®, and IBIS® systems;

- Request the automated correlations, varying the database involved in the three-level of comparisons, according to intra-material, inter-material noiseless, and inter-material noise tests described in section 4.3;
- Assess the research ammunition, determining propellant mass, bullet velocity, bullet material, cartridge case material composition, and bullet Brinell hardness (refer to 4.1.5)
- Assess the geometric features of the marks on fired cartridge cases, determining, presence or absence of anvil mark, depth of firing pin mark, and firing pin mark' center;
- Assess orientation angle of breech face mark on the digitalized images of cartridge cases acquired on each system;
- Develop two programs for data analysis, named *analysis_program.py* and *effectiveness.py*, written in Python language;
- Statistical testing and analyses on the resulting data.

4.1.5 Assessment of the ammunition components

Material compositions of cartridge case, bullet, and primer explosive mixture

To obtain the cartridge case and bullet composition of the research ammunition was utilized a Scanning Electron Microscope model Quatum 200 3D - Dual Beam, manufacture by FEI Company and equipped with EDS detector, Backscattered Electron Detector (BSD), Everhart-Thornley Secondary Electrons Detector (ETD), and Wavelength-Dispersive X-Ray detector (WDS) (refere to Figure 59).

In this chemical microanalysis technique – EDS – the sample is bombarded by a beam of electrons that interact with electrons of atoms present in its surface, ionizing them. This leads to a cascade of electrons from a high state to down one accompanied by X-ray emission, balancing the energy difference between the two electrons' states. The abundance of detected X-Rays (EDS) versus their energy allows the identification of peaks that are characteristic of each chemical element that emitted them. The peak intensity is proportional to the amount of each element allowing their proportional quantification (Goldstein, 2003).

The technique uncertainty was assessed by analyzing a five-pointed gold ring star (08, 10, 12, 14 and 18-carat gold) in addition to the pure gold standard. The results pointed to uncertainties ranging from 2 wt% to 5 wt%. However, this uncertainty may increase depending on the element analyzed (eg carbon, nitrogen, and oxygen do not perform well), sample concentration (low concentrations present a significantly higher uncertainty) and the environment in which it is found. Because of that concentrations below 1 (one) wt% are hardly detected.

Figure 59 – SEM FEI Quantum 200 ED.

In the analyses of the cartridge cases used in this study, it was confirmed the brass main component with variations in the proportions of the components, zinc varying from 23 wt% to 27 wt% and therefore copper found between 73 wt% to 77 wt% (see results in Table 30 on p. 280).

For bullets, the results allows to categorize the bullet material composition (BMC) into 7 (seven) groups (BMC1 to BMC7) detailed in Table 12.

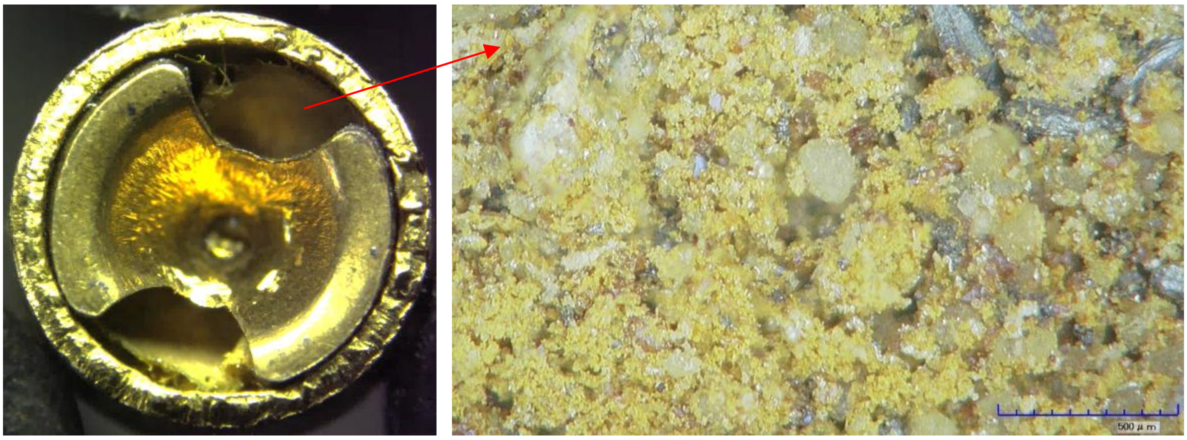
Table 12 – Bullets of the research grouped by bullet material compositions (BMC).

GROUP	MAIN EXTERNAL MATERIAL	COMPOSITION
BMC1	LEAD	99 wt% Pb, 1 wt% Sb
BMC2	BRASS	Core: 99 wt% Pb and 1 wt% Sb; Jacket: 75 wt% Cu, 25 wt% Zn;
BMC3	NICKEL	Core: 99 wt% Pb and 1 wt% Sb; Jacket: 70 wt% Cu, 30 wt% Zn; Thin cover layer: 99 wt% Ni;
BMC4	BRASS	Core: 99 wt% Pb and 1 wt% Sb; Jacket: 70 wt% Cu, 30 wt% Zn;

BMC5	COPPER (but termed GOLD)	Core: 99 wt% Pb and 1 wt% Sb; Thin cover layer: 77 wt% Cu, 18 wt% Zn, and 5 wt% Ni; Jacket: 90 wt% Cu and 10 wt% Zn;
BMC6	COPPER	A solid >99 wt% Cu;
BMC7	COPPER	Thin cover layer: >99 wt% Sn; Core: > 99 wt% C.

Knowing the caliber, form, and material composition makes it possible to categorize the 14 (fourteen) types of bullets of this study according to Table 13.

For the primer explosive mixture, visualized in the photomicrograph of Figure 60b, the chemical microanalysis by Energy Dispersive X-Ray Spectroscopy revealed presence of Barium (Ba), Lead (Pb), Aluminum (Al), Antimony (Sb), Sulfur (S), Nitrogen (N), Oxygen (O), and Carbon (C) (refer to Table 31 on p. 280 of APPENDIX A: RESULTS OF EDS ANALYSIS).



a) **b)**

Figure 60 – Photomicrographs of the: **a)** primer cup, highlighting the anvil, and **b)** explosive mixture.

Firearm details and bullet velocities

The firearms were assessed regarding caliber, type and length of barrel, and manufacturer, as recorded in the Table 33, Table 34, and Table 35 (refer to APPENDIX B: DETAIL OF FIREARMS EMPLOYED ON THE RESEARCH on p. 283).

Considering the length and type of barrel of the firearms and the ammunition types involved in the research, the velocity of the bullets were measured by a Chrony ballistic chronograph, model Alpha, positioned approximately 3.6m (three point six meters) from the muzzle firearm.

Table 13 – Details of 14 (fourteen) types of bullets of this study.

Nominal caliber	***Real caliber (mm / in)***	***Bullet***	***FORM***						***BULLET MATERIAL COMPOSITION (BMC)***						
			LRN	***FMJ***	***FMJ-F***	***SJHP***	***JHP***	***HP***	***1***	***2***	***3***	***4***	***5***	***6***	***7***
.38SPL	**9.06 / 35.67**	**TFB1 and 7, QBI**	✓						✓						
		TFB2 and 3, QBII				✓				✓					
		TFB4, QBIV		✓							✓				
		TFB5, QBV					✓				✓				
		TFB6, QBVI					✓						✓		
9x19mm	**9.04 / 35.59**	**TFB1, QBI**		✓								✓			
		TFB2, QBII					✓					✓			
		TFB3, QBIII					✓						✓		
		TFB4, QBIV						✓						✓	
.40S&W	**10.10 / 39.76**	**TFB1, QBI**			✓							✓			
		TFB2, QBII					✓						✓		
		TFB3, QBIII						✓						✓	
		TFB3*, QBIII*(i)						✓							✓
		QBIV					✓					✓			

(i) – Due to changes in CBC Copper Bullet .40S&W ammunition, ammunition for test firing guns 01 to 10 on this caliber featured **TFB3, QBIII** type of bullet, while guns 11 to 21 **TFB3*, QBIII*** type of bullet (note difference in BMC6 and BMC7 compositions).

According to the Alpha Chrony user's guidebook[15], this chronograph operates by two photosensors (refer to Figure 61). Because the voltage generated by these sensors is proportional to the amount of incident electromagnetic radiation, when a bullet passes between the first detector and the light source, a momentary change in light intensity is detected, tripping a counter. The counter is shut off when the other photosensor detects the bullet passage, also sensing the change in the amount of incident light.

The obtained velocities were recorded in Table 36 (refer to p. 288) of the APPENDIX B: DETAIL OF FIREARMS EMPLOYED ON THE RESEARCH.

Figure 61 – Photograph of the Chrony Alpha Chronograph.

Bullet hardness

The Brinell test was proposed in 1901 as a simple and effective way to measure the hardness of materials. The test consists of applying a known force to press a high rigidity sphere into a solid surface and measure the diameter of the sphere printed on the material (Hill et al., 1989).

Later studies, that related Brinell hardness to tensile strength (Tien, 2008), and to uniaxial properties of the material (Biwa; Storåkers, 1995), helped to popularize it.

Hill et al. (1989) pointed out that the widespread use of this test can be attributed to: the spherical indenter being a precise, yet robust and inexpensive instrument; can be applied

[15] Available at http://www.shootingchrony.com/manual_ASC&AMC.htm#how_it_works [Accessed 08/12/2019].

directly on the material leaving an indent in the surface as the only permanent deformation; there is a coded, and fully objective procedure; and the value obtained is indicative of basic material properties such as tensile strength and hardening capacity.

Leyi et al. (2011) proposed Figure 62 to explain the Brinell test, depicting a spherical tip indenter of diameter *D* on which a load *F* acts. The slow action of this penetrator on the material generates the permanent cavity with height *h* and diameter *d*. The Brinell hardness value obtained with a tungsten carbide tip (HBW) is calculated by equation 4.1.

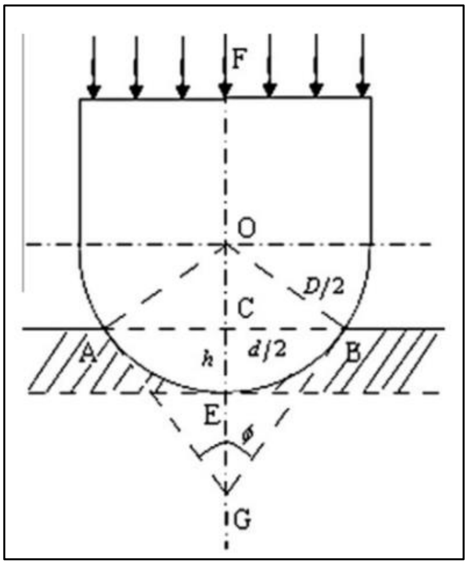


Figure 62 – Brinell hardness measurement principle. *F* is the loading force, *d* is the diameter of the print, and *D* is the diameter of the indenter (Source: Leyi et al., 2011, p. 2131).

$$\text{HBW} = \frac{0.102 \times F}{\pi . D^2 (1 - \sqrt{1 - \frac{d^2}{D^2}})} \, . \qquad 4.1$$

Brinell standardization norm suggests the use of a 10mm sphere with a load of 3000kgf (kilogram-force), but it is possible to reach the same hardness values provided that the selection of load (*F*) and penetrator diameter (*D*) generates an impression of diameter (*d*), under the limits of equation 4.2 (NBR NM ISO 6506-1, 2010).

$$0.24. D \ < d \ < 0.6. D \ . \qquad 4.2$$

To obtain the print diameter within the specified values, the ratio between F and the square of the penetrator diameter must be kept constant, called load factor (FC) and defined by equation 4.3.

$$FC = \frac{F}{D^2}\,. \qquad 4.3$$

ATTACHMENT D (refer to p. 302), taken from NBR NM ISO 6506-1(2010), specifies load factors for different nominal force values and indenter diameter.

Sources that affect Brinell hardness measurement uncertainty include measurement error in print diameter, error in applied force, error in penetrator diameter, failure in the machine or sample stability in measurement, and sample surface quality (Leyi et al., 2011).

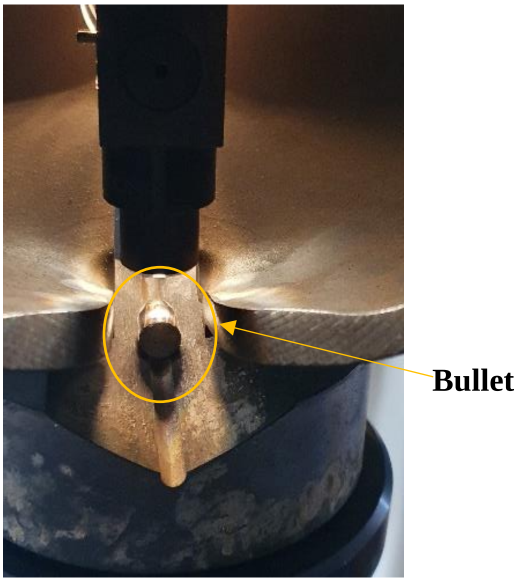
In Brazil, the test is standardized by the *Associação Brasileira de Normas Técnicas* (Brazilian Technical Standards Association) (NBR NM ISO 6506-1, 2010), for metallic materials up to 650 HBW. The norm specifies some important precautions:

- The thickness of the specimen must have at least eight times the print depth;
- To test the largest representative area of the test piece, the largest possible diameter of the indenter must be selected;
- The distance between the edge of the specimen and the center of each impression must be at least two and a half times the average impression diameter;
- The distance between the centers of two adjacent prints must be at least three times the average print diameter;
- The diameter of each impression must be measured in two directions perpendicular to each other. The arithmetic mean of the two readings should be considered in the calculation of Brinell hardness.

Santos (2015) measured the Brinell hardness of .38SPL and 9x19mm bullets (refer to Table 37 and Table 38 on APPENDIX C: BRINELL HARDNESS TEST RESULTS).

The tests were performed using a ZWICK/ROELL model ZHU250 durometer. Tungsten carbide spherical indenters were employed, acting for 20s (twenty seconds) in each test, with a load that varied depending on the sample and diameter of the indenter, but keeping the factor of load constant, as explained for equation 4.3. With the aid of a camera fitted to the durometer, it was possible to measure the diameter of the prints in two perpendicular directions (refer to Figure 63a). For each bullet analyzed, seven impressions were made in different regions, obeying distance from the edge and other indentantions, according to ABNT NBR NM ISO 6506-1, 2010.

These procedures were replicated on this research for the .40S&W bullets, with the results recorded in Table 39 of APPENDIX C: BRINELL HARDNESS TEST RESULTS (refer to p. 291).



a) **b)**

Figure 63 – **a)** ZHU250 durometer performing **b)** hardness test on a bullet, that for the test was positioned on the equipment track.

Propellant mass and composition

For each type of ammunition of the research (refer to Table 4, Table 10, and Table 11) the unfired cartridges were disassembled and the average propellant mass was obtained by the direct measure in a 0.001g precision balance. Scanning electron microscopy images, acquired by Everhart-Thornley Secondary Electrons Detector of ammunition propellant sampled in this study revealed disc-shaped of about 0.80mm diameter and 0.16mm thickness (Figure 64).

Finally the propellant composition, if single-based or double-base, was obtained using a Nicolet IS10 spectrophotometer from Thermo Fisher Scientific, equipped with a diamond lens ATR accessory[16]. The basic principle of FT-IR is to shine a sample with an incident beam containing many frequencies of light and measure how much of that beam is absorbed by it. Varying the frequency combination during a timespan will provide absorption data for

[16] Equipment brochure available at https://assets.thermofisher.com/TFS-Assets/LSG/brochures/BR51502-E-1214M-iS10-L-1.pdf [Accessed 22/11/2019].

each frequency. To obtain the spectrum a mathematical Fourier transformation is applied. The ATR accessory is an infrared spectroscopy advance that enhanced the method regarding preparation and spectral reproducibility. By it, a totally internally reflected infrared beam passes through a sample in contact with a high refractive crystal, generating an evanescent wave. The alteration or attenuation of this wave is collected by the detector and analyzed to generate an infrared spectrum (Schuttlefield; Grassian, 2008; FTIR-ATR, 2019).

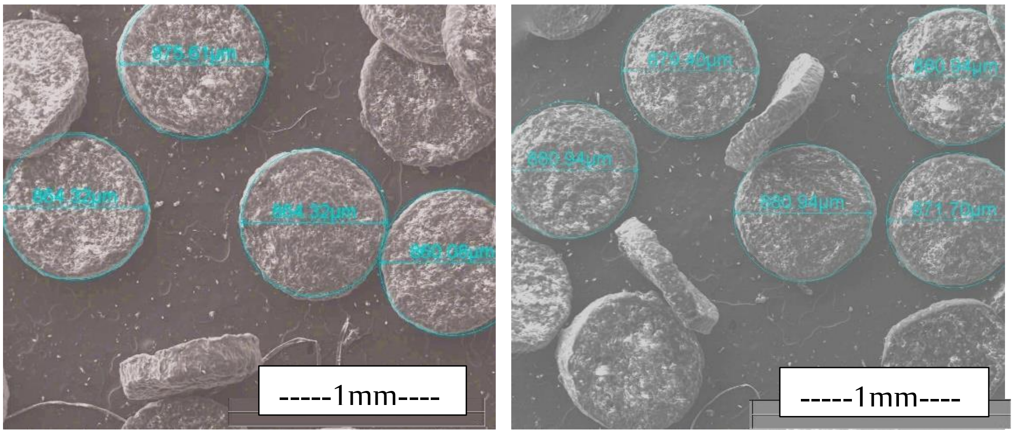


Figure 64 – Scanning electron microscopy image, obtained by Everhart-Thornley Secondary Electrons Detector, of two 9x19mm ammunition propellants.

The obtained propellant mass and composition can be seen in Table 40 and Table 41 (refer to pp. 292 and 295 of APPENDIX D: DETAIL OF AMMUNITIONS EMPLOYED ON THIS RESEARCH).

4.2 DESCRIPTION OF THE THREE SYSTEMS

The selection of the three systems for the experiment replication accrued from author interactions in congress and conferences, from companies' interests, and also from the availability of these systems for Brazilian forensic experts. Other ballistic identification systems are available, however, the research was constrained to these three due to their dominance in the global market (Gerard et al., 2017) and due to the feasibility for completion of the research during its planned time span.

The Arsenal® ABIS (Automated Ballistic Identification System), developed by Russian IT company and manufacturer PAPILLON AO, is informed to be distributed as a single-machine or as networked systems in 25 (twenty-five) metropolises through Russia and in forensic laboratories of 16 (sixteen) countries[17].

The Evofinder® is a product of ScannBI Technology Europe GmbH company, that informs its installation in more than 20 (twenty) countries and 50 (fifty) laboratories. The countries with Evofinder® operation include Austria, USA, Cyprus, Egypt, China, France, Uruguay, Switzerland, Germany, Morocco, Nicaragua, Greece, Finland, Slovenia, Belgium, Colombia, Malaysia, and Brazil[18].

The IBIS® (Integrated Ballistics Identification System) developed by Forensic Technology Inc., a company of the Ultra Electronics group, has been distributed in more than 120 (one hundred and twenty) countries, totalizing more than 700 installations[19].

Table 14 compares the operation of the systems as informed by the developers, considering the versions assessed on this research.

Table 14 – Systems' operational technical data.

TYPE	SYSTEM	Caliber of operation	Scanning time(j) (min:s(k))	Image lateral resolution (μm)	Image vertical resolution (μm)	Image file size (MB(l))
BUL	ARS	1mm to 22mm	5:31	2D - 3 3D - 24	10	8
	EVO	Up to 23mm	4:09	3.5	1	30
	IBIS	4 to 20 mm	23:12	2.7	<0.5	40
CC	ARS	Head – diameter up to 20mm	4:50 (head)	2D - 3 3D - 24	10	16
	EVO	Head – diameter up to 25mm	3:25 (head)	3.5	1	25
	IBIS	Head diameter:2 to 27 mm	9:05	3 to 6	<2	10 to 12

(j) – average time obtained on this research for scanning 9x19mm BUL or CC
(k) – Minute:second
(l) – Megabyte (MB)

[17] http://www.papillon.ru/eng/40/ [Accessed 25/11/2019].
[18] http://evofinder.com/events/page/5/ [Accessed 25/11/2019].
[19] http://www.ultra-forensictechnology.com/about#ibin, [Accessed 23/01/2017].

4.2.1 Arsenal®

Arsenal® is a ballistic identification system designed as an integrated solution from imaging ballistic specimens to making comparison conclusions. The following summarized description of the system is derived from the impressed user guide (PS, 2014) and from the operation of the equipment by the author of this thesis. The Arsenal® main toolbar is shown in Figure 65, containing shortcuts for all applications.

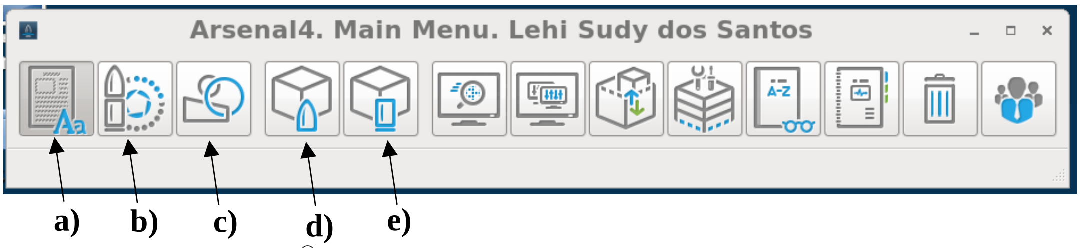


Figure 65 – Arsenal® main toolbar, presenting the applications for: **a)** request acquisition, **b)** digitalize sample, **c)** encode sample, **d)** bullet database, and **e)** cartridge case database.

The first application (Figure 65-a) is designed for entering case-related information and specific parameters about the sample to be scanned, allowing the request of image acquisitions. For each set of fired ammunition components to be scanned, administrative information may be registered, including criminal case number, examiner and laboratory of the examination, and the number of objects linked to the crime scene or collected as test-fires. These objects can be recorded as Evidence Bullets, Test-fired Bullets, Evidence Cartridge Cases, or Test-fire Cartridge Case, allowing management of the database partitions.

The tab *Characteristics* of this application contain the fields to be filled out regarding the caliber and format of each object. From a list of many know calibers and cartridges, parameters of bullets, such as length, diameter, and weight, or for cartridge cases, including length and rim diameter, are automatically completed with predefined values. These parameters are very important because they will be used for the scanner operation.

If the object is being registered as a test-fired, another tab is available for the firearm model, serial number, and the number of land/grooves registration. At completing the information the scanning requests, one for each object, targeted as *Normal*, for standard scanning request, or as *Urgent*, for high-priority request, can be generated.

The next application (Figure 65-b) lists the scanning requests, that can be sorted according to the type of object previously attributed. The object information can be seen and edited. By launching the request, for a specific specimen or for multiple ones, the scanner is activated.

The scanner is the heart of the solution that is designed as a single component that provides “automatic, non-contact image scanning of both the side and the head of bullets and cartridge cases, and semi-automatic scanning of fragments (with manual focusing and positioning of specimens)” (Ibid., p. 8). (refer to Figure 66).

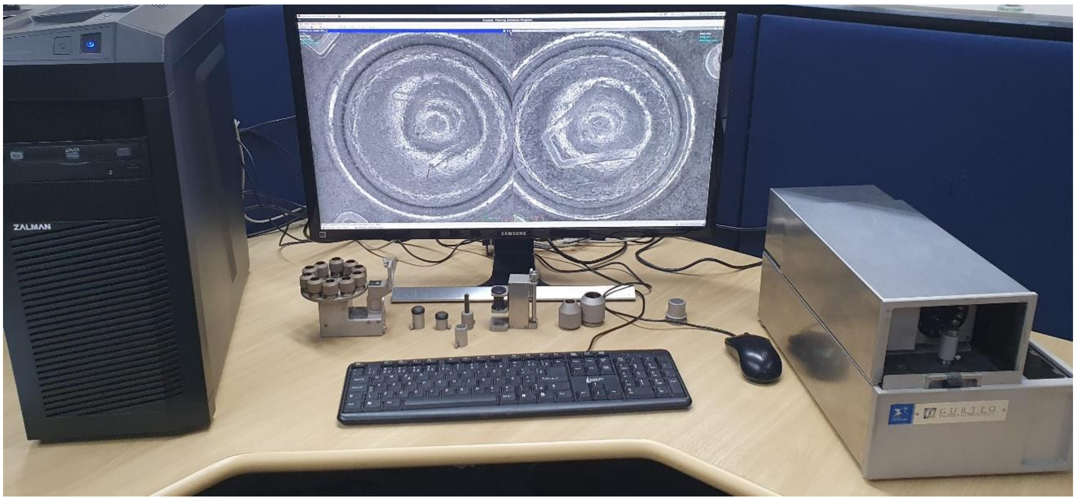


Figure 66 – Photograph of an Arsenal® system, with: scanner (right), bullet and cartridge case holders (center), and desktop computer (left).

The principle of operation of the scanner is the line-scan technique, referred by the developers as a “slit method layer by layer” (Ibid., p. 36). The line-scan technique has been favorably reviewed by Dongguang Li (2009).

If the surface to be scanned is a bullet or cartridge case side, a linear fragment in the longitudinal length of the sample is imaged, followed by the sample rotation at an angle of 0.045 degrees, for another linear fragment acquisition. Because the surface has a 3D topography, the acquisition of a completed 360-degree circumference of the sample generates a layer in which some parts of the image may be in focus and others may not. Therefore, the optical system shifts 0.095mm forward and, by another 360-degree successive linear fragment scanning and rotation, a next layer is captured, which may feature other parts in focus. Successive forward shifts allow other layers acquisitions, up to the depth that the operator has selected. A final collated of the layers is generated with sharp, complete in focus, circumference image (PS, 2014).

For cartridge case head imaging the CCD-sensor moves along its axis for full depth characterization. Before each scanning, the focus is automatically set, being able to capture up to 10 (ten) images; 1 (one) in direct annular and 1 (one) in diffuse annular illumination, and 8 (eight) in 45º sectored lighting. These 10 (ten) images are then collated for full cartridge case head imaging, including FP depth characterization. No orientation is required in relation to CC marks (Ibid.).

Deformed bullets and jacket/shell fragments may also be scanned, including the acquisition of non-consecutive LEA of the same bullet, or marks of significance for identification.

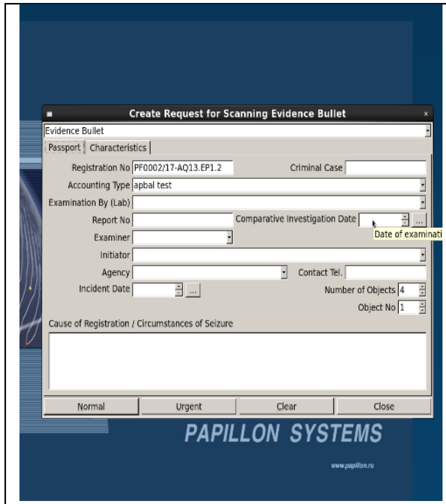
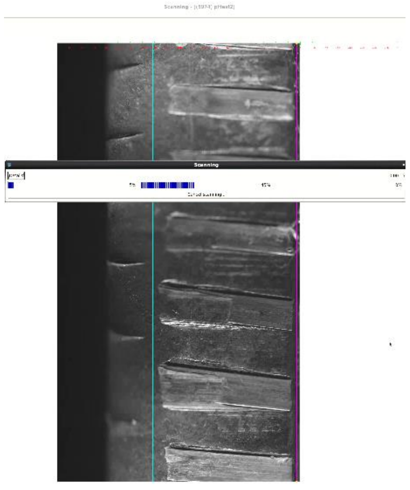
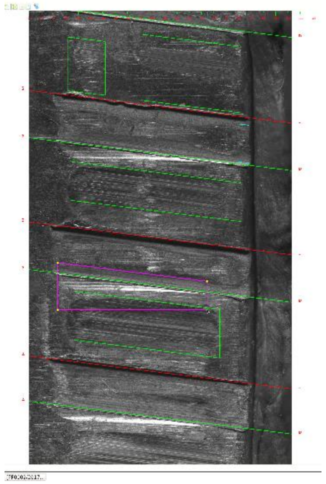
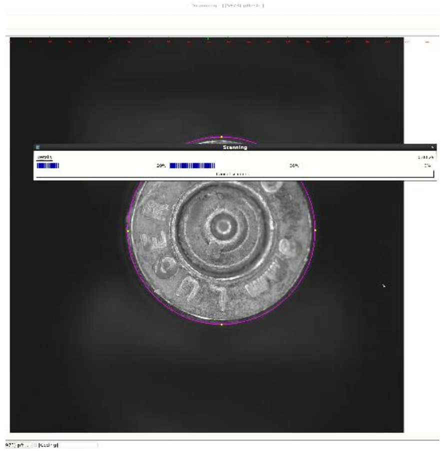
Special holders for bullet or cartridge case are provided to position the specimen for scanning. For cartridge case head scanning an automatic rotating holder is also available, which allows scanning of up to 10 (ten) cartridge cases, one after another, automatically (refer Figure 66). At the end, images acquired must be sent through the encoding stage.

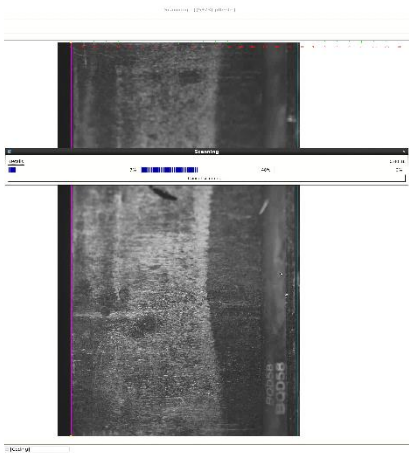
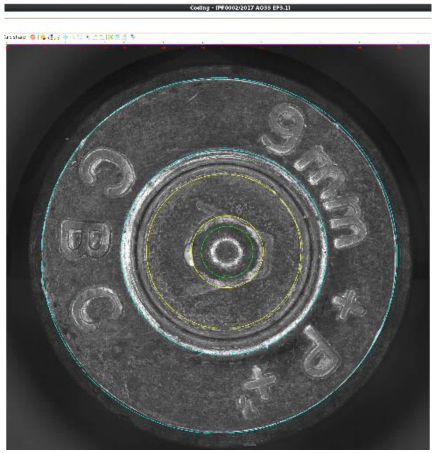
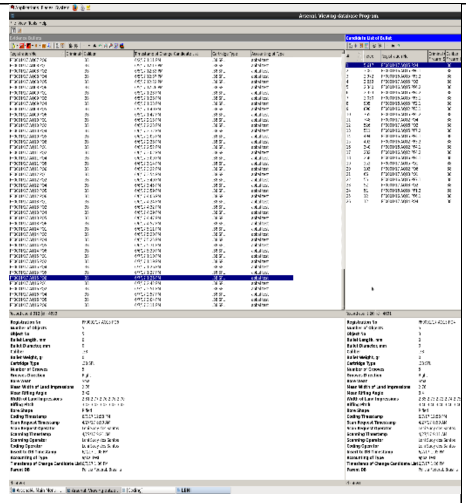
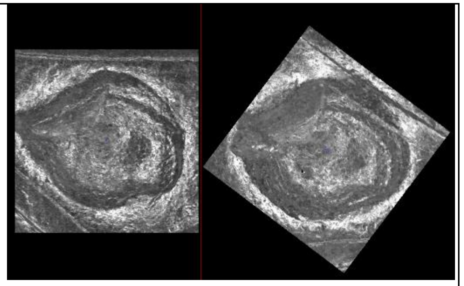
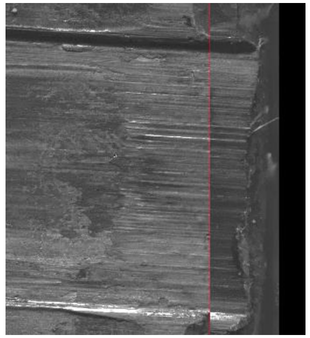
The encoding application (Figure 65-c) is used to manually outline important features of the image so the system can extract unique signatures, by which the exhibits can be compared to the database images. The system features a tool that asks the user to specify the number of LEA/GEA on a bullet image and automatically find and mark the rifling edges. After that skid (primary), LEA, and GEA marks can be assigned.

Impressions produced on a cartridge case through loading, firing, and extraction operations can be delineated. Circles are used to outline the firing pin, drag, extractor, and feed marks, and are used to delimit areas of interest regarding breech face marks, establishing limits for firing pin impression, primer cup, and for the external perimeter of the cartridge case head. The angle between the extractor and ejector marks can be indicated, and circles or rectangles can also be assigned for marks of interest in cartridge case sides (Ibid.). The main ROI, either in bullet or cartridge case images, can be automatically assigned and later adjusted.

After the image is encoded, the data of the specimen is displayed with some fields automatically filled in and others available for user complement. The objective of this descriptive information is to narrow down the number of candidates for correlation, eliminating unnecessary comparisons from within the database. A final *Request Correlation* tab must be filled out, establishing criteria for the search on the database, including dates of interest, types of marks, and/or partition of the database to be searched. After this, the sample is saved into the database and the system initiates the correlations against the relevant subset of the database (Ibid.). These encoding processes can be visualized in the Arsenal® operational description depicted in Table 15.

Table 15 – Illustration of Arsenal® operation.

			
For imaging the sample it is necessary to create a scan request, assigning sample's name, type, and caliber, and recording information of the criminal case. The selected caliber determines the initial operating parameters of the scanner.	To scan a bullet the system rotates it along its longitudinal axis and varies the distance between camera and side surface, thus placing different surface heights in focus in the final image.	Prior to loading a bullet image into the database, the marks of interest (including primary, LEA, and GEA) need to be assigned. The system is capable of automatically marking these areas, but it is necessary to adjust the limit of each LEA and GEA and to position other marks.	The head of the cartridge case is scanned by acquiring complete images of it at different focal lengths, allowing a final collated image that includes the entire firing pin mark in focus.

			 
Scanning the side of the cartridge case is similar to the digitalization of bullets, achieved by rotating the cartridge case and varying the focal length.	Prior to submission to the database, the head of the cartridge case should be outlined, along with the firing pin mark perimeter, and areas of breech face marks internal and external to the primer cup. The system is capable of automatically marking the outskirts of the cartridge case head and outlining other marks.	When sending the encoded image to the database the user selects which type of comparison should be performed, whether against all images in the database or against images in specific partitions.	The results of bullet correlation are available in a single list, and for cartridge cases in double lists (by firing pin and breech face marks). The results can be checked using side-by-side images.

The next two applications of the Arsenal® main toolbar (Figure 65-d and Figure 65-e) are designed to manage the bullet and cartridge case databases. Many resources are available for filtering, sorting, or finding objects within the database. The alphanumeric data of any object can be edited and the system keeps a log of all alterations. The object images can be displayed for assessment of the complete image or of encoded characteristic marks, being possible to measure angles and distances. 3D rendering, coupled with rotation or magnification tools, allows further examination of marks on the images.

Upon uploading to the database each object is correlated against the other samples in the database according to the parameters specified during the enconding stage. This generates candidate lists attached to each object, that is sorted in descending order of their matching scores.

For bullets, a unified score is displayed that considers all types of marks encoded on bullet surfaces. For cartridge cases, candidate lists for firing pin, breech face and ejector marks are available. Split-screen for side-by-side comparisons and a hit log to link two specimens allow finding and recording matches, which is the ultimate goal of the solution (Ibid.).

4.2.2 Evofinder®

Evofinder® BIS is a system designed to capture high-quality surface images of fired bullets and cartridge cases and allows storage of these images for manual or automated ballistic comparisons. The following summarized description of the system is derived from the *Client software operation description* (V.6.3) (STEGC, 2018) and from the operation of the equipment by the author of this thesis.

A regular system network includes three main parts:

- Specimen Analysis System (SAS) - a server for data storage, including images and related information, and for automated correlations between a sample against the others on the database;
- Data Acquisition Stations (DAS) – desktop computer attached to a scanner, designed for ammunition elements digitalization; and
- Expert Workstations (EWS) – is a computer united to work on the acquired images, allowing, between others, request correlation, assess the result list, and side by side comparison of two images for forensic expert decision.

An Evofinder® Scanner Control Center application is shown in Figure 67. Cartridge-Cases EVOFINDER, Bullets EVOFINDER, and *Reference Information Manager* application shortcuts can be seen at the upper center of the image.

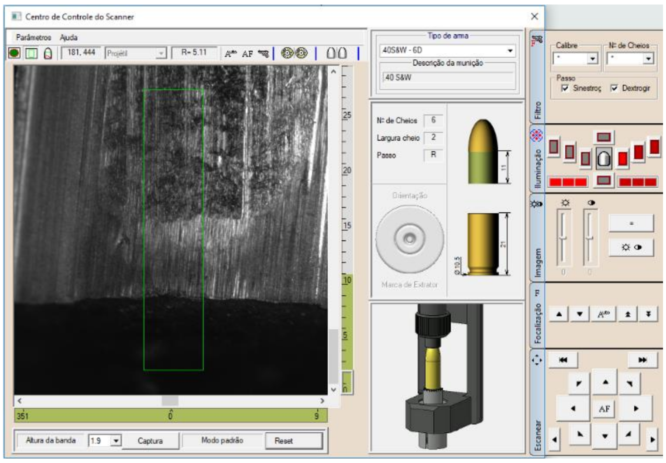


Figure 67 – Evofinder® Scanner Control Center.

To start scanning the user needs to insert the fired ammunition component with the proper holder into the scanner, which will automatically recognize whether is a bullet or a cartridge case to digitalize (refer to Figure 68).

Figure 68 – Evofinder® Data Acquisition Station (DAS) consists of a desktop computer, scanner, and ammunition element holders.

Selecting the firearm system (caliber) specifies the parameters of operation for the scanner, so it can properly digitalize the images of bullets or cartridge cases according to the their specifics.

The *Reference Information Manager* features many properties of firearm systems and correspondent ammunition, including twist direction, number and width of LEA, cartridge case head diameter and side length, and firing pin shape. If a new caliber is not on the extensive pre-defined list within the acquisition software, a new firearm system or ammunition type can be recorded. The firearm system selection for scanning includes the orientation for the cartridge case in the holder as it can be oriented by the ejector, extractor, firing pin drag mark, parallel breech face striae, or another mark as reference.

The imaging technique was developed based on many patent rights of the company, which includes an autofocusing system with depth discrimination achieved by a combination of the focus variation and photometric stereo methods (refer to Focus Variation on p. 89; Photometric stereo on p. 92).

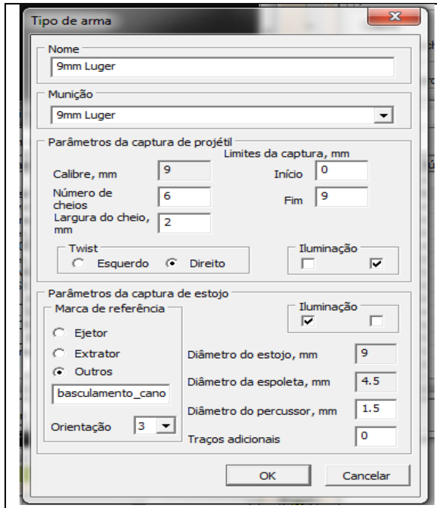
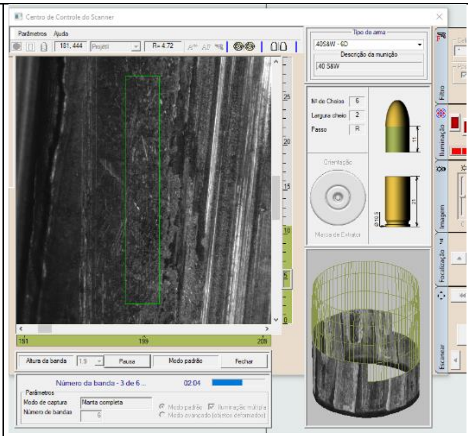
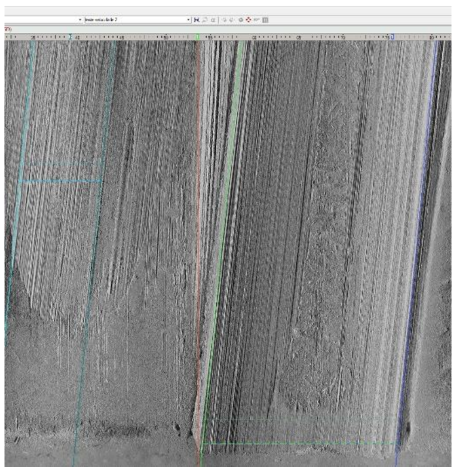
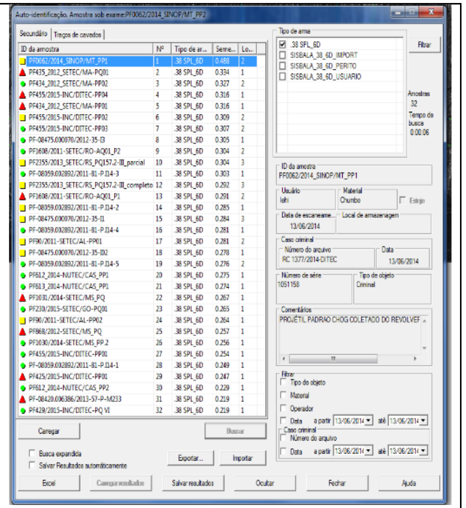
The system is automated for most of the acquisitions, but control buttons are available for managing lighting, focus, brightness, and contrast, preceding image acquisition. For bullet scanning, there is a *Bullet preview* function, which allows delimitation of the right, left, top, and bottom recording area borders, which is particularly helpful for the digitalization of damaged bullets (Ibid.).

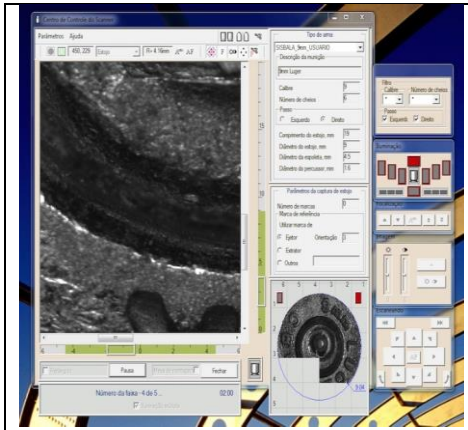
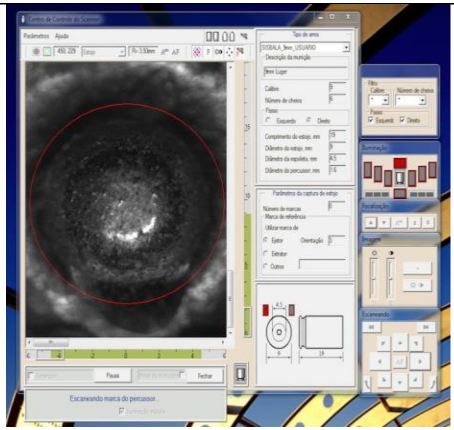
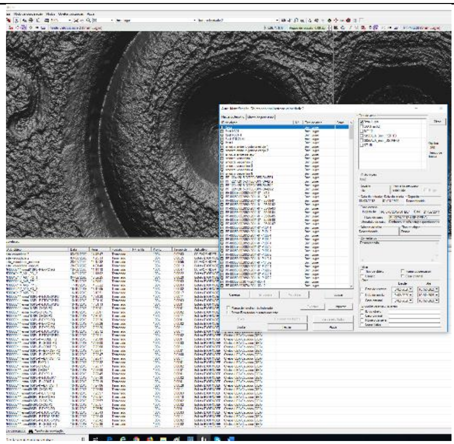
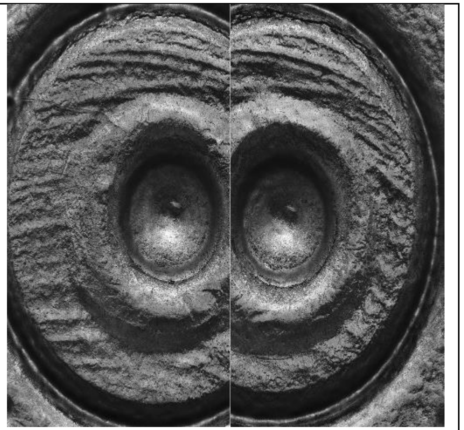
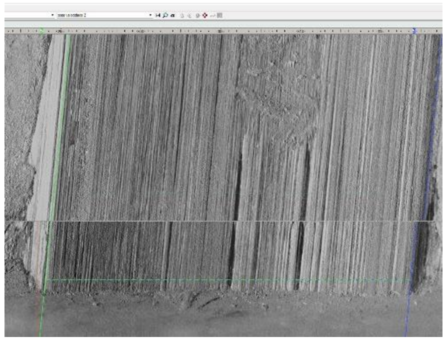
For bullet scanning, the system has two variants, *evolvement* and *fragments*. In both modes, the operator assigns the number and height of the bands, and the system automatically divides the bullet lateral surface accordingly. Standard or Advanced recording modes are available, advisable for pristine or deformed bullets respectively. Additionally, each band is divided into 100 rectangles in standard recording mode, or into less in customized advanced mode (Ibid.).

Bullet digitalization follows two main process, both carried out frame by frame, and achieved by rotating the specimen and scanning the sample from bottom to the top band. In the first process, the system calculates by focus variation measurement the best position for the sharpest imaging. After determining the bullet ideal layer, the system comes back to the initial rectangle for another ordered scanning, and by keeping each rectangle static according to the best focus position previously determined, and by varying the direction of illumination, it acquires many images of each rectangle. The final image is obtained by the collating of the images of all rectangles. This acquisition process can be visualized in the Evofinder® operational description depicted in Table 16.

For cartridge case head digitalization the system utilizes three points to determine the actual base diameter. If the base edge has slopes a specific function can be assigned for higher accuracy acquisition.

Table 16 – Illustration of Evofinder® operation.

<table>
<tr>
<td>
</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>For image capture, it is necessary to select the type of firearm, which will indicate the scanner operating parameters according to bullet or cartridge case dimensions. The sample’s name, and the criminal case to which it is linked, will only be assigned at the end of the image acquisition.</td>
<td>To image, the bullet’s outer circumference is divided into bands and each band built up on rectangles. A profile is constructed by rotating the bullet through its longitudinal axis and automatically or manually focusing each frame.</td>
<td>After capturing the bullet image, areas for automated correlation must be marked. This should be done by assigning rectangles in LEA for secondary marks, assigning areas for primary (skip) marks or for GEA marks of interest.</td>
<td>Captured bullet images are saved into the database and automatic correlations can occur after the marking process. For correlation, it is necessary to select the relevant database partitions and correlation results are available in triple lists, by primary, secondary, or GEA marks.</td>
</tr>
</table>

			 
For cartridge case scanning, its head is divided into frames and the images are captured by moving the cartridge case in two orthogonal axes.	At the end of the cartridge case image acquisition, the operator is asked to adjust firing pin mark's center, which was already scanned, including the complete in focus internal depth of the firing pin mark.	A cartridge case does not need to be marked and can be correlated by request against images of selected database partitions, the results being available by firing pin or breech mark.	The results can be checked by side-by-side images.

The area to be scanned is divided into bands and frames with the process carried out from top to bottom band and from the right to the left frame. In the end, an image is opened for evaluation; circles encompass the firing pin mark and the center of the FP mark can be adjusted. The final step includes a complete internal firing pin mark digitalization in focus.

The side of a cartridge case can be scanned and stored as the same object with the image of the cartridge case base. Both surfaces can be aligned using a reference mark at the edge of the sample that had been identified on both images.

After image acquisition, many fields are available for recording information related to the fired ammunition component, including criminal data, ammunition component material or type, and firearm serial number in case of test-fires. The metadata is recorded at the database, but until this point, no automatic correlation is performed . Prior to this it is necessary to open the relevant image on the correspondent application, Cartridge-Cases EVOFINDER or Bullets EVOFINDER, and add some mandatory marks for bullet images, or optional ones for cartridge case images, before the correlation option becomes available. Each of these applications provides a way to browse the database, with many tools for filtering, selecting, adding, deleting, editing, marking, or comparing images (Ibid.).

In the Bullets EVOFINDER application, a tool was designed to mark areas of interest for automated correlation, being possible to outline primary, LEA, and GEA marks. A particularly useful feature of LEA marking is used to clone the first LEA marked to the other LEAs as all should be comparable in width. The auto-identification is enabled after these marks are manually assigned and these allow for the automated correlation of the marks on the specimen taken as reference, against specimens in selected partitions of the database. The correlation results are displayed in lists peoduced in decreasing order of similarity by the type of mark compared.

For cartridge case auto-identification to be enabled, no marking is required. The auto-identification process of this application allows automatic comparisons, against a specific set of cartridge case images, using breech face mark, or firing pin mark, displaying the correlation result in descending order of similitude by these characteristics. A *breech nonoriented* function is available for improvement of the correlation results where there is no visible orientation mark, in which case the system will rotate the compared objects 360 degrees in search for the best matching position. In both applications, the result list can be checked loading the images for side by side comparison with many tools available to help the user to make a virtual comparison conclusion. In the case of a match, the compared specimens can be recorded by the *Save as linked* control button.

4.2.3 IBIS® TRAX-HD3D™

IBIS® TRAX-HD3D™ is a ballistic identification system designed to capture digital information from fired bullets and cartridge cases, to manage a database of the acquired information, allowing automated correlations between these specimens. The following summarized description of the system is derived from the Training Guides 3.0 (UEFT, 2014) and from the operation of the equipment by the author of this thesis.

A regular system includes five main parts:

- BULLETTRAX™ – integrated software and hardware to automate the collection of 2D images and 3D topographic data from bullets and fragments of bullet jackets;
- BRASSTRAX™ – integrated software and hardware to automate the collection of images from cartridge cases;
- MATCHPOINT™ – the analysis station for the expert to check the correlation result lists and to perform comparisons between images;
- DATA CONCENTRATOR – provide storage services and backup the database (acquired images and associated information), and generally produce correlation requests for the specimens newly entered; and
- CORRELATION SERVER – process the requested correlation and return the result to the *Data Concentrator*, for later analysis on the Matchpoint.

IBIS® TRAX-HD3D™ Bullettrax and Brasstrax are shown in Figure 69.

Figure 69 – IBIS® Bullettrax™ (left) and Brasstrax™ (right) acquisition stations.

The first procedure for image acquisition is to create a CASE, recording the type of event, occurrence date, originated agency, supervisor, and level of restriction of the case. The type of event is utilized to classify and organize the information and includes the assignment of a criminal event, such as robbery, homicide, or illegal firearm possession. In a Bullettrax, bullet exhibit or firearm exhibit can be added to the CASE, in a Brasstrax, cartridge case exhibit or firearm exhibit can be added.

For recording a bullet exhibit, its identification number on the system, category, caliber, number of LEA, twist, and rifling type must be attributed. In case of a cartridge case the required fields are, its identification number on the system, category, caliber, and firing pin shape. Optionally, bullet material, and manufacturer, composition, and breech face for cartridge case, are class characteristics that can be assigned (Ibid.).

The *category* and *date of occurrence* are utilized by the system to define the rules of correlation. Selecting the *category* 'evidence of a crime' forces the system to automatically correlate the entering exhibit against previous and futures records. Whether the *category* is test-fired, designated for recording test-fires from firearm seized in a criminal context, there are two options:

- It is assumed that the firearm may return into circulation within the civilian population and therefore this exhibit will be included in correlations with other previous or future records
- The firearm cycle is assumed as terminated, the reason why the exhibit will only be included in correlations against exhibits with occurrence date preceding the test-fired date of collection (Ibid.).

To add a test-fire for registering a firearm, it is mandatory to attribute its identification number on the system, caliber, make, and type. Optionally its model and serial number can be registered too.

Special holders are provided for positioning a bullet or a cartridge case on the microscopes, and selecting the exhibit register number enables the respective *acquire ROI* (region-of-interest images) function. The principle of operation of the Bullettrax is confocal microscopy[20] (refer to Confocal microscopy on p. 87) while the Brasstrax is an application of the photometric stereo method (refer to Photometric stereo on p. 92).

[20] It is worthy to mention that at the end of this research Ultra Electronics Forensic Technology Inc has launched a new Bullettrax, based on the photometric stereo technique https://www.ultra-forensictechnology.com/en/our-products/ballistic-identification/bullettrax, [Accessed 07/12/2020].

For bullet digitalization, two acquisition types are available, *wrap-around*, or *region(s)*. The former is designed for pristine bullets, or even damaged bullets that can be imaged in one single region, and the latter for damaged bullets that need to be scanned in two or more regions. An *advanced repositioning mode* is available to guarantee that the surface to be acquired is as perpendicular as possible to the microscope lens (Ibid.).

To correctly position the bullet for acquisition the *region selection* and *position controls* are available. They can be used to bring the exhibit into focus and ensure that the bullet surface is perpendicular to the lens. Once position, illumination, and focus were adjusted, the *validation process* displays an image of the exhibit in confocal mode (3D) and certifies that the topography is ready for starting digitalization (Ibid.).

When the image is completely acquired a validation screen displays a 2D and 3D representation of the specimen, that can be manipulated or enhanced for better visualization, including adjusting the illumination set and percentage of elevation, simulation of the material composition, and rendering for a combination of 2D and 3D data.

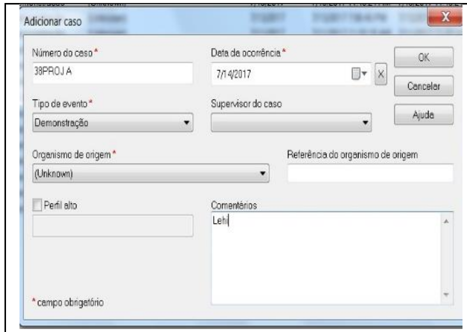
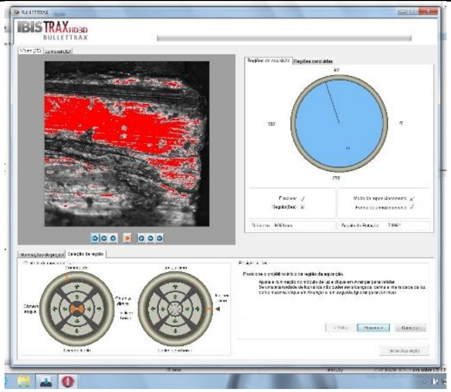
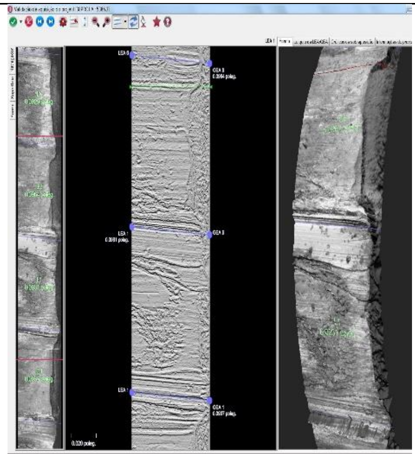
To delimit the LEA and GEA borderlines the system automatically assigns *ancor lines*, that can be verified and adjusted, a process that can be facilitated by inclining the shape of the image or by increasing the 3D elevation, allowing better delimitation of the LEA shoulders at the edge of LEA-GEA transitions.

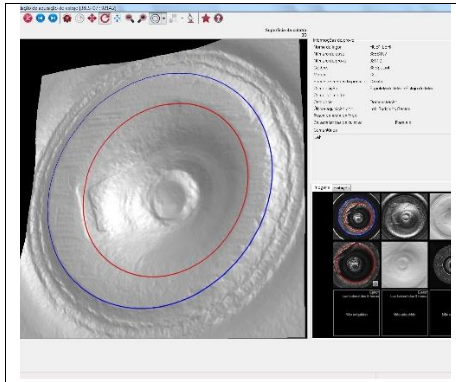
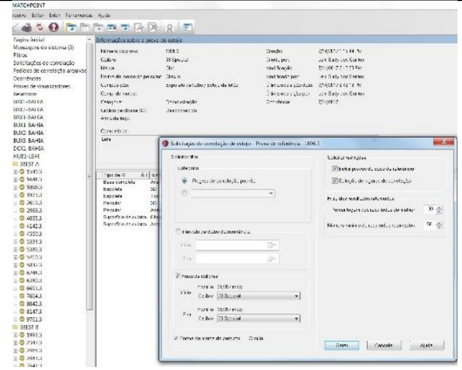
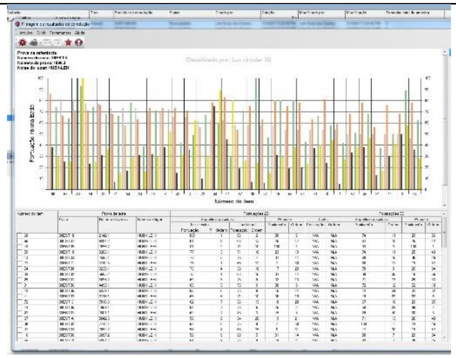
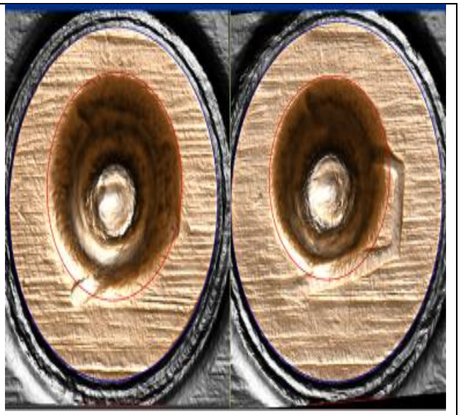
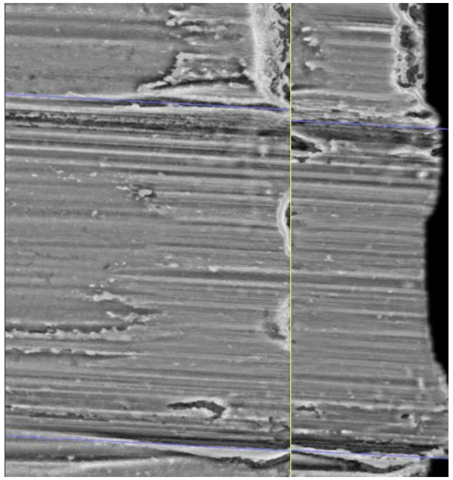
To insert the cartridge case in the Brasstrax it should be properly oriented, and special marks on the holders can be used as a reference for positioning the ejector mark, firing pin drag mark, or extractor mark. For scanning, the ROI (ejector, breech face, firing pin, full headstamp) must be selected and included the 3D acquisition.

The ejector mark must be outlined, the breech face class characteristics assigned, and with light automatically or manually adjusted, the acquisition can be completed automatically. The validation screen is the last process for cartridge case imaging, used to certify that the image meets the recommended quality standard.

The process of bullet and cartridge case acquisition described above include all the marks that are required for automatic correlation. The automatic way for the specimens to be correlated against database image with class-matched characteristics is to submit a case and synchronize it, an automatic process scheduled to occur in a specific hour of each day. Alternatively, a manual synchronization can be launched at any moment. The operation of an IBIS® TRAX-HD3D™ system is depicted in Table 17.

Table 17 – Illustration of IBIS® TRAX-HD3D™ operation.

<table>
<tr>
<td>
</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The first step for image capture in IBIS® is to create a case, for registering data of the occurrence. Pieces of evidence or test-fires (bullets or cartridge cases) can be added to the case, specifying caliber and rifling type for a bullet, or caliber and firing pin shape for a cartridge case.</td>
<td>For bullet scanning, it is necessary to position the bullet at the beginning of the acquisition region and adjust the camera position and the illumination intensity. After that, the bullet is rotated for frame-by-frame acquisition according to the confocal microscopy technique.</td>
<td>After bullet digitalization, the user must verify anchor lines positions, designed to delimit borderlines between LEA and GEA.</td>
<td>For cartridge case scanning, the type of images to be acquired must be selected, including ejector, breech face, firing pin, full headstamp, and 3D. The specimen position and direction must be adjusted, the breech face profile checked, the shape of the ejector outlined, and then the images can be acquired.</td>
</tr>
</table>

			 
A final step includes image validation, with verification of the line delimiting firing pin and breech face areas of interest.	Correlations can be requested manually, against specific caliber ranges and selected database partitions, or through case submission and synchronization, when correlations are automatically performed upon submission of the sample to the database and against images with class-matched characteristics.	The correlation results are displayed in dynamic tables. Cartridge case correlations can be sorted by similarity comparing 2D circular light, 2D sidelight, 2D ejector mark, 2D or 3D firing pin, and 2D or 3D breech face. Bullet correlations can be sorted by Maximum Phase, Peak of the Phase, or Maximum LEA, each one of these 3 (three) correlators available in 2D or 3D, totalizing 6 (six) bullet result lists.	The results can be checked by side-by-side images.

Upon receiving the images the *Data concentrator* creates a ballistic signature of the image and generates an automatic correlation request for the *correlation server*, the image *category*, and the *date of occurrence* being utilized to determine the limit of time criteria, focusing the search on samples of interest. The server also uses the class characteristics of the reference sample, to narrow down the database samples that will be included for automatic correlation. For cartridge cases, the caliber and the firing pin shape are considered, and for bullets, the caliber, number of LEA, twist, and rifling type are class characteristics for filtering the database. The *correlation server* processes the correlation requests and returns the scores to the *data concentrator*, which makes available the results on the *MatchPoint* (Ibid.).

For cartridge cases, 6 (six) scores are provided as results of each correlation, according to correlators as defined in Table 18.

Table 18 – IBIS® cartridge case correlation results.

ACRONYM	**BF2D**	**BF2DSL**	**BF3D**	**EM2D**	**FP2D**	**FP3D**
Termed	Ring light of breech faces 2D	Sidelight of breech faces 2D	Breech faces 3D	Ejector marks 2d	Firing pin 2D	Firing pins 3D

For bullets, scores are generated by comparing the ballistic signature of the LEAs. Each individual LEA of the reference (or questioned sample) is compared against each individual LEA on the test sample. For instance, a comparison of two bullets with 5 (five) LEAs each, will generate 25 (twenty-five) scores. In this example, each set of five scores “can be compared in five possible relative orientations” of the samples (Bachrach, 2006, p. 11), configuring the *phases*. Figure 70 depicts the phase 1 (of 5), when LEA1 is compared to LEA1, LEA 2 to LEA 2, and so on. A counterclockwise rotation of the Bullet 2 will evidence the phase 2, when LEA 1 is compared to LEA 2, LEA 2 to LEA 3, and so on.

In the *Matchpoint*, the results of the correlations are displayed in dynamic tables, and many tools are available to sort the samples according to the correlation scores provided, perform side-by-side comparisons, synchronize movement of the samples in three orthogonal axes, or incline the cartridge case heads for comparison, helping the user to find the hits and establish whether the two samples have been fired by the same firearm.

Considering LEAs comparisons and the *phases*, the system provides six final scores, half regarding 2D image comparison, and half 3D, as detailed in Table 19.

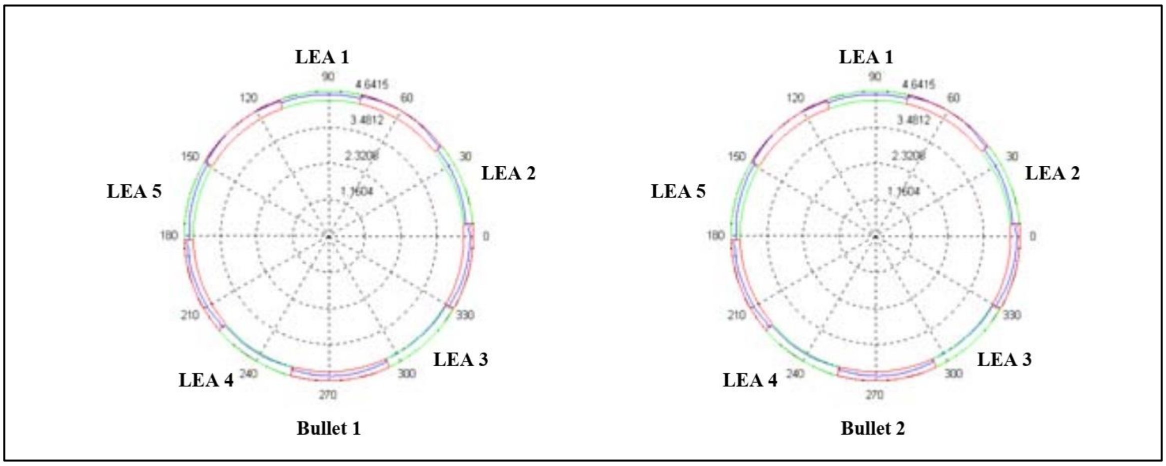


Figure 70 – Phase 1 of 5 possible orientations for these two bullets (Source: Bachrach, 2006, p. 12).

Table 19 – IBIS® bullets correlation results

ACRONYM	**L3DMPH**	**L2DMPH**	**L3DPEK**	**L2DPEK**	**L3DMAX**	**L2DMAX**
Termed	LEA 3D maximum phase	LEA 2D maximum phase	LEA 3D peak of the phase	LEA 2D peak of the phase	maximum LEA 3D	maximum LEA 2D
Definition	the *phase* with the highest average of LEAs comparison scores		the highest LEAs comparison score in the maximum *phase*		the highest LEAs comparison score regardless the *phases*	

4.3 SCANNING SAMPLES AND REQUESTING CORRELATIONS

The ammunition elements were imaged into Arsenal®, Evofinder®, and IBIS® systems and the correlations requested following the steps described in Table 15, Table 16, and Table 17. The resulted were exported into Excel spreadsheets for further evaluation.

Should be noted that because for each questioned sample there are several test-fires from the same firearm, it was engendered a way to avoid the necessity to repeat the correlations including each type of test-fired and excluding others. For instance, a questioned .38SPL bullet has other 18 (eighteen) samples of the same firearm, that can be listed in the correlation results, and therefore the actual position of each test-fired in the result list was always determined disregarding the other samples from the same firearm.

A way to understand this is by considering a list of results, where each candidate is listed as a *match* or a *non-match* to the questioned sample. For this research, as the list is assessed from the first position downwards, the position of a *match* is determined by the number of *non-matches* listed before the position of the candidate, added to one:

$$position\ of\ the\ match = 1 + \ non\_matches\ (before). \qquad 4.4$$

For instance, consider the following first seven candidates listed, where the 'TFB' are *matches,* and the 'bullet from another firearm' are *non-matches*:

1. TFB1.1;
2. TFB1.2;
3. bullet from another firearm;
4. TFB4.2;
5. bullet from another firearm
6. bullet from another firearm;
7. TFB3.1.

Using equation 4.4, we can determine the TFB4.2 position for effectiveness computation:

$$non_{matches}(before)\ = 1\text{ , so}$$
$$position\ of\ the\ match\ (TFB4.2) = 1 + 1 = 2$$

Similarly for TFB3.1:

$$non_{matches}(before)\ = 3\text{ , so}$$
$$position\ of\ the\ match\ (TFB4.2) = 1 + 3 = 4$$

Therefore, in this example, the positions of the matches utilized for effectiveness computation would be the ones recorded in Table 20. The rationality for that is because these would be the positions of each sample in the result list if there was no other test-fired from the same firearm in the database.

Table 20 – Position for effectiveness computation according to equation 4.4.

SAMPLE	POSITION FOR EFFECTIVENESS COMPUTATION
TFB1.1	1
TFB1.2	1
TFB4.2	2
TFB3.1	4

As carried out in the previous assessment (refer to section 3.2.3) the database included in the correlation requests varied in three ways, allowing intra-material, inter-material noiseless, and inter-material noise tests. Table 21 details the number of requested correlations for the research and the database size involved in each test.

Intra-material tests (IM)

The intra-material test (IM) is a comparison between test-fires only. In each caliber, the first collected TFB or TFC, of each type of ammunition, for instance, TFB3.1, or TFC1.1, was correlated against the other samples of the research, being recorded the position in the result list of the other test-fired of the same type, for instance, TFB3.2, or TFC1.2. Therefore, this test assesses only correlations of the same type components, configuring an intra-material test. These correlations were utilized to verify the quality of the marks on bullets and cartridge cases, as well as the ability of the systems to combine them.

Inter-material noiseless tests (IM-N)

The inter-material noiseless tests (IM-N) were carried out requesting for each questioned bullet or cartridge case, correlations against the other samples of the research. Because there are different types of test-fires this implies comparisons of components from different types of ammunition, configuring an inter-material test. The position of all test-fires of the same firearm as the questioned was used to determine the effectiveness of the systems.

Inter-material noise tests (IM-N1 or IM-N2)

The inter-material noise tests (IM-N1 or IM-N2) were replications of inter-material noiseless tests but within a larger database.

Table 21 – Database size on each requested correlation by type of test.

TEST	COMPONENT	CALIBER	Samples of reference	Number of requested correlations	DATABASE SIZE FOR CORRELATION IN EACH SYSTEM		
					Arsenal®	Evofinder®	IBIS®
Intra-material (IM)	BUL	.38SPL	TFB1.1, TFB2.1, etc	**112*(m)***	**303**		
		9x19mm		**112**	**335**		
		.40S&W		**63**	**209**		
	CC	.38SPL	TFC1.1, TFC2.1, etc	**112**	**287**		
		9x19mm		**112**	**335**		
		.40S&W		**63**	**209**		
Inter-material noiseless (IM-N)	BUL	.38SPL	QB1, QB2, etc	**80*(n)***	**303**		
		9x19mm		**112**	**335**		
		.40S&W		**84**	**209**		
	CC	.38SPL	QC1, QC2, etc	**64**	**287**		
		9x19mm		**112**	**335**		
		.40S&W		**84**	**209**		
Inter-material noise1 (IM-N1)	BUL	.38SPL	QB1, QB2, etc	**80**	*(o)*	**1350**	**1300**
		9x19mm		**112**	*(o)*	**474**	**835**
		.40S&W		**84**	*(o)*	**615**	**809**
	CC	.38SPL	QC1, QC2, etc	**64**	*(o)*	**1380**	**1287**
		9x19mm		**112**	*(o)*	**636**	**1035**
		.40S&W		**84**	*(o)*	**797**	**1009**
Inter-material noise2 (IM-N2)	BUL	.38SPL	QB1, QB2, etc	*(o)*	*(o)*	*(o)*	*(o)*
		9x19mm		**112**	*(o)*	**1085**	**1435**
		.40S&W		**84**	*(o)*	**2448**	**2709**
	CC	.38SPL	QC1, QC2, etc	**64**	*(o)*	*(o)*	*(o)*
		9x19mm		*(o)*	*(o)*	**1890**	**2335**
		.40S&W		**84**	*(o)*	**2740**	**2709**

(m) – For intra-material tests, the number of correlations is half of the number of test-fires.
(n) – For inter-material tests, the number of correlations is the number of questioned samples.
(o) – tests did not carry out due to the absence of available noise.

In the inter-material noise tests, the number of requested correlations is the same as the inter-material noiseless test, what differs is the database size included in the correlations. The noise for each test was a set of the same caliber and class characteristic ammunition components images acquired from firearms not related to this study, i.e, in these tests the database involved in each correlation was expanded, allowing to assess the influence of the database growth on the effectiveness of the systems.

Should be noted that for Arsenal® system the equipment provided had no previous registered database, therefore no noise was available, precluding the inter-material noise tests on this system. In the Evofinder® and IBIS® systems, there was 1 (one) noise available in the caliber .38SPL, and 2 (two) noises in calibers 9x19mm and .40S&W. These noises were obtained from real case evidence available in the assessed equipment.

4.4 ANALYSIS PROGRAMS

Table 21 can be used to obtain the total number of requested correlations, multiplying the number of requested correlations by the number of systems the test was carried out (2 or 3), resulting in 5186 requested correlations. For each requested correlation, a system often provides more than one result list, for example two spreadsheets of results are provided by Arsenal® and Evofinder®, whereas with IBIS® one spreadsheet is provided with results that can be sorted by columns with scores for different types of correlators.

To efficiently and accurately process that amount of data two programs were developed and written in Python. The programs were designed to compute the effectiveness of each system as proposed by Santos and Muterlle (2015), and previously described in section 3.2.2, and its implementation allowed results from all the systems and calibers to be analysed.

The first program to be called is the *Analysis_program.py*. As shown in Figure 71, the program opens the spreadsheets of results and finds the position of each match recording it for use and effectiveness determination by the next program; this is referred to as the ranking of matches. Once the ranking of matches was generated, e*ffectiveness.py* is called to determine the effectiveness, assessing the ranking of matches according to the type of effectiveness to be computed. Each type of effectiveness was designed to consider part of the results or to group them according to many possibilities of interest.

Remembering that for each type of test-fire “x” the sample collection was repeated, generating TFBx.1 and TFBx.2, and TFCx.1 and TFCx.2. When computing the effectiveness regarding bullet or cartridge case properties, the program was set up to utilize the positions in the result list of both test-fires of each type of ammunition. On the other hand, for investigating the way systems operates, for instance the combination of correlators, or the database growing impact, the program considered only the best repeated test-fired, i.e, the best result list position between the two test-fires of each type of ammunition.

The set up of the effectiveness.py computation were:

- **For intra-material tests, for bullets or cartridge cases, effectiveness by:**
  - Guns
  - TFB1 x TFB2 (original study)
  - Combination of all correlators
- **For inter-material tests, bullet or cartridge case, effectiveness by:**
  - Guns
  - Test-fires (1 test-fire - first one)
  - Test-fires (2 test-fires – both repeated test-fires)
  - Test-fires (2 test-fires – best repeated test-fired)
  - Questioned x Test-fired (original study)
  - **For Cartridge Case, effectiveness by:**
    - Anvil assessment
    - Depth of firing pin (FP) mark assessment
    - Centralization of FP mark assessment
    - Orientation of breech face (BF) mark assessment
    - Energy of discharge
    - Cartridge case material
    - Gun manufacturer
    - Combination of all correlators
    - Final best condition
  - **For Bullet, effectiveness by:**
    - Barrel type
    - Brinell hardness of bullets
    - Bullet material
    - Gun manufacturer
    - Combination of all correlators
    - Final best condition

Figure 71 and Figure 72 illustrate the algorithm of *Analysis_program.py*. and of e*ffectiveness.py* programs.

Despite the type of effectiveness selected, it is necessary to solve the nonlinear problem of finding *a*, *b* and *c* that best adjust the P(*n*) function (refer to equation 3.1 and to Figure 43 on p. 110) to the data generated at each calculated effectiveness (Γ_1), by equations 3.4 and 3.11. To do that, an "Advanced Process Monitor" (APM) was used, which is optimization software that was utilized for solving nonlinear fitting[21].

The package for solving was put on the folder ‘regression’, downloaded from APM Python Optimization Package[22]. Each time in a test the probabilities to find a match up to position *n* is generated, the data is recorded on a file called *data.csv* for positions 1 to 20. Within the *effectiveness.py* program, when the effectiveness_calc() is called, the solver is utilized by the application ‘regression’ on the server accessed at 'http://apmonitor.com'.

As depicted in Figure 72, at the end of the process the calculated effectiveness (Γ_1) is recorded in the file effectiveness_results.xlsx for the ultimate evaluation.

4.5 DATA VERIFICATION AND INDEPENDENCE

During this research, the author had to frequently interact with companies that develop ballistic identification systems. The necessity for that includes granting access to equipment, explaining the functionalities, and supporting the labor of digitalization of samples and data collection. Despite this, it was maintained independence in the assessment and analysis of the data, and many measures were implemented to ensure it.

For instance, as IBIS® had to be accessed in different laboratories and countries, the samples were codified prior to digitization utilizing random numbers generated through Microsoft Excel’s “random” function. The relationship between the **code** for the **firearm and the type of ammunition** was kept blind to UEFTI’s employees and only accessed by the author of the thesis in the file *dictionary.xlsx*.

Example codes and the respective ammunition elements they represent, as used by the *Analysis_program.py*, are demonstrated in Table 22.

[21] http://apmonitor.com/wiki/index.php/Main/HomePage [Accessed 12/12/2019].
[22] Available at http://apmonitor.com/wiki/index.php/Main/PythonApp [Accessed 12/12/2019].

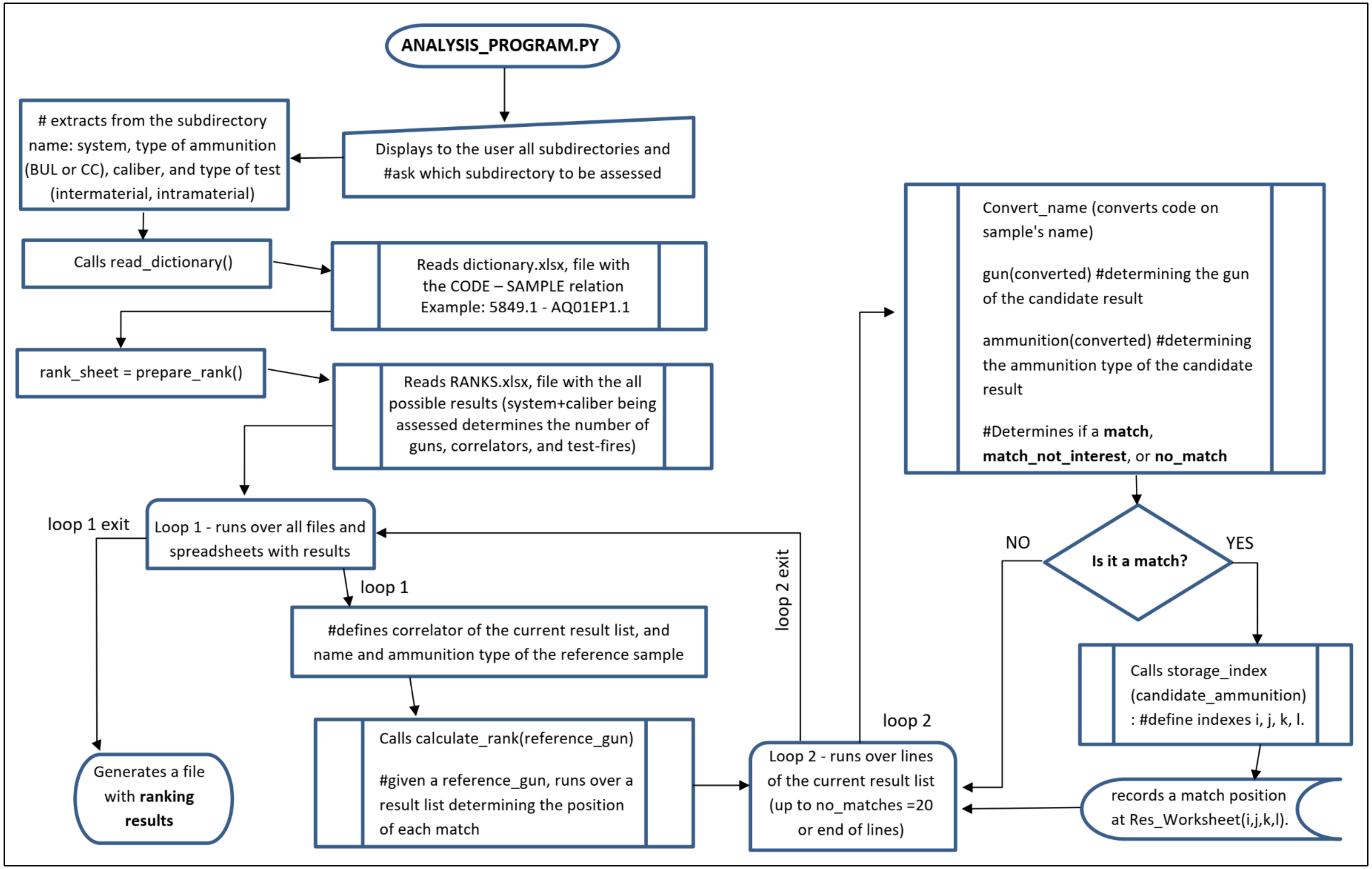


Figure 71 – Process diagram for the *analysis_program.py* algorithm.

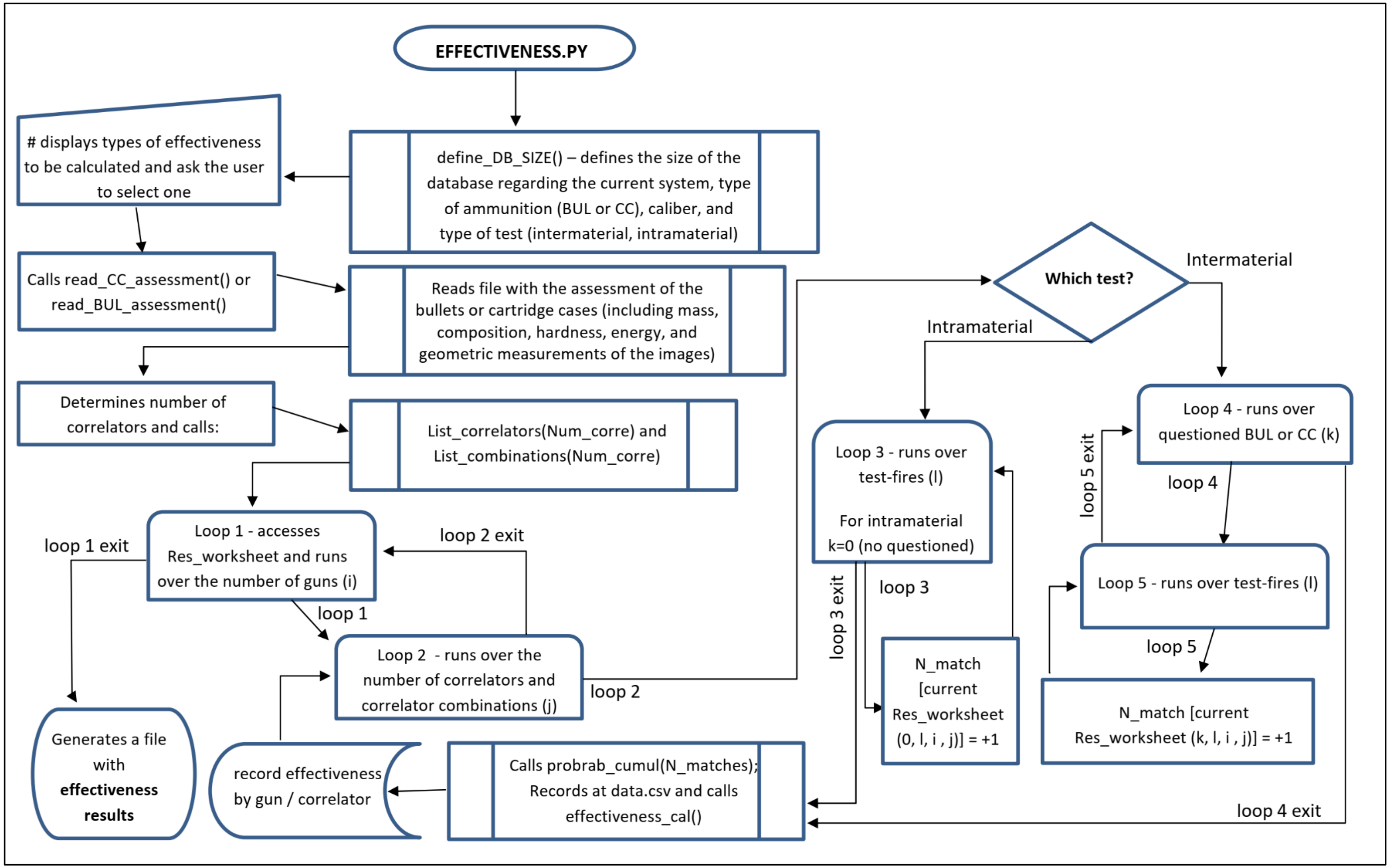


Figure 72 – Example process diagram for the *effectiveness.py* algorithm to calculate effectiveness by gun (other effectiveness types follow a similar algorithm).

Table 22 – Code to sample reference.

AVAILABLE	BLIND TO THE COMPANIES					
CODE	**Reference**	**Caliber**	**Gun**	**Type of component**	**Type of sample**	**Order of the sample**
4438.2	$AQ01PP1.1$	.38SPL	01	BUL	TFB1	First
10346	$AQ31EQII$	9x19mm	31	CC	QC2	First
20528	$AQ21EP3.2$	.40S&W	21	CC	TFC3	Second

Other verification steps were implemented to certify that the program was correctly analyzing the data. The *Analysis_program.py* print at the end of each set of results analyzed the file *logger_analysis*, containing, between others, the number of files read and analyzed, and for each spreadsheet with results, the candidates as ranked, as well as the position of each match found. For instance, Figure 73 shows part of a *logger_analysis.txt* file generated by analyzing results for a 9x19mm cartridge case inter-material noiseless test on system Arsenal®, highlighting some important records for program debugging.

The file and spreadsheet analyzed indicate that it is a result of breech face correlation of QC2 from gun18 of this caliber. The gun for each candidate listed is presented and the asterisks (*) highlight the found matches, the type of test-fire of the match, and the position of the match as calculated by equation 4.4 (refer to p. 162). The *** is an interesting match, as although a sample coming from the same gun as the reference, it is a questioned cartridge case (QC) and therefore not utilized in the context of the current assessment to measure the system effectiveness, that only looks for matches of Questioned samples against Test-fires of the same gun. The final lines record that 112 files contained results were read and analyzed, and from the many checkpoints in the program, no error was detected.

A way to check the accuracy of the result was to apply the *Analysis_program.py* for a small set of files, manually contrasting the *logger_analysis.txt* records with the spreadsheets. After debugging no error was found.

The *Analysis_program.py* also generates for each analysis the *ranking…xlsx* file, containing the records of all matches between Questioned samples and Test-fires for each gun, as can be observed on the *st_index* on the data of Figure 73. The four indexes stand for:

st_index (type of questioned sample; type of test-fired sample; number of the gun; 4.5

the first or the second test-fired by type of correlator)

```
Current analysing  AQ18 EQII.xlsx

Analysing sheet  BREECHFACE
correlator =  BREECH FACE
complete name =  AQ18 EQII
reference gun:  gun18
type of ammunition:  QC2

*candidate_gun:  gun18
candidate_ammunition:  TFC1.1
position_of_match =  1
st_index =  [1, 0, 0, 1]

candidate_gun:  gun31
candidate_ammunition:  QC1
candidate_gun:  gun31
candidate_ammunition:  QC4
candidate_gun:  gun29
candidate_ammunition:  QC1
candidate_gun:  gun31
candidate_ammunition:  TFC3.1
candidate_gun:  gun28
candidate_ammunition:  TFC3.1
candidate_gun:  gun26
candidate_ammunition:  TFC1.1
candidate_gun:  gun29
candidate_ammunition:  QC3
candidate_gun:  gun29
candidate_ammunition:  TFC1.2
candidate_gun:  gun19
candidate_ammunition:  TFC4.1

**candidate_gun:  gun18
candidate_ammunition:  TFC1.2
position_of_match =  10
st_index =  [1, 0, 0, 3]
candidate_gun:  gun29
candidate_ammunition:  QC2
candidate_gun:  gun23
candidate_ammunition:  QC4
candidate_gun:  gun29
candidate_ammunition:  TFC2.1
candidate_gun:  gun29
candidate_ammunition:  TFC3.1
candidate_gun:  gun28
candidate_ammunition:  TFC1.1
candidate_gun:  gun27
candidate_ammunition:  TFC3.2

***candidate_gun:  gun18
candidate_ammunition:  QC1

candidate_gun:  gun29
candidate_ammunition:  QC4
candidate_gun:  gun22
candidate_ammunition:  TFC2.2
candidate_gun:  gun31
candidate_ammunition:  TFC1.2
candidate_gun:  gun30
candidate_ammunition:  QC4
candidate_gun:  gun20
candidate_ammunition:  TFC2.2

matches:  2
matches_not_interest:  1
no_matches : 20

files_read =  112

 files_analysed =  112
Total_errors =  0
```

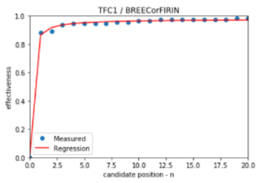
Figure 73 – Instance of *logger_analysis.txt* file generated by *Analysis_program.py* for debugging.

Because the results of assessment published in the paper reproduced on chapter 3 (refer to p. 106) was generated by Excel spreadsheets following the same logic that was utilized to elaborate the *Analysis_program.py*, the application of the program to the correlation results related to the data of chapter 3 allowed another debugging process for the program. Any divergence observed was checked in the original spreadsheet correlation result, and for few differences observed it was concluded that all were errors on the manual assessment of chapter 3, instead of a program error.

The *Analysis_program.py* is an essential step to analyse the results, ultimately being employed to record the matches found on the result lists. The *effectiveness.py* is the program to generate effectiveness as requested by the user. A logger for debugger this program was also implemented, recording the number of matches records from positions 1 to 21, the correspondent cumulative probability, the APM process for solving the non-linear curve fitting, and the consequent effectiveness (Γ_1).

Figure 74 depicts the logger of effectiveness.py for analysis of Arsenal® results with test-fired cartridge cases type 1, by breechface or firing pin correlations. Manual checks were performed on the logger results. Further, the effectiveness generated by the program was compared to all effectiveness manually generated at the paper reproduced in chapter 3 (refer to p. 106). Once again the few differences observed were attributed to error on the manual assessment of chapter 3, instead of a program error, and to differences in the excel solver employed on the manual research compared to the APM monitor solver employed by *effectiveness.py*.

```
TFC1 / BREECorFIRIN


N_matches = [ 0. 99. 1. 5. 1. 0.
0. 0. 1. 0. 1. 0. 1. 0. 0. 0. 0.
0.
0. 1. 0. 2.]
Prob_cum = [[ 0. 0. ]
[ 1. 0.88393]
[ 2. 0.89286]
[ 3. 0.9375 ]
[ 4. 0.94643]
[ 5. 0.94643]
[ 6. 0.94643]
[ 7. 0.94643]
[ 8. 0.95536]
[ 9. 0.95536]
[10. 0.96429]
[11. 0.96429]
[12. 0.97322]
[13. 0.97322]
[14. 0.97322]
[15. 0.97322]
[16. 0.97322]
[17. 0.97322]
[18. 0.97322]
[19. 0.98215]
[20. 0.98215]]
apm 80.43.221.239_regression
<br><pre> ----------------------
-------------------------------
----------
APMonitor, Version 0.8.9
APMonitor Optimization Suite
--------------------------------
--------------------------------



--------- APM Model Size -------
-----
Each time step contains
Objects : 0
Constants : 1
Variables : 5
Intermediates: 0
Connections : 0
Equations : 2
Residuals : 2


Number of state variables: 23
Number of total equations: - 21
Number of slack variables: - 0
-------------------------------
-------
Degrees of freedom : 2

--------------------------------
--------------
Model Parameter Estimation with
APOPT Solver
--------------------------------
--------------


Iter Objective Convergence
0 1.40967E-01 1.00000E+00
1 2.06960E-02 1.12633E-02
2 3.13598E-03 9.82777E-03
3 1.69879E-03 1.09425E-02
4 1.68717E-03 3.73079E-04
5 1.68713E-03 1.84038E-06
6 1.68713E-03 5.53260E-10
7 1.68713E-03 5.53260E-10
Successful solution


-------------------------------
-------------------
Solver : APOPT (v1.0)
Solution time :
2.1199999999999322E-002 sec
Objective : 1.687129431476177E-
003
Successful solution
-------------------------------
-------------------



Solution
a = 0.9754139184951782
b = 0.12559153139591217
```




```
c = 7.448246934672691e-05
k = -0.6219162266589499
area = 0.93125375
gamma1 = 0.945062931855698


effectiveness =
0.945062931855698
```

Figure 74 – Instance of the *logger* file generated by *effectiveness.py* for debugging.

5 PARAMETERS OF INFLUENCE WITH BULLETS

This chapter contains a discussion of the results with bullets, including the impact of some physical and mechanical properties of ammunition elements and firearms on the effectiveness of the systems.

5.1 Types of effectiveness calculated with bullets

Several types of effectiveness were implemented on the analysis programs to investigate factors influencing the possibilities of correctly identify the source firearm by the fired bullet. Initially, one investigation on systems' operation was carried out assessing the impact on effectiveness by the type of correlations each system performs (5.2) and by the number of registered test-fires (5.3). The manufacturer and barrel type of the firearm (5.4), bullets' Brinell hardness (5.5), and their material compositions (5.6), were the main properties investigated as factors of influence in bullet correlations. Additionally, the impact of an expanding database on the systems' effectiveness (5.7), the utility of using the correlation scores to more objectively identify a match or a non-match (5.8), and the performance of the systems in a suggested operating condition by caliber per system (5.9) were discussed.

5.2 Correlators to be examined

Because most systems' automated comparison results in more than one correlation list, it was investigated the system effectiveness considering isolated or set of correlator results in the inter-material noiseless (IM-N) and noise tests (IM-N1, IM-N2).

For the Arsenal® system operating with bullets, this is not an analysis that needed to be carried out because it presents only one list for bullet correlations.

In the Evofinder® system, the bullet correlation results for this research was available by Secondary or Grooves (refer to Figure 75). New software version contains the Primary mark as an addicional correlator, but this was not included in this research. Figure 76 compares the Evofinder® effectiveness considering Groove, Secondary, and combination of these two correlators. Analysis of variance (ANOVA) (refer to 3.2.3) between results for all tests in the three calibers, yields a statistically significant difference in the mean effectiveness by Groove, Secondary, and Secondary or Groove (F-fisher = 69 for F-critical = 4, P-value = $6*10^{-8}$, α=0.05).

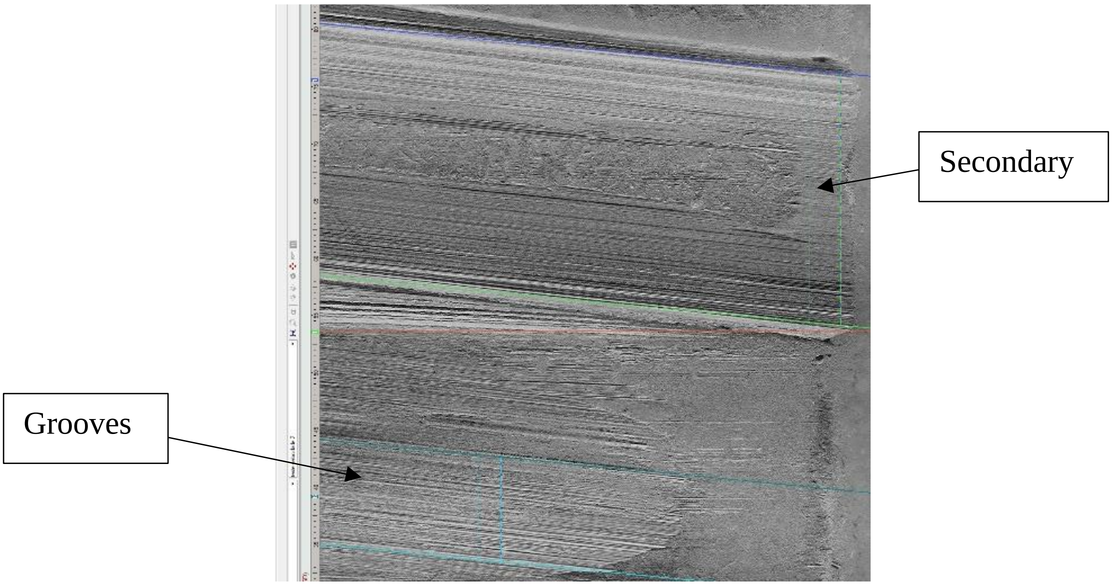


Figure 75 – Annotated marks for bullet automated correlation on Evofinder.

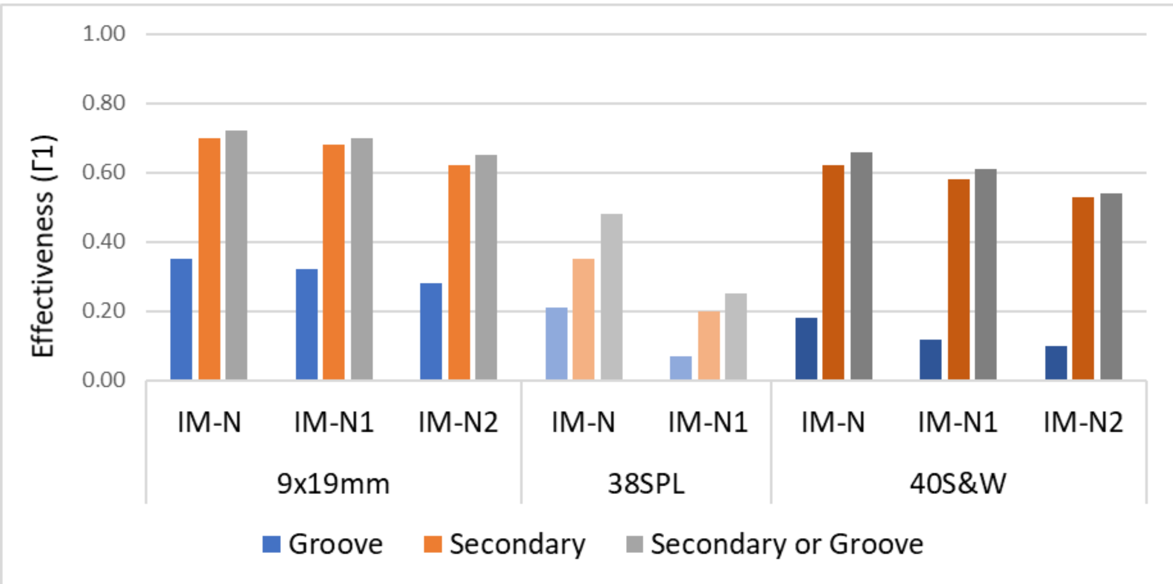


Figure 76 – Evofinder® effectiveness by bullet correlator results.

Compared to Groove, effectiveness by Secondary was in the mean 0.33(±0.13) higher. When considering the higher results by Secondary or Groove, instead of only Secondary, the mean increase on effectiveness was 0.04(±0.04). This comparison demonstrates that on Evofinder® is highly recommended to check the Secondary result list, and use Groove only as a complementation in searching for matches.

In the IBIS® system, although it compares only LEA ROI, the analysis is more complex, as there are six correlators for bullets, termed L3DMPH, L2DMPH, L3DPEK, L2DPEK, L3DMAX, and L2DMAX (refer to Table 19 at p. 161). Figure 77 to Figure 79 compare IBIS® effectiveness by type of correlator, by combinations of 2 (two) correlators, and by the combination of all correlators in each test and caliber.

For all calibers and tests the higher effectiveness by 1 (one) correlator was obtained with L3DPEK or L3DMPH results. For combinations of 2 (two) correlators the higher effectiveness were obtained combining L3DMPH with L3DPEK. Sucessive ANOVA between all tests and calibers revealed statistically reliable differences in the mean effectiveness by 1 (one) compared to combination of 2 (two) correlators, and by 2 (two) compared to combination of all correlators (respectively, F-fisher = 25 for F-critical = 6, P-value = 0.002, α=0.05; and F-fisher = 12 for F-critical = 6, P-value = 0.01, α=0.05).

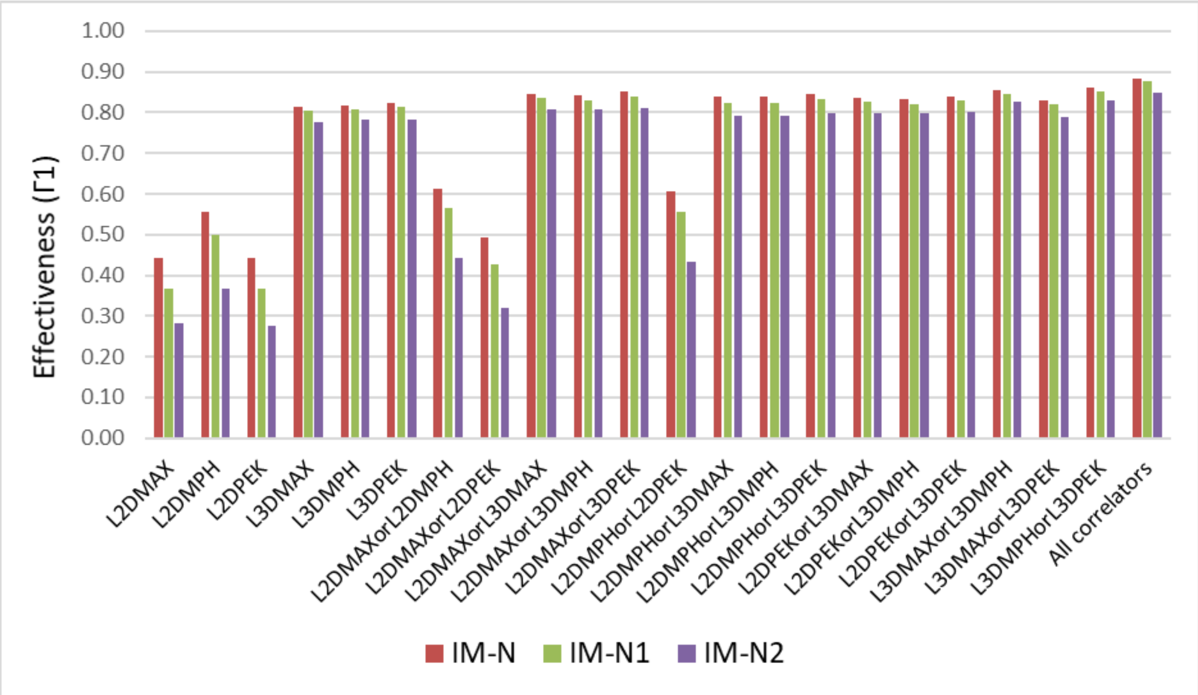


Figure 77 – Comparison of IBIS® effectiveness by correlator and by combination of correlators with 9x19mm bullets.

Contrasting the mean effectiveness by combination of all correlators to the mean effectiveneness by the single correlator with higher effectiveness in each test and caliber, there was a mean increase of 0.06(±0.02). Although ANOVA revealed that this is a statistical significative difference (F-fisher = 24 for F-critical = 6, P-value = 0.002, α=0.05), it is not practical that in all analyses all available results are verified. Therefore, the combination of 2 (two) correlators were investigated, being observed that, if instead of checking all correlators, only the 2 (two) best correlators by caliber were verified, the effectiveness only decreased by 0.02(±0.01).

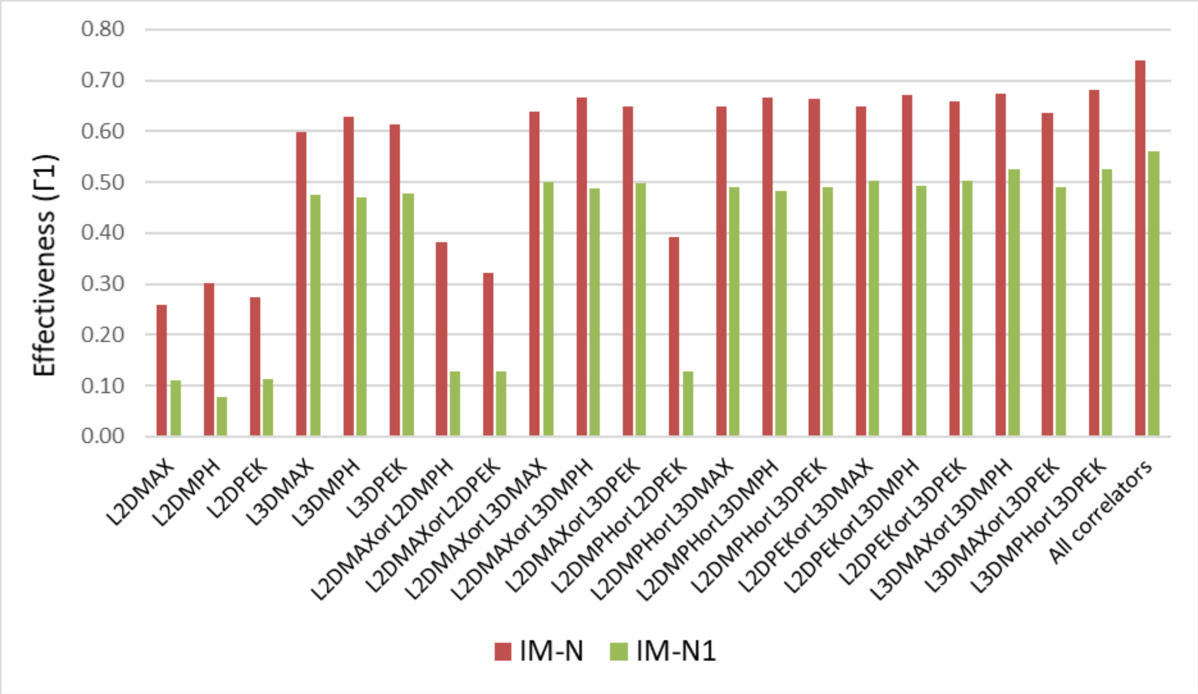


Figure 78 – Comparison of IBIS® effectiveness by correlator and by combination of correlators with .38SPL bullets.

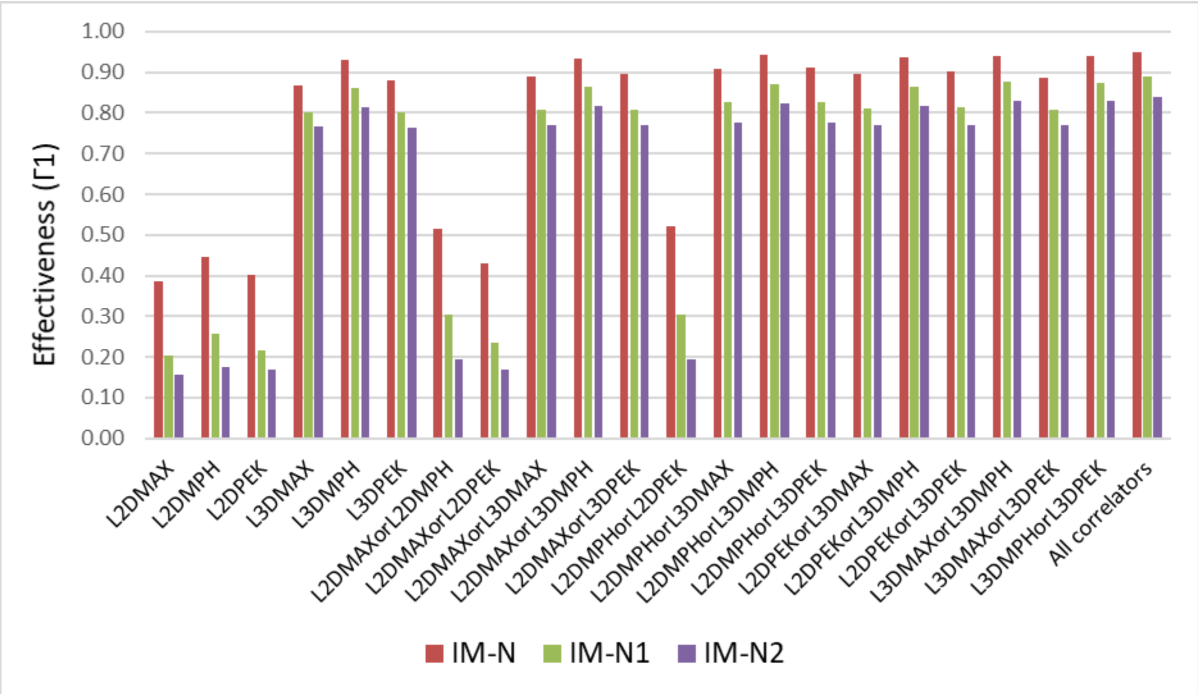


Figure 79 – Comparison of IBIS® effectiveness by correlator and by combination of correlators with .40S&W bullets.

Therefore, the statistical tests in the results support the validity of checking as many correlation result lists in IBIS® as possible. Nevertheless, in laboratories crowded with evidence to process, should be kept in mind that checking the combination of L3DMPH with L3DPEK may represent a considerable time saving in search for hits, with the cost of only 0.02 in the mean effectiveness of the solution.

5.3 Number of test-fired bullets

As the number of test-fires is one parameter that is in the control of the examiners responsible to register a firearm in the system, should be considered that as more test-fires are registered as higher the probability of correct firearm identification (Bachrach, 2006). For instance, a study selected 30 (thirty) 9mm firearms and by collecting 100 (hundred) cartridge cases from each gun aimed to determine the number os test-fires that should be performed to balance systems accuracy with cartridge case acquisition time, concluding that at least 15 (fifteen) test-fires should be collected from each firearm in order to cover the variability observed on the marks of the fired components, this way mitigating false positive or false negative probabilities of error (Law et al., 2017).

In addition to be a very time-consuming approach, a reason to be inadvisable to collect and record so many test-fires from the same firearm is that systems inadvertently include in each correlation result list, all the repeated test-fires. Ideally, if there were more than one test-fire of a registered firearm, the system should include in each correlation list only the repeated test-fired per firearm with the highest correlation score. This would allow users to increase the number of registered test-fires per gun without negatively impacting the correlation result list accuracy, particularly when the test-fires of incorrect firearms feature marks that may look similar to the marks of the correct firearm test-fires.

Considering this limitation of the systems, differences on effectiveness between registering 1 (one) and 2 (two) test-fired bullets per firearm were investigated, as depicted in Figure 80. ANOVA between results for all tests in the three calibers, suportes a statistically significant difference in the mean effectiveness with 2 (two) test-fires and the mean effectiveness with 1 (one) test-fired (F-fisher = 201 for F-critical = 4, P-value = $3*10^{-11}$, α=0.05).

Figure 81 register the increment in effectiveness observed in the graphs of Figure 80.

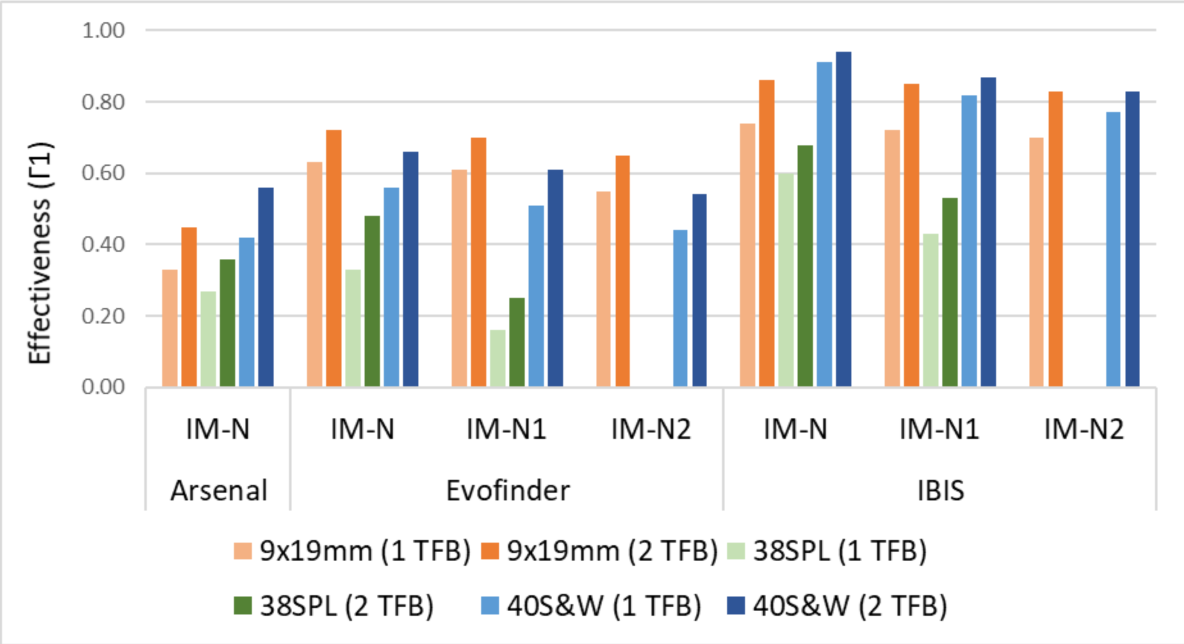


Figure 80 – Comparison of systems' effectiveness with 1 (one) test-fired bullet (TFB) or 2 (two) TFB. For 9x19mm analyzed results without Glock, for Arsenal® the results were obtained from Candidate List, for Evofinder® was considered the lower position in Secondary or Groove result lists, and for IBIS® the lower position between L3DMPH and L3DPEK lists.

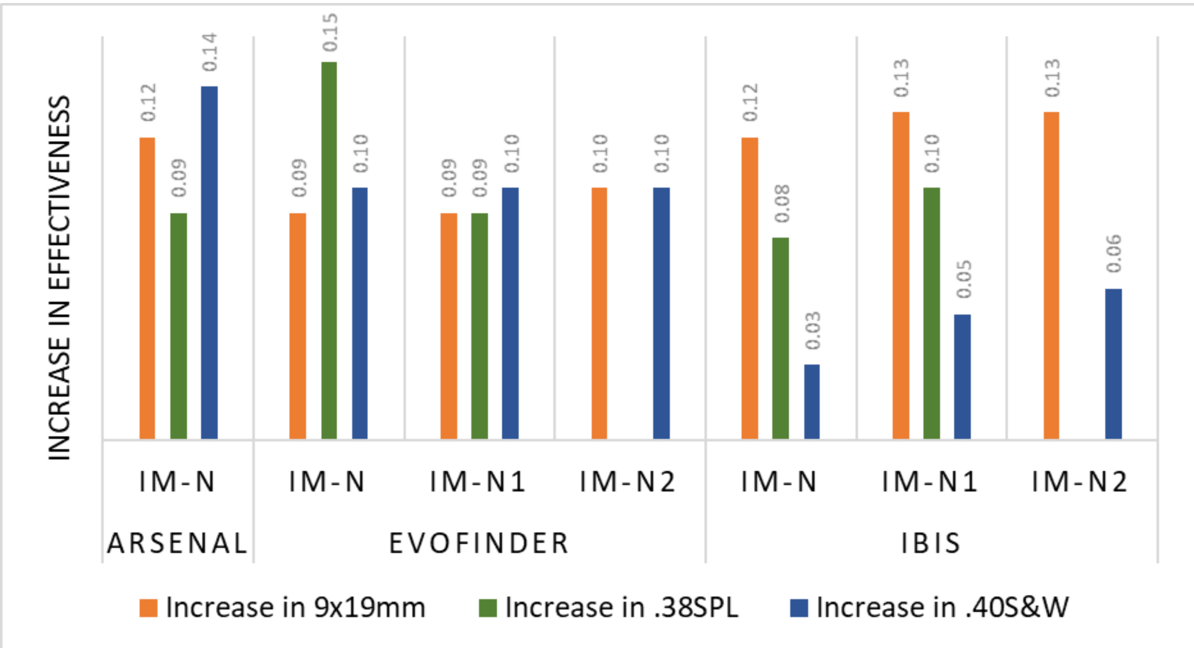


Figure 81 – Increase in systems' effectiveness with 2 (two) TFB compared to 1 (one) TFB (refer to Figure 80).

For each system, the average increase obtained on the effectiveness when registering 2 (two) test-fired bullets compared to only 1 (one) test-fired, was, for Arsenal® 0.12(±0.03), for Evofinder® 0.10(±0.02), and for IBIS® 0.09(±0.04). These results demonstrate the validity of registering at least two test-fires for each firearm. The main reason for that effectiveness increment is that considering the variation from shot to shot in marks imparted into the bullets, as more test-fires are registered in the system as higher the probability of the questioned sample be matched to one of the test-fires.

5.4 Firearm manufacturer and type of barrel

Something that previous studies are consistent in concluding is that the quality of the firearm, and especially the barrel, has a direct impact on the possibilities of ballistic identification, that is, on the likelihood of correct identification of the source firearm. The aforementioned study by Bachrach (2006), for instance, included an analysis of the empirical probability of error by firearm manufacturer, demonstrating that firearms with better quality control in barrel production have a significantly lower probability of error in identification than those that have less consistency in the surface finish, as illustrated in Figure 29 (refer to p. 86). Also, it was observed that if the LEA roughness increases, generally the probability of error decreases.

Therefore, it was expected that in this study the effectiveness of any system would differ from firearm to firearm and that performance can be grouped by firearm manufacturer of by barrel type. To investigate the influence of these two factors on the systems' effectiveness, a computation was implemented in the analysis program to group the position in the result lists of bullet matches by the firearm manufacturer in each caliber and by the type of barrel they feature.

Figure 82, Figure 83, and Figure 84 compare the systems' effectiveness by firearm manufacturers included in this research, for each caliber. For Evofinder®, the results of the "Secondary" were used and for IBIS® the "L3DMPH" correlator, because these correlators resulted in the optimal effectiveness scores from the correlators that were available (refer to section 5.2).

To investigate which firearm manufacturer resulted in poor effectiveness, caliber-focused comparisons were performed. This analysis also helped to explore whether one or more systems had difficulty in correctly correlating them.

In terms of firearm manufacturer, this research included:

- ✓ .38SPL: Taurus, Rossi;
- ✓ .40S&W: Bersa, Taurus, Imbel;
- ✓ 9x19mm: Taurus, FN Browning, Norinco, Jerico, Smith and Wesson, Glock.

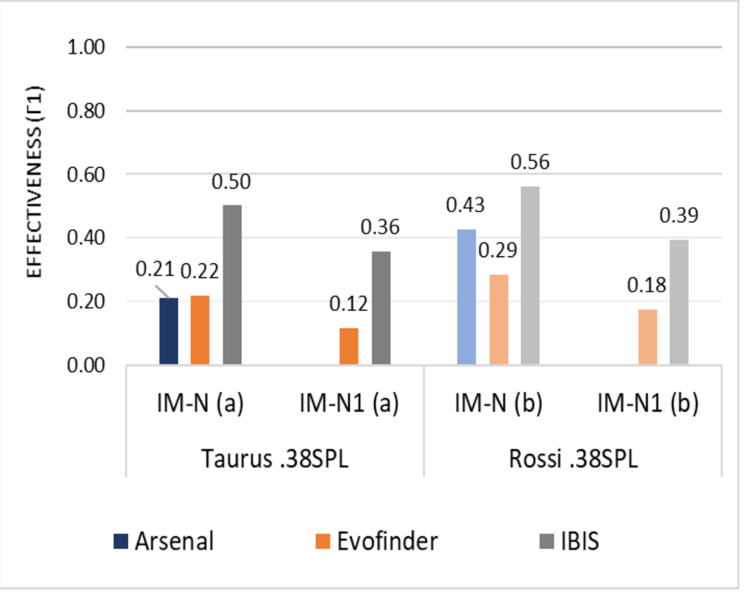


Figure 82 – Systems Systems effectiveness by manufacturer with.38SPL bullets, from: **a)** Taurus and **b)** Rossi revolvers, in the inter-material noiseless (IM-N) and inter-material noise1 (IM-N1) tests, according to the following correlators: Arsenal® – Candidate List, Evofinder® – Secondary, and IBIS® – L3DMPH.

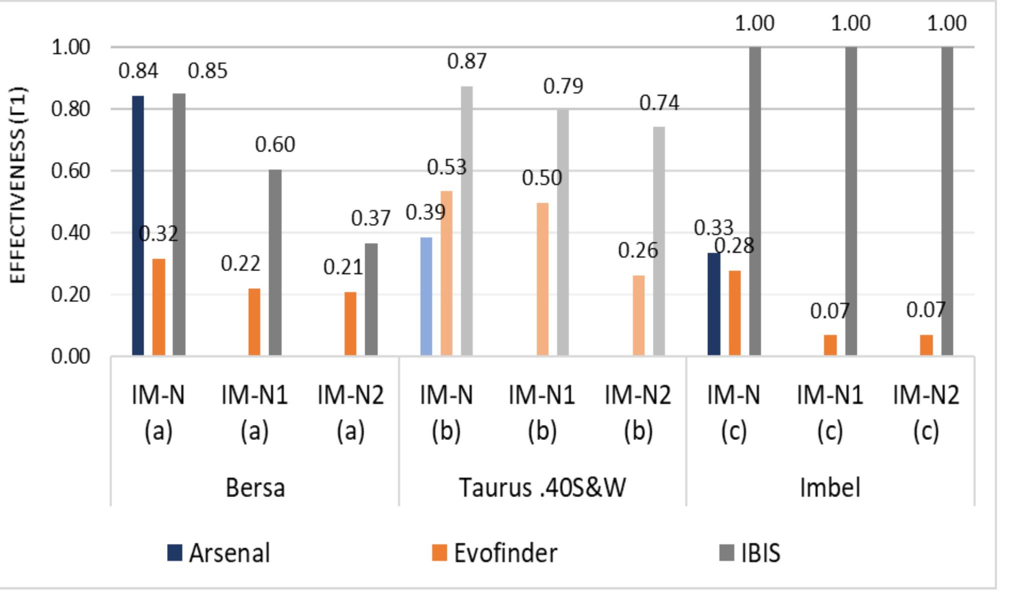


Figure 83 – Systems effectiveness by manufacturer with .40S&W bullets from: **a)** Bersa, **b)** Taurus, and **c)** Imbel pistols, in the inter-material noiseless (IM-N) and inter-material noise1 (IM-N1) and noise2 (IM-N2) tests, according to the following correlators: Arsenal® – Candidate List, Evofinder® – Secondary, and IBIS® – L3DMPH.

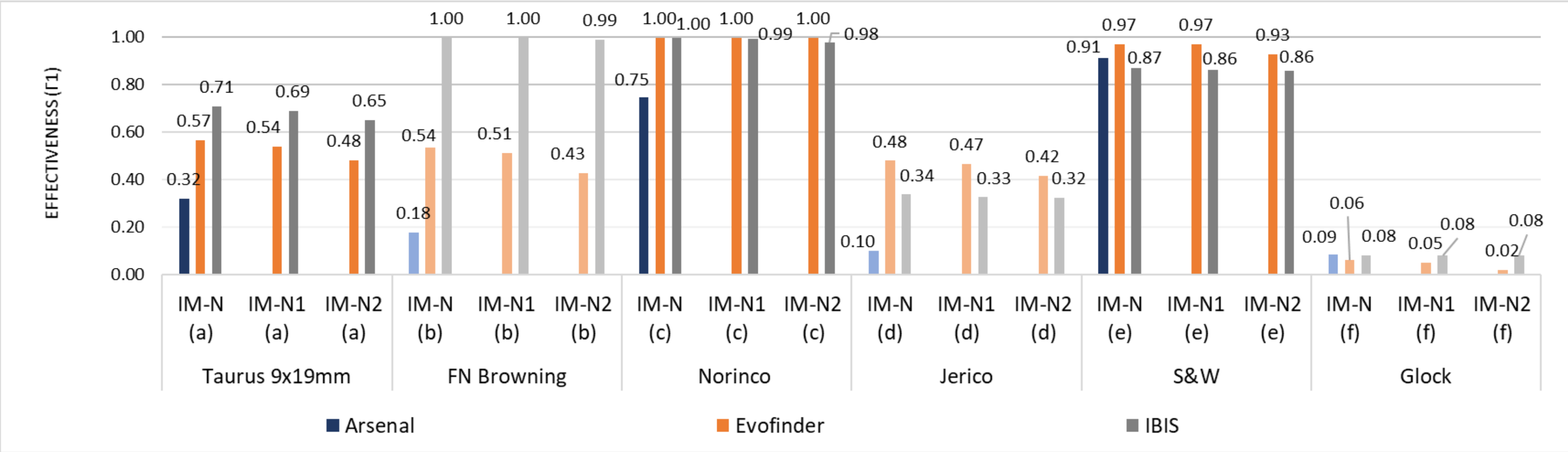


Figure 84 – Systems effectiveness by manufacturer with 9x19mm bullets, from: **a)** Taurus, **b)** FN Browning, **c)** Norinco, **d)** Jerico, **e)** S&W, and **f)** Glock pistols, according to the following correlators: Arsenal® – Candidate List, Evofinder® – Secondary, and IBIS® – L3DMPH.

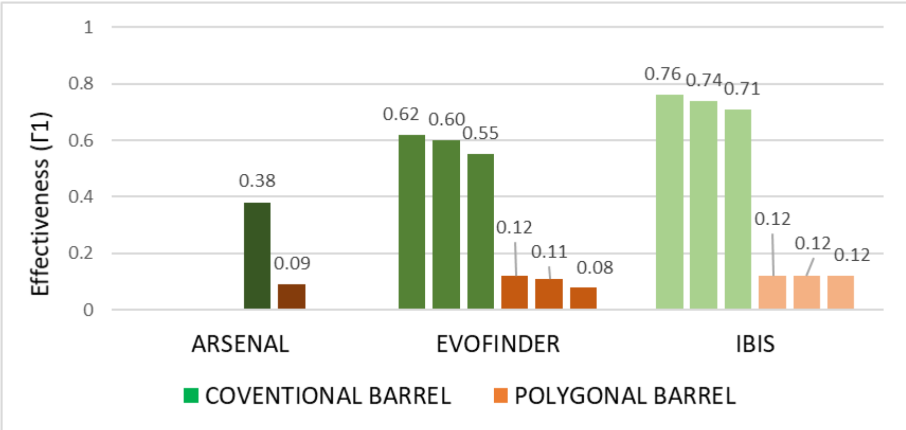


Figure 85 – Systems effectiveness by barrel type, according to the following correlators: Arsenal® – Candidate List, Evofinder® – Secondary, and IBIS® – L3DMPH.

The analysis of the barrels revealed that the Jerico and Glocks pistols are the only pistols of the research with polygonal barrels cold hammering forged, all the others featuring conventional rifled barrels, produced by broaching process (refer to section 2.1.5).

In the .38SPL caliber (refer to Figure 82), although this was the caliber with the lowest overall effectiveness, it was obtained for Rossi revolvers higher effectiveness compared to the effectiveness for Taurus revolvers, in all systems. Arsenal®, Evofinder®, and IBIS® correlations resulted in +0.22, +0.06(±0.005), and +0.05(±0.02) higher effectiveness with Rossi revolvers compared to effectiveness with Taurus.

In the .40S&W caliber (refer to Figure 83), the effectiveness of any system was highly dependant on the firearm manufacturer. While Bersa pistols were well correlated in Arsenal® during inter-material noiseless test (Γ_1 = 0.84), in IBIS® it was well correlated in inter-material noiseless test (Γ_1 = 0.85), but significantly impacted by database growth, resulting in lower effectiveness in the noise tests (Γ_1 = 0.60 and 0.37). In turn, Evofinder®'s effectiveness with Bersa was comparatively poor in all three inter-material tests, noiseless (IM-N) and noises 1 and 2 (IM-N1, IM-N2) (Γ_1 = 0.32, 0.22, and 0.21). Taurus and Imbel were most effectively correlated using IBIS® [(Taurus: Γ_1 = 0.87, 0.79, and 0.74), (Imbel: Γ_1 = 1.00, 1.00, and 1.00)], followed by Evofinder® [(Taurus: Γ_1 = 0.53, 0.50, and 0.26), (Imbel: Γ_1 = 0.28, 0.07, and 0.07)], and then by Arsenal® [(Taurus: Γ_1 = 0.39), (Imbel: Γ_1 = 0.33)].

The difference in performance with Imbel must be noted as it is the only firearm used in this study with a left-handed twist barrel. The IBIS® system uses this class characteristic as a filter for its correlations, whereas the Evofinder® system does not, and as a result may explain the observed effectiveness difference.

Finally, in the 9x19mm caliber (refer to Figure 84) there are some similarities and some differences between the results by firearm manufacturers in each system. Norinco and Smith & Wesson firearms both exhibited good effectiveness in all three systems (Γ_1 = between 1.00 and 0.75), indicating these firearms create unique and reproducible marks for comparison. In the case of Norinco, it is interesting to highlight the similarity of these results in relation to the study carried out with this firearm brand only (Yuesong et al., 2019), where the firearms were also perfectly matched (refer to p. 104). FN Browning had excellent effectiveness when compared using IBIS® (Γ_1 = 1.00, 1.00, and 0.99), with intermediate effectiveness using Evofinder® (Γ_1 = 0.53, 0.51, and 0.43) and poor effectiveness at Arsenal® (Γ_1 = 0.18). This implies there is either a deficiency in the correlation algorithm and/or differences in the quality of the raw data collected from some firearms when imaged using

Evofinder® or Arsenal®. Differences were also observed between Taurus and Jerico with IBIS® outperforming Evofinder® with the Taurus and Evofinder® being more effective with the Jerico [Taurus: (IBIS®, Γ_1 = 0.71, 0.69, and 0.65), (Evofinder®, Γ_1 = 0.57, 0.54, and 0.48) and (Arsenal®, Γ_1 = 0.32)]; Jericó: (Evofinder®, Γ_1 = 0.48, 0.47, and 0.42), (IBIS®, Γ_1 = 0.34, 0.33, and 0.32) and (Arsenal®, Γ_1 = 0.10)].

Continuing to consider the results of the 9x19mm caliber, Glock firearms produced the worst result in all three systems (Γ_1 = between 0.09 and 0.02). This outcome was expected as it is recognized as a firearm brand with a very smooth surface finish, featuring polygonal barrel that frequently lacks identifying marks on the bullets fired through it (Bachrach, 2006; Heard, 2008). Knowing this, a subroutine in the program made a general comparison of effectiveness by barrel type in all systems and tests. Figure 85 depicts the significant reduction in systems' effectiveness for polygonal barrels (Jerico and Glock) compared to conventional ones.

The results across the three calibers and all three systems reinforce the perception that the effectiveness of the algorithms is related to both the quality of the firearm and the presence or absence of visible striae for comparison. The existence of good quality marks (edge of LEA and individual stria) is a critical feature that influences the functionality, performance, and effectiveness of the solutions (see Glock results for a negative instance and Norinco results for a positive instance). For several firearm manufacturers, the systems' effectiveness varied significantly, demonstrating the influence of the algorithm and their methods of comparison in the accuracy of correlations. Since the algorithm is unknown due to proprietory, is not possible at this level of understanding of the solutions, further establish what specific factor is causing the reduction in performance between the systems at this time.

5.5 Bullet hardness

Based on the results obtained through the preliminary study for this research (refer to section 3, at p. 106), the Brinell hardness was the first parameter of influence investigated for bullets. Table 37, Table 38, and Table 39 (refer to p. 290) detail the Brinell hardness results obtained for each type of bullet used in the study. The higher and lower mean bullet Brinell hardness on each caliber can be seen in Figure 86, which also contain the half of the maximum difference in Brinell hardness ($\Delta HBW_{max}^{(caliber)}$) for each caliber, obtained by equation 5.1.

$$\Delta HBW_{max}^{(caliber)} = HBW_{(higher)} - HBW_{(lower)}. \quad (5.1)$$

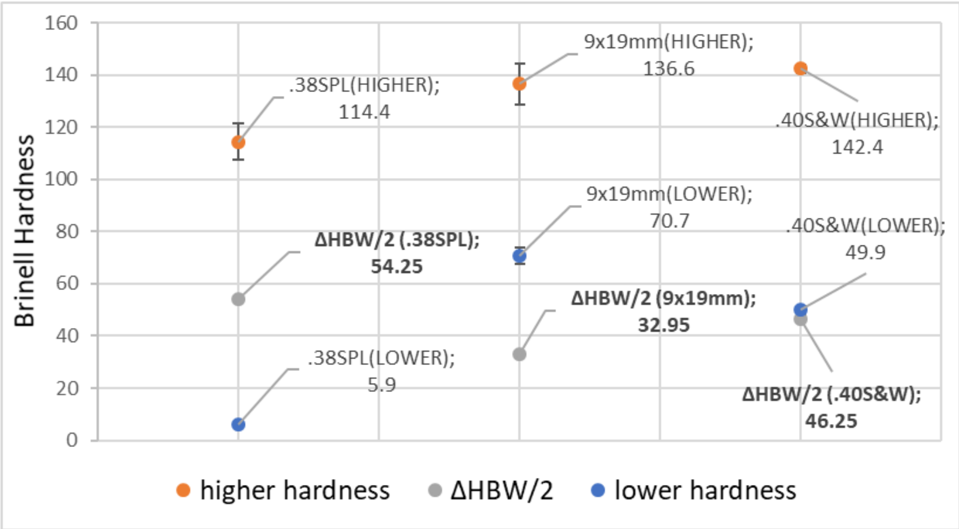


Figure 86 – Higher and lower bullet Brinell hardness in each caliber, highlighting half of the difference in Brinell hardness (ΔHBW).

To test the influence of this bullet property on the systems' effectiveness, the analysis program computed the difference in Brinell hardness between the questioned bullet and the test-fired in each bullet match, separating the positions in correlation result lists of each caliber and system, in two distributions defined by the inequations 5.2 and 5.3.

$$\left|HBW_{(QB)} - HBW_{(TFB)}\right| < \frac{\Delta HBW_{max}^{(caliber)}}{2}, \quad (5.2)$$

$$\left|HBW_{(QB)} - HBW_{(TFB)}\right| \geq \frac{\Delta HBW_{max}^{(caliber)}}{2}. \quad (5.3)$$

The systems’ effectiveness regarding bullet difference in Brinell hardness, for inter-material noiseless tests, can be seen in Figure 87.

ANOVA between results for the noiseless tests in all calibers and systems, yields a statistically significant difference in the mean effectiveness for distribution from inequation 5.2 and the mean effectiveness for distribution from inequation 5.3 (F-fisher = 34 for F-critical = 5, P-value = 0.0001, α=0.05). In all calibers and systems, a higher difference in hardness between the compared bullets resulted in lower effectiveness, on average

0.16(±0.13), 0.18(±0.07), and 0.13(±0.10) effectiveness decrements were obtained in Arsenal®, Evofinder®, and IBIS® systems respectively.

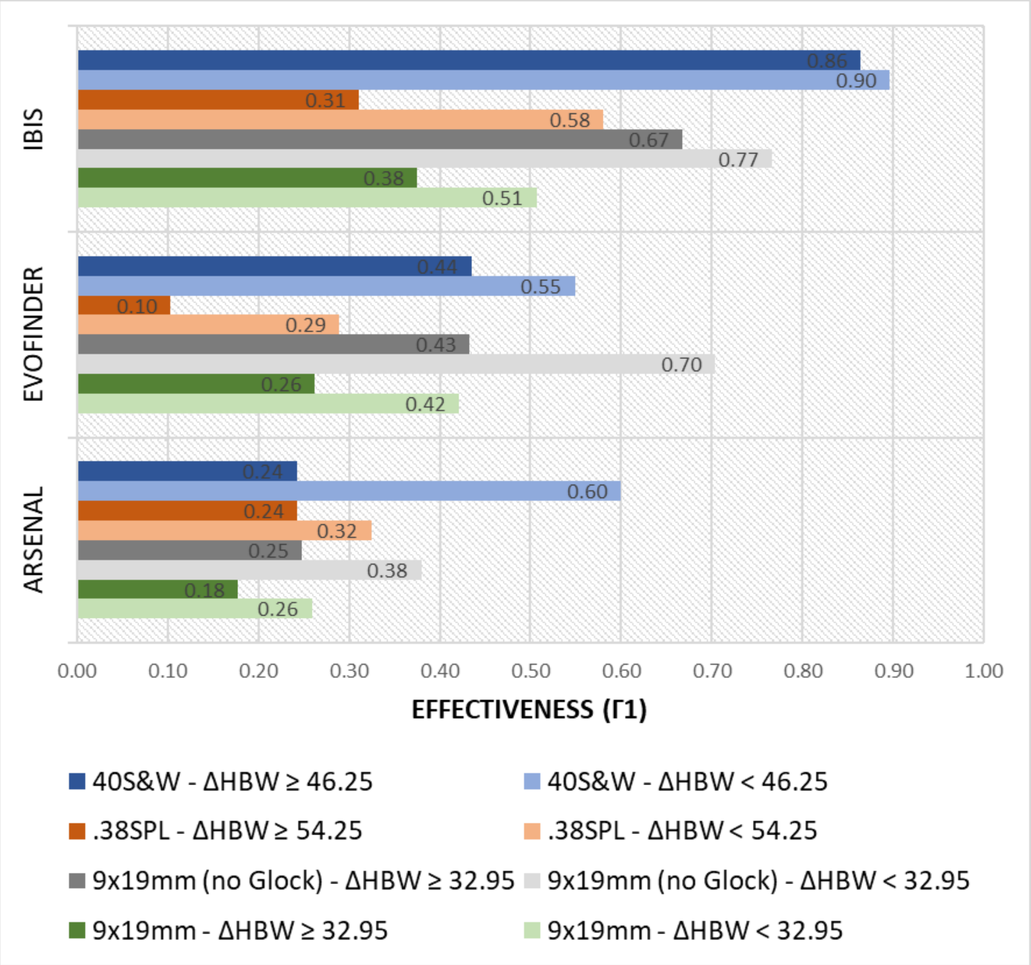


Figure 87 – Bullets Hardness influence on systems' effectiveness in the inter-material noiseless tests of each caliber. The correlation results used for the analyses were: Candidate List in Arsenal®, Secondary in Evofinder®, and L3DMPH in IBIS®.

The variability in hardness within materials appeared to be the major influential factor in the effectiveness with bullets and, as it is independent of the system, it is a characteristic that needs to be carefully considered when establishing protocols for test-firing seized firearms. The types of bullets by caliber that are found in crime scenes need to be assessed regarding material composition, brand, and form, thus driving the selection of the type(s) of ammunition(s) to collect test-fires that will increase the likelihood of identifying the match between two bullets.

Figure 88 computes the difference between the mean Brinell hardness of each type of .40S&W bullets after has been fired and before fired. The three types of jacketed bullets in this caliber (refer to blue results) became softer after the discharge, while the two types of solid piece bullet hardened (refer to yellow results).

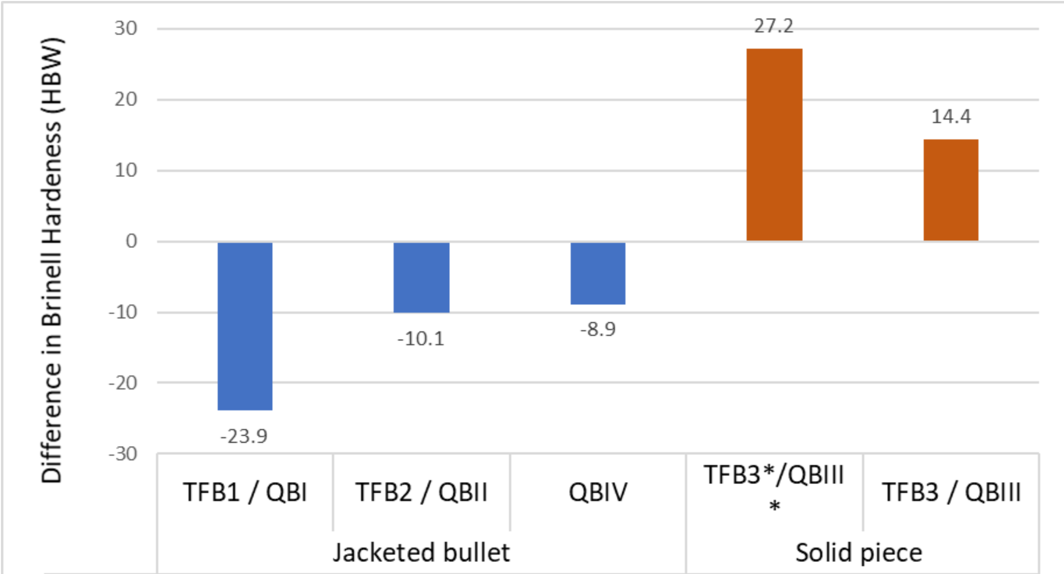


Figure 88 – Difference in mean Brinell hardness (HBW) after the bullet have been fired as compared to before fired.

The observed reduction in hardness may be due to the thickness of the jacket. During firing the jacket is compressed, and may become thinner, therefore, with a softer lead core beneath it, the fired jacket may impose less resistance to the indenter of the machine performing the hardness test.

On the other hand for the solid piece bullet that became harder, two phenomen should be taken into account as the bullet passes through the barrel bore, strain hardening, and heat treatment. During firing, as the bullet is squeezed through the barrel, plastic deformation results in the movement of its interior dislocations, generating more discordances in the crystal structure, which in turn difficulty further plastic deformation, increasing the material hardness. Also, the bullet is subjected to fast heating and subsequent cooling, which may generate diffusion of carbon or nitrogen to the exterior surface layer, also enhancing hardness (Callister, 2007).

5.6 Material composition

The bullet hardness is directly related to its material composition and manufacturing process, and in this research, this influence factor could be investigated in two ways. Firstly, comparing the effectiveness of intra-material and inter-material noiseless tests, further, implementing an effectiveness computation in the analysis program that grouped the results according to the relationship between the material composition of the questioned sample and the material composition of the test-fire in each match.

For each system and caliber, Figure 89 demonstrates that effectiveness decrease by comparing intra-material test, inter-material noiseless tests (both repeated test-fires), and inter-material noiseless tests (best repeated test-fired).

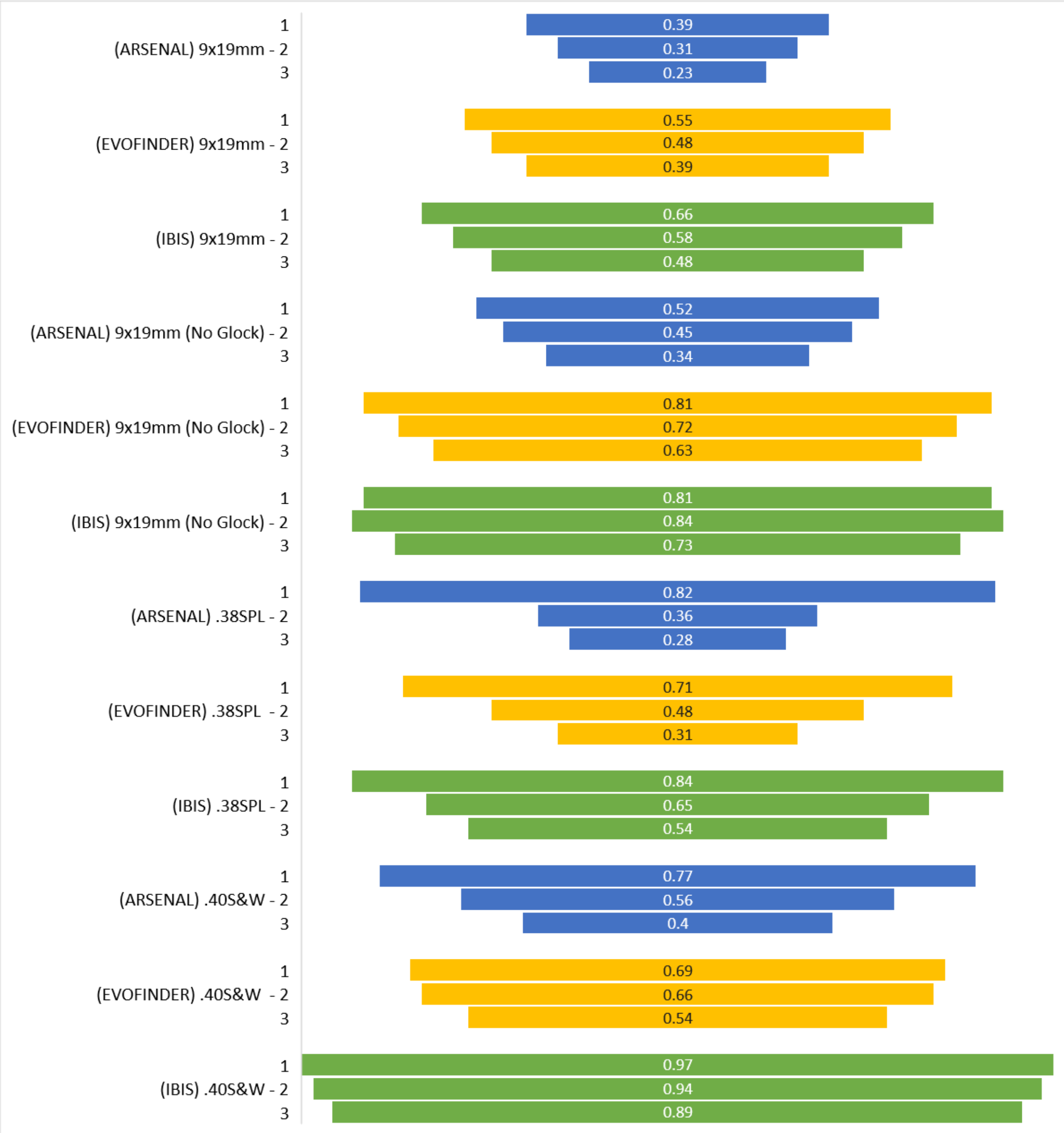


Figure 89 – Comparison of the systems' effectiveness, in each system and caliber, between **1)** intra-material test, **2)** inter-material noiseless test (best repeated test-fired), and **3)** inter-material noiseless test (both repeated test-fires).

As the intra-material and inter-material noiseless tests were conducted using the same database, the main factor influencing the difference in effectiveness between them is the inclusion (inter-material noiseless) or the non-inclusion (intra-material) of different types of bullets correlations. A significant decrease in systems' effectiveness was observed in all calibers and systems when results from different bullet types correlations were included in the analysis. This reduction in effectiveness was most severe when both repeated test-fires were incorporated as compared to just the best one. Figure 90 computes the differences in effectiveness between these tests.

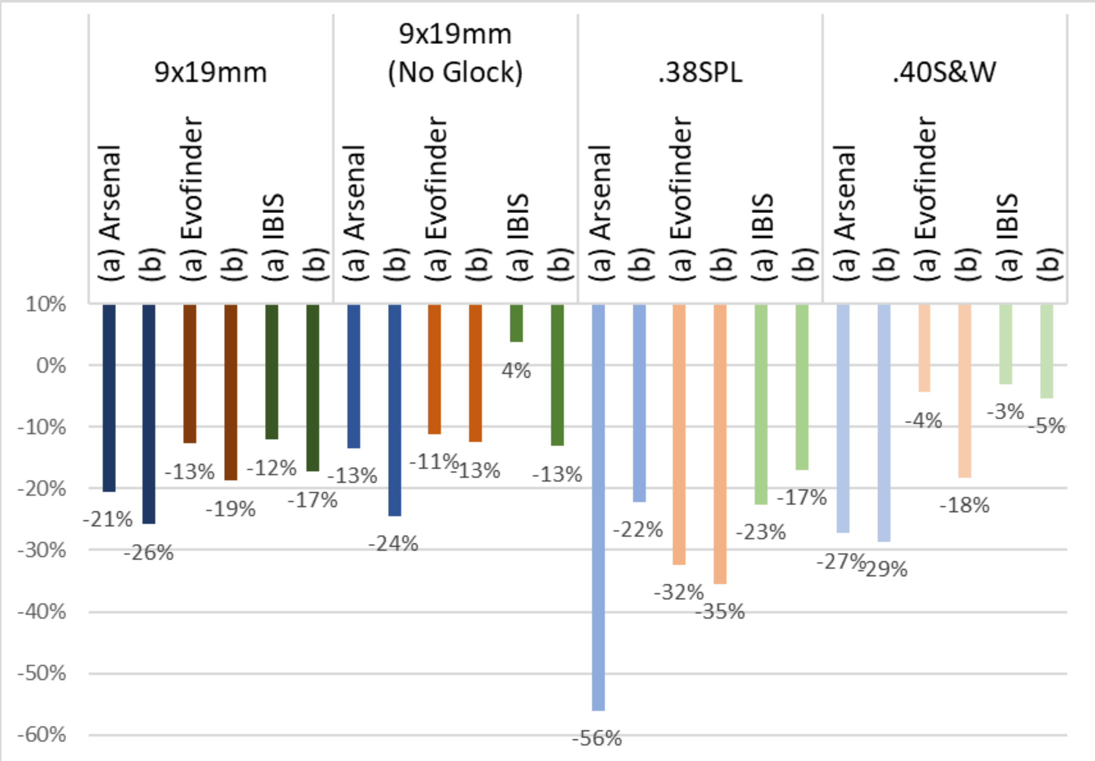


Figure 90 – Differences in systems' effectiveness in the tests of Figure 89, between **a)** intra-material and inter-material noiseless (best repeated test-fired) tests, and **b)** inter-material noiseless (best repeated test-fired) to inter-material noiseless test (both repeated test-fires).

Comparing results by caliber is observable that IBIS® features the lower difference in effectiveness between the tests (refer to shadows of green results in Figure 90), as compared to intermediate decrement in Evofinder® (refer to shadows of orange results), and to highest decreasing in Arsenal® (refer to shadows of blue results). These difference in sensitivity to material composition coincides with the difference in systems' effectiveness by manufacturer (refer to section 5.4). It also observable, for all systems, the highest effectiveness decrement in .38SPL caliber, -56%, -35%, -23% for Arsenal®, Evofinder®, and IBIS®respectively, what once more is in agreement to the fact that the lower effectiveness of the systems by manufacturer was obtained with .38SPL caliber. These data suggest that the material composition is one of the reasons for the 38SPL lower effectiveness, and also the sensitivity to material composition differences is one of the reasons for the observed difference in systems' effectiveness by manufacturer.

To further investigate the influence of bullet material composition in the systems' effectiveness, the external material of bullet compared in each match was verified, according to the following variations per caliber:

- ✓ .38SPL: LEAD, BRASS, NICKEL, GOLD;
- ✓ 9x19mm: BRASS, GOLD, COPPER;
- ✓ .40S&W: BRASS, GOLD, COPPER;

Should be noted that for this investigation all but one of the bullets were termed according to the main external material, as recorded in Table 12 (refer to p. 135). The exception is the bullet termed Gold, which the jacket is composed of copper, nickel, and zinc. Figure 91 and Figure 92 compare the systems' effectiveness considering the possible combinations, in each match, of the bullet material of the questioned sample and of the test-fired.

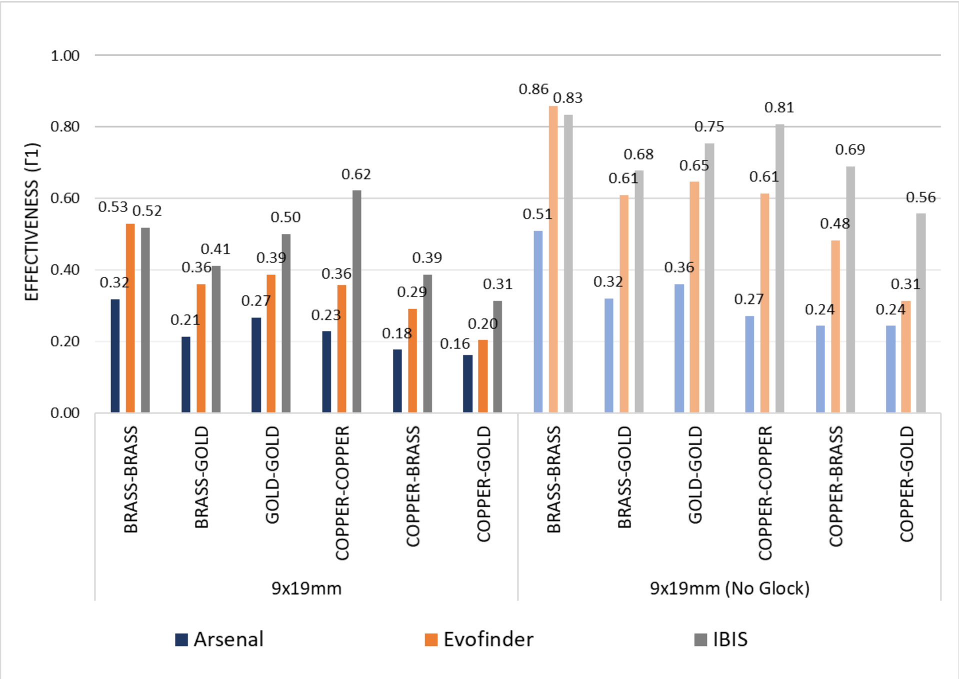


Figure 91 – Systems' effectiveness by material compositions of questioned sample and test-fired on each 9x19mm match, including both repeated test-fired.

The analysis of data related to material composition by caliber and by system is useful for determining firearm test-fire collection protocols. In caliber 9x19mm (refer to Figure 91), particularly considering the 'No Glock' results, if needed to select just one type of ammunition for test-firing, is recommendable the selection of one with a Brass bullet. This will lead to higher performance in finding other Brass bullets (respectively Γ_1 = 0.51, 0.86, and 0.83 for Arsenal®, Evofinder®, and IBIS®), and will not compromise the capabilities of the systems to correlate the Brass test-fired against other types of bullets that may come from crime scenes (Copper or Gold). For instance, Gold-Gold effectiveness in Arsenal®, Evofinder®, and IBIS® were Γ_1 = 0.36, 0.65, and 0.75, while the Brass-Gold respectively Γ_1 = 0.32, 0.61, and 0.68. With Copper the difference is a little higher, with effectiveness in Copper-Copper correlations of Γ_1 = 0.27, 0.61, and 0.81, as compared to Brass-Copper correlation effectiveness of Γ_1 = 0.24, 0.48, and 0.69.

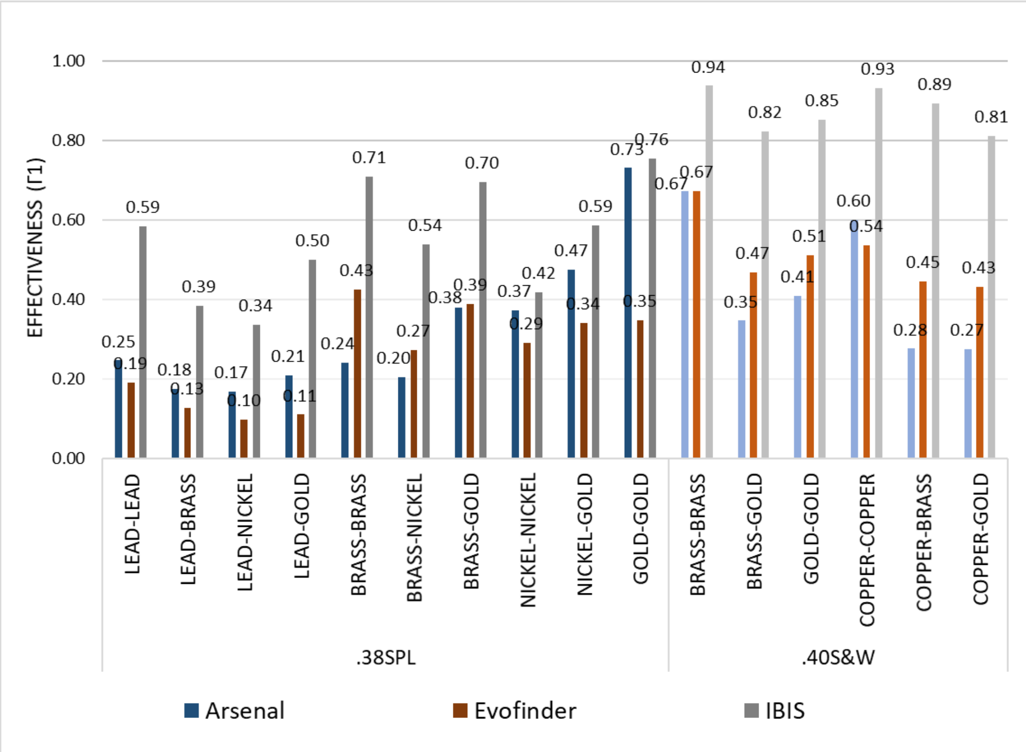


Figure 92 – Systems' effectiveness by material compositions of questioned sample and test-fired on each .38SPL and .40S&W match, including both repeated test-fired.

In .38SPL caliber (refer to Figure 92) the Gold bullet appears as the best recommendation for test-firing ammunition selection. For instance, in Arsenal®, Evofinder®, and IBIS®, Gold-Nickel (Γ_1 = 0.47, 0.34, and 0.59) were even better than Nickel-Nickel (Γ_1 = 0.37, 0.29, 0.42), and Gold-Brass (Γ_1 = 0.38, 0.39, and 0.70) better or very close to Brass-

Brass (Γ_1 = 0.24, 0.43, 0.71), meaning that Gold as a test-fired would not only find other Gold questioned bullets as well Nickel and Brass ones. The exception in this caliber is by the Lead bullet, which as seen in section 5.5, is the one with a greater difference in Brinell hardness. This specificity reflected on this material analyses and suggested the validity of having Lead as another bullet test-fired on this caliber, as Lead-Lead shows better performance (Γ_1 = 0.25, 0.19, and 0.59) as compared to other Lead-any correlations.

In .40S&W caliber the bullet material appears to be less critical for IBIS® than for the other systems. For instance, the selection of Gold as test-fired in IBIS® would lead to very similar effectiveness of finding Gold, Brass, and Nickel (Γ_1 = 0.85, 0.82, and 0.81). On the other systems, Arsenal®, Evofinder®, Brass appears to be the best choice because features higher effectiveness for finding Brass questioned (Γ_1 = 0.67 and 0.67), although this selection would compromise the ability of the system to find Copper and Gold (Arsenal® - Γ_1 = 0.35 and 0.28, and Evofinder® Γ_1 = 0.47 and 0.45).

The type of ammunition used in a shooting, and thus being collected from a crime scene or from a deceased body, is an uncontrollable factor for the laboratory. As a result, the laboratory's analysis protocol needs to consider the type of ammunition most frequently used in crimes within that geographic region, and how material composition can drive the selection for test-firing seized firearms, this way trying to optimize system effectiveness as the database grows in size.

As previously explained (refer to sub-section 4.1.1), the calibers included when designing this research were selected from those commonly used in crimes in Brazil, and therefore their ammunition components are more likely to be recovered at crime scenes. Considering that, the analysis conducted in this section has enabled the suggestion of an operating condition for the systems, including the ammunition to test-fire sized firearms, as further outlined in section 5.9 (suggested operating condition for bullets).

5.7 Database growth

It can be observed in the discussed results of sub-section 5.4, that effectiveness for the same manufacturer or the same type of barrel always decreased in inter-material noise tests (IM-N1 and IM-N2) compared to the effectiveness in the inter-material noiseless tests (IM-N). For instance (refer to Figure 84 and Figure 85), for the IM-N, IM-N1, and IM-N2 tests, effectiveness in Evofinder® for FN Browning were respectively Γ_1 = 0.54, 0.51, and 0.43, and in IBIS® the effectiveness for conventional barrels, Γ_1 = 0.76, 0.74, and 0.71. Because the noise tests were replications of the noiseless tests, with more same class characteristics images in the databases, these decrements demonstrate how the increasing of the database leads to decreasing of the effectiveness. Investigating the decaying profile enables an understanding of the behavior of the solutions in expanding databases, allowing studying the influence of database growth on the systems' effectiveness.

For this investigation, to each questioned bullet correlation request the test-fire within each pair that delivered the optimal score in all available result lists was used to compute effectiveness, which was plotted against the database size. The Levenberg-Marquardt algorithm (Madsen et al., 2004) was subsequently employed to obtain the decay function for each caliber per system. As the Arsenal® database was unable to be expanded, the decay could only be observed and characterized in Evofinder® and IBIS® systems. Figure 93, Figure 94, and Figure 95 depict the effectiveness of these two systems as a function of the database size in the three calibers.

In .38SPL caliber (refer to Figure 93) it were carried out the inter-material noiseless test and 1 (one) inter-material noise test, so the effectiveness (Γ_1) as a function of the database size (i) had two points, and therefore was characterized by the linear function of equation 5.4 with parameters $\Gamma_{1,0}$ and *slope*.

$$\Gamma_1(i) = \Gamma_{1,0} + slope * i \ . \qquad 5.4$$

Table 23 compares the parameters of the .38SPL decay functions obtained with Evofinder® and IBIS®. The intercept to Effectiveness-axis, denoted by $\Gamma_{1,0}$, are respectively 0.55 and 0.78 for Evofinder® and IBIS®, which will be the highest effectiveness of each system on this caliber, the slope, $-2.20\text{x}10^{-4}$ and $-1.30\text{x}10^{-4}$ for each system, a very important parameter to measure how database growth impacts these two solutions on this caliber, because as steeper the negative slope as faster the effectiveness erodes. For instance, in the data of Table 23 can be seen that for Evofinder®, a database of 1000 samples would result in 0.33 effectiveness, while in IBIS® this same database would lead to 0.65 effectiveness. Also assuming this linear decay, a 0.50 effectiveness would be reached by Evofinder® in a database of only 227 samples, against 2154 samples for IBIS®. Nevertheless, should be pointed out, if another inter-material test with additional noise in this caliber was available, it is expected that the linear profile would change to exponential decay observed on the other calibers, which would moderate the impact of the database size on the effectiveness.

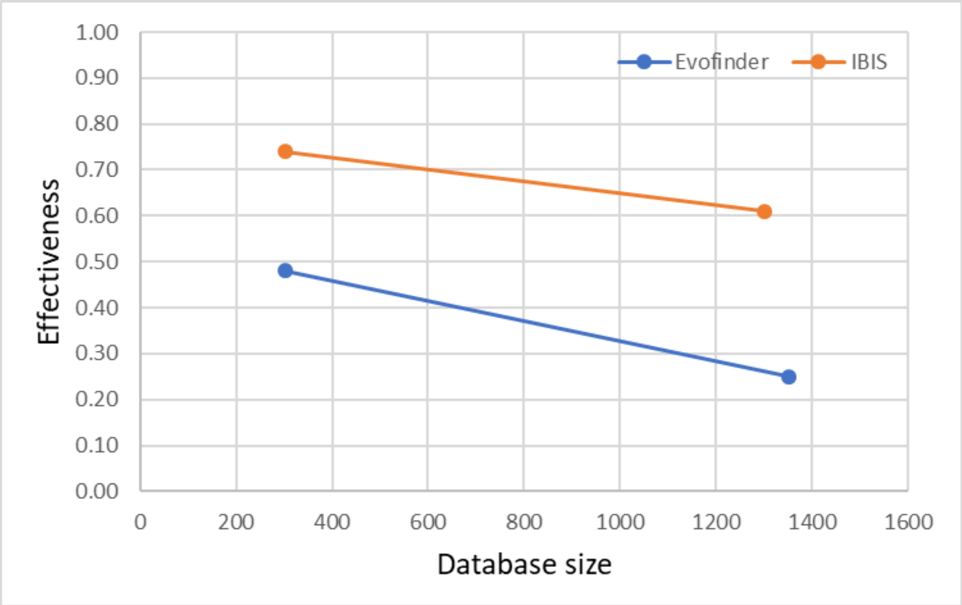


Figure 93 – Effectiveness as a function of database size in .38SPL bullets for Evofinder® and IBIS®, considering the lower position between the repeated test-fires in all correlation result lists.

Table 23 – Parameters and results of interest in the effectiveness as a function of .38SPL bullet database size for Evofinder® and IBIS®.

CALIBER	DECREASING	SYSTEM	FUNCTION	$\Gamma_{1,0}$	slope (10^-4)	Γ_1 (i = 1000)	i (Γ_1 = 0.5)
.38SPL	Linear	EVOFINDER	5.4	0.55	-2.20	0.33	227
		IBIS		0.78	-1.30	0.65	2154

In 9x19mm (refer to Figure 94) and in .40S&W (refer to Figure 95) were carried out the inter-material noiseless test, and 2 (two) inter-material noise tests, so the effectiveness (Γ_1) as a function of the database size (i) had three points for each system and caliber, and the observed decays were characterized by equation 5.5, with parameters $\Gamma_{1,\infty}$, A_1 and t_1.

$$\Gamma_1(i) = \Gamma_{1,\infty} + A_1 * e^{-\frac{i-i_0}{t_1}} . \quad 5.5$$

In this exponential decay, it is possible to obtain the limit when database size **(i)** → ∞, leading to $\boldsymbol{\Gamma_1 = \Gamma_{1,\infty}}$**.** This behavior is desired for ballistic identification systems that tend to have their database growing over time. Although initially, an increasing database size will lead to a decrease in effectiveness, an exponential decay will approach a limit beyond which the correlation effectiveness will no longer be affected by the expansion of the database.

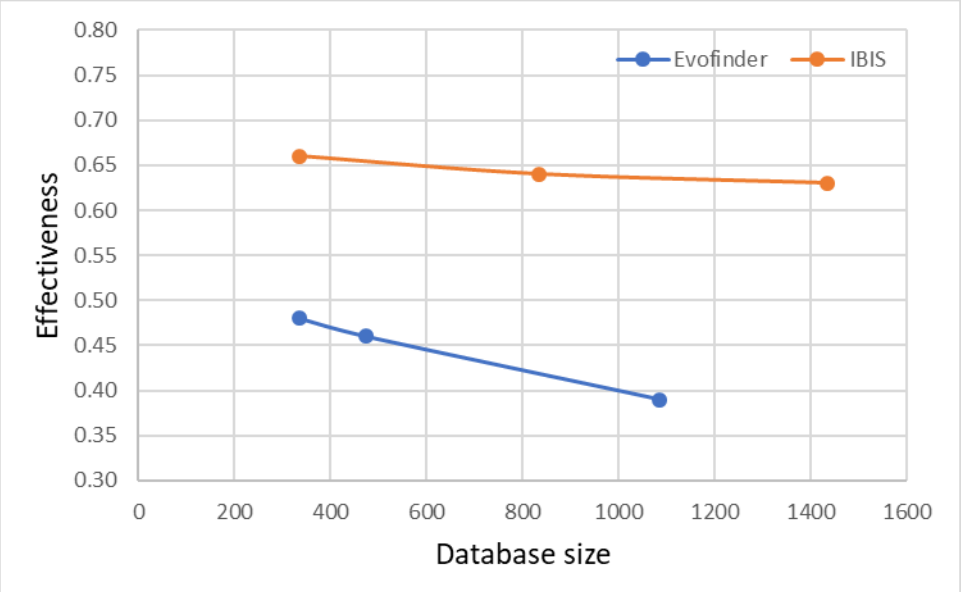


Figure 94 – Effectiveness as a function of database size in 9x19mm bullets for Evofinder® and IBIS®, considering the lower position between the repeated test-fires in all correlation result lists.

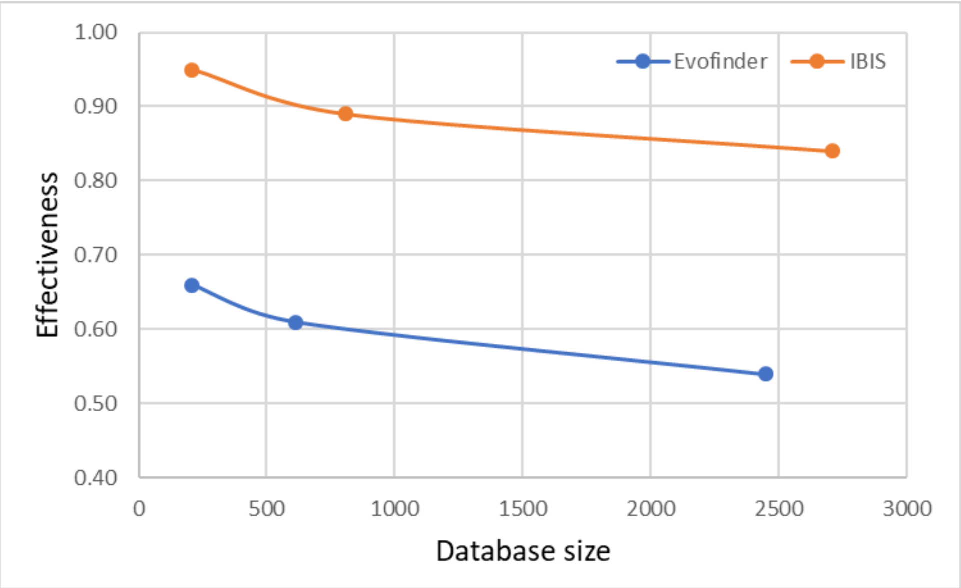


Figure 95 – Effectiveness as a function of database size in .40S&W bullets for Evofinder® and IBIS®, considering the lower position between the repeated test-fires in all correlation result lists.

Solving equation 5.5 for ***i***, results in equation 5.6, which is useful for predicting the database size (*i*) where the effectiveness of interest is reached. Table 24 Table 23 compares the parameters of the 9x19mm and .40S&W decay functions obtained with Evofinder® and IBIS®.

$$i = i_o + t_1 * \left(\ln\left(\frac{A_1}{\Gamma_1 - \Gamma_{1,0}}\right)\right). \qquad 5.6$$

Table 24 – Parameters and results of interest in the effectiveness as a function of 9x19mm and .40S&W bullet database size for Evofinder® and IBIS®.

CALIBER	SYSTEM	DECREASING	FUNCTION	A_1	t_1	$\Gamma_{1,\infty}$	$i(\Gamma_1 = 0.5)$
9x19mm	Evofinder	Exponencial	5.5	0.30	1646	0.23	173
	IBIS			0.018	628	0.62	∄
.40S&W	Evofinder	Exponencial		0.066	956	0.53	∄
	IBIS			0.059	936	0.83	∄

For 9x19mm the minimum effectiveness for Evofinder® and IBIS®, when $\boldsymbol{i} \to \infty$, are 0.23 and 0.62. In other words, according to the data obtained, it is unlikely that a growing database will lead the IBIS® system to effectiveness around 0.5 in this caliber, for instance. On the other hand, for the Evofinder® system, it is obtained by equation 5.6, $i(\Gamma_1 = 0.5) = 173$, that is, the system would be reaching 0.5 effectiveness with a very small database (database of 173 samples).

At this point, it is important to note that the 9x19mm caliber contains results from the Glock pistols, with polygonal barrels, and as they are firearms with very few marks for identification (refer to Figure 84 on p. 181), this certainly contributed to lower effectiveness in this caliber, regardless of the influence of the database size. Also, because IBIS® has specific algorithms to optimize polygonal barrel comparison, as the one features by Glock pistols of this research, this can be a factor that partially explains the difference in the performance of the two systems in this caliber.

In this exponential decay, it is interesting to also evaluate the parameters A_1 and t_1, which dictate how quickly the effectiveness decreases with the database growth. In the 9x19mm caliber the difference in the system's decay was large (Evofinder®, $A_1 = 0.30$ and $t_1 = 1646$; IBIS®, $A_1 = 0.018$ and $t_1 = 628$).

For .40S&W caliber, the data also indicates an exponential decay, with minimum effectiveness limits for the Evofinder® and IBIS® systems at 0.53 and 0.83 (refer to Table 24).

Although these effectiveness values are significantly different, the pattern of decay is similar (Evofinder®, $A_1 = 0.066$ and $t_1 = 956$; IBIS®, $A_1 = 0.059$ and $t_1 = 936$).

It is interesting to interpret these results in the light of previous studies that found that the increase in the database led to linear growth in the position in which the match appears in the results list (De Kinder et al., 2004; De Ceuster; Dujardin, 2015). Although such linearity has been observed, the results obtained in this research, add important understanding to the theme. Some important differences in the method of this research should be addressed, for example, considering the highest-ranked position between two test-fires, selecting the highest-ranked result among the lists of available correlations, and performing tests with a database significantly bigger than those of previous studies (refer to the database size - horizontal axes - Figure 93, Figure 94, and Figure 95).

Therefore, the observed exponential decay is preferable and in favor of the effectiveness of systems even though the database size grows over time. Additionally, what needs to be observed is that even if samples are added to a database, only those that have the same class characteristics and similar individual marks to the questioned sample will negatively affect the effectiveness of the solution. In other words, only ammunition components with marks that, by the correlation algorithm used, obtain higher or equal scores than the searching test-fire will cause a meaningful repositioning within the result lists. However, there is a limitation to this possibility of including potentially harmful noise. For well-developed algorithms, it is expected that a large portion of the images entered will not be better ranked than the correct test-fire, so the introduction of more images will affect the solution's effectiveness more smoothly and, as seen in this research, it may feature a limit for such decay.

This finding is extremely relevant to locations that experience high rates of firearm-related crimes, such as Brazil, and explains why the technologies are still appropriate to succeed in establishing links between shooting incidents.

5.8 Analysis of the correlation scores

Another factor of interest on the effectiveness of the solutions is an analysis of the correlation scores that the systems make available in the result lists, which may be utilized, in theory, to establish more objective identification criteria. The use of the gap measurement between these scores can be used for determining a match, or comparing the score of a match against the distribution of non-match scores allow the establishment of the identification potential error.

The aforementioned Rahm paper (2012, refer to p. 110) is an instance of an attempt to use the gaps observed in the scores of the result lists, having been concluded that:

> Finally we searched the correlation lists for gaps and examined whether they are applicable to indicate corresponding marks. **We found that the existence of a gap may be a hint for a match, but if there is no gap it is not a reliable criterion for exclusion** (Rahm, 2012, p. 177, emphasis added)

In the search for a more objective identification process, that includes an estimate of the error rate, also was used as inspiration for this research the studies by Yuesong et al. (2019, refer to p. 104) and by Roberge et al. (2019, refer to p. 98). These studies included defining two or three-dimensional spaces combining some scores from the same reference versus test-fire correlation.

In terms of gaps, the results of this research did not provide gaps in the scores of many correlations. Additionally, the establishment of two or three-dimensional spaces with the scores was originally intended for this research, but Arsenal® bullet correlations are available only in one score, and although Evofinder® bullet correlation provided up to three scores, the primary was not available for this research, and in many correlations, there was an absence of the ‘Groove’ score. Due to these limitations on data obtained in this research, only scores of individual correlators were analyzed.

Figure 96 to Figure 100 compare the frequencies of matches versus non-match scores per caliber and system. It is interesting to note that many match scores are lower than non-match scores, which indicate a poor accuracy in the employed algorithms. As a way of measuring the utility of the scores for an objective identification, i.e. one that would not require human intervention in the analysis of images, the minimum match score (MSmin) and the maximum non-match score (NMSmax) for each caliber/system/correlator was verified.

Considering the number of available match scores, it was possible to verify which percentage of the non-matches had a lower score than MSmin, i.e. how many non-match scores feature a minimum false-negative rate (FNR). For non-match scores with values above MSmin, other FNR could be established. In the data of this study, the minimum FNR varied between 2% and 7% (refer to Figure 101b).

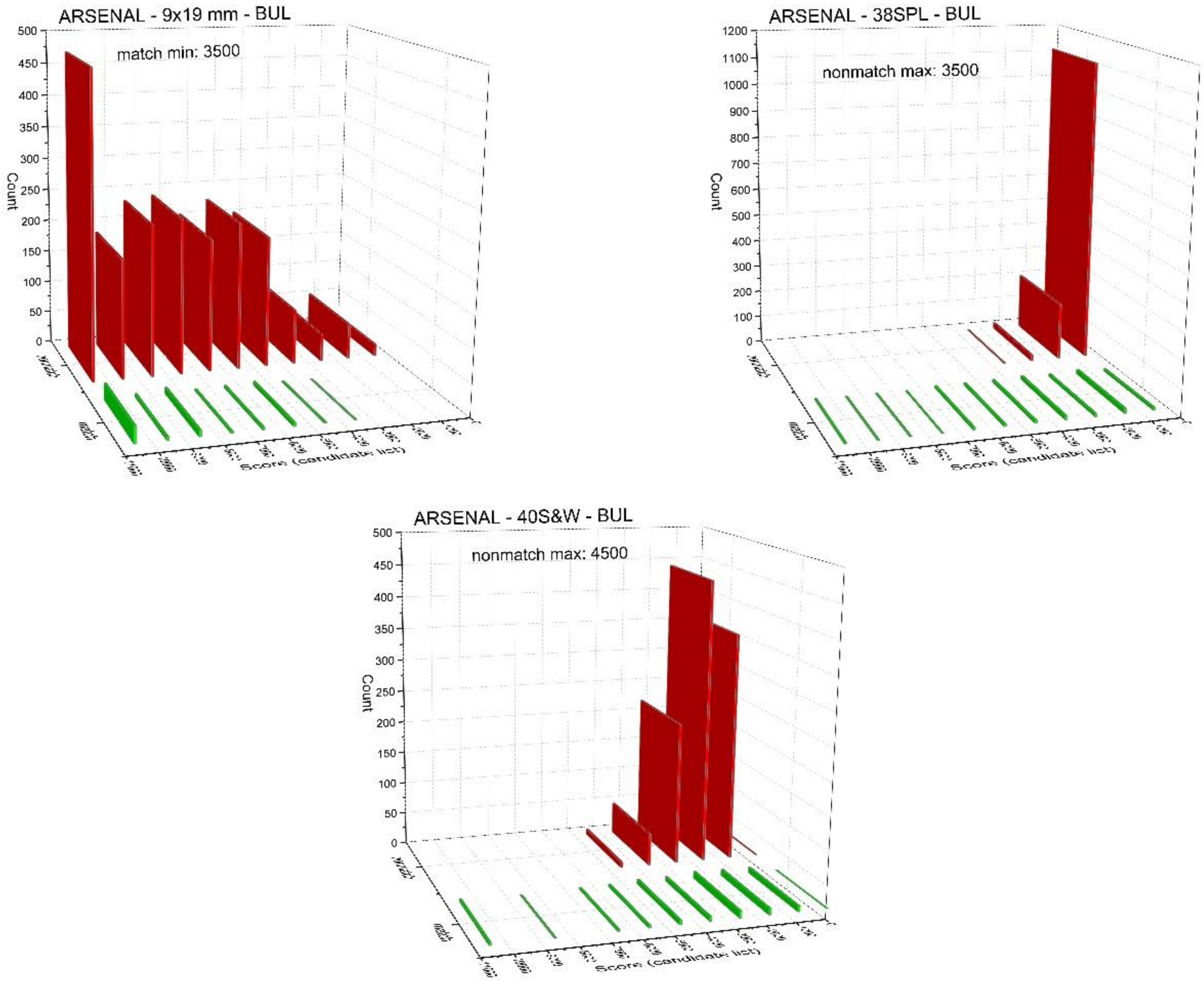


Figure 96 – Histogram of correlation scores for match (green) and non-match (red) in Caditate lists of Arsenal® system.

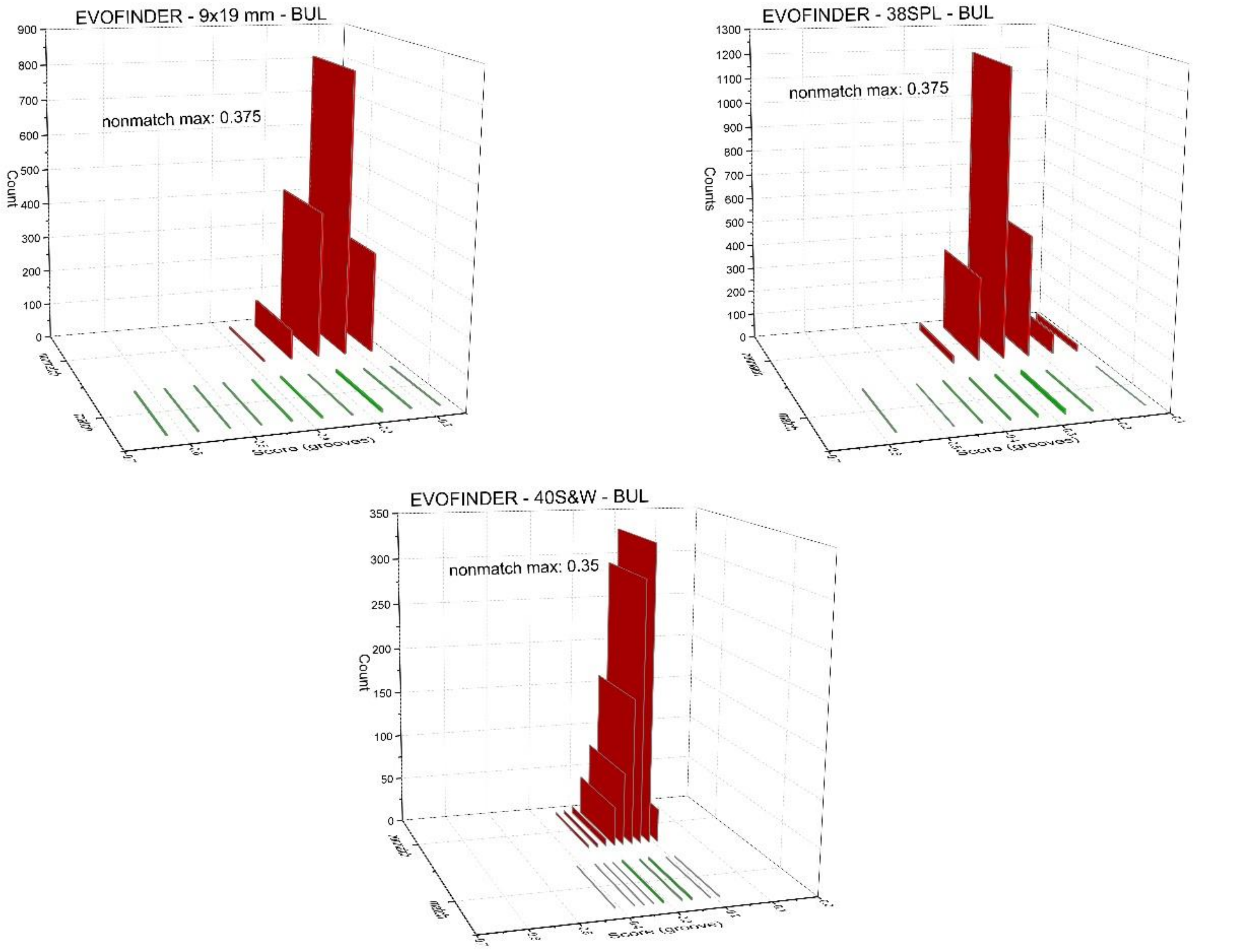


Figure 97 – Histogram of correlation scores for match (green) and non-match (red) in Groove lists of Evofinder® system.

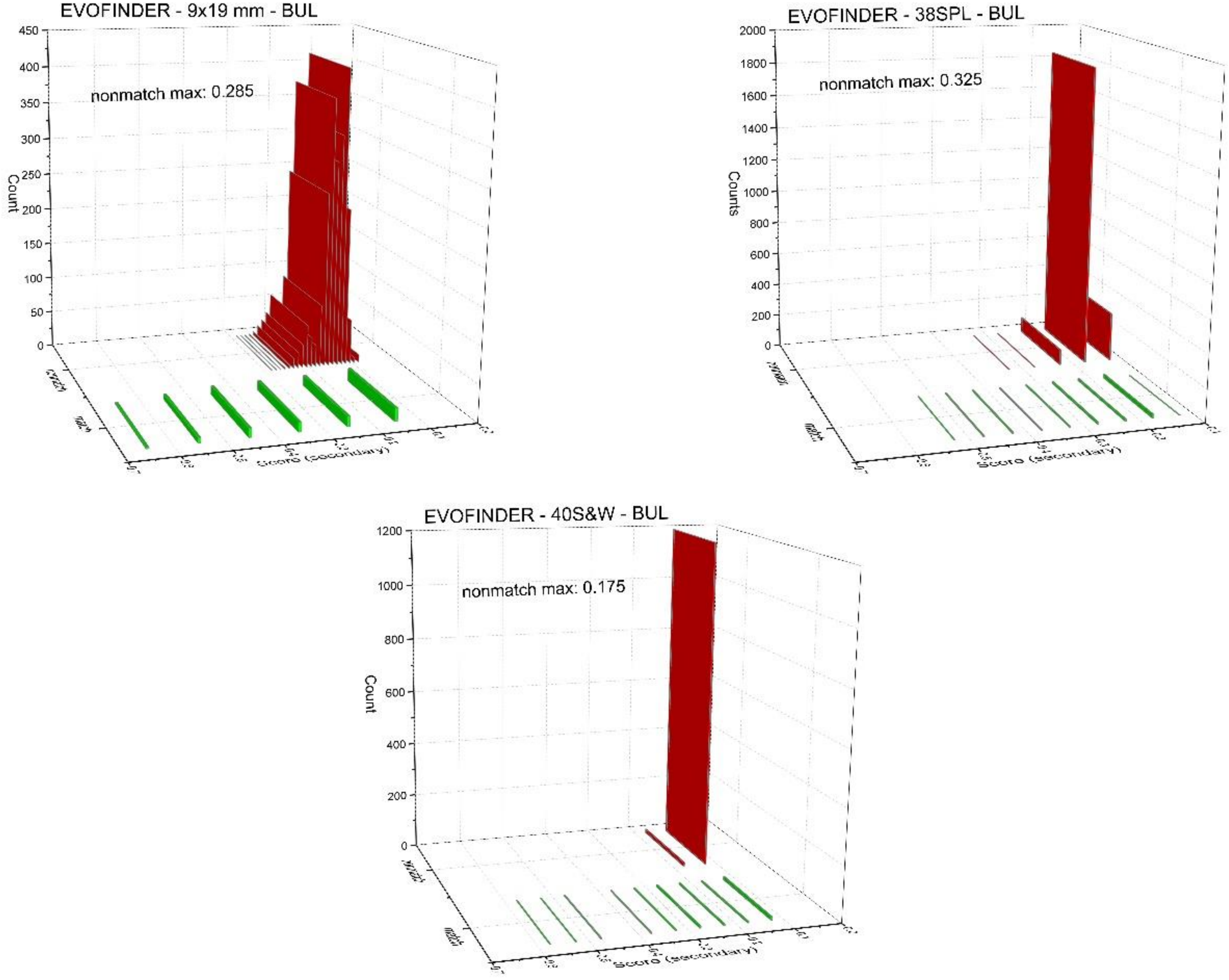


Figure 98 – Histogram of correlation scores for match (green) and non-match (red) in Secondary lists of Evofinder® system.

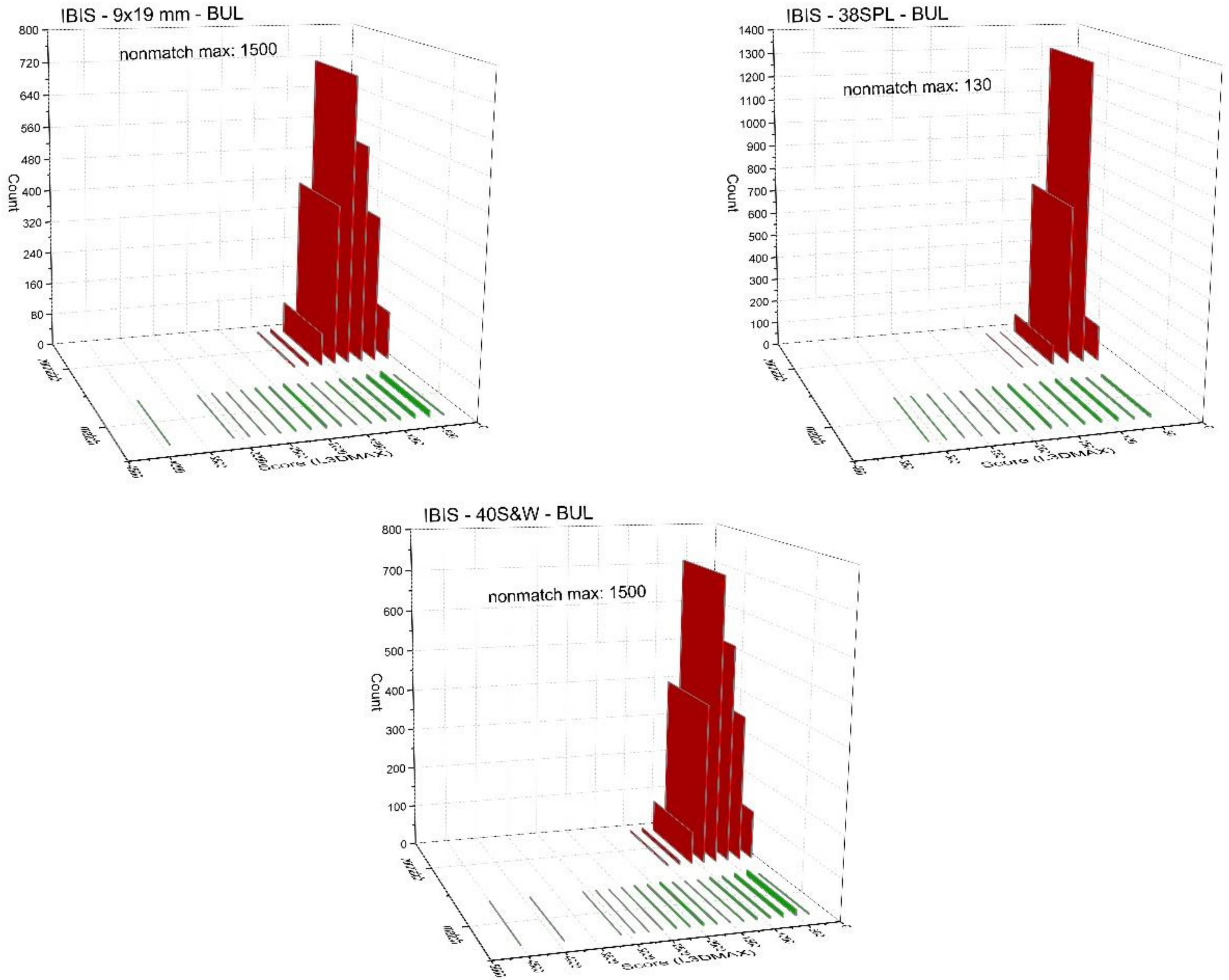


Figure 99 – Histogram of correlation scores for match (green) and non-match (red) in L3DMAX lists of IBIS® system.

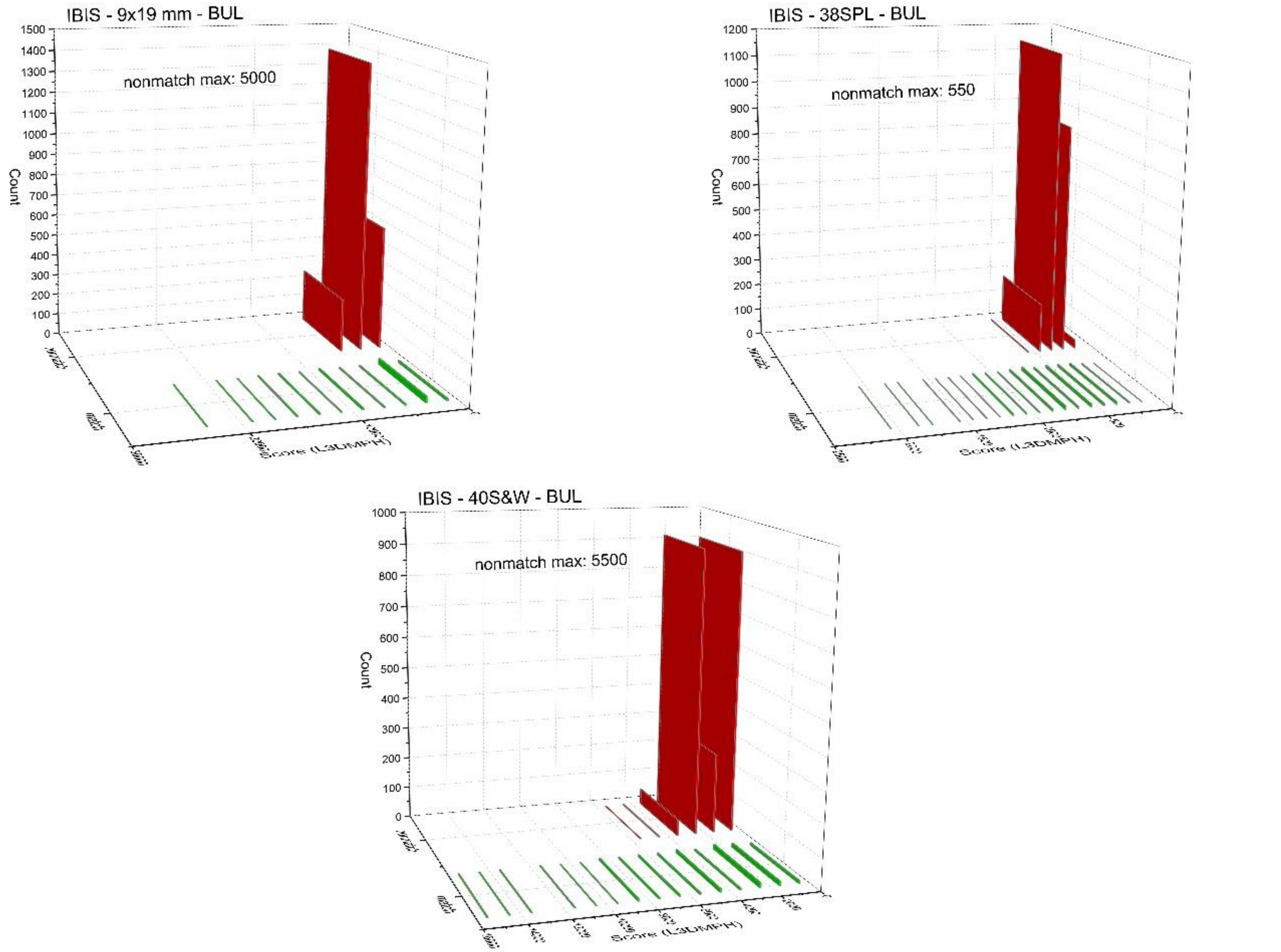


Figure 100 – Histogram of correlation scores for match (green) and non-match (red) in L3DMPH lists of IBIS® system.

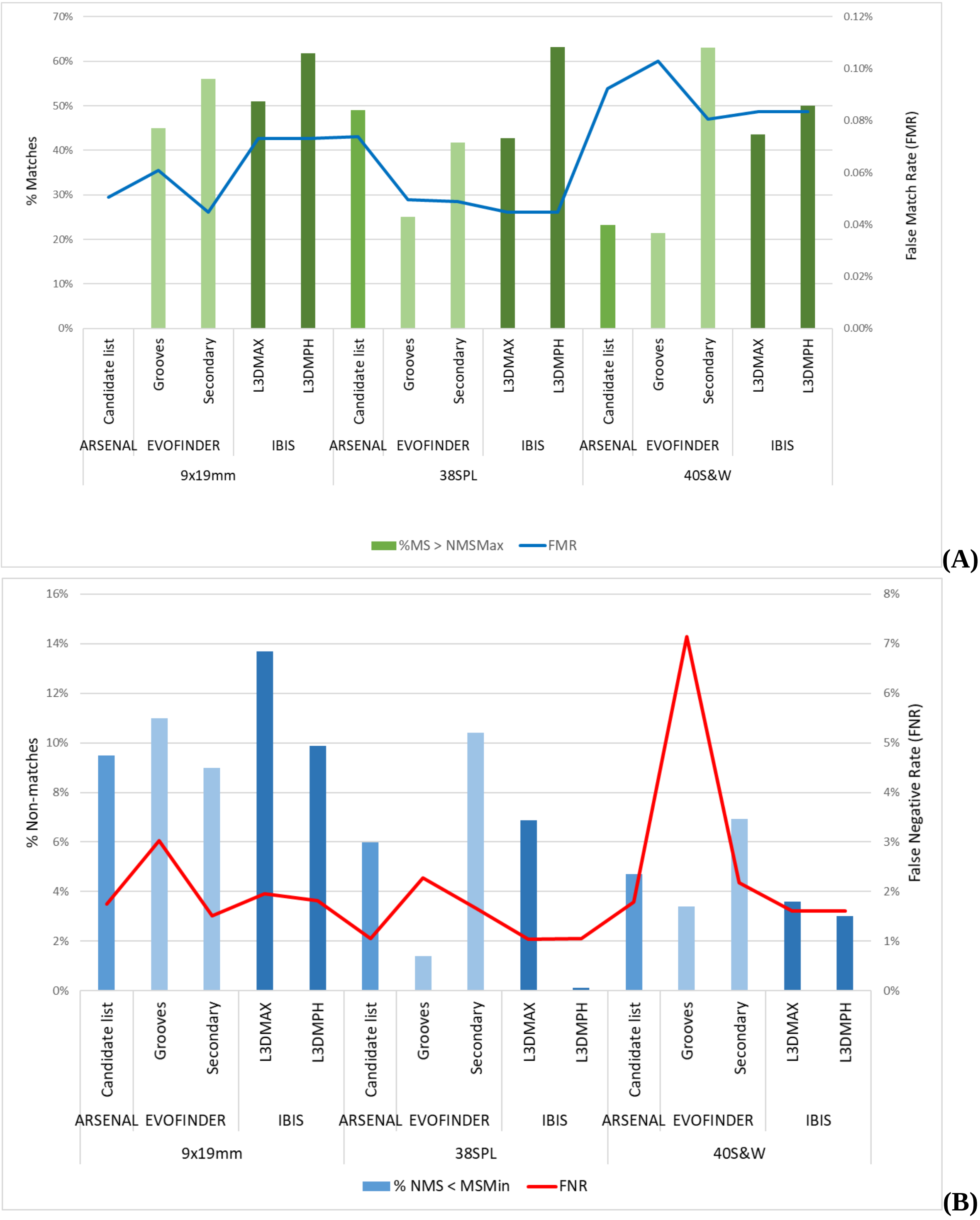


Figure 101 – Percentage **a)** of bullet MS (match score) that features the minimum FMR (blue line) and **b)** of bullet NMS (non-match score) that features the minimum FNR (red line).

Presenting the results respectively for 9x19mm (refer to Figure 101b), .38SPL, and .40S&W bullets, in the Arsenal® Candidate List correlator, only 9%, 6%, and 5% of the non-match scored with minimum FNR. In the Evofinder®, 11%, 1% and, 3%, of the non-match Groove scores, and 9%, 10%, and 7% of the non-match Secondary scores featured a minimum

FNR. In IBIS®, 14%, 7%, and 4% for L3DMAX, and 10%, 0%, and 3% for L3DMPH scored with minimum FNR.

This result means that although the minimum FNR is not negligible, between 2% and 7%, a very small portion of non-match scores can objectively be used, with this error rate, to determine a non-match. This demonstrates that the non-match scores of all systems and calibers are not a good predictor for objectively indicating an exclusion, i.e. a conclusion that two fired bullets came from different firearms.

Another way to evaluate the utility of the scores was by concentrating on the number of non-match scores available, always greater than the number of match scores, and search for matches with a higher score than NMSmax, that is, establishing a false match rate (FMR). The variation observed in the minimum FMR was between 0.04% and 0.10% (refer to Figure 101a), an error rate significantly lower than the minimum FNR. In addition, the percentage of match scores that scored above the NMSmax, that is, that presented minimum FMR, was considerably higher.

In the Arsenal®, the Candidate list presented minimum FMR in 0%, 49%, and 23% of the match scores for 9x19mm, .38SPL, and .40S&W bullets. In the Evofinder®, 45%, 25%, and 21% of Groove scores, and 56%, 42%, and 63% of Secondary scores, fall within the minimum FMR. Finally, in the IBIS®, the minimum FMR was met in 51%, 43%, and 44% of the L3DMAX scores and in 62%, 63%, and 50% of the L3DMPH scores.

Comparing to the FNR analysis, there is no doubt that a larger portion of the match scores fall within the minimum FMR, being an indication of a better chance to use the match score for an objective identification, which is the conclusion that the two samples came from the same firearm. However, the results are still considered timid for such an ambitious goal, and an objective differentiation between match and non-match in all systems and correlators seems premature. In other words, the analysis of any isolated bullet correlator score was not effective to objectively conclude for identification or exclusion.

As performed in the aforementioned studies maybe correlator combinations could increase the percentage of score within minimum FMR or FNR criteria, supporting a more objective identification or exclusion decision-making process.

5.9 Suggested operating condition for bullets

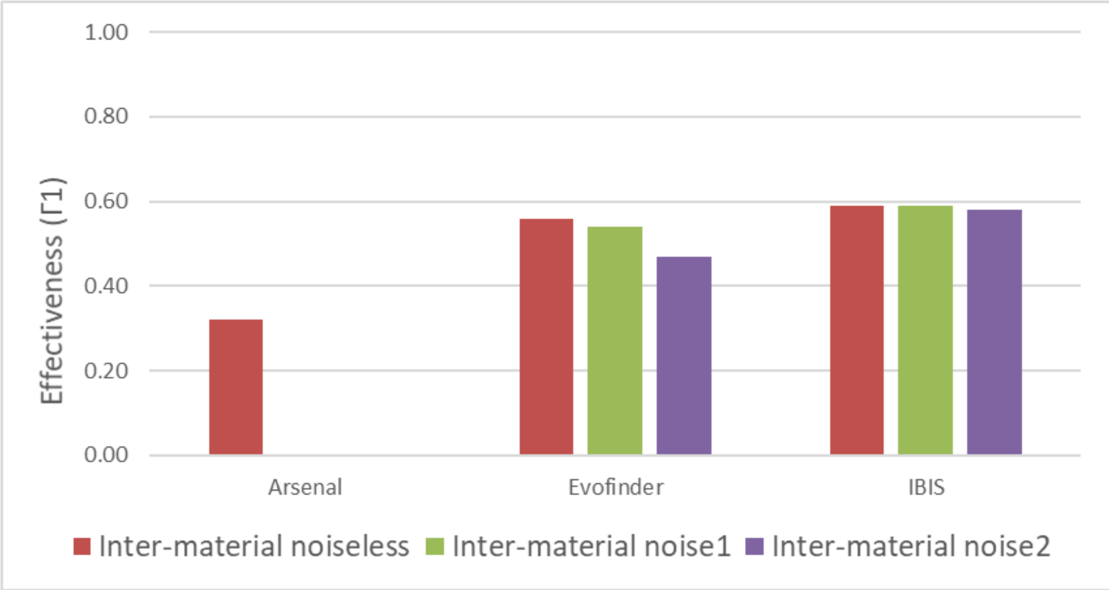
The previous results have resulted in a better understanding of the factors affecting algorithm performance and thus will allow users to develop best practices or protocols to be established to increase the likelihood of correct identification of the firearm and/or to make the identification process more reliable.

The extent of decreasing system effectiveness was quantified by comparing bullets comprised of different material composition and hardness. The difference in performance between the systems was evident and several factors decrease the effectiveness making identification or exclusion more difficult A database of fired bullets from all firearms registered in a country/region is therefore not recommended as it will remain subject to many variables that are difficult to control. However, a specific database of fired components from criminally used firearms will be more efficient if more standardized protocols are established for test-fire ammunition selection and data entry. As more bullet factors that influence correlations are measured and considered in the establishment of protocols, as higher the system effectiveness will be.

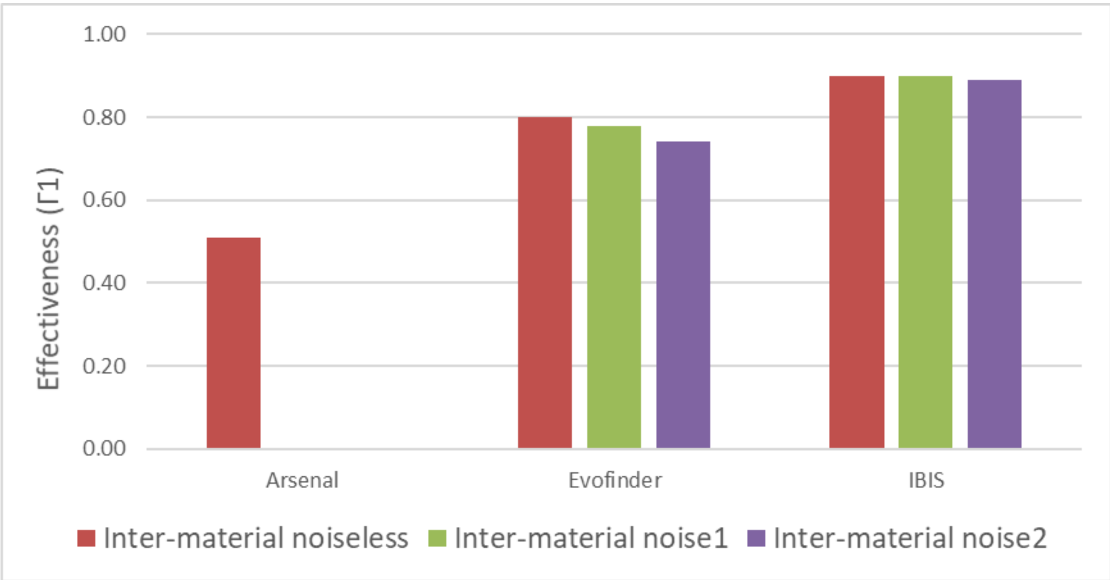
In order to determine a recommended operating condition of a BIS, the main results within this chapter were evaluated to establish the following protocols for registering firearms of each caliber:

- .38SPL: register in any of the systems 2 (two) TFB1 (LRN) and 2 (two) TFB6 (JHP - GOLD), this way it is expected that crimes committed with LRN or with the types of jacketed bullets of this study will be correctly identified during system correlation;
- 9x19mm: register in any of the systems 2 (two) TFB2 (JHP – Brass);
- .40S&W: register 2 (two) TFB1 (FMJ-F) in Evofinder® and Arsenal®, or 2 (two) TFB2 (JHP - GOLD) in IBIS®;
- In Arsenal®, check the Candidate List, in Evofinder® the Secondary or Groove lists, and in IBIS® the L3DMPH or L3DPEK results to more effectively identify associated items within the database.

Figure 102 to Figure 104 are comparative depictions of the final effectiveness obtained by the systems operating according to the suggested condition for each caliber.



(a)



(b)

Figure 102 – Systems' Effectiveness in a suggested operating condition with 9x19mm bullets, for **a)** general results and **b)** no Glock results, considering the best position between the repeated suggested test-fires in all the correlation lists available in each system.

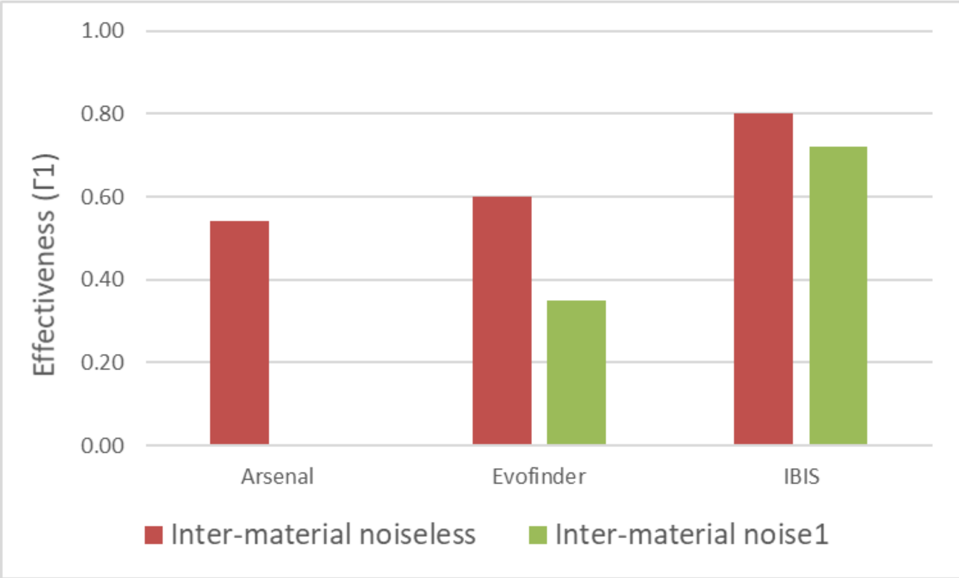


Figure 103 – Systems' Effectiveness in a suggested operating condition with .38SPL bullets, considering the best position between the repeated suggested test-fires in all the correlation lists available in each system.

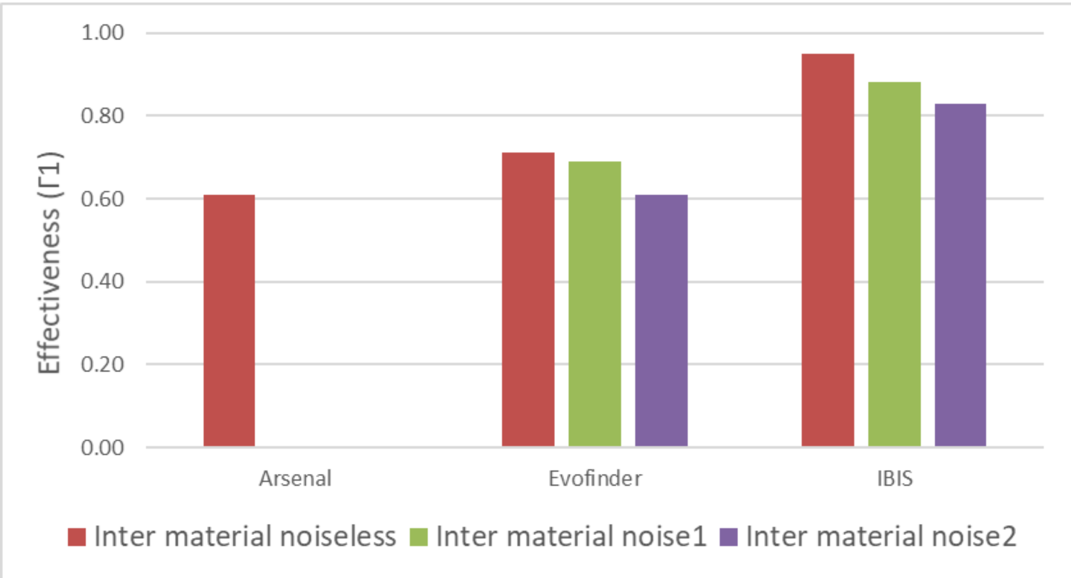


Figure 104 – Systems' Effectiveness in a suggested operating condition with .40S&W bullets, considering the best position between the repeated suggested test-fires in all the correlation lists available in each system.

6 PARAMETERS OF INFLUENCE WITH CARTRIDGE CASES

This chapter contains a discussion of the results with cartridge cases, including the impact of some physical, and geometric properties of the ammunition elements on the effectiveness of the systems correlation.

6.1 Types of effectiveness calculated with cartridge cases

Several types of effectiveness were implemented on the analysis programs to investigate factors influencing the possibilities of correctly identify the source firearm by the fired cartridge case. Initially, one investigation on systems' operation was carried out assessing the impact on effectiveness by the type of correlations each system performs (6.2) and by the number of registered test-fired cases (6.3). The firearm manufacturer (6.4), energy of discharge (6.5), material and type of cartridge cases (6.6), were the main properties investigated as factors of influence in cartridge case correlations. Additionally, geometric variations of the cartridge case marks were evaluated, including the center point of the firing pin mark (6.7.1) and its depth (6.7.2), the presence of the anvil mark (6.7.3), and the orientation of the breech face marks in the images acquired in each system (6.7.4), as well the influence of these features in the systems' effectiveness. Finally, the impact of an expanding database on the systems' effectiveness (6.8), the utility of using the correlation scores provided by the systems in cartridge case correlations, to more objectively identify a match or a non-match (6.9), and the performance of the systems in a suggested operating condition by caliber per system (6.10) were discussed.

In terms of the influencing factors with cartridge cases, as carried out with bullets, some effectiveness were generated considering the lower position of the repeated TFC, while others considering the results of both repeated test-fired. This difference in approach was understood as rational considering that in some analyzes the focus was on the verification of factors that can change the marks on the cartridge cases, so the positions in the list of both repeated test-fired were utilized. On the other hand, for assessments more related to the performance of the systems, such as the correlators do be examined, and the influence of database growing, use the lower position of the repeated test-fired was realized as more similar to what occurs in the practical use of these systems, specifically if having more than one TFC in the database, what matters is to find the one best ranked in the result list.

6.2 Correlators to be examined

In the Arsenal® and Evofinder® systems, to analyse the combination of results by Breech Face and by Firing pin is recommended because both correlation lists are available from cartridge case comparisons.

In the IBIS® system, there is a variety of available lists comparing in 2D images, the sidelight light and the ring light of breech faces, the firing pins, and the ejectors, and in 3D images, the firing pins and the breech faces, respectively termed BF2DSL, BF2D, FP2D, EM2D, FP3D and BF3D (refer to Table 18 at p. 160). Figure 105 to Figure 107 contains a comparison of the effectiveness of the IBIS® systems by type of cartridge case correlator, by combinations of 2 (two) correlators, and by combination of all correlators.

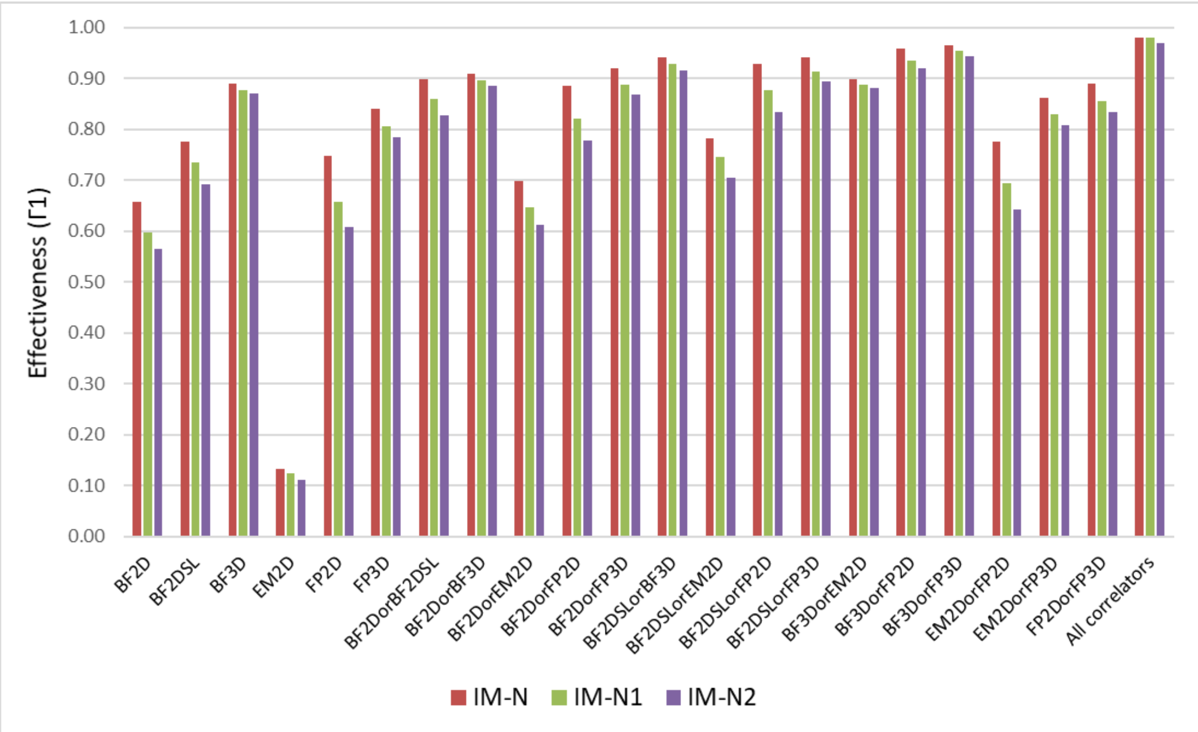


Figure 105 – Comparison of system effectiveness by correlator or by combination of correlators in 9x19mm CC IBIS® results.

Considering just 1 (one) correlator, the higher effectiveness in 9x19mm were obtained with BF3D, while in .38SPL and .40S&W with FP3D. For combinations of 2 (two) correlators, the higher effectiveness were obtained combining BF3D with FP3D. Sucessive ANOVA between all tests and calibers revealed statistically reliable differences in the mean effectiveness by 1 (one) compared to combination of 2 (two) correlators, and by 2 (two) compared to combination of all correlators (respectively, F-fisher = 63 for F-critical = 6, P-value = 10^{-4}, α=0.05; and F-fisher = 93 for F-critical = 6, P-value = $3*10^{-5}$, α=0.05).

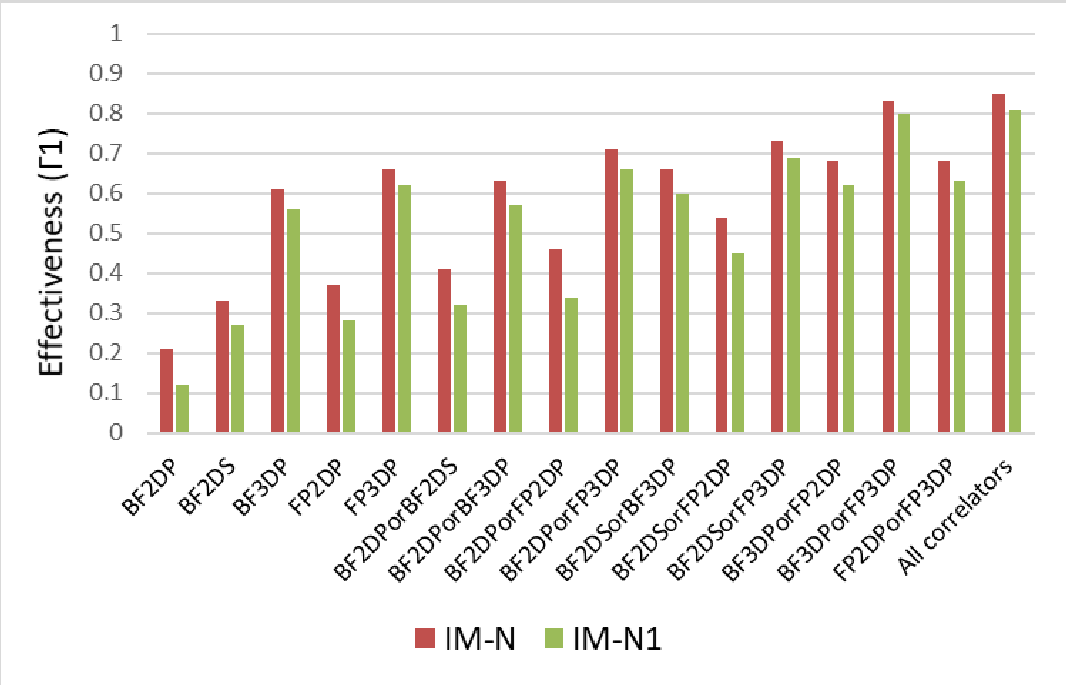


Figure 106 – Comparison of system effectiveness by correlator or by combination of correlators in .38SPL CC IBIS® results.

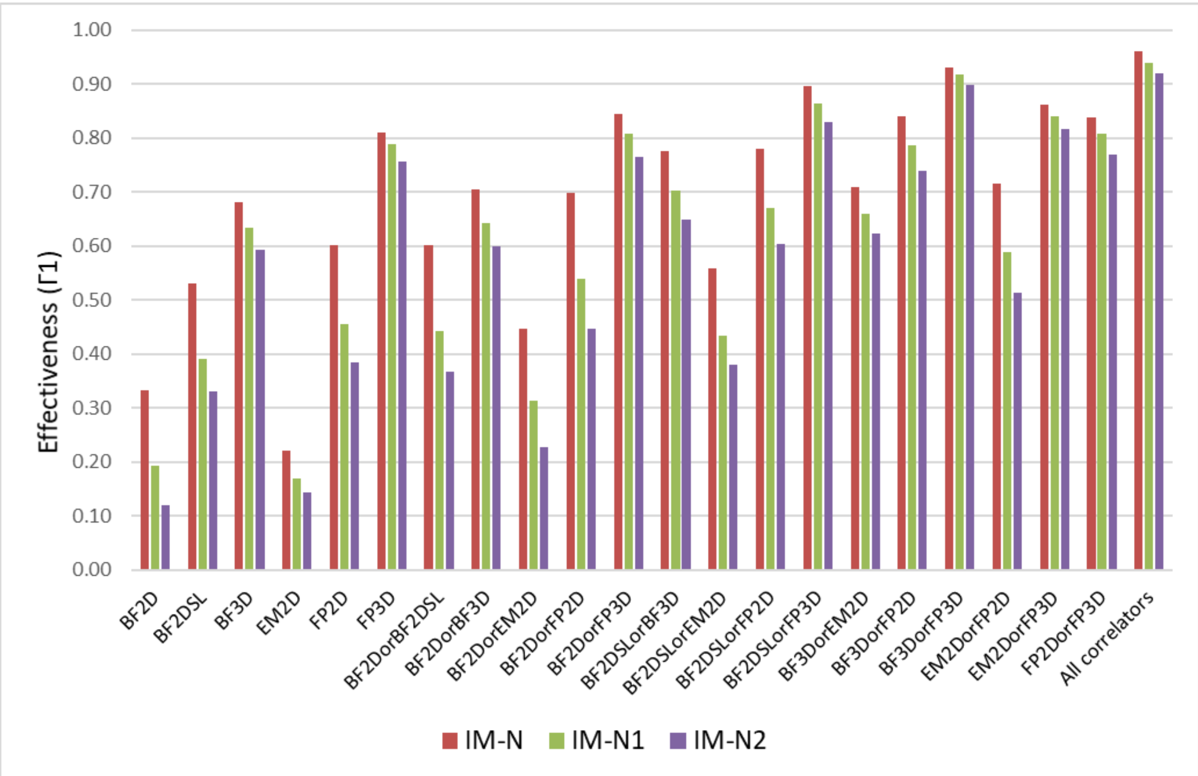


Figure 107 – Comparison of system effectiveness by correlator or by combination of correlators in .40S&W CC IBIS® results.

Contrasting the mean effectiveness by combination of all correlators to the mean effectiveneness by the single correlator with higher effectiveness in each test and caliber, there was a mean increase of 0.14(±0.04). Although ANOVA revealed that this is a statistical significative difference (F-fisher = 99 for F-critical = 6, P-value = $3*10^{-5}$, α=0.05), it is not practical that in all analyses all available results are verified. Therefore, the combination of 2 (two) correlators were investigated, being observed that, if instead of checking all correlators, only the BF3D and FP3D correlators by caliber were verified, the effectiveness only decreased by 0.02(±0.01).

Therefore, the statistical tests in the results suggests, particularly for laboratories crowded with evidence to process, that checking BF3D and FP3D correlation result lists is the best practice in searching for hits, letting the other correlation results for confirmation or specific cases.

6.3 Number of test-fired cartridge cases

As already mentioned, in this research two test-fires were collected for each type of ammunition per firearm. This allowed the accomplishment of the intra-material test, where the effectiveness of the systems was obtained by correlating two cartridge cases of the same ammunition type fired from each firearm, and also the inter-material tests, where each questioned was correlated against the test-fires, allowing analyzes where both repeated test-fired were used, and analyzes in which only the lower position in the result list between two repeated test-fired was considered.

The same observation made in section 5.3 (regarding bullets) is valid for cartridge cases, in the sense that although the more the number of test-fires in the system, the lower the probability of error in the identification (Bachrach, 2006; Law et al., 2017), it is understood to be a deficiency of the systems to list the results of repeated test-fires of the same firearm. This raises potential prejudice in registering a large number of test-fires per firearm, as this would impact correlation results in which the algorithm ranks the cartridge cases from one firearm as similar to another.

Considering this limitation of the systems, to test what would be the impact on the overall effectiveness of the systems if only 1 (one) test-fired cartridge case were collected and registered, compared to registering 2 (one) test-fires, an effectiveness computation was conducted in the results of the inter-material tests considering only the position of the first test-fired of each ammunition type (TFB1.1, TFC2.1, etc.).

Figure 108 compares the effectiveness of the systems considering the first registered test-fired against the effectiveness of the same tests by the best result between two repeated test-fires of each type. Breech Face or Firing Pin results were used for Arsenal® and Evofinder® and BF3D or FP3D for IBIS®. A statistically significant difference in the mean effectiveness with 2 (two) test-fires cartridge case and the mean effectiveness with 1 (one) test-fired was supported by ANOVA between results for all tests in the three calibers, (F-fisher = 71 for F-critical = 4, P-value = $1*10^{-7}$, α=0.05).

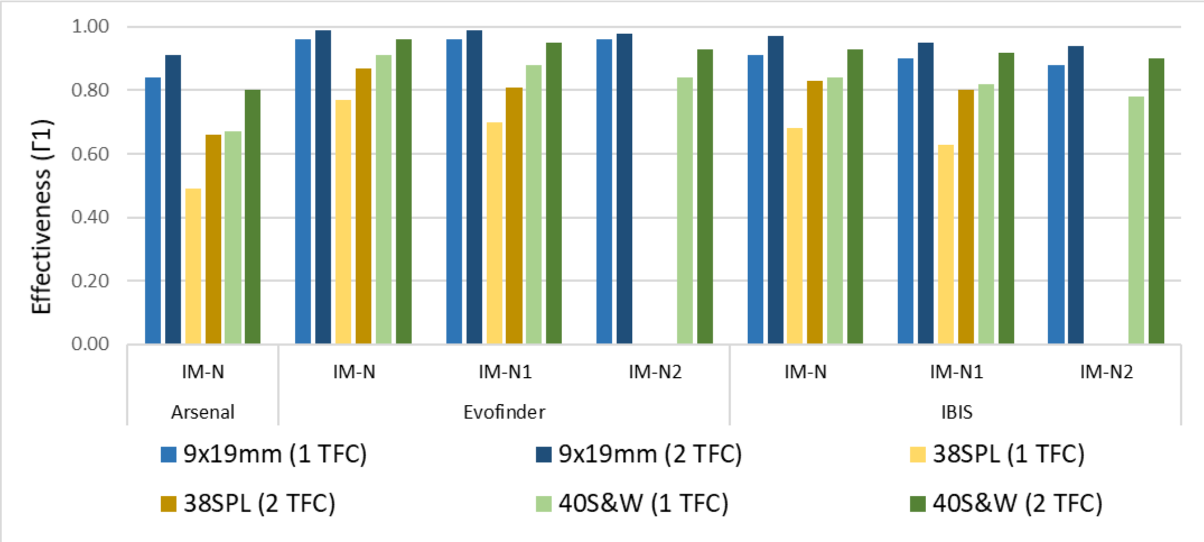


Figure 108 – Comparison of systems' effectiveness with 1 (one) TFC or 2 (two) TFC. In Arsenal® and Evofinder® the best results for Breech Face or Firing Pin were used, and for IBIS® the lower position between BF3D and FP3D lists.

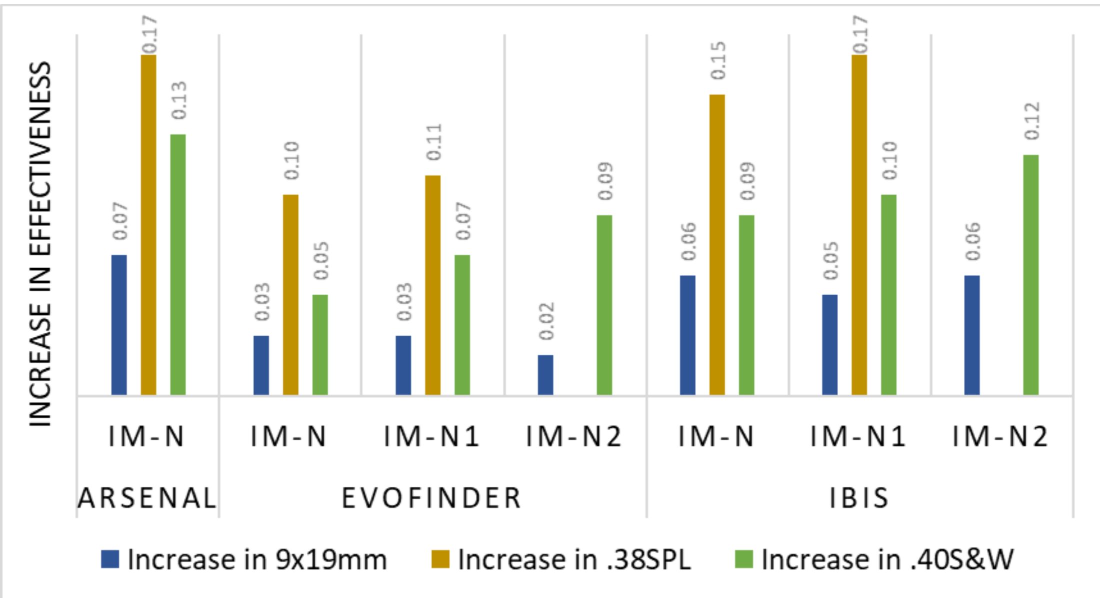


Figure 109 – Increase in systems' effectiveness with 2 (two) TFC compared to 1 (one) TFC.

Figure 109 computes the effectiveness increment observed in the graphs of Figure 108. Mean increment of 0.12(±0.03) in Arsenal®, of 0.06(±0.03), in Evofinder® and of 0.10(±0.04) in IBIS® were obtained on the effectiveness of systems operating with 2 (two) test-fires cartridge cases compared to the use of only 1 (one), demonstrating the validity of registering at least two test-fires of each type of cartridge ammunition used for registration. As observed for bullets, the main reason for these results, it that as more test-fired cartridge cases are registered in the system as higher the probability of the questioned sample to be matched to one of the test-fires.

6.4 Firearm manufacturer

The existence of identifying marks that are reproducible from shot to shot is a *sine qua non* condition to correct match the fired cartridge case to its source. Because of that, the effectiveness of the systems by firearm manufacturer was verified with cartridge cases.

As in the analysis of bullets, the comparison by caliber allows verifying firearm manufacturer that, regardless of the system, present less effectiveness in cartridge case correlations, while others in which only specific systems had difficulty in properly correlate them.

Figure 110, Figure 111, and Figure 112 compare the effectiveness of the systems by firearms manufacturers included in this research in each caliber, both for correlation by the firing pin (FP) as by the breech mark (BF). In the case of the IBIS® system, as it presents results of correlations in 2D and 3D, the latter was chosen, because as best discussed in section 6.2, were the correlators with greater effectiveness in this system.

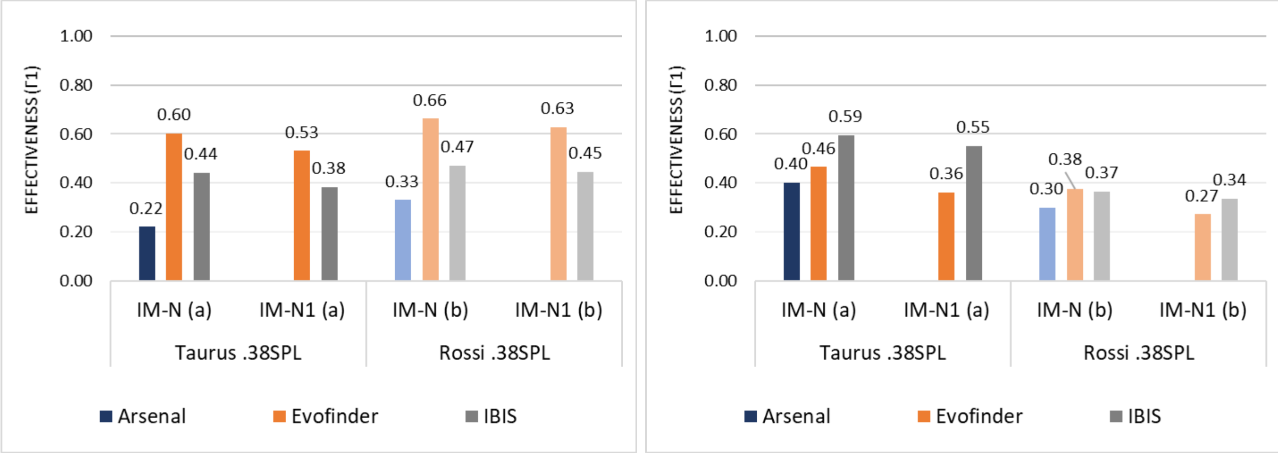
In the .38SPL caliber, in all systems the correlations by breech marks of the Rossi firearms were more effective than the Taurus firearms, with Rossi higher in Evofinder® (Γ_1 = 0.66 and 0.63), intermediate at IBIS® (Γ_1 = 0.47 and 0.45) and lower at Arsenal® (Γ_1 = 0.33). In the correlations by firing pin marks, in all systems, the effectiveness was better with Taurus revolvers than with Rossi, with Taurus higher at IBIS® (Γ_1 = 0.59 and 0.55), intermediate at Evofinder® (Γ_1 = 0.46 and 0.36), and lower at Arsenal® (Γ_1 = 0.40).

With 9x19mm and .40S&W pistols, the Evofinder® system showed effectiveness above 0.90 in several firearms manufacturers, both by breech face as by firing pin, demonstrating that lower effectiveness in other systems is due to deficiencies in their correlation algorithms or in the imaging process, and not the absence of marks in specific firearms. Because of its higher effectiveness, the results of the Evofinder® were used as a reference to compare with the effectiveness of the other two systems, as included in Table 25. The values used in these comparisons were the averages of the available effectiveness for the inter-material tests performed on each caliber, that is, 1 (one) test at Arsenal® and 3 (three) tests at Evofinder® and IBIS®.

Compared to the effectiveness of the Evofinder® system by breech face, the Arsenal® system showed an average -0.60(±0.17) lower effectiveness, and IBIS® on average -0.20(±0.15) lower effectiveness. For the firing pin marks, in comparison with the Evofinder® system, Arsenal®'s effectiveness was on average very similar to Evofinder®, with a difference for more in 0.02(±0.23), and the effectiveness of the IBIS® system on average -0.21(±0.16) lower than on Evofinder®.

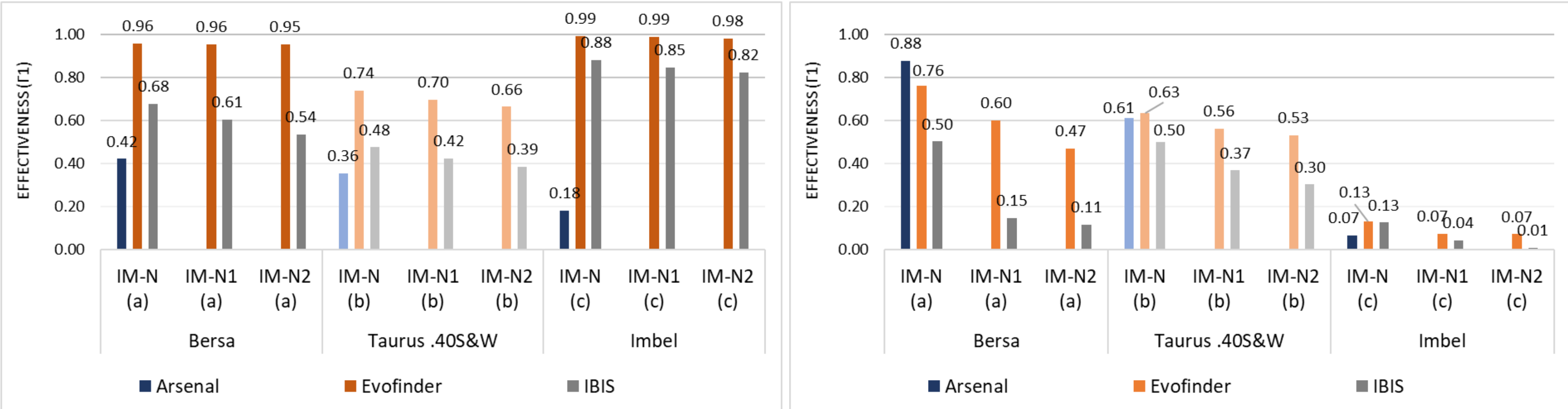
The results obtained reinforce the perception that among the firearm manufacturers there is a great variety of quality in the marks for comparison that significantly impact the possibilities of correct identification. However, this factor is, in the state of the art of the development of comparison algorithms by breech face and firing pin, difficult to be properly evaluated, because between the systems there are great differences in performance. There was no example of a firearm with effectiveness above 0.90 in all systems, on the other hand, in terms of poor efficiency, only the IMBEL pistols, in comparisons by firing pin marks, showed effectiveness below 0.14 in all systems and tests. This poor result with IMBEL is an example of how the absence of marks prevents effective correlation in any system. On the other hand, the differences between the systems, with various firearm manufacturers in which the performance was strong in one system and inferior in others, reveal deficiencies in the correlation algorithms or in the raw data collected that need to be identified through an analysis of the images involved.

In the next sections, various parameters of influence on the effectiveness of the systems in the correlation with cartridge cases will be evaluated. It is noteworthy that the analysis made by firearm manufacturer results were performed using the position in the result lists of all test-fired cartridge cases from each firearm. In the other sections, in many tests, the effectiveness was obtained from a restricted set of test-fires, as in the case of analyzes that considered the best repeated test-fired. Another difference is the type of correlator considered, as in certain analyzes only was checked the effectiveness by firing pin mark while in another by breech mark, and in some by the combination of these two correlators. These differences in approach make it difficult to compare the results, in terms of systems' effectiveness, in this section to the next ones.



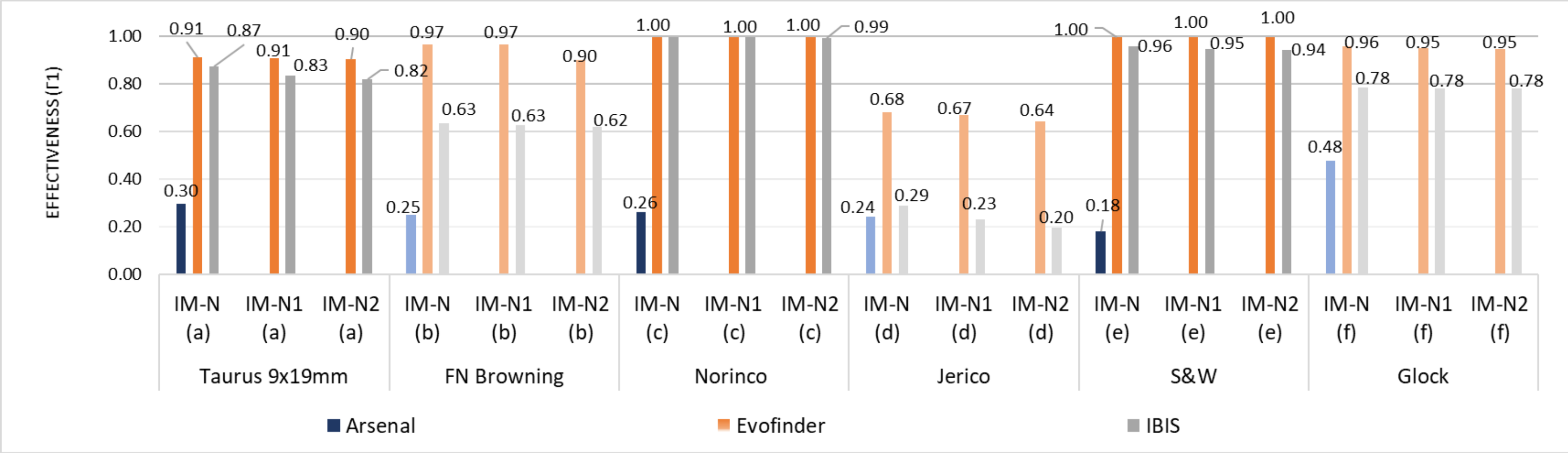
(I) **(II)**

Figure 110 – Systems effectiveness by manufacturer with.38SPL cartridge cases, comparing **(I)** breech face and **(II)** firing pin marks from: **a)** Taurus and **b)** Rossi revolvers, in the inter-material noiseless (IM-N) and inter-material noise1 (IM-N1) tests.

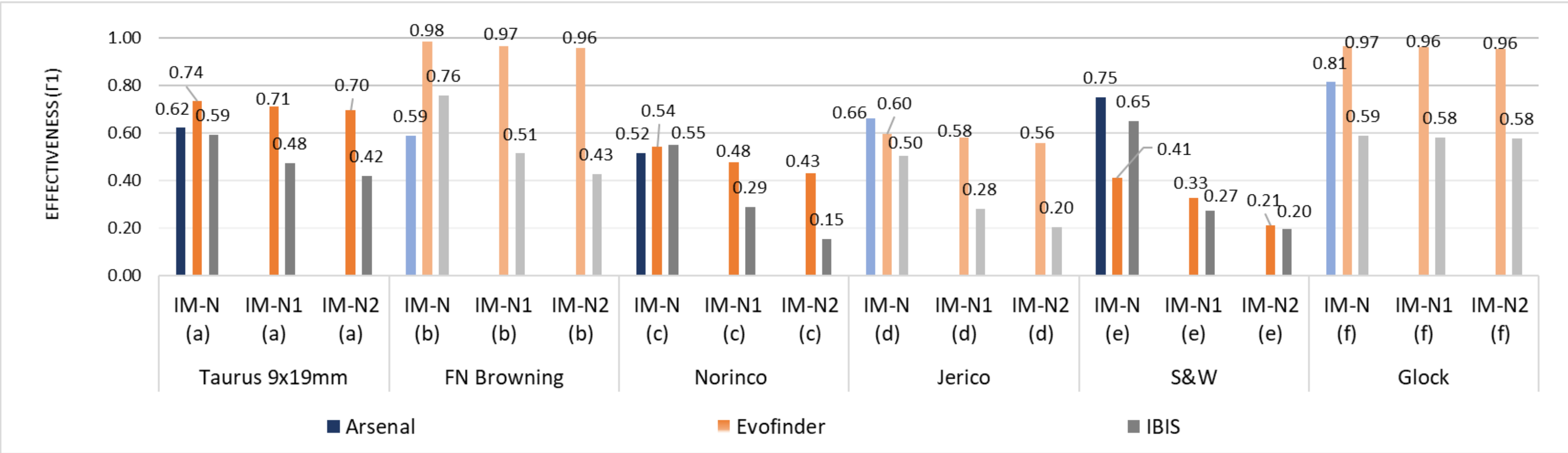


(I) **(II)**

Figure 111 – Systems effectiveness by manufacturer with .40S&W cartridge cases, comparing **(I)** breech face and **(II)** firing pin marks from: **a)** Bersa, **b)** Taurus, and **c)** Imbel pistols.



(I)



(II)

Figure 112 – Systems effectiveness by manufacturer with 9x19mm cartridge cases, comparing **(I)** breech face and **(II)** firing pin marks from: **a)** Taurus, **b)** FN Browning, **c)** Norinco, **d)** Jerico, **e)** S&W, and **f)** Glock pistols.

Table 25 – Comparative effectiveness of the systems with cartridge cases.

CALIBER	MANUFACTURE	BREECH FACE (BF)			FIRING PIN (FP)		
		EVOFINDER	ARSENAL	IBIS	EVOFINDER	ARSENAL	IBIS
9x19mm	TAURUS	0.91	-0.61(p)	-0.07	0.72	-0.09	-0.22
	FN BROWNING	0.94	-0.69	-0.32	0.97	-0.38	-0.40
	NORINCO	1.00	-0.74	0.00	0.48	0.03(q)	-0.15
	JERICO	0.67	-0.42	-0.43	0.58	0.08	-0.25
	S&W	1.00	-0.82	-0.05	0.32	0.43	0.06
	GLOCK	0.95	-0.47	-0.17	0.96	-0.15	-0.38
.40S&W	BERSA	0.96	-0.53	-0.35	0.61	0.27	-0.35
	TAURUS	0.70	-0.34	-0.27	0.58	0.03	-0.19
	IMBEL	0.99	-0.81	-0.14	0.09	-0.03	-0.03

(p) – in red lower effectiveness compared to Evofinder® effectiveness
(q) – in blue higher effectiveness compared to Evofinder® effectiveness

6.5 Energy of discharge

As explained in section 2.1.3, the velocity of the bullet is a product of the pressure generated by the combustion of the propellant. Therefore, the bullet velocity must, among other factors, be possible related to the amount of propellant available in each ammunition. In addition, can affect the bullet velocity, the type and length of the barrel through which it is accelerated, the drag to which it is subjected, whether aerodynamic in the bullet tip, or friction in contact with the barrel bore, as well the propellant composition.

All types of ammunition included in this study were disassembled and sampled for the amount of propellant (refer to Table 40 on p. 292). On the other hand, considering the variations in length and type of barrel in each caliber (refer to Table 33, Table 34, and Table 35, on pp. 283-286) bullet velocity were obtained for each type of ammunition in the study (refer to Table 36 on p. 288). Finally, the propellants of each type of ammunition were examined by FTIR, with the spectra and results included in Table 41 (refer to 292).

Trying to understand the factors influencing the velocity of the bullet, the propellant and bullet mass ratio, defined in equation 6.1 by the quotient of the propellant mass to the bullet mass, was plotted against the bullet velocities measured in each type and length of the barrel, as can be seen in Figure 113, Figure 114, and Figure 115.

$$\frac{Propellant_{\ (mass)}}{Projectile_{\ (mass)}}. \qquad 6.1$$

A strong relationship between the mass ratio and bullet velocities was observed in the .38SPL and .40S&W calibers and with some variations in the 9x19mm caliber.

In .38SPL caliber (refer to Figure 113) velocity was higher in the longest barrel (COB = 4”) in relation to the shorter one (COB = 3”), the difference was greater between these barrels for ammunition with more propellant, demonstrating that there was better utilization of the burning propellant in the largest barrel. The increase in velocity between ammunition 1, 2, 3, and 4 can be attributed to the increase in mass ratio and to the change of propellant type from single to double-base. Among type 4 and 5 ammunition, despite the same mass ratio and propellant compositions, there was a decrease in velocity, which may be due to variation in the shape of the bullet, as there is smaller aerodynamic drag in the FMJ-ST bullet of type 4 ammunition, and higher in JHP-ST bullet of ammunition 5 (refer to Figure 41 on p. 109).

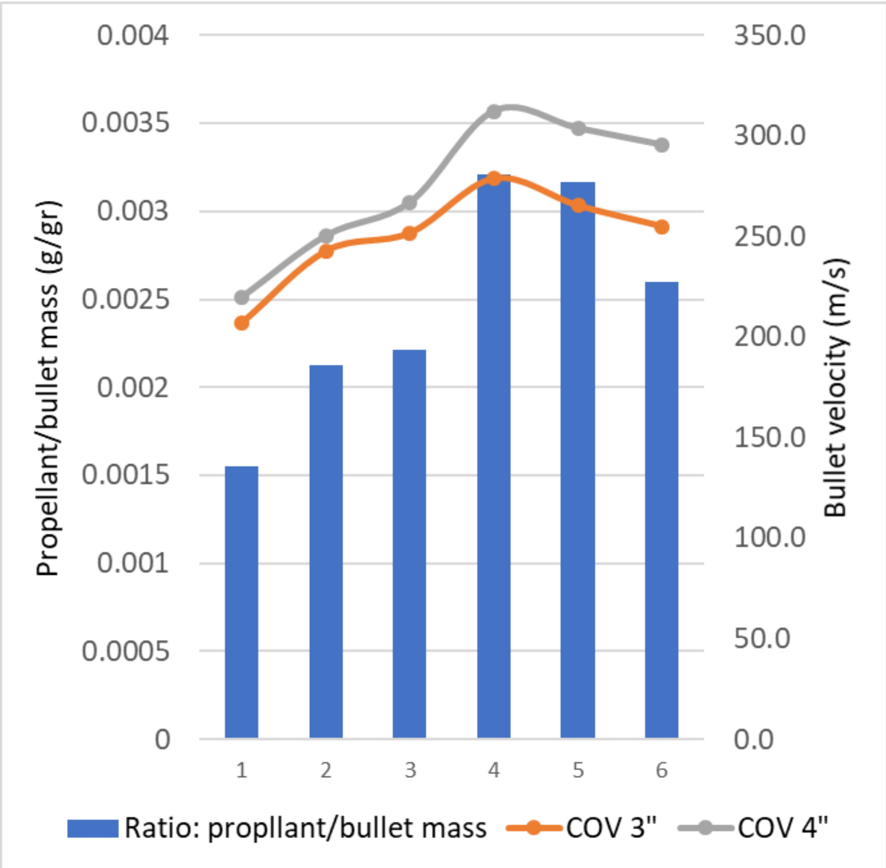


Figure 113 – Influence of propellant and bullet mass ratio on the velocity of .38SPL bullets fired from conventional barrels with 3" length (COV 3") and from conventional barrels with 4" length (COV 4").

In the .40S&W caliber (refer to Figure 114), the increase in velocity followed the increment in the mass ratio, and the increase is more pronounced from type 1 to type 2 ammunition, which is a fact consistent with, in addition to the increase in the mass ratio, the change of composition from single-base to double-base propellant (refer to steeper slope from type 1 to 2 compared to type 2 to 3 on Figure 114).

In the 9x19mm caliber (refer to Figure 115), comparing the types of ammunition 1 and 2, there was a decrease in velocity in the Jericho and COB 4.8 ", and a slight increase in the Glock and COB 3.7". In the first case, the increase in mass ratio seems to have been a less influential factor than the increase in aerodynamic drag due to the variation in the shape of the bullet, from FMJ to JHP (refer to Figure 55 on p. 130). In the second case, there was a balance of the largest drag with the increase of the mass ratio, causing the velocity to increase only slightly. The difference between the two situations makes sense when comparing similar barrels. The Jericho polygonal barrels showed much more marks in the study than the Glock polygonal barrels (and therefore had higher effectiveness – refer to Figure 84 on p. 181) which implies that the Jerico barrel offers greater friction to the passage of the bullet, and therefore the increase in drag was more significant in the Jerico barrels than on the Glocks. In the conventional barrels, the largest barrel, COB 4.8", offers an increase in drag for longer than in the smaller barrel, COB 3.7", explaining why in the largest barrel the drag was more influential. Still in the 9x19mm caliber, from ammunition type 2 to 3, despite the decrease in mass ratio, the increase in velocity observed in all types of barrels can be explained by the change in the chemical composition of the propellant, which changed from single-base to double-base. Finally, from type 3 to 4, which presented propellants with the same chemical composition, double-base, there was an increase in mass ratio but no increment in the velocity. As the bullet of ammunition type 4 is a solid piece of copper, featuring less Brinell hardness, is possible that its contact with barrel bore has a larger area, leading to higher frictional drag, i.e, more friction compensated the more mass ratio, keeping the velocity indivertible.

The importance of these factors for the study of this research lies in the relationship, discussed in section 2.1.3 (refer to p. 50) between the velocity of the fired bullet and the pressure generated by the gases from the combustion of the propellant (refer to equation 2.7 on p. 53). The generation of marks on the cartridge case during the firing of the ammunition results from plastic deformations suffered by it. That is, it receives permanent deformations when violently strikes the harder surfaces of the breech face, combustion chamber, firing pin, extractor, and ejector. Therefore, a variation in these marks is expected depending on the discharge pressure.

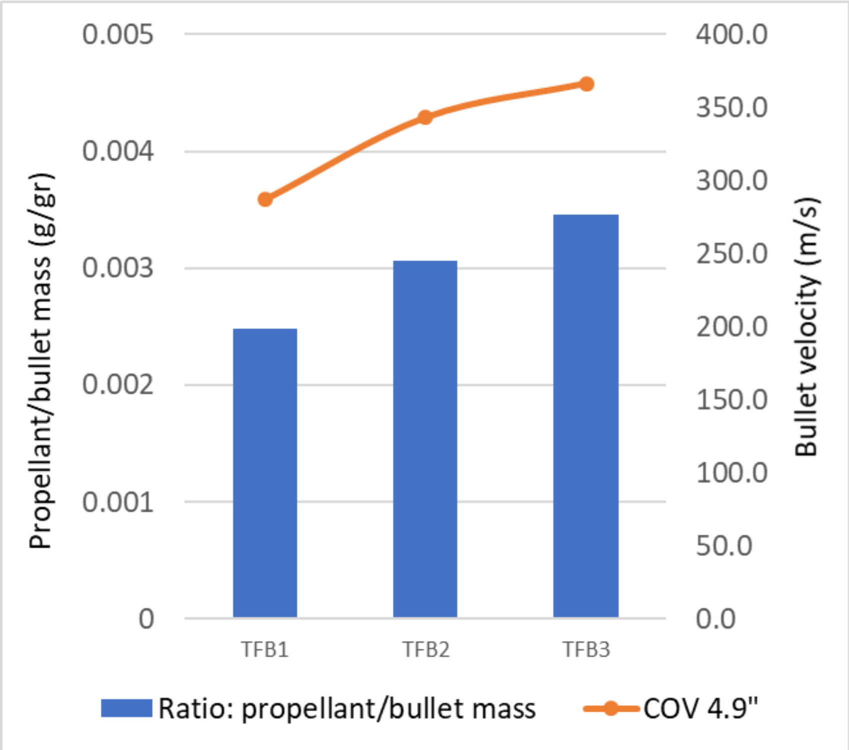


Figure 114 – Influence of propellant and bullet mass ratio on the velocity of .40S&W bullets fired from conventional barrels with 4.9" length (COV 4.9").

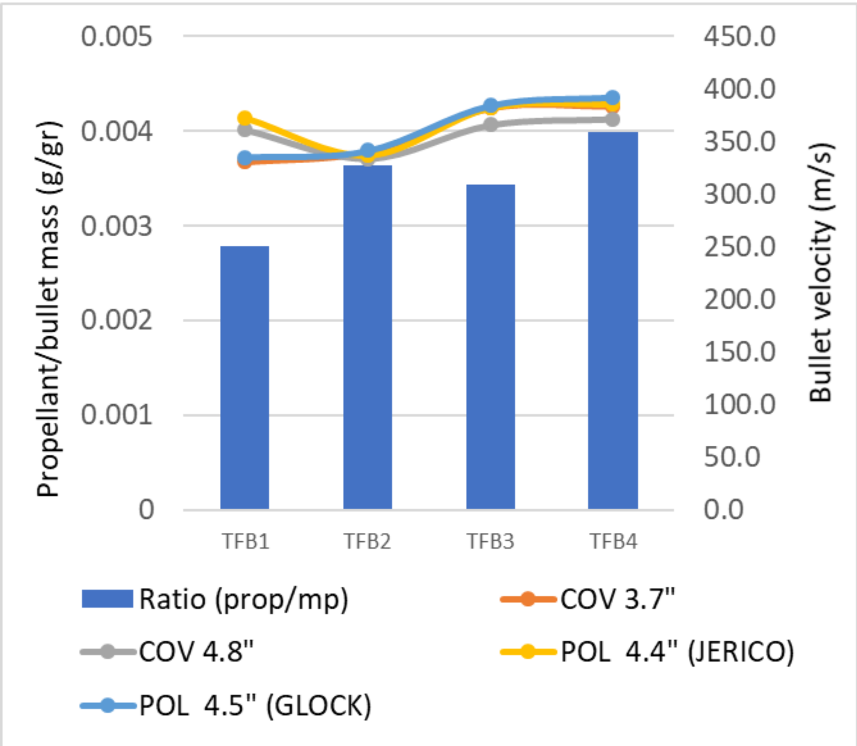


Figure 115 – Influence of propellant and bullet mass ratio on the velocity of 9x19mm bullets fired from conventional barrels with 3.7" length (COV 3.7"), from conventional barrels with 4.8" length (COV 4.8"), and from polygonal barrels with 4.5" length (POL 4.5").

To test this hypothesis a subroutine was implemented in the analysis program to compute the difference in bullet kinetic energy (*ΔBKE*) of the questioned and test-fired bullets related to the types of ammunition involved in each cartridge case match, as defined in equation 6.2. This difference in bullet kinetic energy can also be termed a difference in energy of discharge, as the interest here is to measure the impact of this property on the cartridge cases correlation effectiveness.

$$\Delta\mathrm{BKE} = \left| BKE_{(QB)} - BKE_{(TFB)} \right| \qquad 6.2$$

To test the influence of this factor on the effectiveness of the systems, in the analysis program two distributions were created for each caliber and system, according to the maximum difference in bullet kinetic energy of each caliber ($\Delta BKE_{max}^{(caliber)}$), expressed in inequations 6.3 and 6.4.

$$\Delta BKE < \frac{\Delta\mathrm{BKE}_{max}^{(caliber)}}{2}, \qquad 6.3$$

$$\Delta BKE \geq \frac{\Delta\mathrm{BKE}_{max}^{(caliber)}}{2}. \qquad 6.4$$

The kinetic energy variation observed in each caliber was:

$$\frac{\Delta BKE_{max}^{(9x19mm)}}{2} = 71.69J\ ,$$

$$\frac{\Delta BKE_{max}^{(38SPL)}}{2} = 139.26J\ ,$$

$$\frac{\Delta BKE_{max}^{(40S\&W)}}{2} = 60.66J\ .$$

Considering both repeated test-fired cartridge case match positions in the correlation result lists, the program generated two distributions by inequations 6.3 and 6.4 and computed the systems' effectiveness for each caliber by firing pin and by breech face. The means and standard deviations of the inter-material noiseless test results of these distributions are shown in Figure 116, Figure 117, and Figure 118.

ANOVAs were carried out in the breech face and the firing pin results for the noiseless tests in all calibers and systems. For breech face results a statistically significant difference was obtained between the mean effectiveness for inequation 6.3 distribution and the mean effectiveness for inequation 6.4 distribution (F-fisher = 34 for F-critical = 5, P-value = 0.0001, α=0.05). For firing pin, ANOVA resulted in no evidence against the null hypothesis, i.e, there is no significant difference in the mean effectiveness for distribution from inequation 6.3 and the mean effectiveness for distribution from inequation 6.4 (F-fisher = 2.4 for F-critical = 5.3, P-value = 0.159, α=0.05).

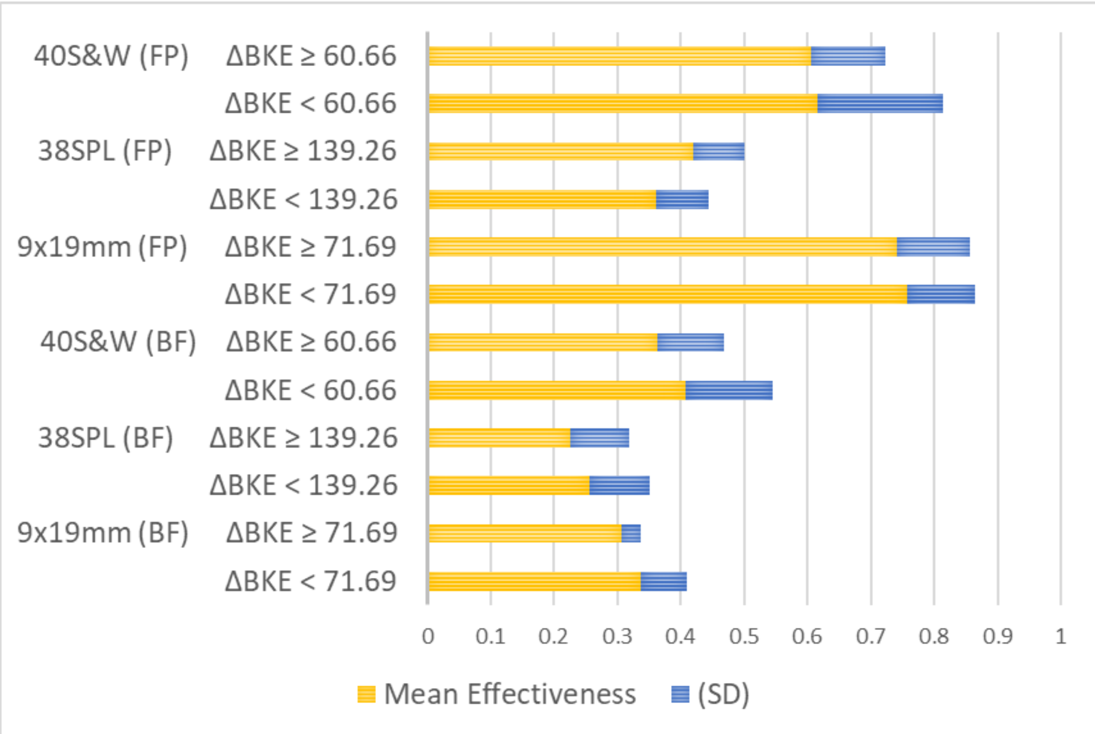


Figure 116 – Effectiveness regarding the energy of discharge difference for Arsenal® Breech face (BF) and Firing pin (FP) in the inter-material noiseless test results.

Although these results indicate that differences in the energy of discharge have a meaningful statistical influence on the effectiveness by breech face, and a negligible one by firing pin, it was important to weigh the impact degree of the energy of discharge differences in each system.

IBIS® was the system more affected by this variable, with a higher difference in energy of discharge between the compared cartridge cases resulting in the mean, -0.09(±0.04) lower effectiveness by breech face, and -0.12(±0.08) lower effectiveness by firing pin, revealing that this factor has meaningful influence in this system for both correlators.

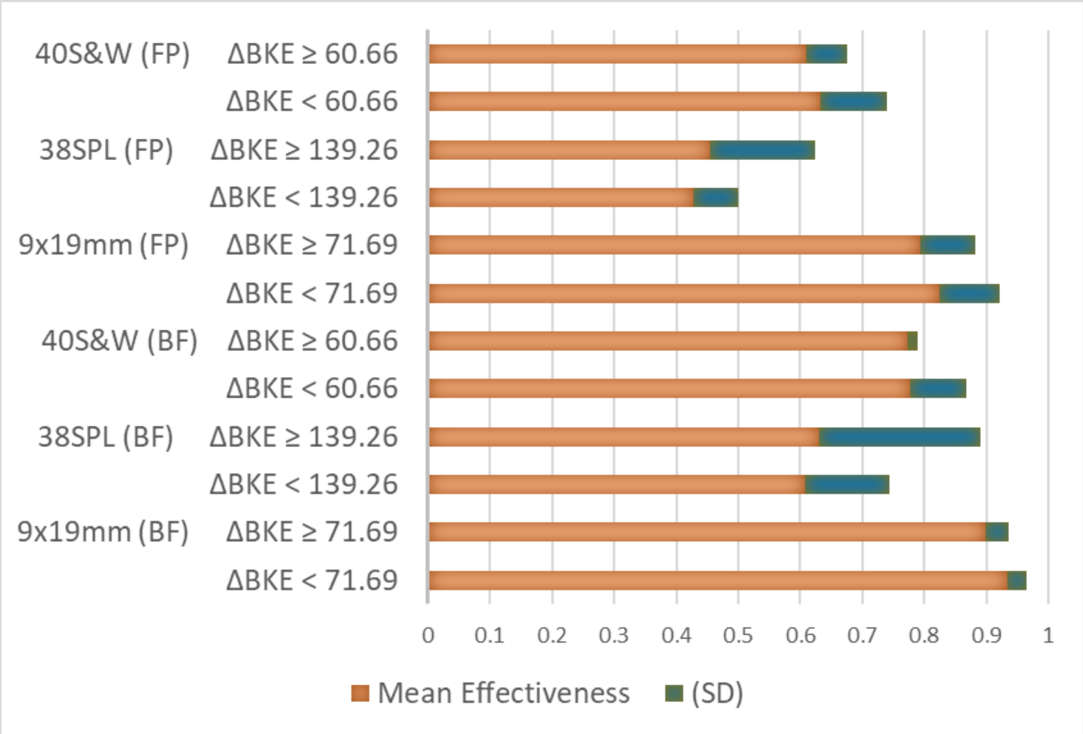


Figure 117 – Effectiveness regarding the energy of discharge difference for Evofinder® Breech face (BF) and Firing pin (FP) in the inter-material noiseless test results.

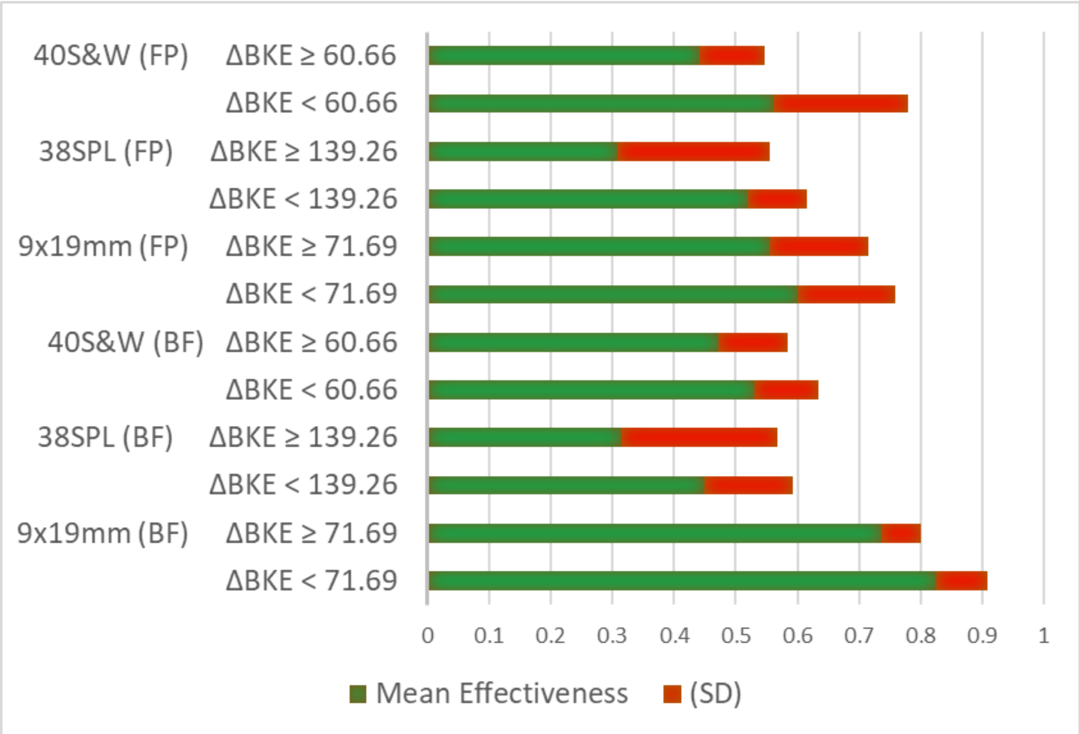


Figure 118 – Effectiveness regarding the energy of discharge difference for IBIS® Breech face (BF) and Firing pin (FP) in the inter-material noiseless test results.

For Arsenal® system a higher difference in energy of discharge between the compared cartridge cases resulted in the mean, -0.04(±0.0008) lower effectiveness by breech face and +0.01(±0.04) higher effectiveness by firing pin.

Finally, for the Evofinder® system, the impact of differences in the energy of discharge was less meaningful, with a higher difference in energy of discharge between the compared cartridge cases resulting in -0.006(±0.03) lower mean effectiveness by breech face and in -0.009(±0.03) by firing pin.

Therefore, although the ANOVA revealed a reliable influence of energy of discharge on the effectiveness by breech face, in Evofinder® this was indeed numerically negligible [-0.006(±0.03)], with intermediate decrement in Arsenal® [-0.04(±0.0008)], and more meaningful in IBIS® [-0.09(±0.04)]. On the other hand, for firing pin, despite the fact that ANOVA in the combined results revealed no evidence against the null hypothesis, it was observed that numerically the influence of energy of discharge on the mean effectiveness was actually low in Arsenal® and Evofinder®, respectively +0.01(±0.04) and -0.009(±0.03), but not negligible in IBIS®, where a higher difference in energy of discharge affecting the mean effectiveness by firing pin in -0.12(±0.08).

The main factor of influence investigated in this sub-section is the pressure of discharge, related to the energy of discharge. The results demonstrated that propellant mass and composition, bullet mass, composition and shape, and barrel type and length are variables that have a direct impact on the bullet velocity and, therefore, the study of the impact of the energy of discharge, measured by the bullet kinetic energy, on the correlation effectiveness, has the advantage of reducing the number of variables that need to be controlled or studied. Not only was relevant the statistical tests that support the influence of energy of discharge on the effectiveness of breech face correlations, and did not support the influence on the effectiveness of firing pin correlations, as also the weighting of the degree of influence of the energy of discharge in each system.

6.6 Material and types of TFC

Another important factor in the generation of marks on the cartridge cases during deflagration is their material composition. In this study, two types of cases were used, one composed basically of brass and the other, although internally made of brass, covered with a thin nickel layer (refer to Figure 5 on p. 43).

In order to investigate the direct influence of cartridge case material composition on the systems' performance, effectiveness computation was implemented in the analysis program, separating the match results into 3 (three) distributions, according to the possible combinations of the questioned and of the test-fired cartridge cases, termed Brass-Brass, Brass-Nickel, and Nickel-Nickel. This resulted in the effectiveness of the inter-material noiseless tests, by breech face and by firing pin, depicted in Figure 119 and Figure 120.

Analyzing the results of these three graphs, there are effectiveness differences by the cartridge case material, which becomes notable when they are independent of the system. In the caliber 9x19mm (blue results), there is no significant difference for Breech Face, but for firing pin it is possible to observe in all systems higher effectiveness with Brass cases. In the .38SPL caliber (green results), both Breech face and Firing pin have higher effectiveness with nickel-plated cases. In the .40S&W (Orange results) caliber, no higher effectiveness was observed, independent of the system in either type of cartridge case or correlators.

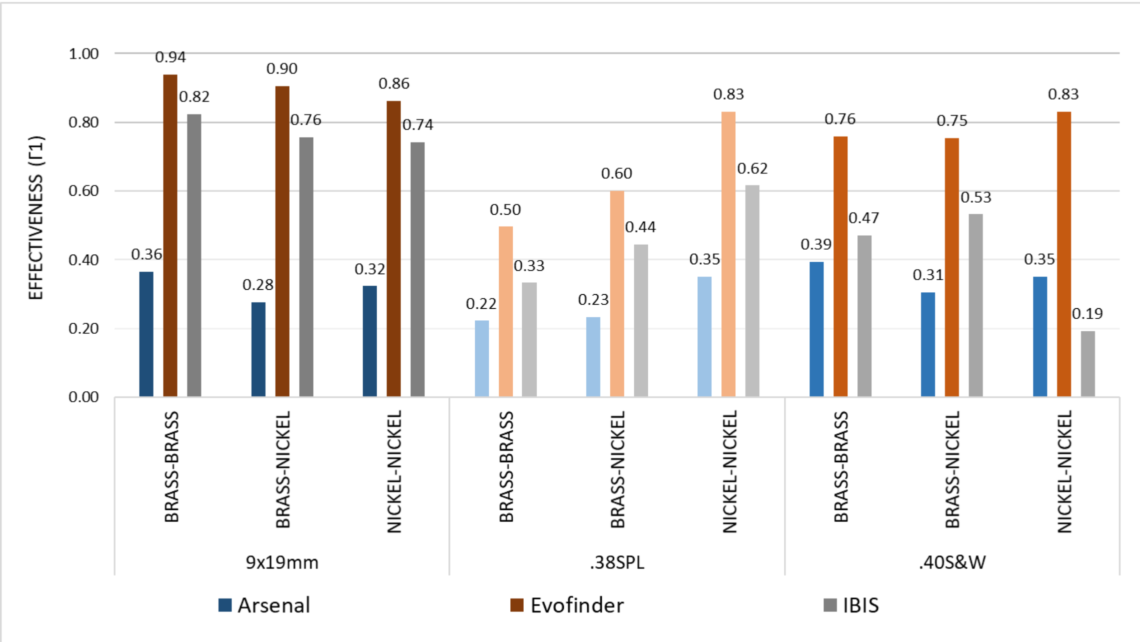


Figure 119 – Effectiveness by breech face correlations considering material compositions of questioned samples and test-fired on each match, including both repeated test-fired.

Compared to the energy of discharge, discussed in the previous section, the impact of material composition on effectiveness was much higher, with absolute variations on the effectiveness of Arsenal®, Evofinder®, and IBIS®, ranging by breech face respectively from 0.01 to 0.13, 0.01 to 0.33, and 0.02 to 0.34, and by firing pin from 0.00 to 0.24, 0.01 to 0.33, and 0.01 to 0.37.

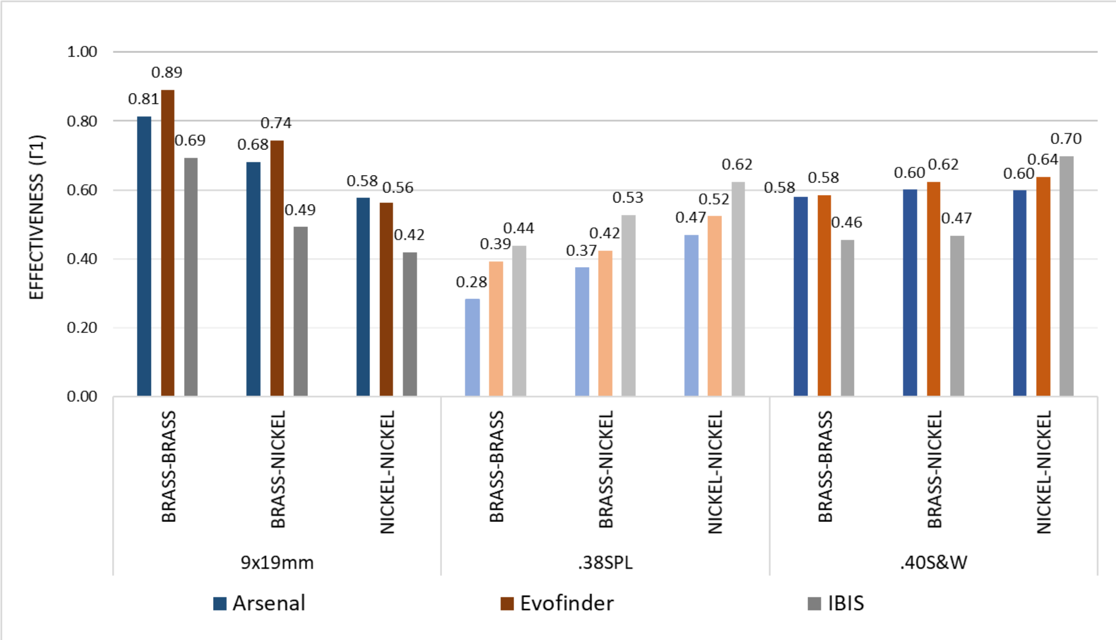


Figure 120 – Effectiveness by firing pin correlations considering material compositions of questioned samples and test-fired on each match, including both repeated test-fired.

Separating the results in the types of ammunition by caliber is another way of measuring the influence of the type of cartridge case on the effectiveness. The graphics of Figure 121, Figure 122, and Figure 123 compare the effectiveness of the systems by the type of test-fired, considering the best repeated test-fired and the lower position in the result lists among all available correlators. Together with the results by type of material, this analysis can be decisive for choosing the ideal ammunition type for collecting test-fires by caliber.

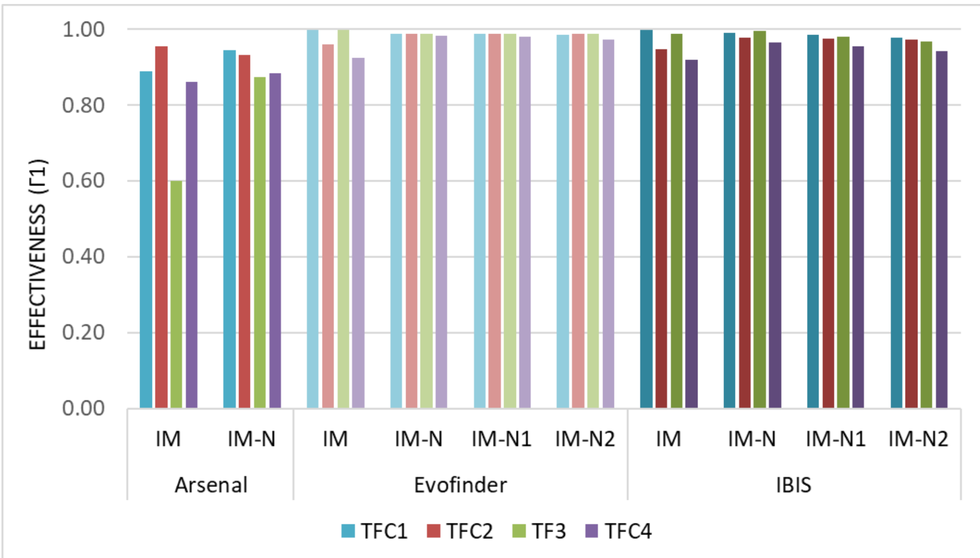


Figure 121 – Systems' effectiveness by type of 9x19mm test-fired cartridge case, considering the best position between the repeated test-fires in all the correlation lists available in each system.

In the 9x19mm caliber, the differences are subtle and the data only suggest avoiding the TFC4 cartridge case. In the .38SPL caliber, the variations were more significant, and while TFC2 or TFC6 are not recommended for selection to test-firing, on the other hand, TFC3 showed higher effectiveness in all tests and systems in this caliber, which is a result consistent with the analysis of effectiveness by material cartridge case, since in this caliber the nickel-plated cartridge cases had better performance and TFC3 is exactly of this composition.

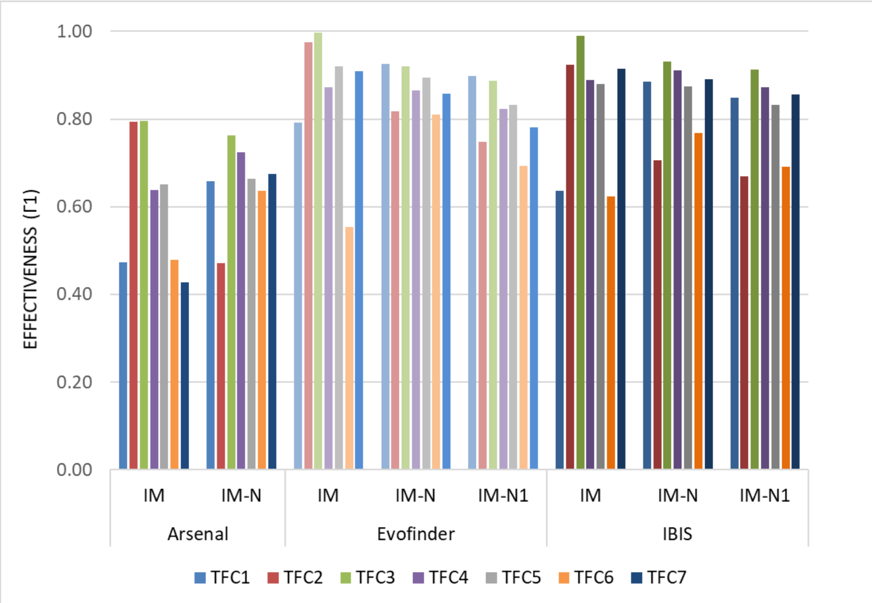


Figure 122 – Effectiveness by type of .38SPL test-fired cartridge case, considering the best position between the repeated test-fires in all the correlation lists available in each system.

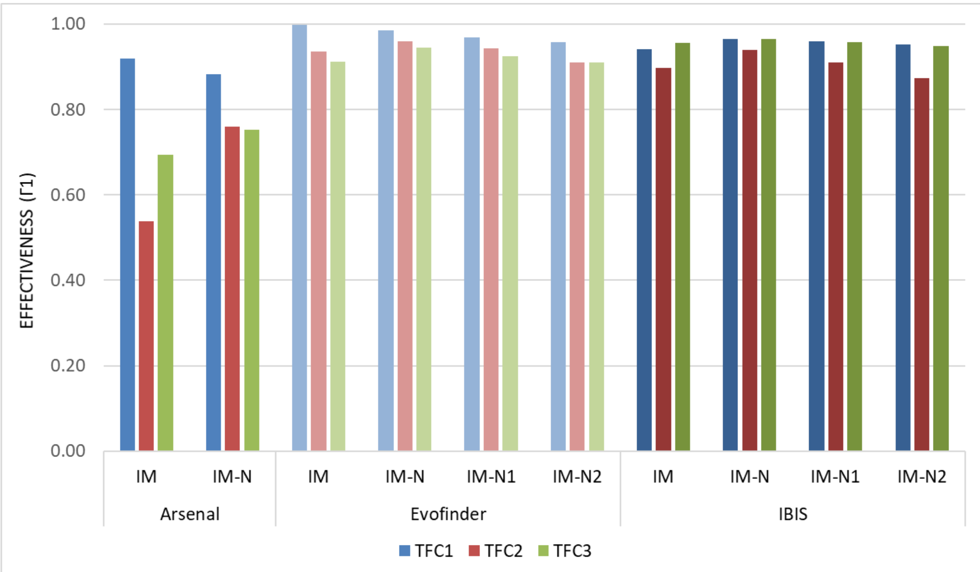


Figure 123 – Effectiveness regarding type of .40S&W test-fired cartridge case, considering the best position between the repeated test-fires in all the correlation lists available in each system.

Finally, in the .40S&W caliber, TFC1 performed consistently better than the others in Arsenal® and Evofinder®, and TFC1 and TFC3 were similar correlated in IBIS®.

Although the isolated analysis of data related to material composition by caliber and system is useful for establishing protocols for collecting test-fired cartridge cases, in the same way that was observed in the study with bullets, the choice of ammunition for collecting test-fires should not only consider these effectiveness differences per cartridge case material, but also the type of fired ammunition components most commonly found at crime scenes in a locality.

In addition to the results discussed in previous sections, regarding the lists of results to consider (6.2) and the number of test-fires (6.3), the results of this section led to the suggested operating condition for cartridge cases, further discussed in section 6.10.

6.7 Geometric features of the CC marks

In addition to the variables discussed in the previous three sections, geometric variations in the marks generated on the cartridge case bases can, in theory, influence the results of the correlations, such as firing pin mark center point and depth, presence of anvil mark, and the orientation angle of the breech face marks. These variations were also assessed aiming to find an explanation for the performance observed by firearm manufacturers.

6.7.1 Center point of the firing pin mark

In terms of centralization of the firing pin marks, analysis of the study images revealed that they vary intra-firearm, that is, the central point of the firing pin impact, can vary significantly from one shot to another in the same firearm. To assess the influence of this variable on the systems' effectiveness, the firing pin mark' center FPMC(x_c, y_c), was first analyzed for each cartridge case of the study, obtained by the relative distances in two orthogonal axes, as illustrated in Figure 124 and determined by equation 6.5. In this measure, the unit corresponds to the distance from the center of the primer cup to its edge. The analysis of the dispersions of the FPMC (refer to Figure 125 to Figure 130) allowed obtaining the frequency histogram for each caliber, revealing approximately normal distributions with medians and standard deviations as recorded in Figure 126, Figure 128, and Figure 130.

After obtained the FPMC for each cartridge case of the study, the vector difference between the firing pin marks' center (FPD) for each questioned and test-fired cartridge cases match, was obtained by equation 6.6.

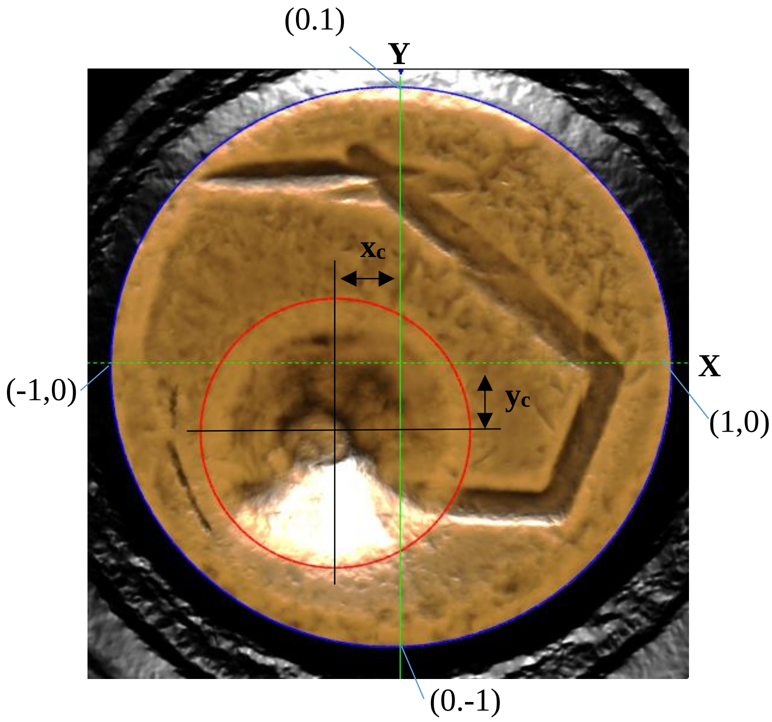


Figure 124 – Determination of firing pin mark's center (FPMC) (IBIS® image).

$$FPMC = \sqrt{(x_c)^2 + (y_c)^2}\,, \qquad 6.5$$

$$FPD = \sqrt{(x_{c1} - x_{c2})^2 + (y_{c1} - y_{c2})^2}\,. \qquad 6.6$$

Finally, effectiveness computation was implemented in the analyses program, separating the positions in the correlation result lists for each system and caliber according to two criteria, expressed in the inequations 6.7 or 6.8.

$$FPD < \text{Median of FPMC distribution}_{caliber}\,, \qquad 6.7$$

$$FPD \geq \text{Median of FPMC distribution}_{caliber}\,. \qquad 6.8$$

Table 26 contains means effectiveness with respective standard deviations dividing the results into these two criteria, for analyses considering both repeated test-fires.

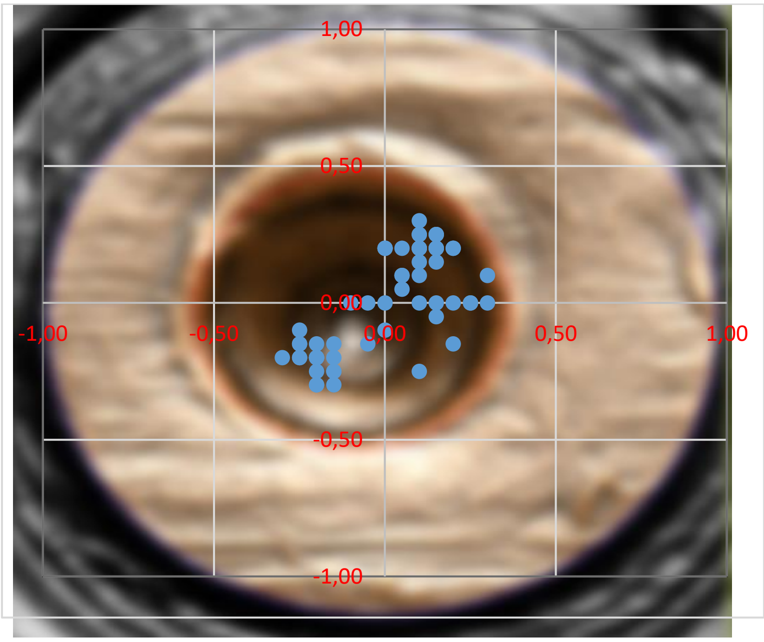


Figure 125 – Dispersion of firing pin marks' center (blue dots) in .38SPL CC (IBIS® image).

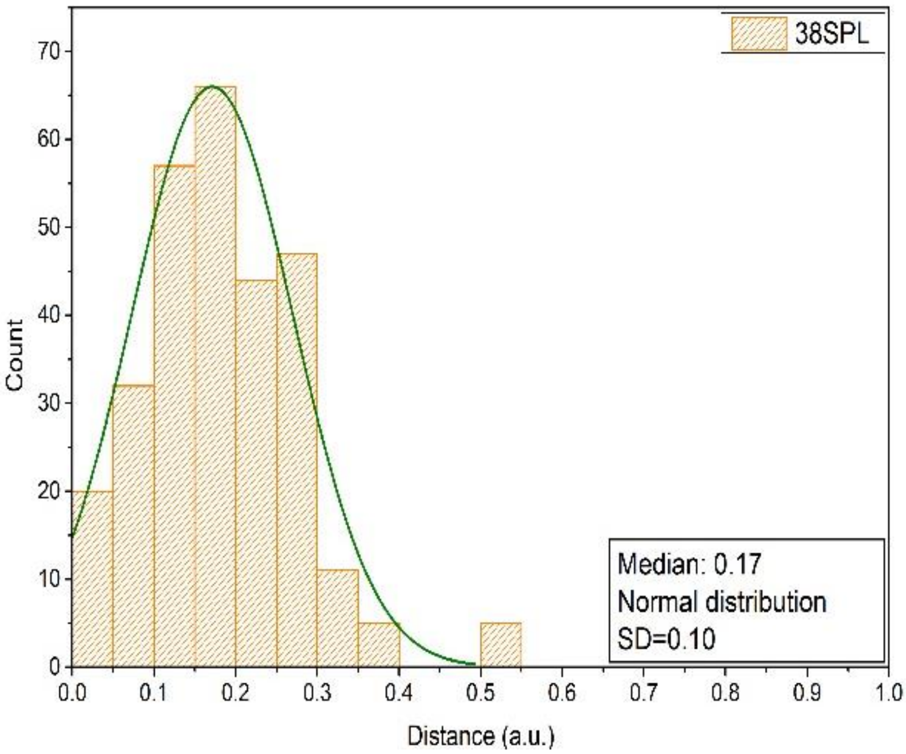


Figure 126 – Frequency histogram of firing pin marks' center (FPMC) in .38SPL CC.

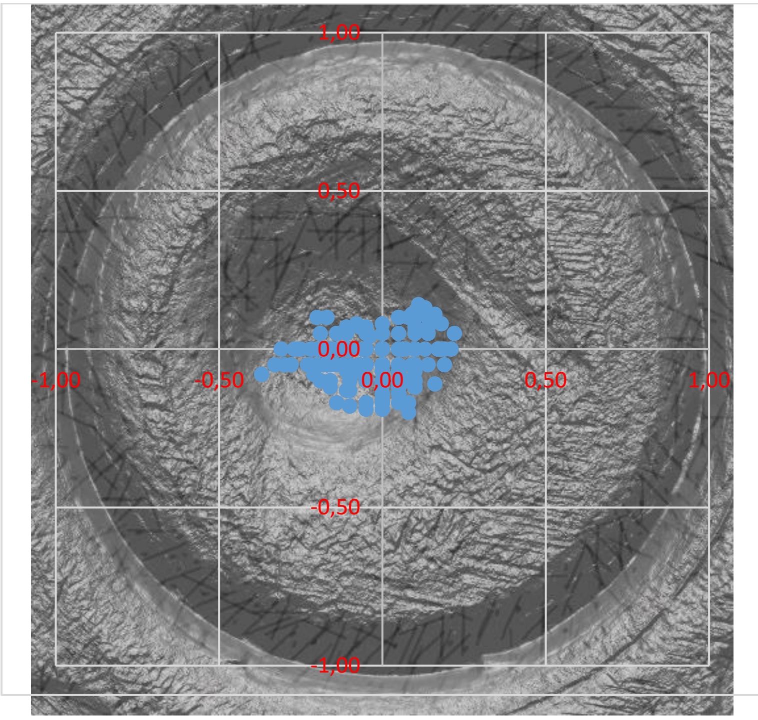


Figure 127 – Dispersion of firing pin marks' center (blue dots) in 9x19mm CC (Evofinder® image).

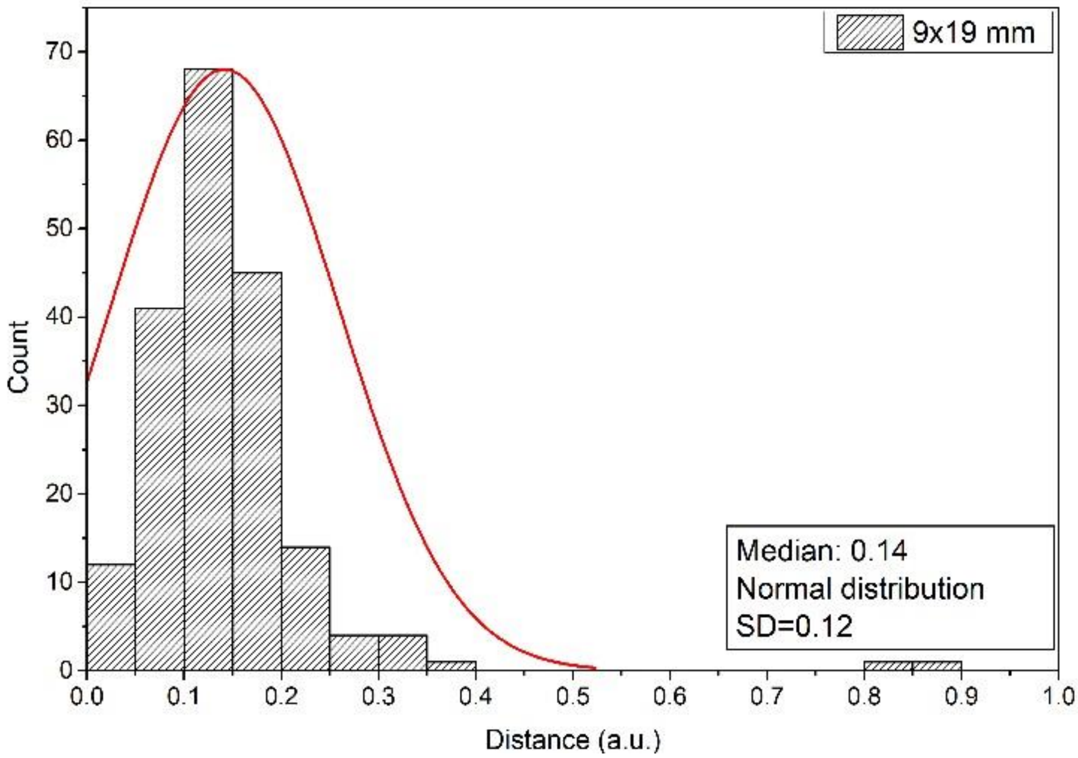


Figure 128 – Frequency histogram of firing pin marks' center (FPMC) in 9x19mm CC.

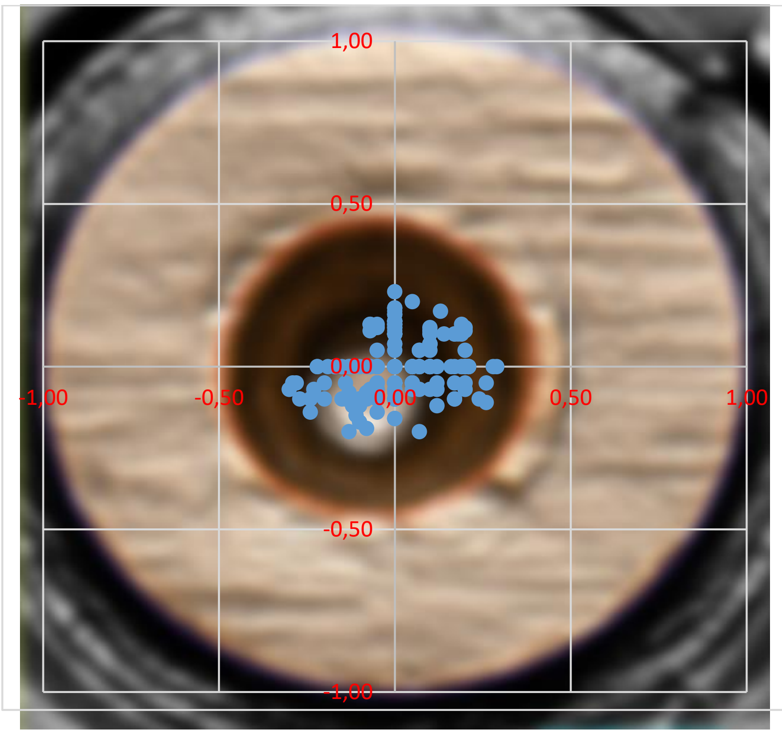


Figure 129 – Dispersion of firing pin marks' center (blue dots) in .40S&W CC (IBIS® image).

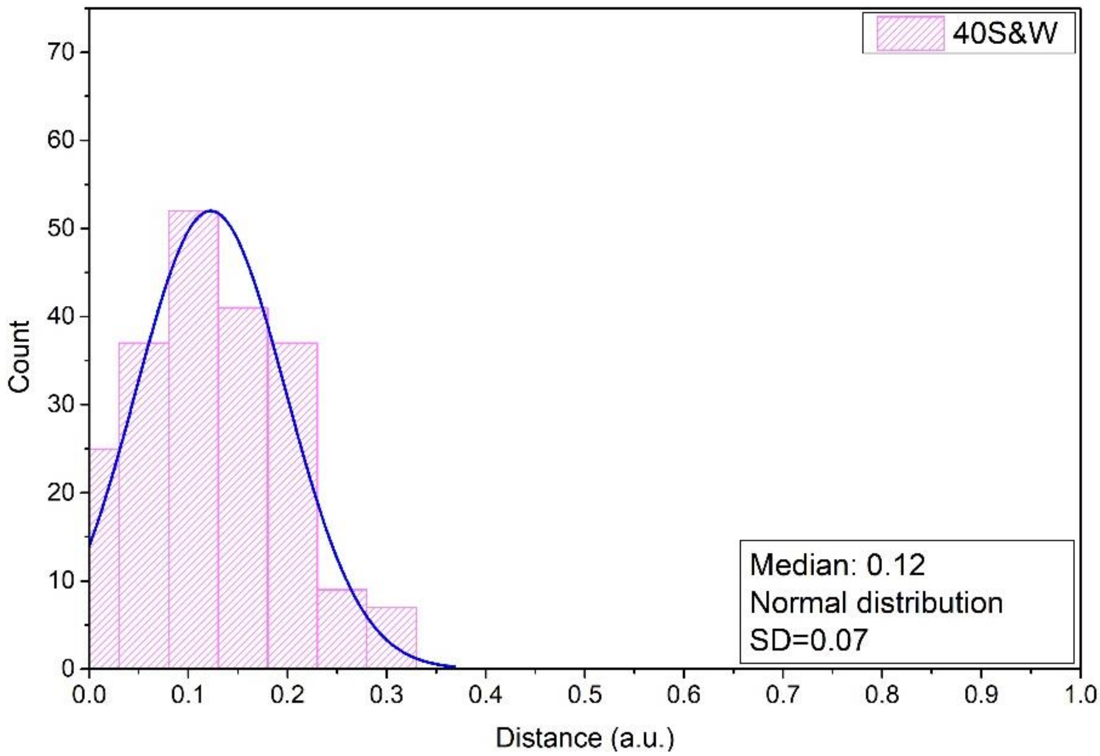


Figure 130 – Frequency histogram of firing pin marks' center (FPMC) in .40S&WCC.

Table 26 – Mean effectiveness regarding difference between the firing pin marks' center (FPD).

Caliber	Median	System	Mean Γ_1 (SD) (FPD < Median)	Mean Γ_1 (SD) (FPD ≥ Median)	*P-value*[(r)]	*Supported hypothesis*
9x19mm	0.14	Arsenal	0.75(±0.10)	0.78(±0.20)	0.65	*h0*[(s)]
		Evofinder	0.82(±0.09)	0.76(±0.14)	0.15	*h0*
		IBIS	0.60(±0.14)	0.55(±0.14)	0.15	*h0*
.38SPL	0.17	Arsenal	0.37(±0.08)	0.38(±0.10)	0.73	*h0*
		Evofinder	0.45(±0.08)	0.42(±0.10)	0.50	*h0*
		IBIS	0.54(±0.14)	0.48(±0.10)	0.30	*h0*
.40S&W	0.12	Arsenal	0.62(±0.14)	0.54(±0.17)	0.06	*h0*
		Evofinder	0.63(±0.08)	0.59(±0.06)	0.29	*h0*
		IBIS	0.48(±0.08)	0.52(±0.17)	0.61	*h0*

(r) – ANOVA, significance level 5%
(s) – h0: all mean effectiveness criterions are statistically indistinguishable

ANOVA performed on the results of the noiseless inter-material tests obtained in each system and caliber, significance level of 0.05, did not indicate any statistically significant difference in mean effectiveness of the two distributions defined by 6.7 or 6.8 (refer to P-value column in Table 26). That is, the correlation algorithms are not affected by the variation of the vector difference of firing pin mark central points, and this is not a factor that can explain the differences in results observed between systems and between manufacturers in section 6.4.

6.7.2 Depth of firing pin mark

Another variation observed between the firing pin marks in the images of the study was in relation to its depth. Even intra-firearm, between one shot and another, it is observed that there is a significant difference in the depth of the generated mark. To evaluate this parameter, the first cartridge case collected from each firearm was select to obtain the reference depth (dp_r), and this was compared to all other cartridge cases firing pin depth from that same firearm (dp_{cc}), obtaining for each cartridge case a firing pin mark relative depth (*Rdp*), such as depicted in Figure 131 and defined in equation 6.9.

Analysis of frequency histograms of the firing pin mark relative depth (*Rdp*) revealed distributions that were best represented by Lorentz distributions (refer to Figure 132, Figure 133, and Figure 134).

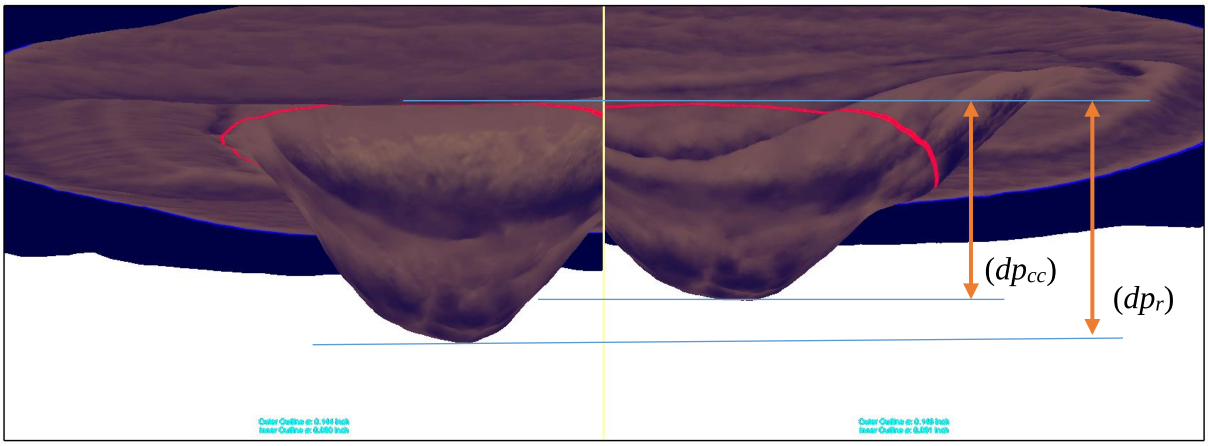


Figure 131 – Determination of firing pin marks relative depth (*Rdp*) (IBIS® image).

$$Rdp = \frac{dp_{cc}}{dp_r} \quad (6.9)$$

The Lorentz distribution, also name Cauchy-Lorentz, has no defined mean or standard deviation so that the distribution is characterized by the parameters x_0 and γ. x_0 is the location parameter that represents the peak of the distribution, and as this is a symmetric distribution x_0 coincides with the median of the values. γ is the scale parameter, which specifies the half-width at half-maximum. Figure 135 illustrates these parameters, where it is observed that the 2γ is also equal to half of the interquartile range, a parameter that divides 50% of the distribution centered on x_0, leaving the other 50% of the distribution in two equal intervals of distributions greater or less than $x_0 \pm \gamma$.

In view of the characteristics of this distribution observed in the histograms of relative depth frequency of the firing pin mark, the parameter 2γ was used to study the influence of the depth difference between the questioned and the test-fired cartridge cases. An effectiveness computation was implemented in the analysis program, dividing the match positions in the correlation result lists for each system and caliber into two distributions expressed in inequations 6.10 and 6.11.

$$\left| Rdp_{\,(questioned)} - Rdp_{\,(TFC)} \right| < 2 * \gamma \, , \quad (6.10)$$

$$\left| Rdp_{\,(questioned)} - Rdp_{\,(TFC)} \right| \geq 2 * \gamma \, . \quad (6.11)$$

Table 27 contains the mean and standard deviation effectiveness by firing pin correlation, considering both repeated test-fires, obtained by dividing the results into these two criteria related to differences in relative firing pin mark depth (*ΔRdp*). ANOVAs were performed on the results of the inter-material noiseless tests obtained in each system and caliber.

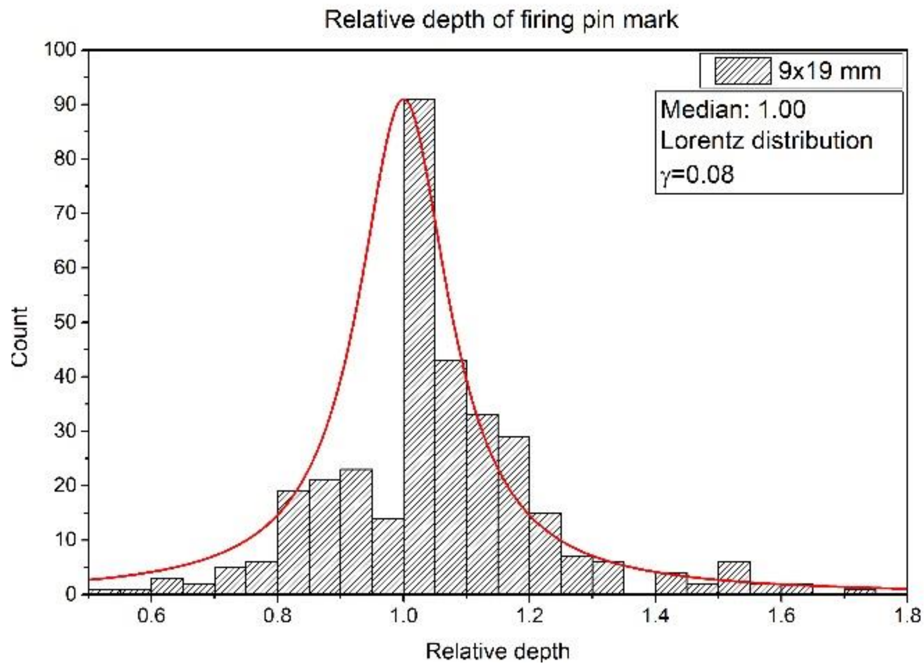


Figure 132 – Frequency histogram of firing pin mark relative depth (*Rdp*) in 9x19mm CC.

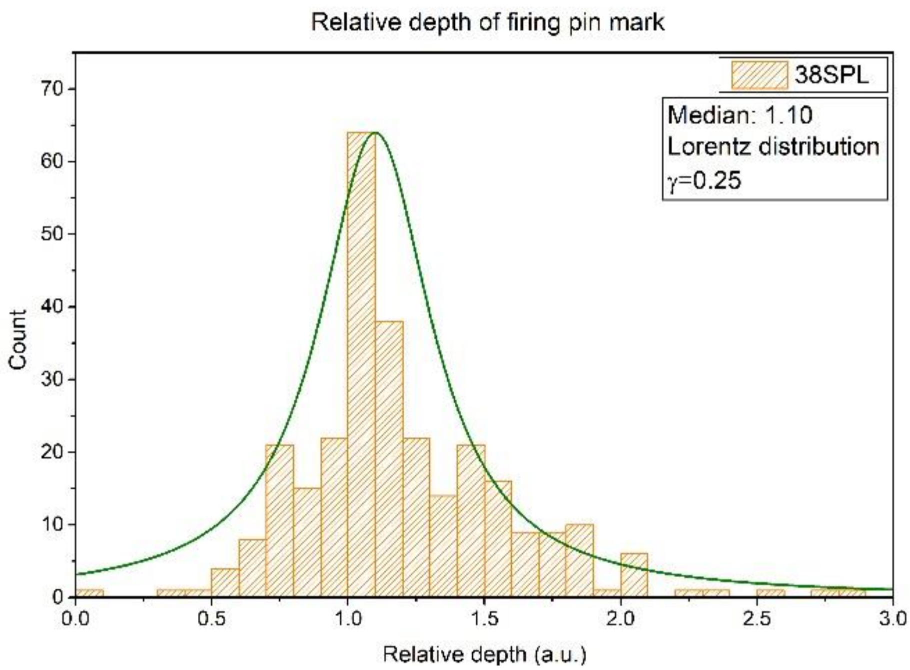


Figure 133 – Frequency histogram of firing pin mark relative depth (*Rdp*) in .38SPL CC.

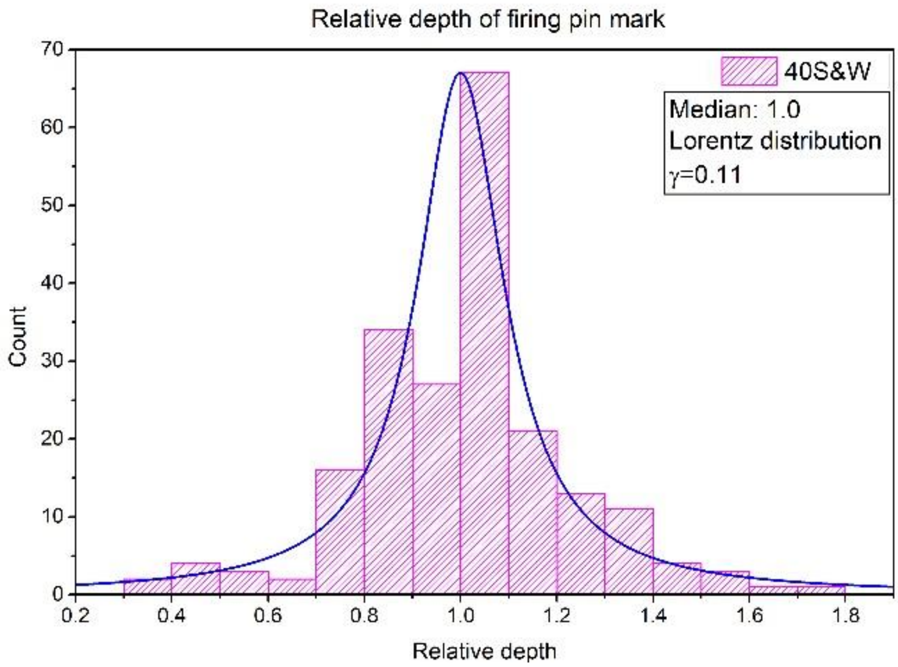


Figure 134 – Frequency histogram of firing pin mark relative depth (*Rdp*) in .40S&W CC.

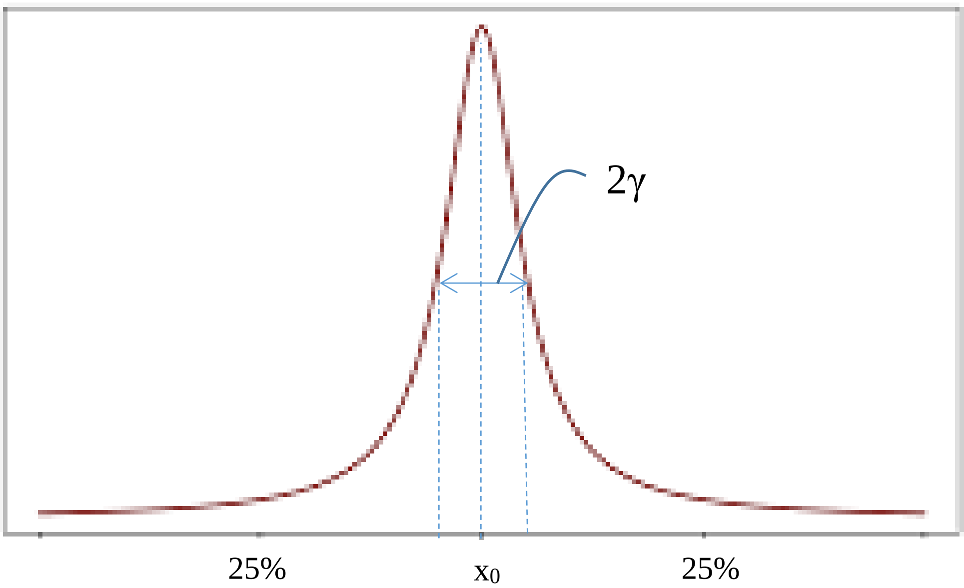


Figure 135 – Parameter x_0 and γ in Lorentz distribution.

In .40S&W caliber all systems showed a statistically distinguishable effectiveness difference, which is an indication that, when the difference in relative firing pin mark depth was greater than twice the parameter γ, the accuracy of the system comparing the firing pin marks meaningfully decrease.

Table 27 – Mean effectiveness regarding difference in relative firing pin mark depth (*ΔRdp*).

Caliber	2*γ	System	Mean Γ_1 (SD) ($\Delta Rdp < 2*\gamma$)	Mean Γ_1 (SD) ($\Delta Rdp \geq 2*\gamma$)	*P-value*(t)	*Supported hypothesis*
9x19mm	0.16	Arsenal	0.73(±0.11)	0.77(±0.10)	0.010	*h1*(u)
		Evofinder	0.84(±0.10)	0.75(±0.07)	0.017	*h1*
		IBIS	0.61(±0.16)	0.54(±0.09)	0.173	*h0*(v)
.38SPL	0.50	Arsenal	0.37(±0.09)	0.37(±0.10)	0.953	*h0*
		Evofinder	0.45(±0.08)	0.39(±0.11)	0.220	*h0*
		IBIS	0.56(±0.10)	0.40(±0.12)	0.008	*h1*
.40S&W	0.22	Arsenal	0.66(±0.14)	0.45(±0.16)	0.007	*h1*
		Evofinder	0.69(±0.05)	0.45(±0.13)	0.039	*h1*
		IBIS	0.55(±0.10)	0.34(±0.10)	0.023	*h1*

(t) – ANOVA, significance level 5%.
(u) – h1: the mean effectiveness criterions are statistically distinguishable
(v) – h0: all mean effectiveness criterions are statistically indistinguishable

In the other calibers, it should be mentioned that the lower effectiveness of the IBIS® system in the 9x19mm caliber coincides with the fact that its results were not sensitive to the difference in the depths of the firing pin mark. A similar fact is observed in the .38SPL caliber, where the Arsenal® and Evofinder® systems had the lower effectiveness and also showed results that in the Analysis of Variance were not sensitive to differences in the depth of the firing pin. Another way to analyze and understand these results is obtained by checking the influences of the difference in depth of the firing pin mark by system, and comparing them with the comparative performance in each caliber (refer to Table 27), being possible to observe a general rule by system:

- In the Arsenal® system, the effectiveness was affected by this variable in the .40S&W and 9x19mm calibers, and there is no evidence against the null hypothesis in the results of the .38SPL caliber, in this last caliber Arsenal® had lower effectiveness than IBIS®;
- Similarly, with the Evofinder® system, the effectiveness was affected by this variable in the .40S&W and 9x19mm calibers, and there is no evidence against the null hypothesis in the results of the .38SPL caliber, in this last caliber Evofinder® had lower effectiveness than IBIS®;
- On the other hand, in the IBIS® system, the effectiveness was affected by this variable in the .40S&W and .38SPL calibers, and there is no evidence against

the null hypothesis in the results of the 9x19mm caliber, in this last caliber IBIS® had lower effectiveness than Arsenal® and Evofinder®.

Therefore, when a system had higher effectiveness compared to the others, the influence of the difference in depth of the firing pin mark was invariably observed. The influence of this variable was not only supported by the analysis of variance in each caliber per system in which the effectiveness was lower compared to other(s). Therefore, this reinforces the hypothesis in favor of the significant influence of the difference in depth of the firing pin mark. For cartridge cases where this hypothesis was not supported by the analysis of variance, the system's effectiveness was poor, which indicates that other factors may be decreasing the effectiveness and therefore masking the influence of the variable studied in this section.

6.7.3 Anvil mark

When analyzing the depth of the firing pin mark, it was noted early on that some cartridge cases featured a negative of the anvil on the bottom of the firing pin mark. In the image of Figure 136, obtained by X-ray microtomography from the base of a cartridge, the position in which the anvil is located opposite to the primer cup external surface can be observed.

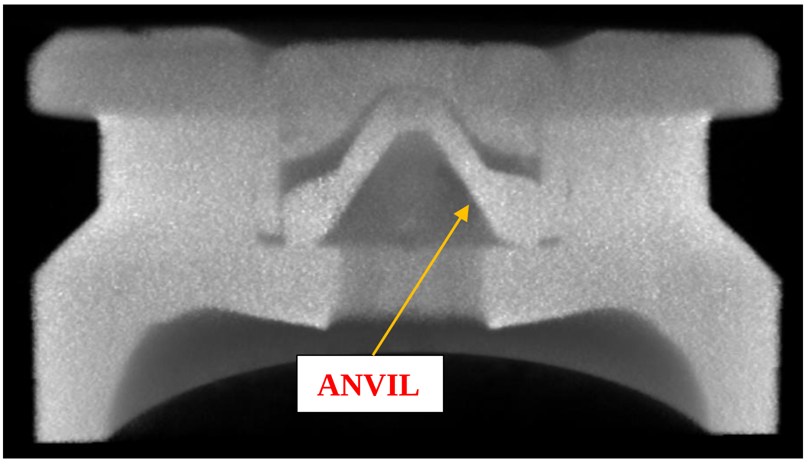


Figure 136 – X-ray microtomography showing the position of the anvil inside the primer cup.

When the firing pin mark features a negative from the anvil mark, there is a major change in the topography of the internal surface of the mark, and given the possibility that this characteristic will deteriorate the effectiveness of the correlations, all the cartridge cases were checked for the presence or not of anvil mark on the internal surface of the firing pin mark.

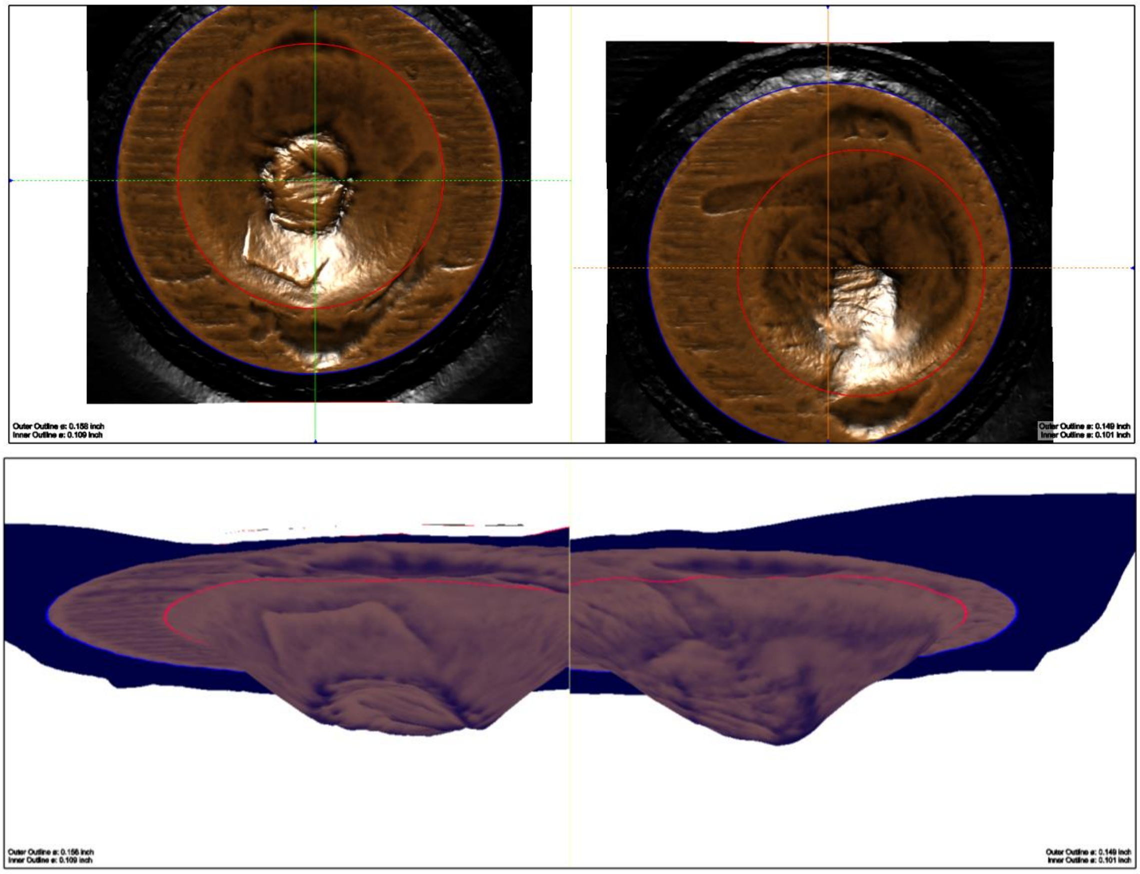


Figure 137 – Comparison of firing pin marks with (left) and without (right) anvil mark (IBIS® image).

In Figure 137 it is possible to verify individual marks when analyzing the marks of the firing pin in the traditional way (upper part of the figure), but it is also evident that there are significant differences in the images caused by the presence of the anvil mark in the firing mark of the cartridge case on the left. The IBIS® system allows a different comparison from the traditional one, by allowing the complete inversion of the firing pin mark (bottom of the figure). With the inverted firing pin mark, the difference in the topography of its internal surface is evident when there is an anvil mark.

In the anvil mark check carried out in the cartridge cases, no mark of this nature was observed in the 9x19mm or .40S&W cases, however, in the .38SPL caliber, this characteristic was observed in 103 of the 288 cases. On average, 6 of each 18 cartridge cases collected from .38SPL revolvers featured an anvil mark.

To evaluate the influence of this characteristic on the effectiveness of the correlations, effectiveness computation was implemented in the analysis program that separated the match results according to four criteria expressed in the conditions of the expressions 6.12 to 6.15.

$$Anvil\ True_{(questioned)}\ \boldsymbol{AND}\ Anvil\ True_{(TFC)}\ , \qquad 6.12$$

$$Anvil\ True_{(questioned)}\ \boldsymbol{AND}\ Anvil\ False_{(TFC)}\ , \qquad 6.13$$

$$Anvil\ False_{(questioned)}\ \boldsymbol{AND}\ Anvil\ True_{(TFC)}\ , \qquad 6.14$$

$$Anvil\ False_{(reference)}\ \boldsymbol{AND}\ Anvil\ False_{(TFC)}\ . \qquad 6.15$$

The effectiveness of firing pin mark (FP3D on IBIS) correlations, of the inter-material noiseless tests according to these conditions, by system, can be seen in Figure 138.

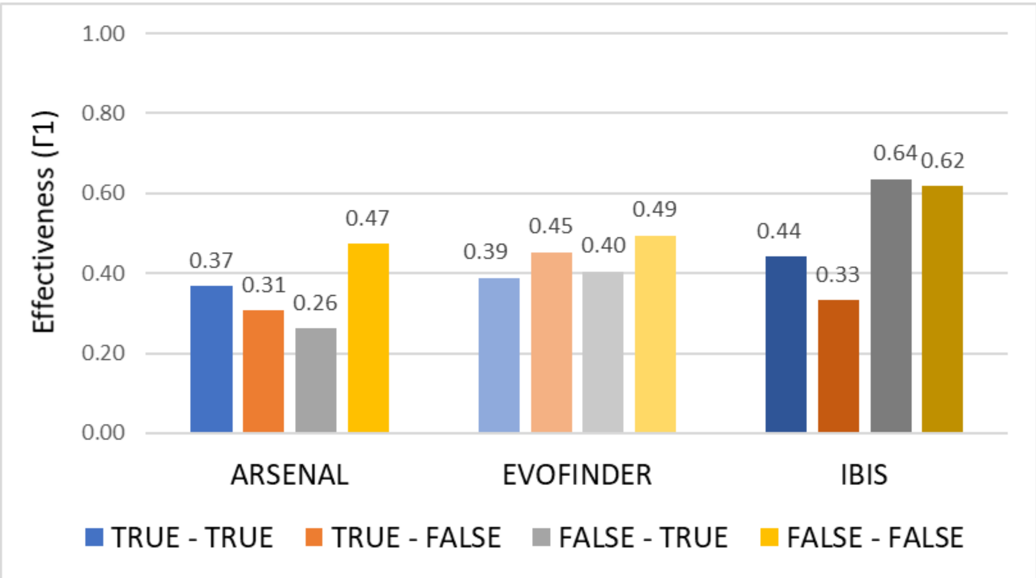


Figure 138 – Systems' effectiveness regarding the presence (TRUE) or the absence (FALSE) of Anvil mark in the questioned and test-fired cartridge cases of each match.

The influence of the presence of anvil marks on the effectiveness of the systems can be seen in the results. The systems' effectiveness for condition 6.15, that is, the absence of anvil mark in the two cartridge cases compared (Γ_1: Arsenal® - 0.47, Evofinder® - 0.49, IBIS® - 0.62) were significantly higher than the mean effectiveness in the other 3 (three) conditions, which involve the presence of anvil mark in 1 (one) or in the 2 (two) cartridge cases compared (Γ_1: Arsenal® - 0.31, Evofinder® - 0.42, IBIS® - 0.47). That is, the presence of anvil mark negatively impacted the systems' results.

Additionally, for condition 6.14 in IBIS® results, the anvil mark presence only in the test-fired, and not in the questioned cartridge case, did not influence the effectiveness. In this condition, Arsenal® and Evofinder® had their effectiveness reduced in comparison to the condition of absence of the anvil mark in both cartridge cases. This difference in the influence of anvil mark between systems may be one of the reasons why the IBIS® system was more effective than other systems in this caliber by firing pin mark.

6.7.4 Breech face mark orientation angle

A fourth and last geometric feature investigated as a possible influence factor on the effectiveness of correlations with cartridge cases was the orientation angle of the breech mark in the acquired images.

There are 360 degrees of freedom in the position in which the cartridge case can be inserted in the scanner. This implies that each comparison of two cartridge cases from the same firearm has up to 180 degrees of angular difference between them, clockwise or counterclockwise, to reach a correct match position.

To evaluate this parameter, the first cartridge case collected from each firearm was chosen as a reference sample, i.e, the position it was acquired in each system was termed the 0 degrees position, for comparison to all other cartridge cases from the same firearm. In the ballistic comparison to the reference, the rotation angle necessary for each cartridge case to reach the correct match position was defined as the breech face mark orientation angle (*BFOA*) in that system.

The three geometric characteristics previously analyzed, centralization, depth, and anvil mark on firing pin marks do not depend on the system in which they were digitilized, as they are physical characteristics of the fired cartridge case. On the other hand, the characteristic analyzed in this section varies from system to system, as they were positioned for acquisition, and therefore the determination of the orientation of each cartridge case had to be done in each system.

Initially, this analysis was carried out in the three systems, but in many comparisons carried out in the Arsenal® system (reference sample against other cartridge cases of the same firearm), the result was inconclusive, that is, the image did not feature resolution or quality that would allow determining the correct match position. In this way, as the results in this system would be greatly compromised by the absence of data, this analysis was completed only in the Evofinder® and IBIS® systems.

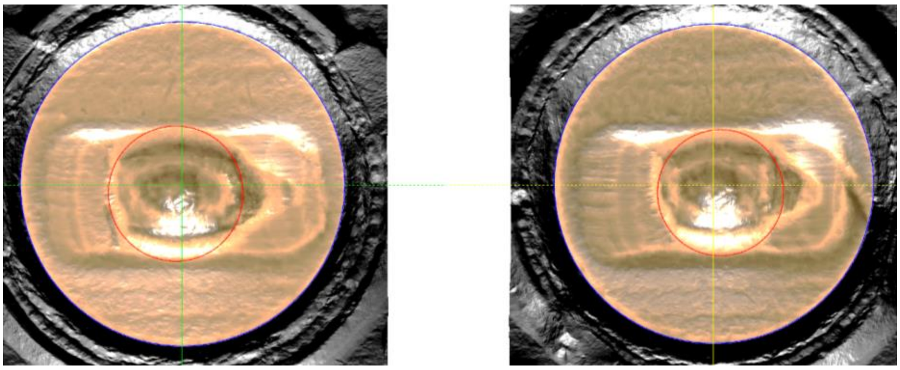


Figure 139 – Determination of breech face orientation angle on CC discharged on Glock pistols (IBIS® image).

In the 9x19mm caliber, the analysis was performed in all the cartridge cases collected, however, it was observed that in the firearms number 34 to 45, breech face orientation angle varied only between 0 and 11 degrees in both systems. That is, this is not a significant variable in these firearms. As can be seen in the image of Figure 139, this is due to the unconventional shape of the firing pin mark on these firearms, shaped by a rectangular firing pin aperture, which facilitates the correct orientation at the time of acquisition. To avoid the influence of the characteristic of these firearms, which could mask the results in relation to the other firearms, in which this orientation is truly variable, in the caliber 9x19mm the calculations of effectiveness, in both systems, were made with results by breech face mark (BF3D in IBIS) for firearms 18 to 33.

Figure 140 and Figure 141 images depict the correct match position of two compared cartridge cases, on the left the first collected from each reference (reference sample in this analysis), and on the right, one of the other cartridge cases collected from the same firearm. In Figure 140 image, the sample on the right needed to be rotated 135 degrees counterclockwise, in relation to the digitalization position, in order to achieve this position of correct alignment with the reference sample on the left, therefore its *BFOA* in Evofinder® was -135 degrees. Similarly, in Figure 141, the orientation for the correct match position was obtained by rotating the right sample 180 degrees in relation to its digitization position, therefore its *BFOA* in IBIS® was 180 degrees.

The analysis of the frequency histograms of breech face orientation angle (*BFOA*) in each caliber and system revealed distributions that were better represented by Lorentz distributions (refer to Figure 142 to Figure 147).

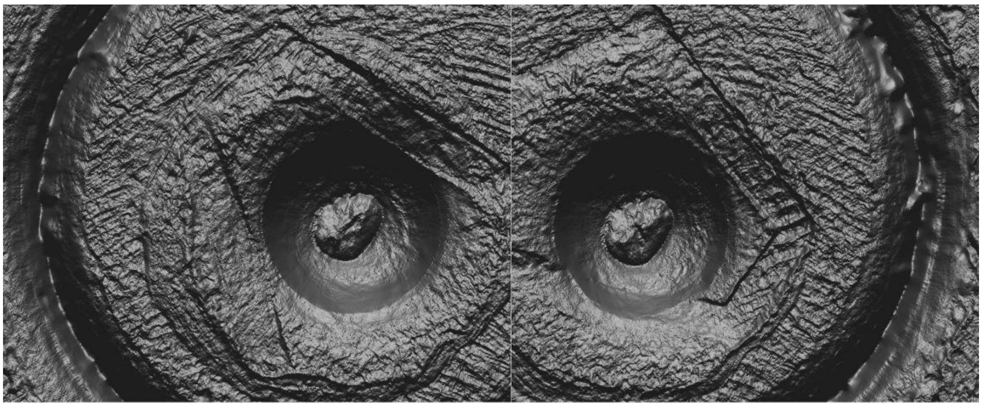


Figure 140 – Determination of breech face orientation angle (Evofinder® image).

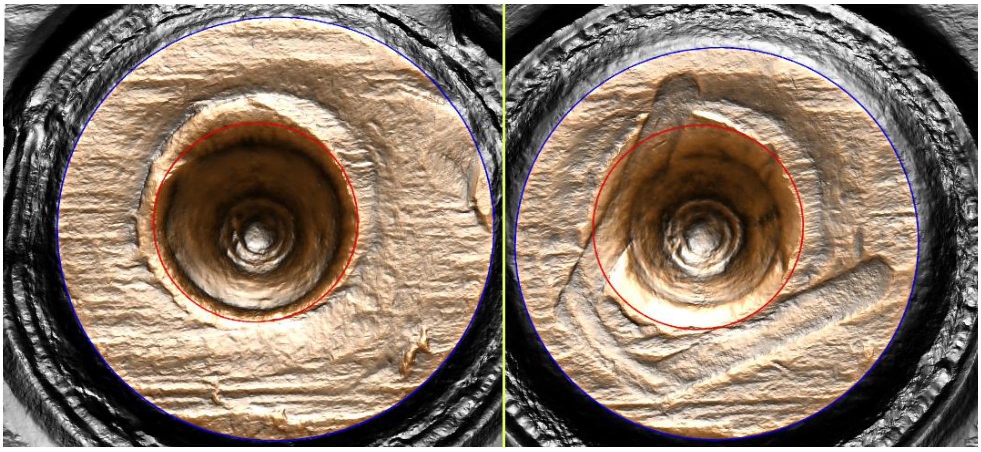


Figure 141 – Determination of the breech face orientation angle (IBIS® image).

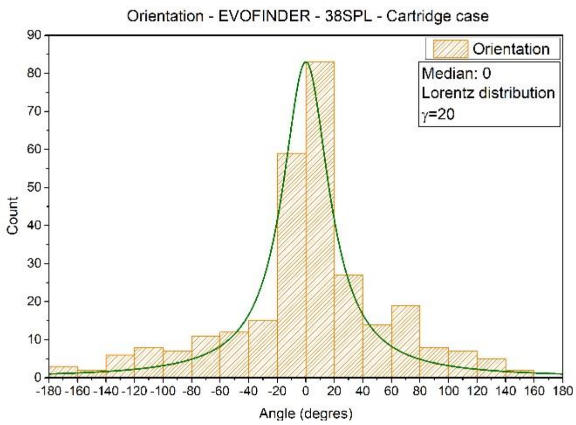


Figure 142 – Frequency histogram of breech face orientation angle (*BFOA*) in Evofinder® .38SPL CC images.

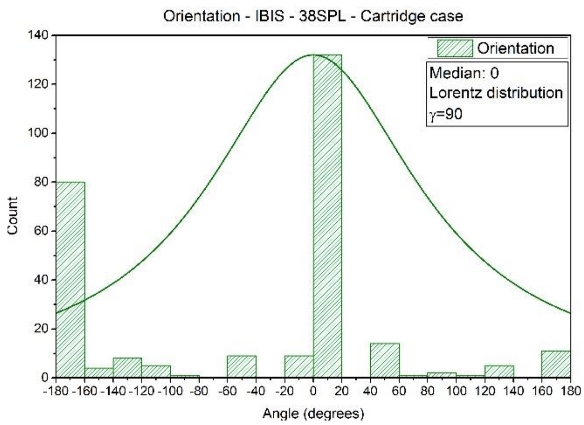


Figure 143 – Frequency histogram of breech face orientation angle (*BFOA*) in IBIS® .38SPL CC images.

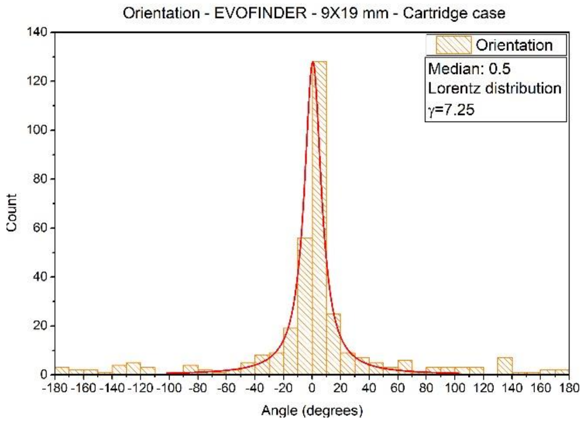


Figure 144 – Frequency histogram of breech face orientation angle (*BFOA*) in Evofinder® 9x19mm CC images.

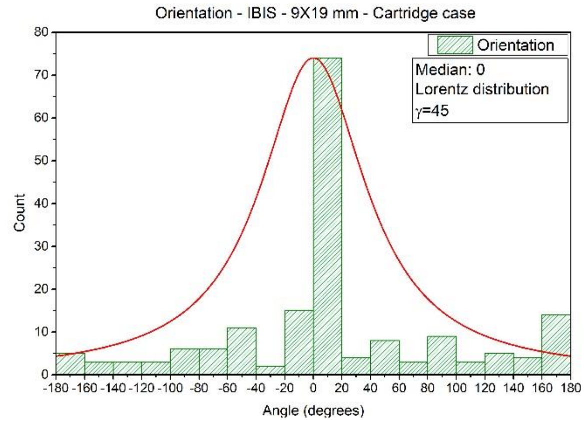


Figure 145 – Frequency histogram of breech face orientation angle (*BFOA*) in IBIS® 9x19mm CC images.

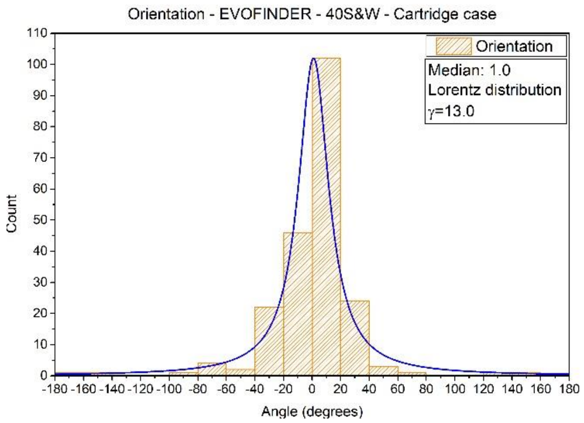


Figure 146 – Frequency histogram of breech face orientation angle (*BFOA*) in Evofinder®.40S&W CC images.

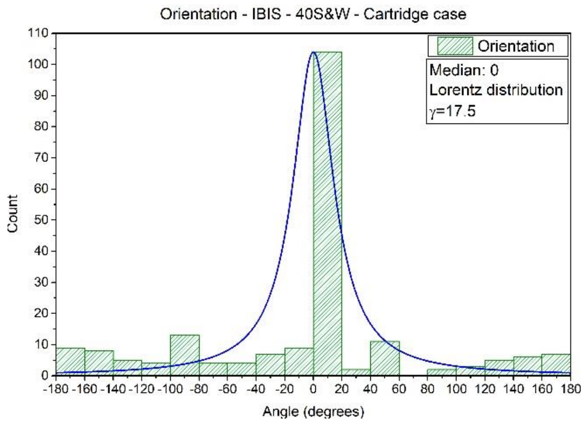


Figure 147 – Frequency histogram of breech face orientation angle (*BFOA*) in IBIS®.40S&W CC images.

Given the characteristics of Lorentz distribution, discussed in section 6.7.2, and considering that the angular difference in orientation of two cartridge cases may vary between 0 to 180 degrees, the parameter γ, which divides each symmetrical side of the distributions in half of the values, was used to study the influence of the breech face orientation angle difference between the questioned and the test-fired cartridge cases.

Effectiveness computation was implemented in the analysis program, dividing the match results according to the difference of the breech face orientation angle (*ΔBFOA*), dividing the results into two distributions expressed in inequations 6.16 and 6.17.

$$\left|BFOA_{(questioned)} - BFOA_{(TFC)}\right| < \gamma\,, \qquad 6.16$$

$$\left|BFOA_{(questioned)} - BFOA_{(TFC)}\right| \geq \gamma\,. \qquad 6.17$$

Table 28 contains the means and standard deviations effectiveness by breech face correlations, considering both repeated test-fires, obtained by separating the results in these two criteria related to the difference of the breech face orientation angle (*ΔBFOA*), and analyses of variance were performed on the results of the inter-material noiseless tests of each system and caliber.

Table 28 – Mean effectiveness regarding difference of the breech face orientation angle (*ΔBFOA*).

Caliber	γ	System	Mean Γ_1 (SD) *ΔBFOA < γ*	Mean Γ_1 (SD) *ΔBFOA ≥ γ*	*P-value*$^{(w)}$	*Supported hypothesis*
9x19mm	7.25	Evofinder	0.96(±0.04)	0.90(±0.03)	0.044204	*h1*$^{(x)}$
	45.00	IBIS	0.79(±0.08)	0.80(±0.03)	0.765207	*h0*$^{(y)}$
.38SPL	20.00	Evofinder	0.62(±0.20)	0.62(±0.12)	0.921103	*h0*
	90.00	IBIS	0.44(±0.15)	0.46(±0.16)	0.366041	*h0*
.40S&W	13.00	Evofinder	0.81(±0.03)	0.73(±0.07)	0.124047	*h0*
	17.50	IBIS	0.59(±0.10)	0.42(±0.13)	0.366041	*h0*

(w) – ANOVA, significance level 5%;
(x) – h1: the mean effectiveness criterions are statistically distinguishable.
(y) – h0: all mean effectiveness criterions are statistically indistinguishable.

The only set of data whose influence of the difference of the breech face orientation angle was statistically significant was in the Evofinder® system, caliber 9x19mm. It is interesting to note that this was the approximate Lorentz distribution with the lowest scale parameter (γ = 7.25). This means that in this caliber the breech face orientation angle (*BFOA*) was closer to the median (median = 0.5) than in the other calibers, and there was a significant effectiveness decrease in the Evofinder® breech face correlation that were acquired with an angular difference above 7.25 in relation to the reference cartridge case.

As this was a result specific to a system and caliber, there is no evidence in favor of this parameter being a general influencing factor on the effectiveness of automated cartridge case correlations.

6.8 Database growth

In the same way as carried out with bullets, the inter-material noiseless and with noise tests allowed studying the impact of the database growth on the effectiveness of the systems. The effectiveness curves were obtained as a function of the database size. The lower position between two repeated test-fires in all available results lists was used for effectiveness computation. Once again the effectiveness was plotted against the database size, and the Levenberg-Marquardt algorithm (Madsen et al., 2004) was used to obtain the decay function in each caliber per system, as depicted in Figure 148, Figure 149, and Figure 150, and Table 29 contains the parameters of each adjusted curve.

In the .38SPL caliber (refer to Figure 148), as there are only two inter-material tests, noiseless and noise1, the decay functions were a straight line, characterized by equation 5.4 (refer to p. 192).

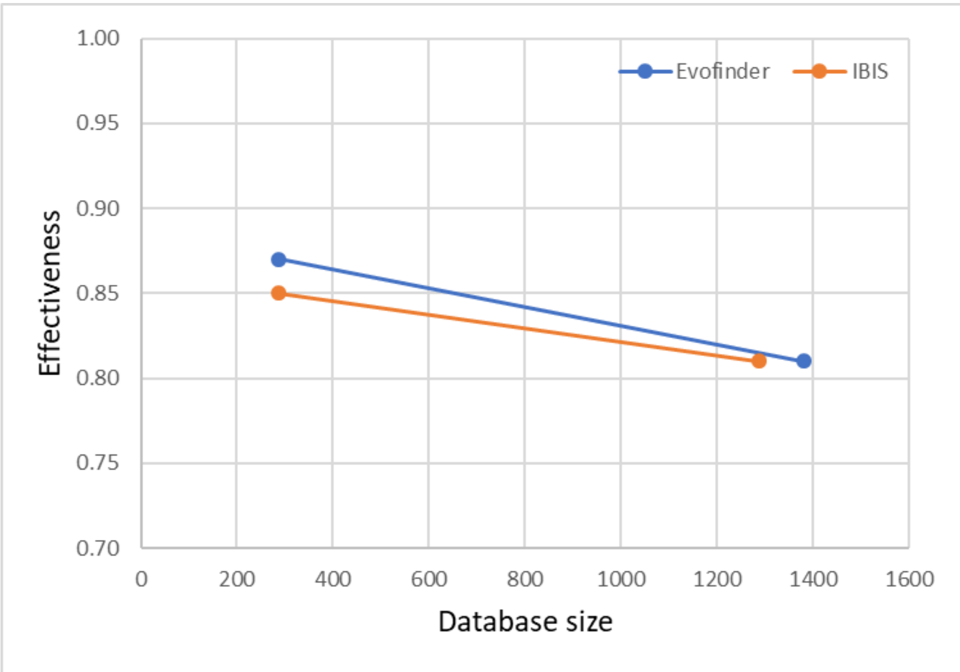


Figure 148 –Effectiveness as a function of database size in .38SPL cartridge cases for Evofinder® and IBIS®, considering the lower position between the repeated test-fires in all correlation result lists.

When comparing the parameters featuring the behavior of the systems (refer to Table 29) the Evofinder® featured an intercept point to the **Y**-axis and a slope of 0.89 and $-5.5*10^{-5}$, and the IBIS® 0.86 and $-4*10^{-5}$. The first parameter is the maximum effectiveness of the system on that caliber, and the second the decay rate. Comparing the two systems in 38SPL caliber, the two parameters are quite similar, and contrasting the observed decay with the results of bullets (refer to section 5.7 on p. 191), the impact of the cartridge case database growth was significantly less, actually, these decays are on the order of 10 times less than the decays observed with bullets.

Table 29 – Parameters and results of interest in the effectiveness as a function of cartridge case database size for Evofinder® and IBIS®.

CALIBER	SYSTEM	DECREASING	FUNCTION	$\Gamma_{1,0}$	slope (10^-5)	Γ_1 (i = 1000)	i (Γ_1 = 0.5)
.38SPL	EVOFINDER	Linear	5.4	0.89	-5.49	0.83	7027
	IBIS			0.86	-4.00	0.82	9037
CALIBER	**SYSTEM**	**DECREASING**	**FUNCTION**	**A or A_1**	**t or w**	**$\Gamma_{1,\infty}$**	**i(Γ_1 = 0.5)**
9x19mm	Evofinder	Inverse polynomial	6.18	-0.01	1263	0.98	∄
	IBIS			-0.01	1685	0.97	∄
.40S&W	Evofinder	Exponencial	5.5	0.02	2520	0.91	∄
	IBIS			0.02	674	0.92	∄

Assuming the linear decaying with .38SPL cartridge cases, a 0.50 effectiveness would be reached by Evofinder® in a database of 7027 samples, and by IBIS® with 9037 samples.

On the other hand, with 9x19mm (refer to Figure 149) and .40S&W (refer to Figure 150) cartridge cases, inter-material test was three times replicated, varying the database size for noiseless, noise 1, and noise 2 tests.

The 9x19mm cartridge case (refer to Figure 149) effectiveness (Γ_1) as a function of database size (i) was characterized by equation 6.18.

$$\Gamma_1(i) = \Gamma_{1,0} + \frac{A}{\left(1 + A_1 * \left(2 * \frac{(i - i_c)}{w}\right)^2 + A_2 * \left(2 * \frac{(i - i_c)}{w}\right)^4 + A_3 * \left(2 * \frac{(i - i_c)}{w}\right)^6\right)} \quad . \qquad 6.18$$

In this decay profile, it is possible to observe that, as the powers in the denominator are always positive, the higher the parameter **w** the lower the denominator. Since the parameter A is negative (-0.01 for both systems), this implies a smaller Γ_1. That is, in this inverse polynomial, **w** can be understood as a factor that measures the decay of Γ_1, such that the greater the **w** the greater the decay of Γ_1. In the comparsion of the two systems in this caliber (refer to Table 29), similar behaviour in terms of decay function is observed, since the initial effectiveness are very similar, 0.99, 0.98 as well the final one, 0.98 and 0.97, respectively in Evofinder® and IBIS®. As such small decay, the conclusion is that the introduction of 9x19mm cartridge case noises, between 636 and 2335 samples, were insufficient to measure the impact of the database growth on the effectiveness of the solutions.

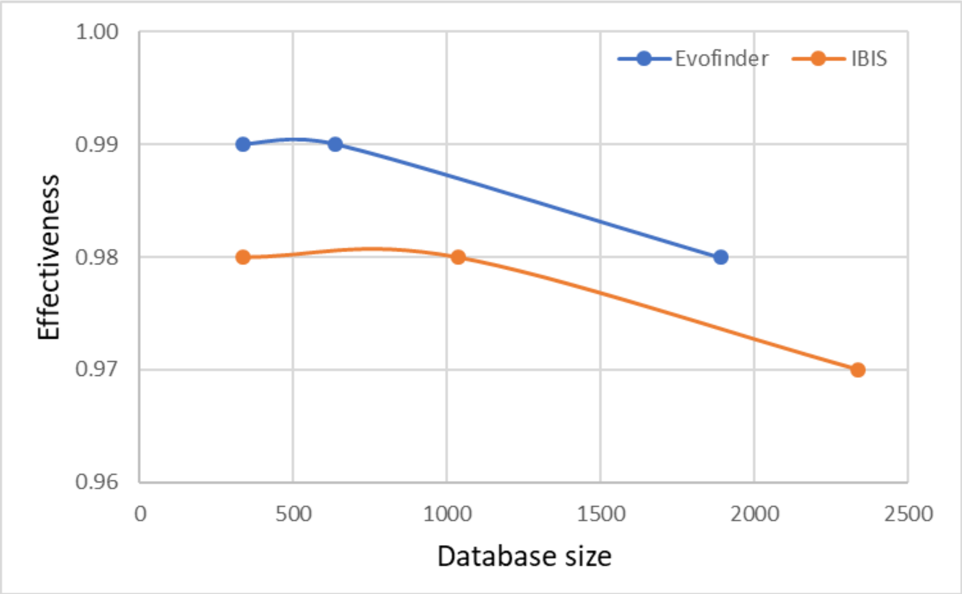


Figure 149 – Effectiveness as a function of database size in 9x19mm cartridge cases for Evofinder® and IBIS®, considering the lower position between the repeated test-fires in all correlation result lists.

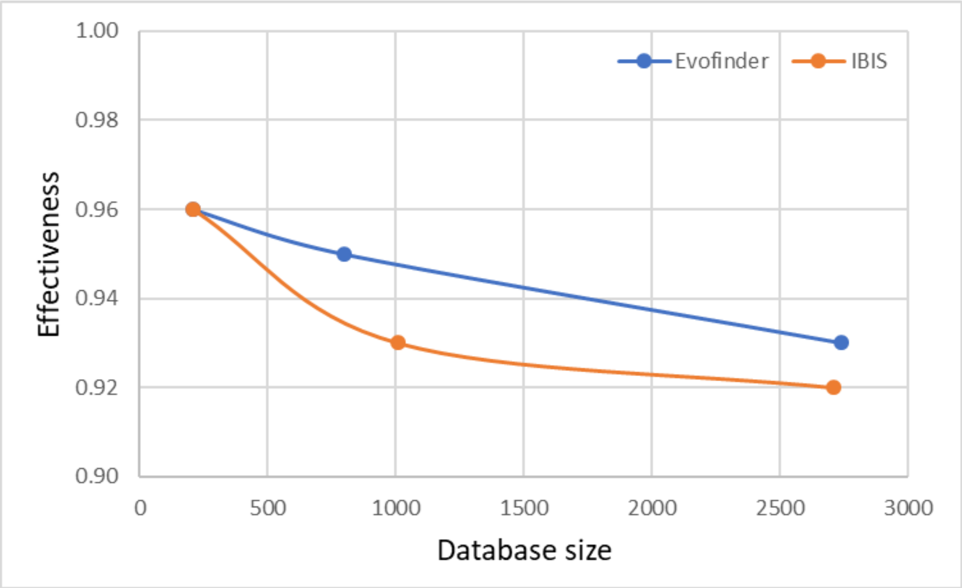


Figure 150 – Effectiveness as a function of database size in .40S&W cartridge cases for Evofinder® and IBIS®, considering the lower position between the repeated test-fires in all correlation result lists.

Finally, in the .40S&W caliber (refer to Figure 150), the data revealed the same exponential decay observed in bullets, with initial effectiveness equal in both systems to 0.96 and minimum limits for the Evofinder® and IBIS® systems at 0.91 and 0.92 (refer to Table 29).

In the analysis of the impact of the growth of the database on the effectiveness of the solutions with bullets, the exponential decay, which implies that the database growth is less critical than previously thought, was regarded as extremely promising for the application of these technologies.

More significant were the results with cartridge cases, which feature a considerably lower effectiveness decay profile, even though the database involved in the tests was larger, up to 2740 ammunition elements. Even with .38SPL cartridge case, which is sometimes difficult to correlate because there is no orientation mark, such as ejector, firing pin drag mark, or extractor mark, and considering the data limitation of this study, which forced a linear decay, a limit between 7000 to 10000 thousand cartridge cases would be necessary for effectiveness to decrease to 0.5.

Therefore, the 9x19mm cartridge case observed decay seems to be absolutely negligible, and in the .40S&W caliber the desired exponential decay, with minimum limits above 0.90 of effectiveness, was obtained. Once again, these are extremely relevant data to defend the application of these technologies in places with a high concentration of ammunition and firearms-related crimes.

6.9 Analysis of the correlation scores

As with bullets, another aspect of interest in the correlations carried out by the systems is the assigned score. The existence of gaps between match or non-match scores can be used in the implementation of a more objective identification routine or the evaluation of the score of each match against the non-match score distribution can help to estimate the identification error rate. With the aid of the analysis program, match and non-match distributions, both by breech face and firing pin, in all calibers and systems, were obtained (refer to Figure 151 to Figure 156).

The visual analysis comparing the distribution of scores raises relevant points. In the results for Arsenal® by breech face, and for IBIS® by firing pin, there are several instances where the match and non-match distributions are not significantly different in terms of scores.

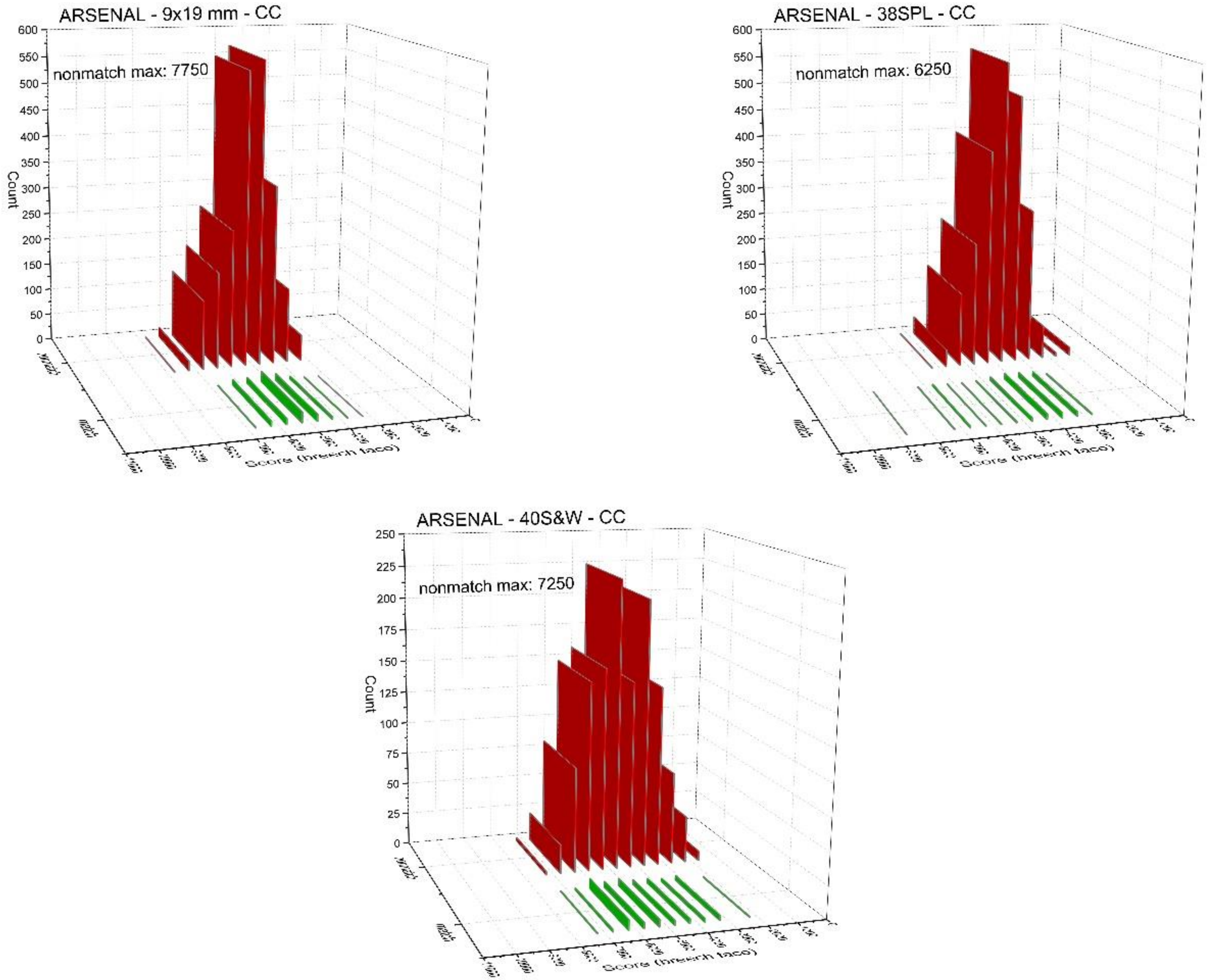


Figure 151 – Histogram of correlation scores for match (green) and non-match (red) in Breech Face lists of Arsenal® system.

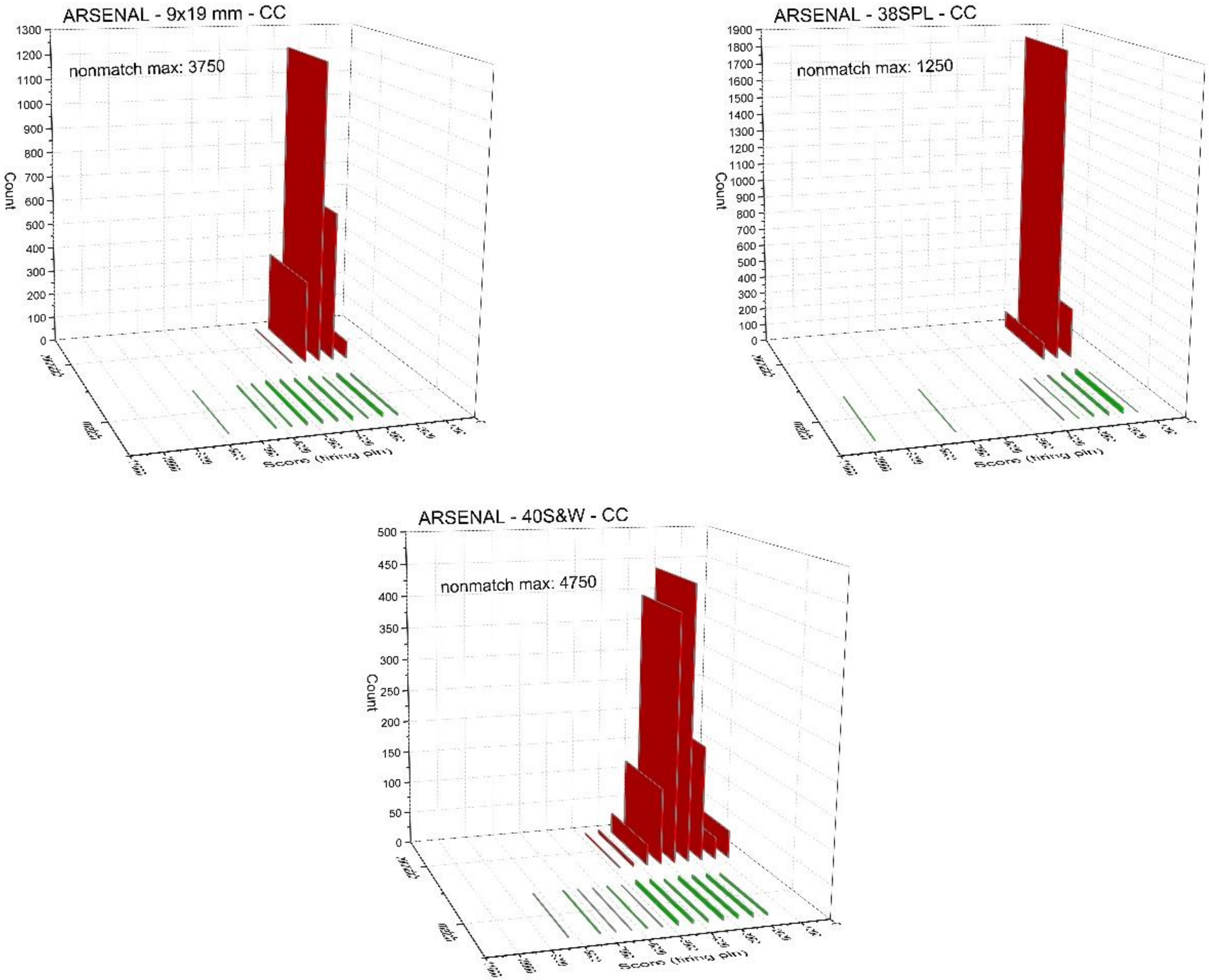


Figure 152 – Histogram of correlation scores for match (green) and non-match (red) in Firing Pin lists of Arsenal® system.

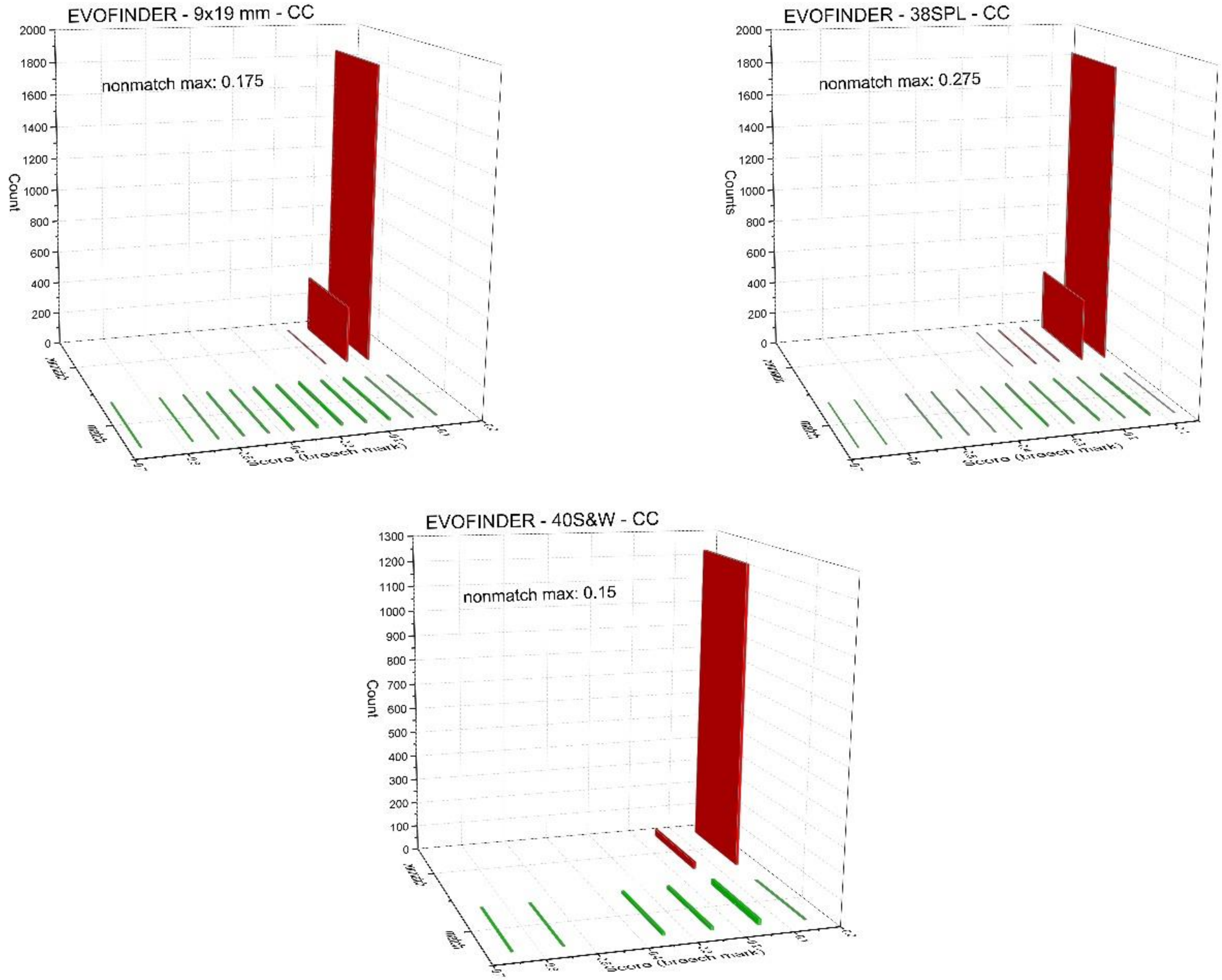


Figure 153 – Histogram of correlation scores for match (green) and non-match (red) in Breech Face lists of Evofinder® system.

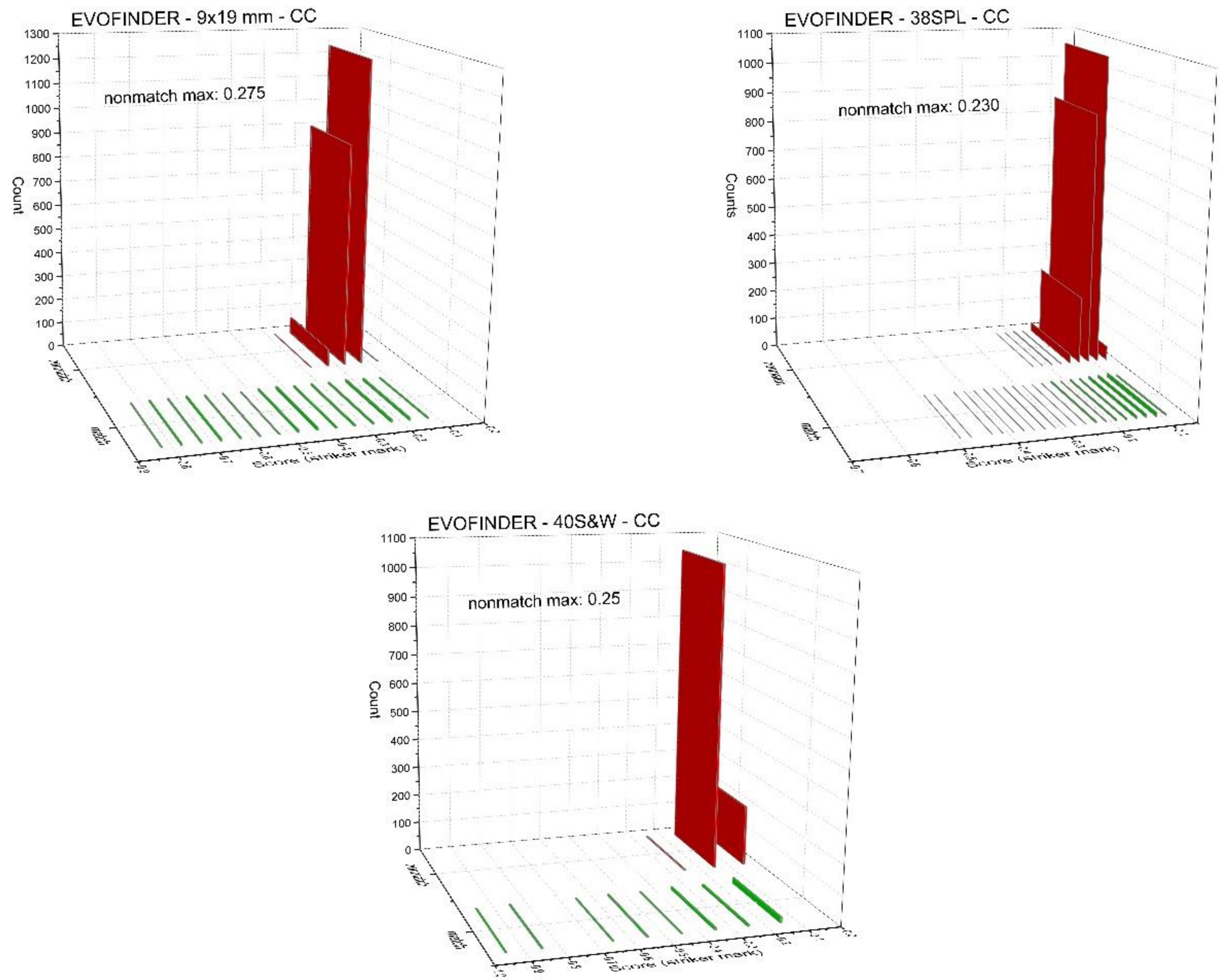


Figure 154 – Histogram of correlation scores for match (green) and non-match (red) in Striker lists of Evofinder® system.

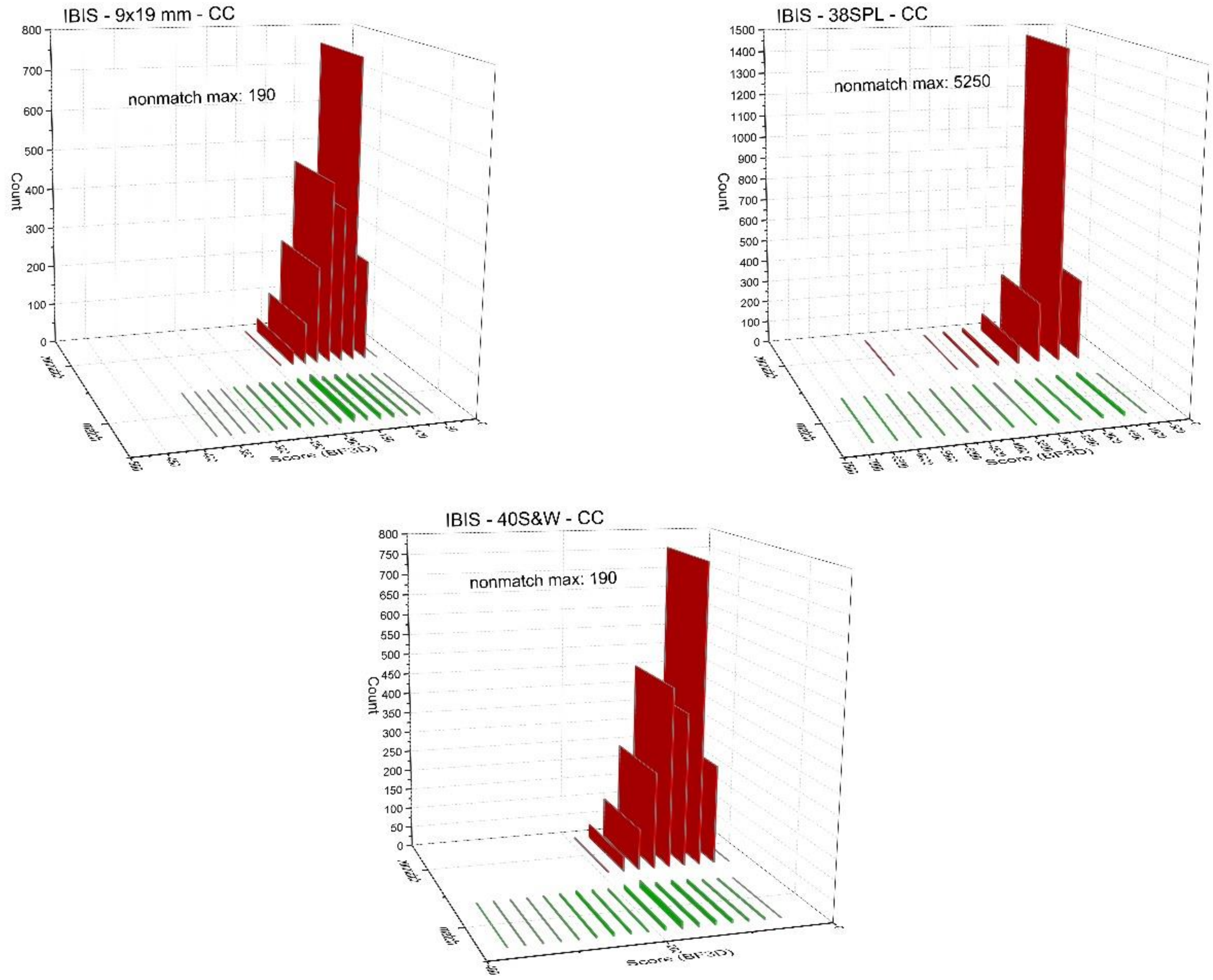


Figure 155 – Histogram of correlation scores for match (green) and non-match (red) in BF3D lists of IBIS® system.

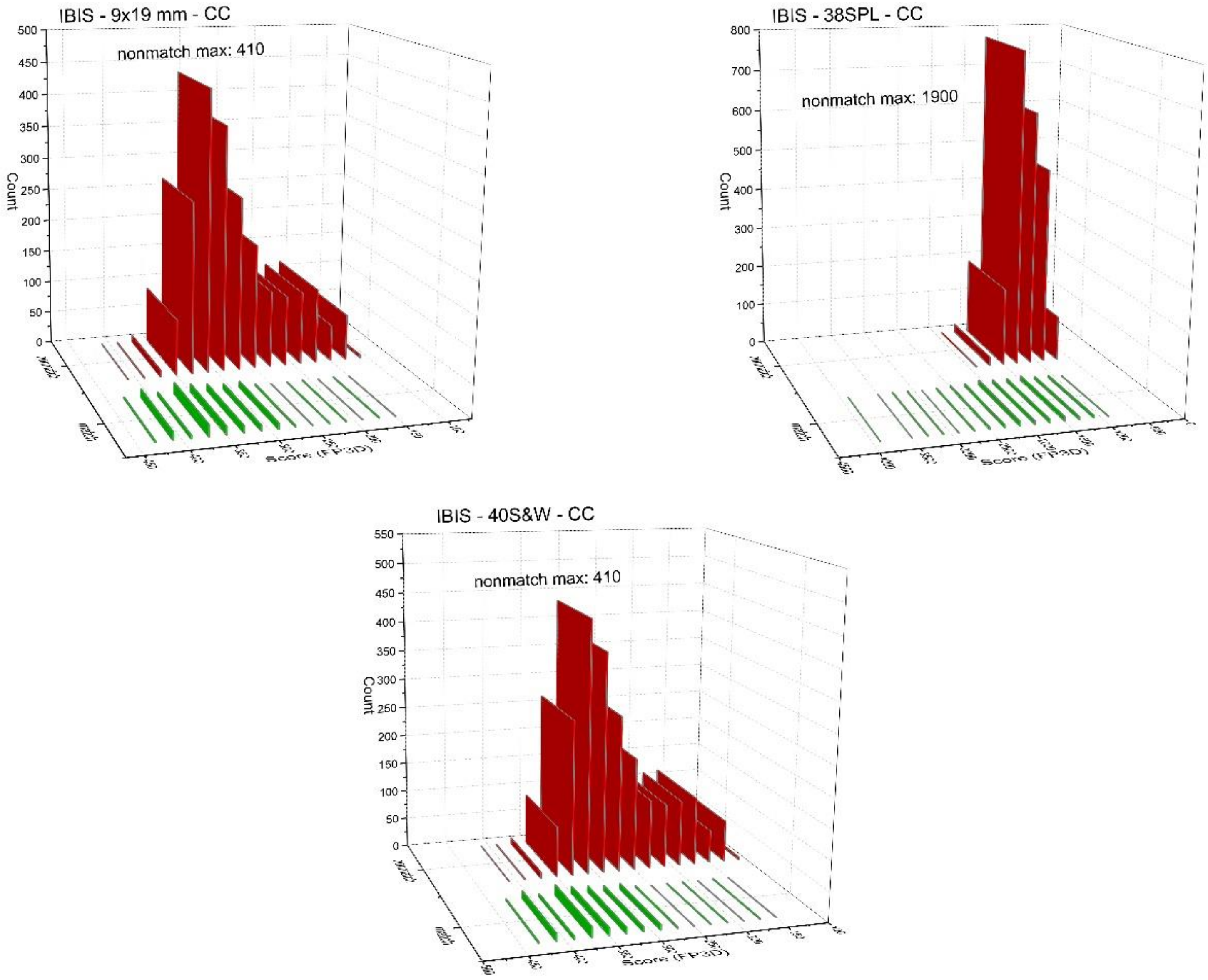
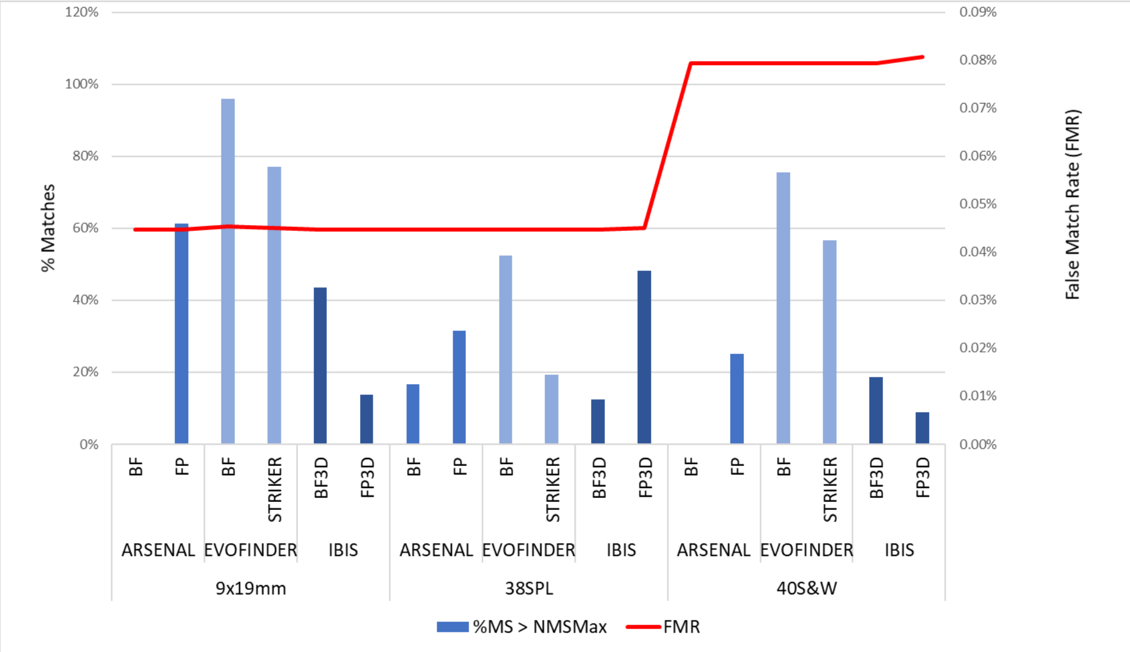
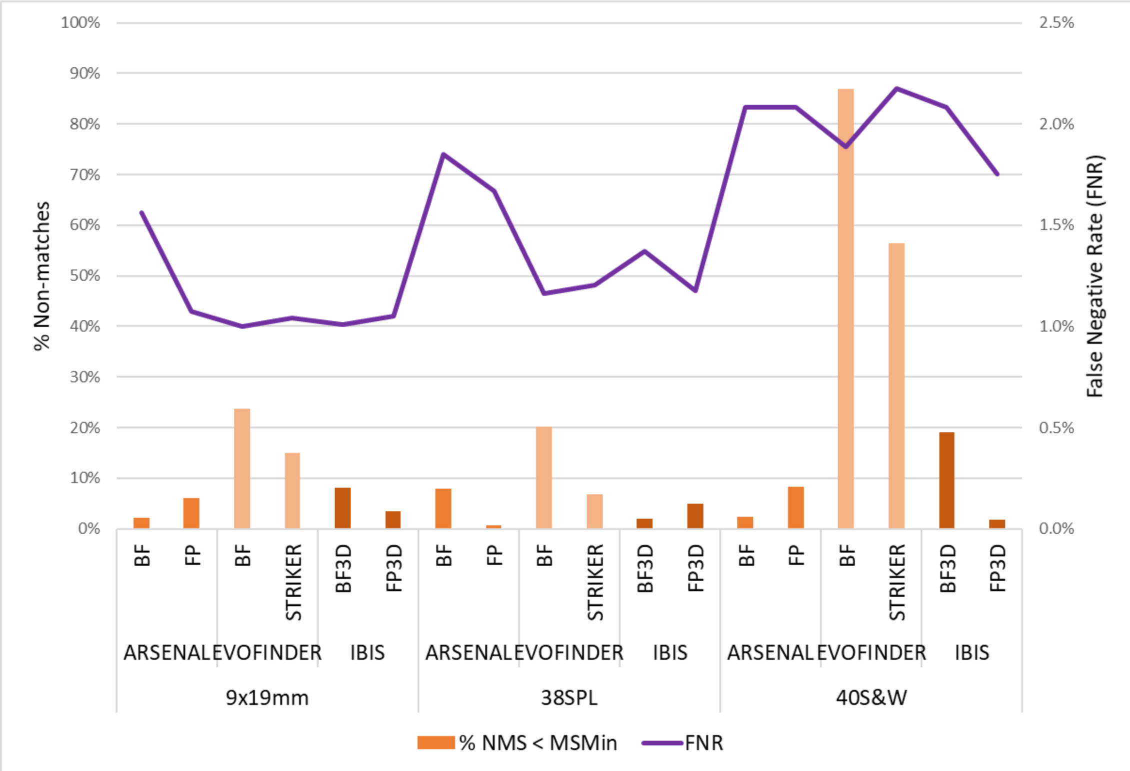


Figure 156 – Histogram of correlation scores for match (green) and non-match (red) in FP3D lists of IBIS® system.



(A)



(B)

Figure 157 – Percentage **a)** of cartridge case MS (match score) that features the minimum FMR (red line) and **b)** of cartridge case NMS (non-match score) that features the minimum FNR (purple line).

This deficiency in the algorithms in question can be compared with the graphs of the analysis by firearm manufacturer (refer to section 6.4), where is seen a poor performance by breech face of Arsenal® in all calibers, and of IBIS® with some firearms in 9x19mm and .40S&W (refer to Figure 110 to Figure 112 in p. 215 to 216).

To estimate an error rate related to the results from the score, for each caliber/system/correlator the minimum match score (MSmin) and the maximum non-match score (NMSmax) were determined. Considering the number of available match and non-match scores, it was possible to establish a minimum false match rate (FMR) and a minimum false-negative rate (FNR), which varied respectively between 0.04% and 0.08% (refer to Figure 157a), and between 1.1% and 2.2% (refer to Figure 157b). In Figure 157a it is also possible to observe the percentage of matches with a score higher than NMSmax, that is, matches with minimum FMR, and in the Figure 157b the percentage of non-matches with a score lower than MSmin, in other words, non-matches with minimum FNR.

The results of the Evofinder® system are highlighted, for 9x19mm and .40S&W, which presented 96% and 75% of the breech face match score and 77% and 57% of the firing pin match scores, with FMR between 1/2240 and 1/1260. Additionally, in the .40S&W caliber, 87% and 57% of the breech face and firing pin non-match scores featured FNR between 1/53 and 1/46. Another good result, in terms of the number of matches with minimum FMR, was Arsenal® by firing pin in the 9x19mm caliber, with 61% of the match scores.

Estimates of error rates in cartridge cases were much better than obtained with bullets. In this sense, it becomes more plausible to establish objective protocols when results such as Evofinder® in the .40S&W caliber are available. Nevertheless, small FNR are needed, which is dependant on studies with more known matches, and algorithms that score a higher part of non-matches within the FNR. Addicionally, more matches within minimum FMR, would allow a more reliable objective identification process and safer exclusion decisions.

6.10 Suggested operating condition for cartridge cases

The feasibility of a work analysis protocol with these systems must consider the variables of influence and the factors that can lead to a greater increase in the probability of correct identification of the firearm.

The previous results indicated geometric factors that apparently have no influence on the results of the systems, such as the variation in the center point of the firing pin mark or the angle of orientation of the breech face when inserted in the scanner, and others with influence such as depth of firing pin mark and presence of anvil mark on firing pin mark, all results that, if correctly addressed, can be used to refine the correlation algorithms.

The difference in firing energy, and associated with it, the materials and types of cartridge cases involved, revealed that the material composition has much more influence on the effectiveness of the systems than the energy of discharge. The observed variations are, however, smaller than in relation to the variables with bullets, in such a way that the database of cartridge case may have a greater probability of success. However, standardization and the establishment of best practices are still necessary for greater effectiveness of the solutions in solving crimes committed with firearms.

In order to determine an ideal final operating condition of the systems with cases, the main results discussed above were considered, including the types of cases with the best effectiveness in each caliber, however, as the influencing factors are more critical in relation to bullets, it became recommended the use of cartridge cases from test-fired bullets collection, as discussed in section 5.9 (refer to p. 204), leading to the following definitions, for a final suggested operating condition with cartridge cases:

- 38SPL: register in any system 2 (two) TFC1;
- 9x19mm: register in any system 2 (two) TFC2;
- .40S&W: register 2 (two) TFC1 for Evofinder® and Arsenal®, or 2 (two) TFC2 for IBIS®;
- In Arsenal® and Evofinder® check the lists by Breech Face and by Firing Pin and in IBIS® the BF3D or FP3D results.

Figure 158 to Figure 160 are comparative depiction of the final effectiveness obtained by the systems appling the final best condition with cartridge cases.

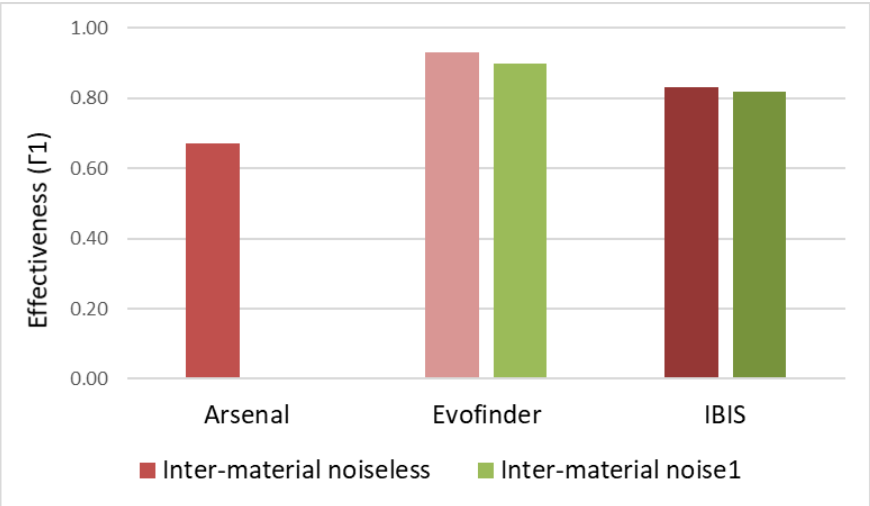


Figure 158 – Systems' Effectiveness in a suggested operating condition with .38SPL CC, considering the best position between the repeated suggested test-fires in all the correlation lists available in each system.

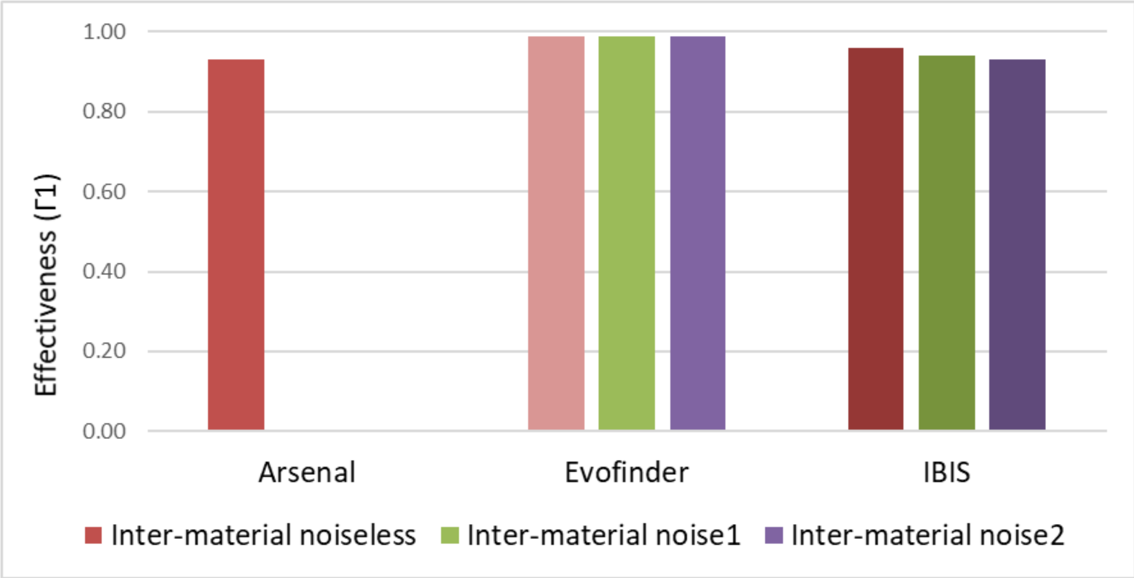


Figure 159 – Systems' Effectiveness in a suggested operating condition with 9x19mm CC, considering the best position between the repeated suggested test-fires in all the correlation lists available in each system..

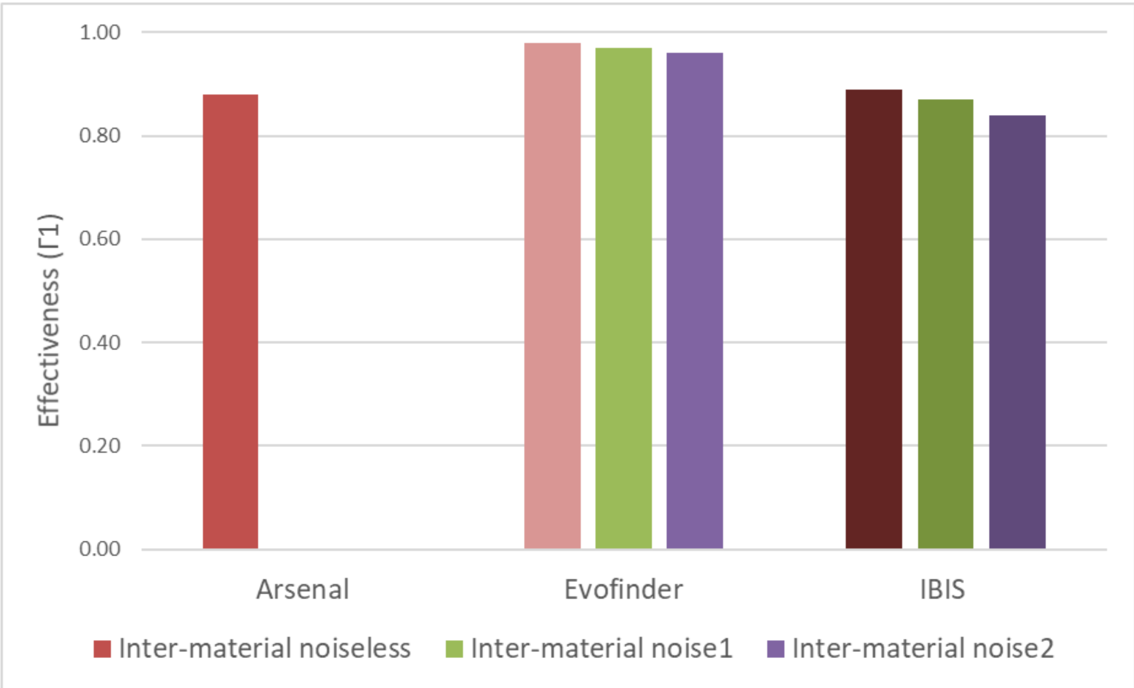


Figure 160 – Systems' Effectiveness in a suggested operating condition with .40S&W CC, considering the best position between the repeated suggested test-fires in all the correlation lists available in each system.

7 CONCLUSIONS AND FUTURE WORK

This chapter contains a review of the factors investigated regarding the effectiveness of ballistic identification systems, and also suggestions for future studies.

7.1 Conclusions

Before highlighting the main conclusions of this study is worth to reemphasize the research question that drove this research (refer to p. 39, emphasis added):

> it is well-established that many firearms, bullet, and cartridge case features affect the impressed marks on fired ammunition components. This raises the question to what degree these features vary and how that influence BIS effectiveness. **Therefore, the primary research question is which firearm and ammunition properties most influence BIS effectiveness?**

In order to answer this very comprehensive question, a firearm and ammunition set were used to test three ballistic identification systems. An effectiveness criterion, based on the accuracy of the result lists provided by these systems, was utilized as a dependant variable to measure the influence of many firearm and ammunition properties. Many aspects of how the systems operate, especially regarding the type of comparisons they perform, were addressed in conjunction with the properties investigated as potential factors of influence.

Because the results provided by the systems were made available in thousands of spreadsheets a computer program was developed to automated the systems' effectiveness computation regarding all the features and aspects of interest. The obtained effectiveness was then analysed, allowing the following conclusions.

7.1.1 Parameters of influence with bullets

The most relevant result obtained in relation to parameters influencing the effectiveness of systems with bullets was the exponential decay observed with the database growth in the results of the caliber 9x19mm and .40S&W, both in the Evofinder® as IBIS® systems.

The exponential decay pattern of effectiveness as a function of database size (refer to equation 5.5 on p. 193) contains minimum effectiveness, determined by the parameter y_o, and decay factors A_1 and t_1, which measures how quickly the growth of the database erodes the effectiveness of the solution. In the 9x19m caliber it was obtained minimum effectiveness in

Evofinder® and IBIS® systems of 0.23 and 0.62, and a significant difference in the decay profile. With the data obtained, it is unlikely that a growing database will lead the IBIS® system to effectiveness around 0.5 in this caliber, while Evofinder® would be reaching this effectiveness with a very small database (database of 173 samples). In the .40S&W caliber, although the minimum effectiveness also showed a substantial difference, 0.53 and 0.83 for Evofinder® and IBIS®, the decay factors were more similar in the two solutions. In 38SPL caliber, the impact of the database size was more meaningful, and because there was only one noise test, the decaying obtained was characterized by a linear function. Assuming this linear decaying, a 0.5 effectiveness would be reached by Evofinder® in a database of only 227 samples, against 2154 samples for IBIS®.

It is interesting to interpret these results in the light of previous studies that found that the increase in the database led to linear growth in the position in which the match appears in the results list (De Kinder et al., 2004; De Ceuster; Dujardin, 2015). Although such linearity has been observed, the results obtained in this research, add important understanding to the theme. Some important differences in the method of this research should be addressed, for example, considering the highest-ranked position between two test-fires, selecting the highest-ranked result among the lists of available correlations, and performing tests with a database significantly bigger than those of previous studies (refer to the database size - horizontal axes - Figure 93, Figure 94, and Figure 95).

Therefore, the observed exponential decay is preferable and in favor of the effectiveness of systems even though the database size grows over time. Additionally, what needs to be observed is that even if samples are added to a database, only those that have the same class characteristics and similar individual marks to the questioned sample will negatively affect the effectiveness of the solution. In other words, only ammunition components with marks that, by the correlation algorithm used, obtain higher or equal scores than the searching test-fire will cause a meaningful repositioning within the result lists. However, there is a limitation to this possibility of including potentially harmful noise. For well-developed algorithms, it is expected that a large portion of the images entered will not be better ranked than the correct test-fire, so the introduction of more images will affect the solution's effectiveness more smoothly and, as seen in this research, it may feature a limit for such decay. This finding is extremely relevant to locations that experience high rates of firearm-related crimes, such as Brazil, and explains why the technologies are still appropriate to succeed in establishing links between shooting incidents.

Another important factor of influence investigated was the Brinell hardness measured in the bullets, which allowed to measure the influence of this mechanical property in the systems' effectiveness. The .38SPL bullets of the study featured the greatest difference in Brinell hardness (ΔHBW), ranging from 5.9 to 114.4 HBW. In the 9x19mm and .40S&W bullets, the hardness ranged between 70.7 to 136.6 HBW and 49.9 to 142.4 HBW.

By computing the difference in Brinell hardness between the questioned and the test-fired bullets on each match, it was possible to conclude, supported by ANOVA in data from all systems and calibers, that higher hardness difference resulted in meaningful lower effectiveness. On average, 0.16(±0.13), 0.18(±0.07), and 0.13(±0.10) effectiveness decrements were obtained in the systems Arsenal®, Evofinder®, and IBIS® for hardness differences above half of ΔHBW in each caliber.

This influence of Brinell hardness on effectiveness was reflected in the comparison of intra-material to inter-material noiseless test, that is, in the analysis of effectiveness regarding the bullet material. As seen, the caliber with the highest ΔHBW was 38SPL, which was the one that consequently showed the greatest effectiveness difference between tests that did not compare different types of bullets (intra-material) and tests with different types of bullets compared (inter-material noiseless), with effectiveness decreasing for Arsenal®, Evofinder®, and IBIS® by -0.46, -0.23, -0.19. In other calibers, the effectiveness decrease between these tests ranged between -0.03 and -0.08 in all systems.

The practical importance of these results was reflected in the establishment of the operating condition for each caliber, which was suggested with the intention of increasing the probability of correct identification. While in the 9x19mm and 40S&W calibers it was possible to recommend one type of bullet for test-firing seized firearms, in the .38SPL it was concluded by the need to register TFB1 and TFB6 per revolver.

A critical point for correct identification is the quality of the generated marks, which is sometimes overemphasized as dependent on the firearm manufacturer. The variation of effectiveness by firearm manufacturer was indeed very obvious to note on the results of the study. Nevertheless, some firearms featured low effectiveness regardless of the system, while others led to high effectiveness in one system and poor in another.

For instance, in 9x19mm caliber, while Norinco and Smith & Wesson featured high effectiveness in all systems (Γ_1 = between 1.00 and 0.75), and Glock presented very low effectiveness regardless of the system (Γ_1 = between 0.09 and 0.02), FN Browning was well identified in IBIS® (Γ_1 = 1.00, 1.00, and 0.99), but with lower effectiveness in Evofinder® (Γ_1 = 0.53, 0.51, and 0.43) and in Arsenal® (Γ_1 = 0.18).

What these results imply is that no doubt the presence of unique and reproducible marks is necessary for the correct operation of the systems, in some instances the low effectiveness can be something not intrinsic to the firearm, as it was well correlated in one system and not in another, indicating a potential flaw in some of the correlation algorithms or in the image acquisition.

In this sense, the analysis that was made on the types of correlators to be analyzed and on the number of TFBs to register is relevant. For Evofinder® the correlation by Secondary was on average 0.33(±0.13) higher than the correlation by Groove, while checking these two result lists increases the effectiveness of the system by 0.04(±0.04). In IBIS®, the analysis of all correlators increases effectiveness by 0.06(±0.02), but, as there are 6 (six) lists to check, if only the two best correlators are chosen to be verified, it can mean a significant time saving, for only 0.02(±0.01) effectiveness decrement. Regarding the number of test-fired bullets, an average increase of 0.10(±0.03) was obtained on the effectiveness of systems operating with 2 (two) test-fired bullets compared to the use of only 1 (one) test-fired, demonstrating the validity of entering at least two test-fired of each type of ammunition used for firearm registration.

7.1.2 Parameters of influence with cartridge cases

As occurred with bullets, the data obtained on the three calibers and two systems, revealed that the database growing is less critical for systems' effectiveness than previously thought. Compared to bullet results, the decaying of effectiveness as a function of database size was significantly lower with cartridge cases. For instance, a linear decaying was also obtained for .38SPL cartridge cases as a function of the database, but with moderate slopes compared to bullet results, such that 0.5 effectiveness would be reached by Evofinder® in a database of 7027 samples, and by IBIS® with 9037 samples. In .40S&W caliber, the data repeated the exponential decay, with initial effectiveness for Evofinder® and IBIS® equal to 0.96 and minimum limits in 0.91 and 0.92. On the other hand, the decaying observed with 9x19mm cartridge cases was characterized by an inverse polynomial, and the decreasing was in the order of 0.01. The conclusion was that the introduction of 9x19mm cartridge case noises, ranging from 636 to 2335 samples, was insufficient to measure the impact of the database growth on the effectiveness of the solutions.

The generation of marks on the cartridge case during the firing of the ammunition results from plastic deformations suffered by it. That is, it receives permanent deformations when violently strikes the harder surfaces of the breech face, combustion chamber, firing pin, extractor, and ejector. Therefore, a variation in these marks is expected depending on the discharge pressure and on cartridge case material composition. In the assessment of the ammunition components properties, was observed a strong relationship between the velocity of the fired bullet and the propellant and bullet mass ratio (refer to Figure 113, Figure 114, and Figure 115). The variations observed could be explained considering the amount and composition of the propellant, the type and length of the barrel, and drag to which the bullet is subjected, whether aerodynamic, generated by the ar compressing in front of its tip, or friction resulted from the contact with the barrel bore. This result was relevant because it means that the influence of all these variables on the possibilities of correct identification of the cartridge case can be indirectly evaluated by analyzing the energy of discharge, obtained by measuring the bullet velocities, and assessing the influence of the kinetic energy on systems' effectiveness.

The maximum kinetic energy variation observed in the caliber 9x19mm, .38SPL, and .40S&W were 71.79J, 139.26J, and 60.66J. The division of the matches into two distributions, considering the energy difference between the questioned and test-fired cartridge case, allowed investigating the influence of energy of discharge on breech face and firing pin correlations. ANOVAs revealed a reliable influence of energy of discharge on the effectiveness by breech face and no evidence against the null hypothesis by firing pin. However, for Evofinder® breech face correlations this influence indeed numerically negligible, resulting in low -0.006(±0.03) effectiveness, intermediate decrement in Arsenal® [-0.04(±0.0008)], and more meaningful in IBIS® [-0.09(±0.04)]. On the other hand, for firing pin, it was observed that numerically the influence of energy of discharge on the mean effectiveness was actually low in Arsenal® and Evofinder®, respectively +0.01(±0.04) and -0.009(±0.03), agreeing with ANOVA results, but not negligible in IBIS®, where a higher difference in energy of discharge affecting the mean effectiveness by firing pin in -0.12(±0.08).

Compared to the energy of discharge, the impact of material composition on effectiveness was much higher, with absolute variations on the effectiveness of Arsenal®, Evofinder®, and IBIS®, ranging by breech face respectively from 0.01 to 0.13, 0.01 to 0.33, and 0.02 to 0.34, and by firing pin from 0.00 to 0.24, 0.01 to 0.33, and 0.01 to 0.37.

Such as in the bullet analysis, it was possible to verify the effectiveness by firearm manufacturer, been observed some firearm manufacturers with high effectiveness in one system, and poor in another. For instance, with pistols, the Evofinder® system showed effectiveness above 0.90 in several firearms manufacturers, both by breech face as by firing pin, demonstrating that lower effectiveness in other systems with de same firearm manufacturers is due to deficiencies in their correlation algorithms or image acquisition, and not the absence of marks in certain firearms. Compared to the effectiveness of the Evofinder® by breech face, the Arsenal® system showed an average of -0.60(±0.17) lower effectiveness, and IBIS® on average -0.20(±0.15) lower effectiveness. For the firing pin marks, in comparison with the Evofinder®, Arsenal's effectiveness was on average very similar, with a mean difference for more in 0.02(±0.23), and the effectiveness of the IBIS® system on average -0.21(±0.16) lower.

One way to further investigate factors influencing the effectiveness of cartridge cases was to assess the geometric features of the marks imparted into the fired cases, having been evaluated firing pin mark' center and depth, presence of anvil mark, and the orientation of the breech face marks. These variations were also assessed aiming to find an explanation for the differences in performance observed between systems by firearm manufacturer .

In terms of centralization of the firing pin marks, analysis of the acquired images revealed that they vary intra-firearm, that is, the central impact point of the firing pin, can vary from one shot to another in the same firearm. The measure of the position of the center point of the firing pin mark revealed that the distance to the center point of the primer cup is normally distributed, with medians and standard deviations of 0.14(±0.12), 0.17(±0.10), and 0.12(±0.07), for 9x19mm, .38SPL, and .40S&W calibers. By calculating for each match the vectorial difference of firing pin mark centralization, and using the median of each caliber as split point, two distributions of matches were generated to investigate the possible impact of this variable. No statistically meaningful effectiveness difference in these two match distributions was observed, and therefore the systems seem not sensitive to this variable.

The same approach was employed to test other geometric features on the cartridge case marks: obtain the distribution of the measures between the questioned and the test-fired cartridge cases, use a parameter (median or scale parameter) to divide the distribution, and computing the effectiveness for each distribution.

For the firing pin mark depth, the distributions obtained were best represented by Lorentz distributions (refer to Figure 137, Figure 138, and Figure 139), characterized by the parameters x_0 and γ, which features the values 1.00 and 0.08, 1.10 and 0.25, 1.0, and 0.11, in calibers 9x19mm, .38SPL, and .40S&W. In each caliber per system with high effectiveness, the results supported the hypothesis that when the difference in relative firing pin mark depth was greater than twice the parameter γ, the effectiveness was significantly lower, being reduced on average by -0.13 and -0.15 in Evofinder® and IBIS®. This hypothesis was not supported by the analysis of variance, in calibers by systems with poor effectiveness, which indicated that other factors may be decreasing this effectiveness and therefore masking the influence of the firing pin mark depth.

Regarding the anvil mark, no mark was observed in the 9x19mm or .40S&W cartridge cases, however, in 103 of the 288 .38SPL cartridge cases was observed this specific mark. The effectiveness of systems for the absence of anvil mark in the two cartridge cases compared in each match (Γ_1: Arsenal® - 0.47, Evofinder® - 0.49, IBIS® - 0.62) were significantly higher than the mean effectiveness in the other 3 (three) conditions, which involved the presence of anvil mark in 1 (one) or 2 (two) cartridge cases compared (Γ_1: Arsenal® - 0.31, Evofinder® - 0.42, IBIS® - 0.47). That is, the presence of the anvil mark negatively impacted the systems' results.

The fourth and last geometric feature investigated on the marks of cartridge cases was the orientation angle of the breech face mark in the acquired images. The distribution of angles was also best represented by Lorentz distributions (refer to Figure 142 to Figure 147). The parameter γ was employed to split the difference of the breech face orientation angle obtained between the compared cartridge cases of each match, and only in the 9x19mm Evofinder® results was observed a meaningful effectiveness difference. As this was a result specific to a system and caliber, there is no evidence in favor of the difference of the breech face orientation angle being a general influencing factor on the effectiveness of automated cartridge case correlations.

Additionally to the ammunition component properties and geometric features, some assessment was carried out regarding the systems' operation. In terms of correlation result lists to be checked, in the Arsenal® and Evofinder® systems, the combination of results by Breech Face and by Firing pin is recommended because both correlation lists are available for cartridge case comparisons. In IBIS, analyses of the BF3D and FP3D results lead to effectiveness increments of 0.08, 0.16, 0.12 in the three calibers, as compared to the effectiveness of just one correlator, the best one. On the other hand, checking all correlators is too much more time consuming for only 0.02(±0.01) effectiveness gain. Regarding the number of test-fired, an average increase of 0.09(±0.05) was obtained on the effectiveness of systems operating with 2 (two) test-fires compared to the use of only 1 (one), demonstrating the validity of registering at least two test-fires of each type of ammunition used for registration firearms on each caliber.

7.1.3 Analyses of the correlation scores

One of the desired devolpement of these technologies is to allow a more objective ballistic comparison decision process that includes a estimated error rate of the decision. To the test the feasibily of using the correlation scores for such ambitious goal, the match and non-match distribution of each caliber/system/correlator was analysed. With bullets the scores allow the establishment of a minimum false negative rate (FNR) and a minimum false match rate (FMR), which varied between 2% and 7% and between 0.04% and 0.10%.

In the Arsenal® Candidate List correlator, only 9%, 6%, and 5% of the non-match for 9x19mm, .38SPL, and .40S&W bullets scored with minimum FNR. In the Evofinder®, 11%, 1% and, 3%, of the non-match Groove scores, and 9%, 10%, and 7% of the non-match Secondary scores, featured a minimum FNR. In IBIS®, 14%, 7%, and 4% for L3DMAX, and 10%, 0%, and 3% for L3DMPH score with minimum FNR.

As seen, although the minimum FNR is not negligible, between 2% and 7%, a very small portion of non-match scores can objectively be used, with this error rate, to determine a non-match. This demonstrates that the non-match scores of all systems and calibers are not a good predictor for a non-match with bullets, meaning an exclusion, which is a conclusion that two bullets came from different firearms.

On the other hand, in the Arsenal®, the Candidate list presented minimum FMR in 0%, 49%, and 23% of the match scores for 9x19mm, .38SPL, and .40S&W bullets. In the Evofinder®, 45%, 25%, and 21% of Groove scores, and 56%, 42%, and 63% of Secondary scores, fall within the minimum FMR. Finally in the IBIS®, the minimum FMR was met in 51%, 43%, and 44% of the L3DMAX scores and in 62%, 63%, and 50% of the L3DMPH scores.

Comparing to the FNR analysis, there is no doubt that a larger portion of the match scores fall within the minimum FMR, being an indication of a better chance to use the match score for an objective identification, which is the conclusion that the two bullets came from the same firearm.

However the results are still considered timid for such an ambitious goal, and an objective differentiation between match and non-match in all systems and correlators seems premature. In other words, the analysis of any isolated bullet correlator score is not recommendade for an objective identification or exclusion.

For cartridge cases the minimum false match rate (FMR) and a minimum false negative rate (FNR), varied between 0.04% and 0.08%, and between 1.1% and 2.2%. The better results in theses analysis was obtained with Evofinder® scores. For 9x19mm and .40S&W cartridge cases, 96% and 75% of the breech match score, and 77% and 57% of the firing pin match scores, scored with minimum FMR. Additionally, in the .40S&W caliber, 87% and 57% of the breech face and firing pin non-match scores featured minimum FNR.

Estimates of error rates in cartridge cases were much better than obtained with bullets. In this sense, it becomes more plausible to establish objective protocols when results such as Evofinder® in the .40S&W caliber are available. Nevertheless, small FNR are needed, which is dependant on studies with more known matches, and algorithms that score a higher part of non-matches within the FNR. Addicionally, more matches within minimum FMR, would allow a more reliable objective identification process and safer exclusion decisions.

7.2 Future Work

As could be seen in this research firearms and ammunition can vary in many properties and features, and therefore is a challenge to any research regarding firearm identification to include a representative sample of this variability. Assuming this limitation the first natural step to more accurately assess the conclusions of this research is to include more firearms. The calibers and ammunition types included were considered as representative of what is commonly related to crimes in Brazil, but, although it was included many firearm manufacturers, there is no equality in the number of the firearm per brand. Therefore to more properly weigh the conclusions, and to discard the possibility that some results are related to a specific firearm, it is suggested replication of the study, expanding the calibers and the firearm manufacturers assessed, with the caveat to include an equivalent number of firearms on each brand or caliber.

For sure this expansion could bring more difficult to control some parameters, and the suggestion is that some results more strong proved on this research should be used as filters for this research expansion, for instance, avoiding firearms that had poor effectiveness in all systems, or next time avoiding comparison of ammunition components with a low likelihood of correlation as the ones that featured much difference in hardness. The expansion of the research should focus on other properties not addressed on this research, as the hardness of cartridge cases, the material and composition of the primer cup, the microscopic structure of the barrel bore internal surface, and the difference in conventional rifling process.

Another limitation of the study was the absence of damage bullets. The inclusion of damage bullets would be useful particularly in the investigation regarding the way correlations are performed and results made available, including the correlators to be examined, the quantity of control bullets and the analyses of the correlation scores.

Some influence factors were investigated obtaining the distribution of the measures between the questioned and the test-fired cartridge cases, using a parameter (median or scale parameter) to divide the distribution, and computing the effectiveness for each slice of the distribution. So the conclusion of influence or not influence is related to how the distribution was split. Other criteria of division should be tested. For instance, regarding the energy of discharged it was concluded for a very small influence in the effectiveness for half of the maximum difference in bullet kinetic energy of each caliber. An analysis of many other differences in kinetic energy could reveal a point beyond which the difference in energy becomes more meaningful to the effectiveness, or more strongly support the conclusion of this thesis on this particular matter.

The expansion also could be applied for expanding the understanding regarding the geometric features of the cartridge case marks. For instance orientation angle of the breech mark and the center point of the firing pin mark were found not significantly influential. But different distributions of these features could reveal the limits of this no influence.

In terms of differences in systems performance regarding firearm manufacturers, and considering especially the poor results in one system while higher in another, an assessment of the images, looking for clues on the reasons for the difference observed should be conducted especially by those with availability of the respective algorithm. The same approach should be conducted to investigate why some results were particularly poor regarding some variables in one system.

The effectiveness as a function of the database size should be further investigated. In the caliber 38SPL, more noise should be added for assessment if the exponential decay pattern appears. The decaying in the 9x19mm cartridge case also needs larger data to properly found the limits in which the database size on this caliber starts to erode the results. Even regarding results that featured the desire exponential decay, more noise could be useful to verify if the predications of minimum effectiveness are confirmed.

Finally, the use of scores in searching for a more objective decision process is very promising, especially considering some studies mentioned in the thesis. The verification of the score combinations that would diminish the error rates for identification or exclusion, increase the percentage of matches or non-matches scores within the minimum error rates, or lead to larger gaps between known match or non-matches scores and the respective limit for an objective decision, is suggested as a further study on this subject.

REFERENCE LIST

ABOELKHAIR, M.S.; YAKOUT, H. Effect of Bullet Shape on the Power of Fire in Personal Defense Hand Held Weapons. **Studies in System Science**, 1(1): 1-16, 2013.

ADDINALL, K.; ZENG, W.; BILL, P.; WILCOCK, P.T; BLUNT, L. The effect of primer cup material on ballistic toolmark evidence. **Forensic Science International,** 298: 149–156, 2019.

AKÇAI, M. Internal and Transitional Ballistic Solution for Spherical and Perforeted Propellants and Verification with Experimental Results. **Journal of Thermal Science and Technology,** 37(1): 35-44, 2017

ANSI/SAAMI Z299.3. **Voluntary Industry Performance Standards for Pressure and Velocity of Centerfire Pistol and Revolver Ammunition for the Use of Commercial Manufacturers.** United States of America: Sporting Arms and Ammunition Manufacturers' Institute, Inc, 2015. Available at: https://saami.org/wp-content/uploads/2019/02/ANSI-SAAMI-Z299.3-CFP-and-R-Approved-2015-12-14-Posting-Copy.pdf [Accessed 11/11/2019].

ASME B46.1-2009. **Surface Texture:** Surface Roughness, Waviness, and Lay. New York: The American Society of Mechanical Engineers, 2010.

BACHRACH, B. **A statistical validation of the individuality of guns using 3D images of bullets:** final report, in: Tech. Rep. NCJ 213674. Rockville, MD: National Criminal Justice Reference Service, Mar 2006.

BANNO, A.; MASUDA, T.; IKEUCHI, K. Three dimensional visualization and comparison of impressions on fired bullets. **Forensic Science International**, 140: 233-240, 2004.

BECK, Wolfgang; EVERS, Jürgen; GÖBEL, Michael; OEHLINGER, Gilbert; KLAPÖTKE, Thomas M. The Crystal and Molecular Structure of Mercury Fulminate. **Journal of Inorganic and General Chemistry**, 633: 1417-1422, 2007.

BELL, Suzanne; MORRIS, Keith. **An Introduction to Microscopy.** Boca Raton, Florida: CRC Press, 2010.

BIASOTTI, A.A. A statistical study of the individual characteristics of fired bullets. **Journal of Forensic Sciences**, 4(1): 34–50, 1959.

BIASOTTI, A. A.; MURDOCK J. Firearm and Toolmark Identification. **Modern Scientific Evidence: The Law and Science of Expert Testimony**, 2(23): 140, 1997. (unchanged on pp. 516 of 2002, 2nd Edition).

BIWA, S.; STORÅKERS, B. An analysis of fully plastic Brinell indentation. **Journal of the Mechanics and Physics of Solids,** 43: 1303-1333, 1995.

BLATEYRON, François. Ch 5 Chromatic Confocal Microscopy. In: Leach, Richard (ed.). **Optical Measurement of Surface Topography.** Berlin: Springer, 2011. pp. 71–106.

BOLTON-KING, Rachel. **Classification of Barrel Rifling Transitons for the Forensic Identification of Firearms.** 2012. Doctoral Thesis (Doctor of Philosophy) – Nottingham Trent University, United Kindom, 2012.

BOLTON-KING, Rachel S.; EVANS, J Paul O.; SMITH, Clifton L.; PAINTER, Jonathon D.; ALLSOP, Derek F.; CRANTON, Wayne M. What are the Prospects of 3D Profiling Systems Applied to Firearms and Toolmark Identification? **AFTE Journal**, 42(1): 23-33, 2010.

BONFANTI, M. S.; DE KINDER, J. The influence of manufacturing processes on the identification of bullets and cartridge cases—a review of the literature. **Science & Justice,** 39(1): 3-10, 1999a.

BONFANTI, M. S.; DE KINDER, J. The influence of the use of firearms on their characteristic marks. **AFTE Journal,** 31(3): 318–323, 1999b.

BOX, George E. P.; HUNTER, J. Stuart; HUNTER, William G. **Statistics for Experimenters:** Design, Innovation, and Discovery. New Jersey: John Wiley & Sons, 2005.

B-GL-306-006/FP-001. **Field Artillery**, Volume 6, Ballistics and Ammunition. Canada: 1992.

CALLISTER, William D Jr. **Materials Science and Engineering:** An Introduction. 7th ed. United States of America: John Wiley & Sons, 2007.

CARLUCCI, Donald E.; JACOBSON, Sidney S. **BALLISTICS:** Theory and Design of Guns and Ammunition. New York: CRC Press, 2007.

COMPANHIA BRASILEIRA DE CARTUCHOS. ***Informativo Técnico nº 32: Munições e Cartuchos para Uso Policial*** [Title in English: Technical Note nº 32: Ammunition and Cartridges for Police Use]. Brasil: CBC, 2018.

CHU, W.; THOMPSON, R. M.; SONG, J.; VORBURGER, T. V. Automatic identification of bullet signatures based on consecutive matching striae (CMS) criteria. **Forensic Science International**, 231: 137-141, 2013.

COMINATO, L.; VALLE, F.; PIERINI, G.; BONINI, P.; BISCARINI, F.; D'ELIA, M. Flattening mountains: Micro-fabrication of planar replicas for bullet lateral striae analysis. **Forensic Science International**, 247: 97-104, 2015.

CORK, Daniel L.; ROLPH, John E.; MEIERAN, Eugene S.; PETRIE, Carol V. **Ballistic Imaging.** Washington, D.C: The National Academies Press, 2008.

CRAWFORD, Vincenzo D. **Class, Individual, and Sub-Class Characteristics of Firearm & their Constituents.** Jamaica: University of Technology, 2010. Available at https://www.academia.edu/12309195/Class_Characteristics_Individual_Characteristics_and_Sub-Class_Characteristics_Of_Firearms_and_their_Constituents, (Accessed 26/12/2019).

CUNICO, Edimar. **Perícia em locais de morte violenta:** criminalística e medicina legal. Curitiba, Paraná: Author edition, 2010. ISBN 978-85-9105-540-3.

DANZL, Reinhard; HELMLI, Franz; SCHERER, Stefan. Focus Variation – a Robust Technology for High Resolution Optical 3D Surface Metrology. **Journal of Mechanical Engineering**, 57(3): 245-256, 2011.

DE KINDER. Ballistic fingerprinting databases. **Science & Justice**, 42: 197-2003, 2002.

DE KINDER, Jan; TULLENERS, Frederic; THIEBAUT, Hugues. Reference ballistic imaging database performance. **Forensic Science International**, 40: 207-2015, 2004.

DE CEUSTER, J.; HERMSEN, R.; MASTAGLIO, M.; NENNSTIEL, R. A discussion on the usefulness of a shared European ballistic image database. **Science & Justice**, 52(4): 237-242, 2012.

DE CEUSTER, Jan; DUJARDIN, Sylvain. The reference ballistic imaging database revisited. **Forensic Science International**, 248: 82-87, 2015.

DE GROOT, P. J. The Meaning and Measure of Vertical Resolution in Optical Surface Topography Measurement. **Applied Sciences**, 7: 54-59, 2017.

DI MAIO, Vincent J. M. **Gunshot Wounds Practical Aspects of Firearms, Ballistics, and Forensic Techniques**. Second Edition. New York: CRC Press LLC, 1999.

DONG, F.; ZHAO, Y.; LUO, Y.; ZHANG, W.; LI, W. Objective evaluation of similarity scores derived by Evofinder® system for marks on bullets fired from Chinese Norinco QSZ-92 pistols. **Forensic Sciences Research**, 2019. DOI:10.1080/20961790.2019.1642984.

EUROPEAN CHEMICALS AGENGY. **Support Document for Identification of Lead Styphnate as a Substance of Very High Concern Because of Its Cmr Properties.** ECHA, 2011. Available at https://web.archive.org/web/20141022103059/http://echa.europa.eu/documents/10162/13638/svhc_supdoc_lead_styphnate_en.pdf, (Accessed 22/11/2019).

*FÓRUM BRASILEIRO DE SEGURANÇA PÚBLICA. **Anuário Brasileiro de Segurança Pública 2017*** [Title in English: Brazilian Public Security Yearbook]. São Paulo: FBSP, 2017.

FTIR-ATR. **FT-IR Spectroscopy Attenuated Total Reflectance (ATR).** 2019. Available at https://web.archive.org/web/20070216065646/http://las.perkinelmer.com/content/TechnicalInfo/TCH_FTIRATR.pdf (Accessed 22/11/2019).

GAGLIARDI, Pete. **The 13 critical tasks: an inside-out approach to solving more gun crime.** Second Edition. Quebec, Canada: Forensic Technology WAI Inc, 2014.

GHANI, Nor Azura MD; LIONG, Choong-Yeun; JEMAIN, Abdul Aziz. Analysis of geometric moments as features for firearm identification. **Forensic Science International**, 198: 143–149, 2010.

GERADTS, Zeno J.; BIJHOLD, Jurrien; HERMSEN, Rob; MURTAGH, Fionn. Image matching algorithms for breech face marks and firing pins in a database of spent cartridge cases of firearms. **Forensic Science International**, 119: 97-106, 2001.

GERARD, J.; CROOKES, R.; ELLIOTT, S.; HELLENBACH, M.; STAMOS, A.; POOLE, H.; BOWEN, E. The sharing of ballistics data across Europe and neighbouring territories. **Science & Justice**, 57(5): 384-393, 2017.

GERULES, G.; BHATIA, S. K.; JACKSON, D. E. A survey of image processing techniques and statistics for ballistic specimens in forensic science. **Science & Justice**, 53: 236-250, 2013.

GOLDSTEIN, J. **Scanning electron microscopy and x-ray microanalysis.** New York: Kluwer Adacemic/Plenum Pulbishers, 2003.

GRZYBOWSKI, Richard; MILLER, Jerry; MORAN, Bruce; MURDOCK, John; NICHOLS, Ron; THOMPSON, Robert. Firearm/Toolmark Identification: Passing the Reliability Test under Federal and State Evidentiary Standards. **AFTE Journal**, 35: 209-241, 2003.

HALL, A.L. The missile and the weapon. **AFTE Journal**, 12(4): 85, 1980 [Reprinted from The Buffalo Medical Journal, June 1900].

HAMBY, J. E.; BRUNDAGE, D.; THORPE, J. The identification of bullets fired from 10 consecutively rifled 9mm Ruger pistol barrels: A research project involving 507 participants from 20 countries. **AFTE Journal**, 41: 99-110, 2009.

HAMBY, J. E.; NORRIS, S.; PETRACO, N. D. K. Evaluation of GLOCK 9mm Firing Pin Aperture Shear Mark Individuality Based on 1,632 Different Pistols by Traditional Pattern Matching and IBIS Pattern Recognition. **Journal of Forensic Sciences**, 61(1): 170-176, 2016.

HAMBY, J.E. and THORPE, J. The history of Firearm and Toolmark identification. **AFTE Journal**, 30th Anniversary Issue, 31(3): 1999. Reprinted and available at http://www.firearmsid.com/A_historyoffirearmsID.htm (Accessed 29/02/2020)

HEARD, Brian J. **Handbook of firearms and ballistics: examining and interpreting forensic evidence**. Segunda edição. Chichester: John Wiley & Sons, 2008.

HELMLI, Franz. Ch 7 Focus Variation Instruments. In: Leach, Richard (ed.). **Optical Measurement of Surface Topography.** Berlin: Springer, 2011. pp. 131–167.

HILL, R.; STORAKERS, B.; ZDUNEK, A. A Theoretical Study of the Brinell Hardness Test. **Proceedings of the Royal Society of London.** Mathematical and Physical Sciences, Series A, 423: 301-330, 1989.

IKEUCHI, K. Determining Surface Orientations of Specular Surfaces by Using the Photometric Stereo Method. **IEEE Transactions on Pattern Analysis and Machine Intelligence**, PAMI-3(6): 661-669, 1981, doi: 10.1109/TPAMI.1981.4767167.

INSTITUTO DE PESQUISA ECONÔMICA APLICADA; *FÓRUM BRASILEIRO DE SEGURANÇA PÚBLICA* (Org.). **Atlas da violência 2019** [Title in English: Atlas of Violence 2019]. Brasília; Rio de Janeiro; São Paulo: IPEA; FBSP, 2019.

ISO FDIS 25178-606. Geometrical Product Specification (GPS) – Surface Texture: Areal: 606. Nominal Characteristics of Non-Contact (Focus Variation) instruments**. International Organization for Standardization**, Geneva, 2015.

JENZEN-JONES, N.R.; SCHROEDER, Matt. **An Introductory Guide to the Identification of Small Arms, Light Weapons, and Associated Ammunition.** Geneva: Small Arms Survey, Graduate Institute of International and Development Studies, 2018. 352p.

JOHNSON, M. K.; COLE, F.; RAJ, A.; ADELSON, E. H. Microgeometry capture using an elastomeric sensor. **ACM Transactions on Graphics**, 30: 1–8, 2011.

JOST, Marcelo; SANTOS, Lehi Sudy dos; SATO, Eduardo Makoto. **Balística**. Brasília: Academia Nacional de Polícia, 2014.

KAPŁONEK, Wojciech; NADOLNY, Krzysztof; KRÓLCZYK, Grzegorz M. The Use of Focus-Variation Microscopy for the Assessment of Active Surfaces of a New Generation of Coated Abrasive Tools. **Measurement Science Review**, 16(2): 42-53, 2016.

KOPEL, David B.; BURNETT, H. Sterling. **Ballistic Imaging: Not Ready for Prime Time**. The National Center for Policy Analysis: POLICY BACKGROUNDER nº 160, Apr 2003.

LAW, E. F.; MORRIS, K. B., JELSEMA, C. M. Determining the number of test fires needed to represent the variability present within 9 mm Luger firearms. **Forensic Science International, 276: 126-133, 2017.**

LEACH, Richard. Ch 2 Some Common Terms and Definitions. In: Leach, Richard (ed.). **Optical Measurement of Surface Topography.** Berlin: Springer, 2011. pp. 15–22.

LELOG˘LU, U.M.; DEVIREN, M.; SERMEN, C. ; BALCI, K. Mermi c¸ekirdekleri u¨zerindeki set izlerinin otomatik es¸lenmesi, (Title in English: Automatic matching of land marks on bullets). **Sinyal I˙s¸leme ve Uygulamaları Kurultayı**. Antalya, Turkey: 2000.

LESHNER, Alan I.; ALTEVOGT, Bruce M.; LEE, Arlene F.; MCCOY, Margaret A.; KELLEY, Patrick W. **Priorities for Research to Reduce the Threat of Firearm-Related Violence.** Washington, D.C: The National Academies Press, 2013.

LEYI, G.; WEI, Z.; JING, Z.; SONGLING, H. Mechanics analysis and simulation of material Brinell hardness measurement. **Measurement**, 44: 2129-2137, 2011.

LI, Dongguang. **Ballistics Image Processing and Analysis for Firearm Identification.** Image Processing, Yung-Sheng Chen (Ed.), pp. 141-174, 2009. ISBN: 978-953-307-026-1.

LIAO, M.; HUANG, X.; YANG, R. Interreflections removal for photometric stereo by using spectrum-dependent albedo. **IEEE Conference on Computer Vision and Pattern Recognition (CVPR),** pp. 689–696, 2011.

MADSEN, K.; NIELSEN, H. B.; TINGLEFF, O. **Methods for Non-Linear Least Squares Problems** (2nd Edition). University of Denmark: Informatics and Mathematical Modelling Technical, April 2004.

MAGTECH Ammunition. **HAND GUN AMMUNITION**, 2016. Available at http://www.magtechammunition.com/products/handgun-ammunition/ (Accessed 14/05/2016).

MONSON, Keith L. Computer Correlation of Cartridge Cases Using Breech Face Marks. **Records of AFTE Annual training seminar**, Illinois, 1988.

MORAN, B. A Report on the AFTE Theory of Identification and Range of Conclusions for Toolmark Identification and Resulting Approaches to Casework. **AFTE Journal**, 34(2): 117-235, 2002.

NATIONAL RESEARCH COUNCIL. **Strengthening Forensic Science in the United States:** A Path Forward. Washington D.C: The National Academy Press, 2009.

NBR NM ISO 6506-1. ***Materiais metálicos – Ensaio de Dureza Brinell Parte 1: Método de ensaio.*** Rio de Janeiro: *Associação Brasileira de Normas Técnicas*, 2010.

NICHOLS, Ronald G. Consecutive matching striations (CMS): Its definition, study and application in the discipline of firearms and tool mark identification. **AFTE Journal**, 35(3): 298–306, 2003.

NICHOLS, Ronald G. Defending the Scientific Foundations of the Firearms and Tool Mark Identification Discipline: Responding to Recent Challenges. **Journal of Forensic Sciences**, 52(3): 586-594, 2007.

OLIVEIRA JÚNIOR, M. L. L. de. **Estudo da Confiabilidade de um Sistema de Identificação Balística para Estojos e Projéteis de Munições Calibre .38.** 2015. Graduate project (Mechanical Science) – Faculty of Technology, University of Brasilia, Brazil, 2015.

PAPPILON Systems. **ARSENAL Automated Ballistic Identification System by Surface Markings on Fired Bullets and Cartridge Cases:** User Guide. Russia: PS, April 2014.

RABELLO, Eraldo. **Balística Forense.** 3ª edition. Porto Alegre: Sagra-DC Luzzato, 1995.

RAHM, Joachim. Evaluation of an electronic comparison system and implementation of a quantitative effectiveness criterion. **Forensic Science International**, 214: 173-177, 2012.

RIVA, F.; CHAMPOD, C. Automatic Comparison and Evaluation of Impressions Left by a Firearm on Fired Cartridge Cases. **Journal of Forensic Sciences**, 59(3): 1-11, 2014.

ROBERGE, Danny; BEAUCHAMP, Alain; LÉVESQUE, Serge. Objective Identification of Bullets Based on 3D Pattern Matching and Line Counting Scores. **International Journal of Pattern Recognition and Artificial Intelligence**, 33(11): 2019.

SAKARYA, Ufuk; LELOGLU, Ugur Murat; TUNALI, Erol. Three-dimensional surface reconstruction for cartridge cases using photometric stereo. **Forensic Science International**, 175: 209–217, 2008.

SANTOS, Lehi S. ***Avaliação de Parâmetros que Afetam a Efetividade da Comparação Balística Automatizada*** **(Title in english: Evaluation of Parameters Affecting the**

Effectiveness of Automated Ballistic Comparison). 2016. Dissertation (Master in Mechanical Science) – Faculty of Technology, University of Brasilia, Brazil, 2015.

SANTOS, Lehi. S; MUTERLLE, Palloma. V. Influence of Bullet Material on the Effectiveness of Automated Comparison. **23rd ABCM International Congress of Mechanical Engineering** – COBEM. Rio de Janeiro, 2015.

SANTOS, Lehi. S.; MUTERLLE, Palloma. V. Influence factors regarding the effectiveness of automated ballistic comparison on .38 Special caliber bullets and cartridge cases. **Journal of Forensic Sciences**, 63(6): 1846-1853, 2018.

SARIBEY, A. Y.; HANNAM, A. G..; TARIMCI, C. An Investigation into Whether or Not the Class and Individual Characteristics of Five Turkish Manufactured Pistols Change During Extensive Firing. **Journal of Forensic Sciences**, 54(5): 1068-1072, 2009.

SCANNBI Technology Europe GmbH Company. **Ballistics Identification System EVOFINDER® Client software operation description (V.6.3).** STEGC, 2018.

SCHUTTLEFIELD, Jennifer D.; GRASSIAN, Vicki H. ATR–FTIR Spectroscopy in the Undergraduate Chemistry Laboratory. Part I: Fundamentals and Examples. **Journal of Chemical Education**, 85(2): 279, 2008.

SCHWARTZ, Adina. A Systemic Challenge to the Reliability and Admissibility of Firearms and Toolmark Identification**. The Columbia Science and Technology Law Review**, 6:1-42, 2005.

STEFANOPOULOS, P. K.; FILIPPAKIS, K.; SOUPIOU, O. T.; PAZARAKIOTIS, V. C. Wound ballistics of firearm-related injuries—Part 1: Missile characteristics and mechanisms of soft tissue wounding. **International Journal of Oral and Maxillofacial Surgery**, 43: 1445–1458, 2014.

SCHWOEBLE, A. J.; EXLINE, D. L. **Current methods in forensic gunshot residue analysis**. London: CRC Press, 2000, 171p.

SONG, J.; VORBURGER, T. V.; CHU, W.; YEN, J.; SOONS, J. A.; OTT, D. B.; ZHANG, N. F. Estimating error rates for firearm evidence identications in forensic science. **Forensic Science International**, 284: 15–32, 2018.

THOMAS, J.; LEARY, R. Improving accuracy and effectiveness of forensic ballistics analysis and technology. **Science & Justice**, 50(1): 30, 2010.

THOMPSON, Robert M. **Firearm identification: in the Forensic Science Laboratory.** Virginia, USA: National District Attorneys Association, 2010.

TIEN, Tzu-Li. The indirect measurement of tensile strength for a higher temperature by the new model IGDMC (1, n). **Measurement**, 41(6): 662–675, 2008.

TOCHETTO, Domingos. **Balística Forense: Aspectos técnicos e jurídicos.** Porto Alegre: Sagra Luzzato, 1999.

TULLENERS, F. Technical Evaluation: **Feasibility of a Ballistics Imaging Database for All New Handgun Sales October 2001**. California Department of Justice.

Ultra Electronics Forensic Technology Inc. **IBIS TRAX-HD3D / BRASSTRAX 3.0 *Guia de Treinamento* / BULLETTRAX 3.0 *Guia de Treinamento* / MATCHPOINT 3.0 *Guia de Treinamento*.** Quebec, Canadá: UEFT, 2014.

VALLE, Francesco; BIANCHI, Michele; TORTORELLA, Silvia; PIERINI, Giovanni; BISCARINI, Fabio; D'ELIA, Marcello. Nanotechnology for forensic sciences: Analysis of PDMS replica of the case head of spent cartridges by optical microscopy, SEM and AFM for the ballistic identification of individual characteristic features of firearms. **Forensic Science International**, 222: 288-297, 2012.

VORBURGER, T. V.; SONG, J.; PETRACO, N. Topography measurements and applications in ballistics and tool mark identifications. **Surface Topography**: Metrology and Properties, 4: 1-35, 2016. DOI:10.1088/2051-672X/4/1/013002.

WAISELFISZ, Julio Jacobo. **Mapa da violência 2013: mortes matadas por armas de fogo.** Rio de Janeiro: Cebela/Flacso, 2013.

WAISELFISZ, Julio Jacobo. **Mapa da Violência 2016: Homicídios por armas de fogo no Brasil.** Rio de Janeiro: Flacso-Brasil, 2016.

WARLOW, Tom. **Firearms, The Law, And Forensic Ballistics**. Second Edition. Flórida: CRC Press LLC, 2005.

WERNER, D.; BERTHOD, R.; RHUMORBARBE, D.; GALLUSSER, A. Manufacturing of firearms parts: Relevant sources of information and contribution in a forensic context. **WIREs Forensic Sci.,** e1401, 2020. https://doi.org/10.1002/wfs2.1401.

WELLER, T.; ZHENG, A.; THOMPSON, R.; TULLENERS, F. Confocal Microscopy Analysis of Breech Face Marks on Fired Cartridge Cases from 10 Consecutively Manufactured Pistol Slides. **Journal of Forensic Sciences**, 57(4): 912-917, 2012.

WHEELER, Barbara P.; WILSON, Lori J. **Practical Forensic Microscopy: A Laboratory Manual**. Chichester, England: John Wiley & Sons Ltd, 2008.

WHELEN, Townsend. **Small Arms Design and Ballistics, Volume 2**. Gergetown: Small Arms Technical Publishing Company, 1947.

WILSON, Richard S.; JOPEK, Lukasz; BATES, Christopher D. Sharing Ballistics Data across the European Union. **COMPUTATION TOOLS 2010:** The First International Conference on Computational Logics, Algebras, Programming, Tools, and Benchmarking. Portugal, 2010.

WOODHAM, R. J. Photometric stereo: A reflectance map technique for determining surface orientation from image intensity. **SPIE Proceedings**, 155: 136-143, 1978.

WU, Ying. **Radiometry, BRDF and Photometric Stereo.** Northwestern University. Available at http://users.eecs.northwestern.edu/~yingwu/teaching/EECS432/ /lighting.pdf (Accessed 28/03/2020).

XIE, F.; XIAO, S.; BLUNT, L.; ZENG, W.; JIANG, X. Automated bullet-identification system based on surface topography techniques. **Wear**, 266: 518-522, 2009.

YUESONG Li; SHENG Lin; YAPING Luo; ZHONGLIANG Mi. Performance Evaluation of a Registered Ballistic Database Using the Evofinder® System. **Journal of Forensic Sciences**, 64(5): 1335-1344, 2019.

APPENDIX A: RESULTS OF EDS ANALYSIS

Table 30 – Chemical Analysis of cartridge case by Energy Dispersive X-Ray Spectroscopy (EDS) in Scanning Electron Microscope.

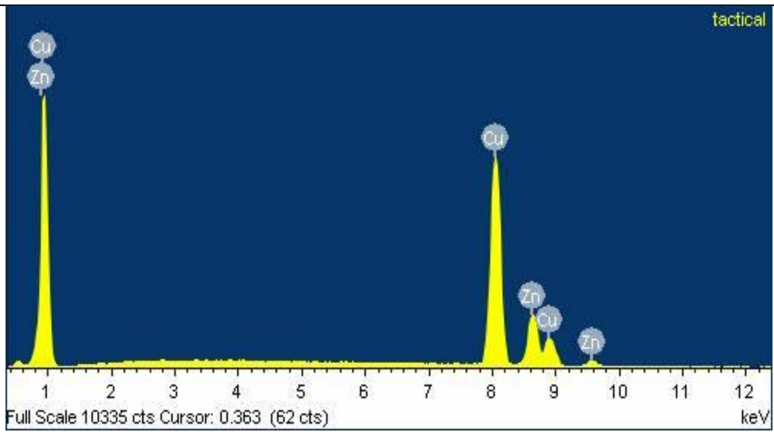
<table>
<tr><td></td><td>
</td></tr>
<tr><td>BRASS</td><td>COPPER (75 wt%) and ZINC (25 wt%)</td></tr>
<tr><td>BRASS</td><td>COPPER (73% wt%) and ZINC (27% wt%)</td></tr>
</table>

Table 31 – Chemical Analysis of primer compounds by Energy Dispersive X-Ray Spectroscopy (EDS) in Scanning Electron Microscope.

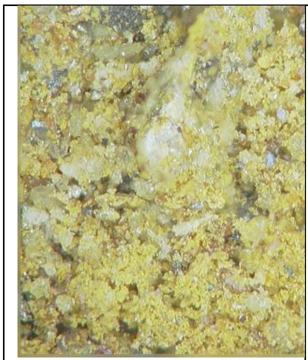
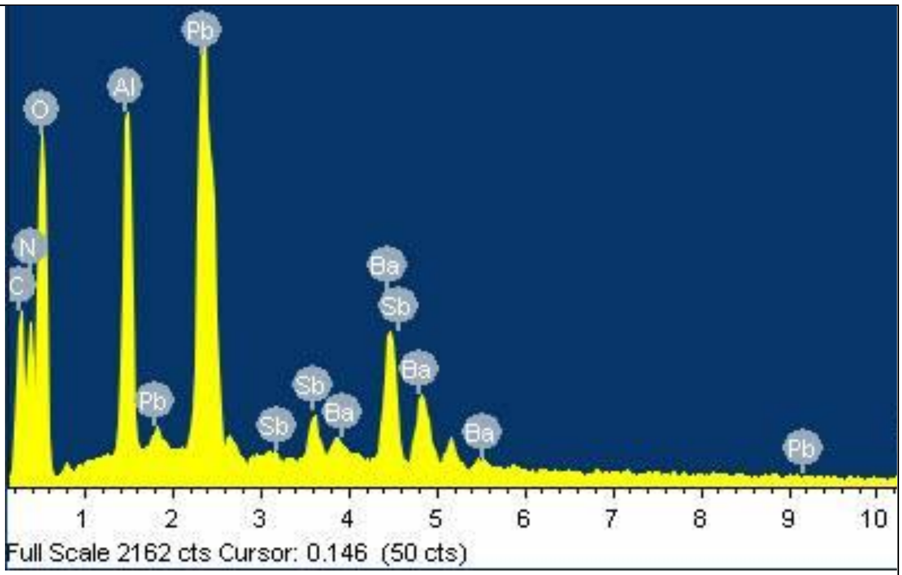
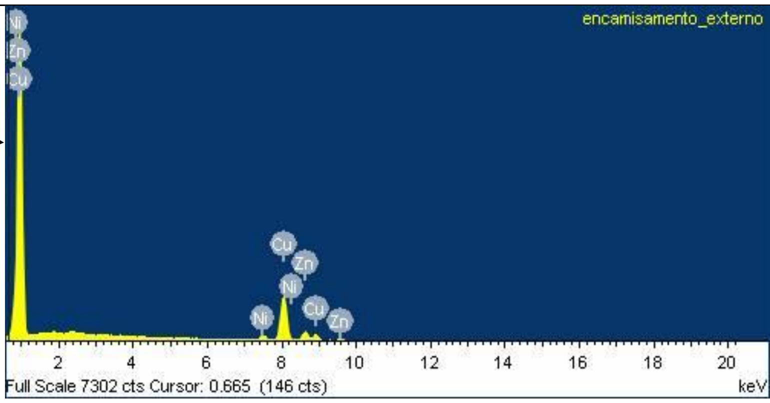
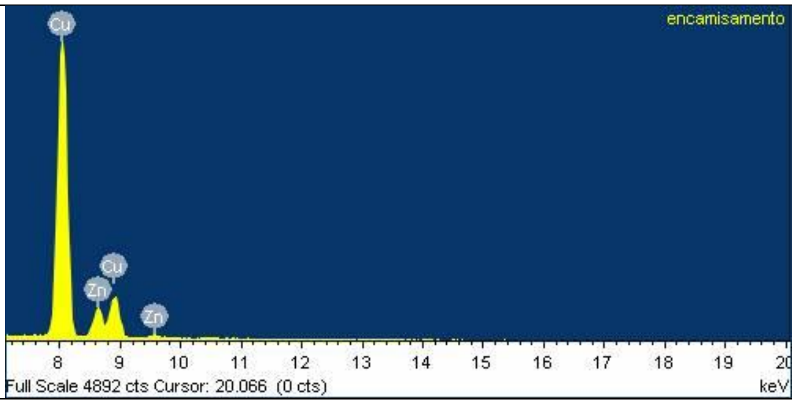
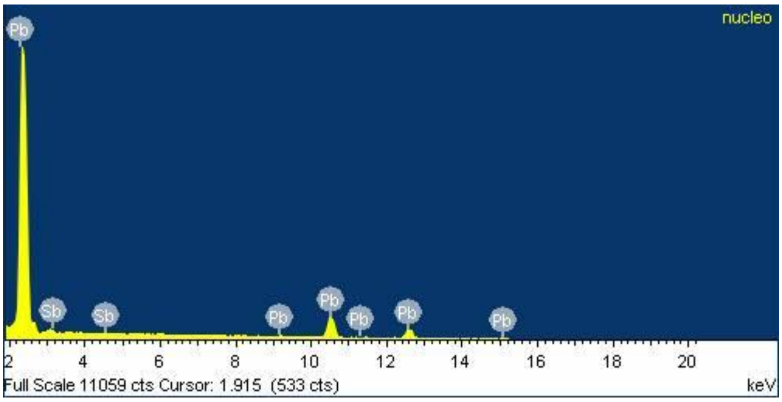
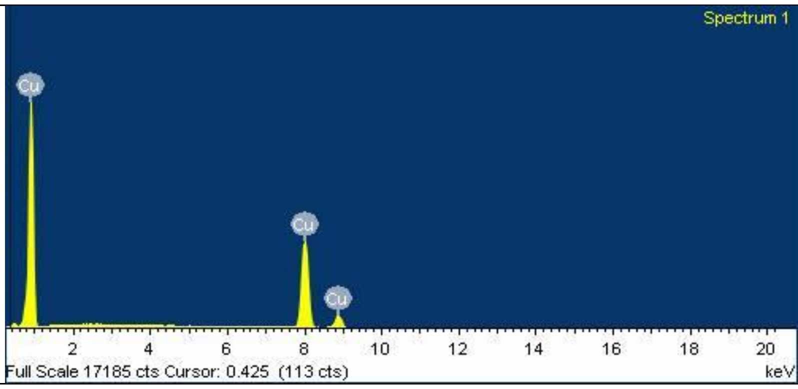
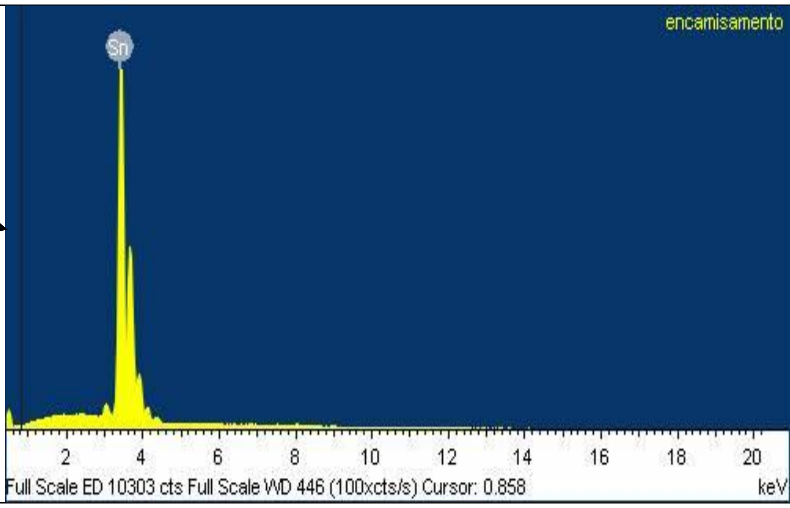
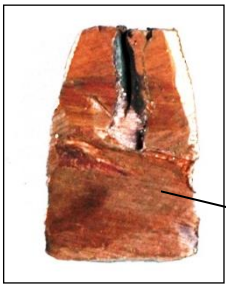
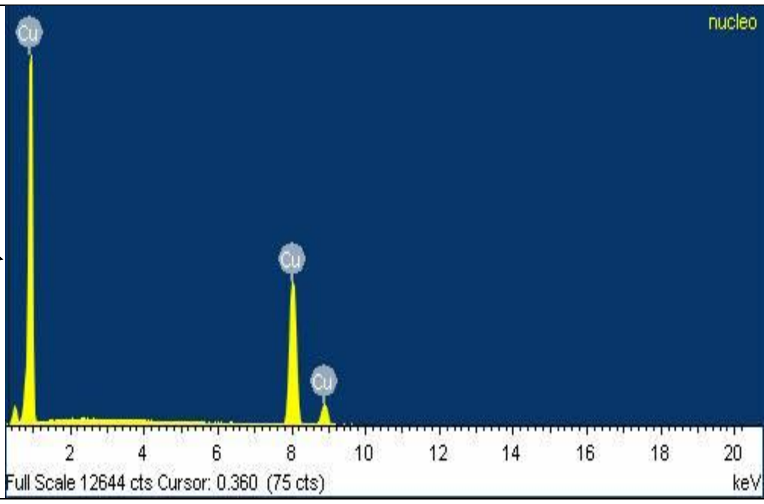
<table>
<tr><td></td><td>
</td></tr>
<tr><td>Primer compound (Gold 9x19mm primer)</td><td>BARIUM (Ba), LEAD (Pb), ANTIMONY (Sb) and ALUMINUM (Al),</td></tr>
</table>

Table 32 – Chemical Analysis of bullets by Energy Dispersive X-Ray Spectroscopy (EDS) in Scanning Electron Microscope.

	
G-JHP (thin layer)	COPPER (77 wt%), ZINC (18 wt%) and NICKEL (5 wt%)
	
G-JHP (jacket)	COPPER (90 wt%) and ZINC (10 wt%)
	
G-JHP (core)	LEAD (99 wt%) and ANTIMONY (1wt%).

	
C-HP (external and internal)	COPPER (>99 wt%)
	
C/T-HP (thin layer)	TIN (>99 wt%)
	
C/T-HP (core)	COPPER (>99 wt%)

APPENDIX B: DETAIL OF FIREARMS EMPLOYED ON THE RESEARCH

Table 33 – Detail of the .38SPL and .357MAG revolvers for this research.

Gun	Type	Brand	Model	Barrel (inch)	Caliber	Serial Number	Rifling	Rifling profile	Firing pin aperture	History
1	Revolver	Taurus	80	4.0	.38SPL	133291	6R	COV[(z)]	Circular	Police academy
2	Revolver	Taurus	80	2.5	.38SPL	466573	6R	COV	Circular	Police academy
3	Revolver	Taurus	80	2.5	.38SPL	466568	6R	COV	Circular	Police academy
4	Revolver	Taurus	82	3.0	.38SPL	409467	6R	COV	Circular	Police academy
5	Revolver	Rossi	97	3.0	.357MAG	F013615	6R	COV	Circular	Police academy
6	Revolver	Rossi	97	3.0	.357MAG	F013616	6R	COV	Circular	Police academy
7	Revolver	Rossi	97	3.0	.357MAG	F013058	6R	COV	Circular	Police academy
8	Revolver	Rossi	97	3.0	.357MAG	F054100	6R	COV	Circular	Police academy
9	Revolver	Rossi	97	3.0	.357MAG	F054120	6R	COV	Circular	Police academy
10	Revolver	Taurus	66	3.0	.357MAG	IE162224	5R	COV	Circular	Police academy
11	Revolver	Taurus	66	3.0	.357MAG	IE162265	5R	COV	Circular	Police

										academy
12	Revolver	Taurus	66	3.0	.357MAG	IE162221	5R	COV	Circular	Police academy
13	Revolver	Taurus	66	3.0	.357MAG	IE162222	5R	COV	Circular	Police academy
14	Revolver	Taurus	80	4.0	.38SPL	2031906	5R	COV	Circular	Police academy
15	Revolver	Taurus	66	3.0	.357MAG	IE162219	5R	COV	Circular	Police academy
16	Revolver	Taurus	66	3.0	.357MAG	IE162267	5R	COV	Circular	Police academy

(z) – COV = conventional rifled barrel

Table 34 – Detail of the 9x19mm pistols for this research.

Gun	Type	Brand	Model	Barrel (inch)	Caliber	Serial Number	Rifling	Rifling profile	Firing pin aperture	History
18	Pistol	Taurus	PT908	3.7	9x19mm	TOA 31285	6R	COV*(aa)*	Circular	Seized
19	Pistol	FN Browning	Hi-Power	4.7	9x19mm	T 345252	6R	COV	Circular	Seized
20	Pistol	Taurus	PT92 AFS	4.8	9x19mm	TNL 30638	6R	COV	Circular	Seized
21	Pistol	Taurus	PT92 AF	4.8	9x19mm	TOG 08513	6R	COV	Circular	Seized
22	Pistol	Taurus	PT92 AFS	4.8	9x19mm	TNL 30637	6R	COV	Circular	Seized
23	Pistol	Taurus	PT92 AF	4.8	9x19mm	TOA 31246	6R	COV	Circular	Seized

24	Pistol	Taurus	PT92 AF	4.8	9x19mm	TOA 31184	6R	COV	Circular	Seized
25	Pistol	Taurus	PT92 AF	4.8	9x19mm	TOA 31098	6R	COV	Circular	Seized
26	Pistol	Taurus	PT917	4.8	9x19mm	TSI 11122	6R	COV	Circular	Seized
27	Pistol	Taurus	PT92 AF	4.8	9x19mm	TVE 04539	6R	COV	Circular	Seized
28	Pistol	Taurus	PT92 AF	4.8	9x19mm	TOA 31238	6R	COV	Circular	Seized
29	Pistol	Taurus	PT908	3.7	9x19mm	TOA 31288	6R	COV	Circular	Seized
30	Pistol	Norinco	NZ75	4.8	9x19mm	303143	6R	COV	Circular	Seized
31	Pistol	Jerico	941F	4.4	9x19mm	151734	6R	POL[(bb)]	Circular	Seized
32	Pistol	Jerico	941F	4.3	9x19mm	151715	6R	POL	Circular	Seized
33	Pistol	Smith and Wesson	59	4.0	9x19mm	A 352177	6R	COV	Circular	Seized
34	Pistol	Glock	G17	4.5	9x19mm	LWZ790	6R	POL	Rectangular	Police Officer
35	Pistol	Glock	G19	4.0	9x19mm	LSP209	6R	POL	Rectangular	Police Officer
36	Pistol	Glock	G17	4.5	9x19mm	HPM175	6R	POL	Rectangular	Police Officer
37	Pistol	Glock	G17	4.5	9x19mm	LWZ405	6R	POL	Rectangular	Police Officer
38	Pistol	Glock	G26	3.4	9x19mm	LXB544	6R	POL	Rectangular	Police Officer
39	Pistol	Glock	G19	4.0	9x19mm	LSP212	6R	POL	Rectangular	Police Officer

40	Pistol	Glock	G19	4.0	9x19mm	LSP776	6R	POL	Rectangular	Police Officer
41	Pistol	Glock	G19	4.0	9x19mm	LSR665	6R	POL	Rectangular	Police Officer
42	Pistol	Glock	G19	4.0	9x19mm	LSP300	6R	POL	Rectangular	Police Officer
43	Pistol	Glock	G19	4.0	9x19mm	LSP256	6R	POL	Rectangular	Police Officer
44	Pistol	Glock	G17	4.5	9x19mm	HPM173	6R	POL	Rectangular	Police Officer
45	Pistol	Glock	G26	3.4	9x19mm	LUG105	6R	POL	Rectangular	Police Officer

(aa) – COV = conventional rifled barrel; *(bb)* – POL = polygonal rifling.

Table 35 – Detail of the .40S&W pistols for this research.

Gun	**Type**	**Brand**	**Model**	**Barrel (inch)**	**Caliber**	**Serial Number**	**Rifling**	**Rifling profile**	**Firing pin aperture**	**History**
01	Pistol	Bersa	Thunder 40	4.0	.40S&W	908860	6R	COV*(cc)*	Circular	Seized
02	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW86219	6R	COV	Circular	Seized
03	Pistol	Taurus	PT24/7 PRO	4.3	.40S&W	SCO19402	6R	COV	Circular	Seized
04	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW87386	6R	COV	Circular	Seized
05	Pistol	Taurus	PT24/7 PRO	4.3	.40S&W	SFZ86923	6R	COV	Circular	Seized
06	Pistol	Taurus	PT100 AF	4.8	.40S&W	SAU89685	6R	COV	Circular	Seized

07	Pistol	Taurus	PT100 AF	4.8	.40S&W	SZI09996	6R	COV	Circular	Seized
08	Pistol	Taurus	PT100 P	4.9	.40S&W	SCU63893	6R	COV	Circular	Seized
09	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW95806	6R	COV	Circular	Seized
10	Pistol	Taurus	PT840	4.3	.40S&W	SDX79717	6R	COV	Circular	Seized
11	Pistol	Taurus	PT840 P	4.3	.40S&W	SIX42759	6R	COV	Circular	Seized
12	Pistol	Imbel	MD7	5.0	.40S&W	EQA 08143	6L	COV	Circular	Seized
13	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBY 32672	6R	COV	Circular	Seized
14	Pistol	Taurus	PT100 AF	4.8	.40S&W	SRJ 77543	6R	COV	Circular	Seized
15	Pistol	Taurus	PT 940	3.9	.40S&W	STL 07157	6R	COV	Circular	Seized
16	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW 95801	6R	COV	Circular	Seized
17	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW 95603	6R	COV	Circular	Seized
18	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW 88480	6R	COV	Circular	Seized
19	Pistol	Taurus	PT840	4.3	.40S&W	SDX7 8479	6R	COV	Circular	Seized
20	Pistol	Taurus	PT100 AF	4.8	.40S&W	SBW 95982	6R	COV	Circular	Seized
21	Pistol	Taurus	PT24/7 PRO DS	4.3	.40S&W	SDO 69218	6R	COV	Circular	Seized

(cc) – COV = conventional rifled barrel

Table 36 – Bullet velocity per type of ammunition and firearm (regarding barrel type and length).

CALIBER	Firearm / Ammunition		Velocity measured	Average Velocity	Velocity SD	Firearm / Ammunition		Velocity measured	Average Velocity	Velocity SD
9x19mm	Pistol - Taurus - PT92 AF - TOA 31246 - Barrel 4.8"	9x19 mm Full Metal Jacket	318.2	330.8	7.7	Pistol - Taurus - PT908 - TOA 31285 - Barrel 3.7"	9x19 mm Full Metal Jacket	361.5	361.5	9.9
			330.8					345.5		
			332.2					363.6		
		9x19mm Jacketed Hollow Point	340.6	340.6	3.1		9x19mm Jacketed Hollow Point	334.0	334.0	7.6
			337.9					337.6		
			344,0					323.0		
		9 mm +P+ Gold Jacketed Hollow Point	381,9	381.9	5.0		9 mm +P+ Gold Jacketed Hollow Point	363.6	366.1	9.0
			380.4					366.1		
			389.7					380.2		
		9x19mm Copper Jacketed Hollow Point	383.7	383.7	7.1		9x19mm Copper Jacketed Hollow Point	374.4	371.7	2.0
			382.9					370.6		
			395.5					371.7		
	Firearm / Ammunition		**Velocity**	**Average Velocity**	**Velocity SD**	**Firearm / Ammunition**		**Velocity**	**Average Velocity**	**Velocity SD**
	Pistol - Glock - G17 - LWZ790 - Barrel 4.5"	9x19 mm Full Metal Jacket	335.2	335.2	3.4	Pistol - Jerico - 941F - 151715 - Barrel 4.4"	9x19 mm Full Metal Jacket	355.3	372.2	10.6
			334.4					372.2		
			340.7					374.8		
		9x19mm Jacketed Hollow Point	347.0	341.5	5.2		9x19mm Jacketed Hollow Point	335.4	337.1	3.4
			341.5					341.9		
			336.7					337.1		
		9 mm +P+ Gold Jacketed Hollow Point	387.8	384.4	3.0		9 mm +P+ Gold Jacketed Hollow Point	381.8	381.8	0.2
			381.8					381.9		
			384.4					381.5		
		9x19mm Copper Jacketed Hollow Point	417.2	392.3	15.8		9x19mm Copper Jacketed Hollow Point	391.8	385.4	5.9
			387.8					380.0		
			392.3					385.4		

CALIBER	Firearm / Ammunition		Velocity measured	Average Velocity	Velocity SD	Firearm / Ammunition		Velocity measured	Average Velocity	Velocity SD
.38 SPL	Revolver - Rossi - 97 - F013615 - Barrel 3.0"	.38 SPL Lead Roudn Nose	209.9	207.0	2.4	Revolver - Taurus - 80 - 2031906 - Barrel 4.0"	.38 SPL Lead Roudn Nose	226.2	219.9	9.6
			207.0					219.9		
			205.2					207.4		
		.38 SPL Semi-Jacketed Hollow Point	222.4	242.8	13.1		.38 SPL Semi-Jacketed Hollow Point	250.4	250.4	11.8
			242.8					259.3		
			246.7					235.9		
		.38 SPL +P Semi-Jacketed Hollow Point	238.6	251.8	8.6		.38 SPL +P Semi-Jacketed Hollow Point	268.1	267.1	0.8
			251.8					267.1		
			254.8					266.6		
		.38 SPL +P Full Metal Jacket Silver Tip	289.6	278.9	6.7		.38 SPL +P Full Metal Jacket Silver Tip	312.3	312.3	3.3
			278.9					312.4		
			277.4					306.7		
		.38 SPL +P Jacketed Hollow Point Silver Tip	269.7	265.3	4.0		.38 SPL +P Jacketed Hollow Point Silver Tip	303.6	303.6	4.8
			265.3					305.1		
			261.7					296.2		
		.38 SPL +P Gold Jacketed Hollow Point	255.0	255.0	12.2		.38 SPL +P Gold Jacketed Hollow Point	295.4	295.4	5.1
			248.7					302.5		
			272.2					292.7		

CALIBER	Firearm / Ammunition		Velocity measured	Average Velocity	Velocity SD
.40 S&W	Pistol - Taurus - PT100 - SQL59084 - Barrel 4.9"	.40S&W Full Metal Jacket Flat	282.8	286.8	2.7
			286.8		
			288.0		
		.40S&W Gold Jacketed Hollow Point	348.5	343.0	8.0
			332.8		
			343.0		
		.40S&W Copper Jacketed Hollow Point	368.8	366.3	3.7
			366.3		
			361.6		

APPENDIX C: BRINELL HARDNESS TEST RESULTS

Table 37 – Brinell hardness test*(dd)* results on .38SPL bullets.

Bullet status	FIRED BULLET						NOT FIRED BULLET					
Bullet type	**TFB1 and 7, QBI**	**TFB2, QBII**	**TFB3**	**TFB4, QBIV**	**TFB5, QBV**	**TFB6, QBVI**	**TFB1 and 7, QBI**	**TFB2, QBII**	**TFB3**	**TFB4, QBIV**	**TFB5, QBV**	**TFB6, QBVI**
Mean (HBW)	5.0	90.8	103.1	95.2	116.2	108.5	5.9	89.1	97.5	92.8	114.4	107.7
SD (HBW)	0.3	4.7	6.3	9.9	7.1	5.1	0.4	4.4	5.8	11.0	6.9	6.7
General mean (considering fired and not fired bullet) (HBW)	**5.4**	**89.9**	**100.3**	**94.0**	**115.3**	**108.1**						
General SD (HBW)	0.6	4.6	6.6	10.3	7.0	5.9						

(dd) - Condition of the test: for TFB1: Tip: 1mm, Load: 2.5kgf, F/D2: .2.5kgf/mm2; For TFB2 to TFB6: Tip: 2.5mm, Load: 15.625kgf, F/D2: 2.5 kgf/mm2.
Source: Santos, 2015.

Table 38 – Brinell hardness test*(ee)* results on 9x19mm bullets.

Bullet status	FIRED BULLET				NOT FIRED BULLET			
Bullet type	**TFB1, QBI**	**TFB2, QBII**	**TFB3, QBIII**	**TFB4, QBIV**	**TFB1, QBI**	**TFB2, QBII**	**TFB3, QBIII**	**TFB4, QBIV**
Mean (HBW)	138.6	143.7	140.2	70.9	136.6	133.1	134.7	70.7
SD (HBW)	11.3	9.1	6.8	3.4	7.9	4.5	5.0	3.3
General mean (considering fired and not fired bullet) (HBW)	**137.5**	**138.4**	**137.5**	**70.8**				
General SD (HBW)	9.7	8.9	6.5	3.3				

(ee) - Condition of the test: Tip: 1mm, Load: 10kgf, F/D^2: 10 kgf/mm^2.
Source: Santos, 2015.

Table 39 – Brinell hardness test[(ff)] results on .40S&W bullets.

Bullet status	NOT FIRED BULLET				
Bullet type	TFB1 / QBI	TFB2 / QBII	TFB3 / QBIII	TFB3*/QBIII*	QBIV
Measurements (HBW)	141.0	144.7	49.2	48.8	133.7
	142.2	133.6	51.4	49.4	136.6
	143.9	138.0	50.7	51.6	138.8
Mean (HBW)	**142.4**	**138.8**	**50.4**	**49.9**	**136.4**
SD (HBW)	**1.5**	**5.6**	**1.1**	**1.5**	**2.6**

FIRED BULLET						
	Area of test	**TFB1 / QBI**	**TFB2 / QBII**	**TFB3 / QBIII**	**TFB3*/ QBIII***	**QBIV**
Measurements (HBW)	LEA	126.3	124.6	58.9	77.3	125.3
		139.4	105.8	74.3	77.2	131.1
		145.7	143.9	66.4	81.6	129.6
	LEA Mean	**137.1**	**124.8**	**66.5**	**78.7**	**128.7**
	LEA SD	**9.9**	**19.1**	**7.7**	**2.5**	**3.0**
	GEA	97.4	125.6	63.6	73.2	121.6
		117.4	143.8	62.2	75.9	129.1
		84.8	128.5	63.6	77.1	128.5
	GEA Mean (HBW)	**99.9**	**132.6**	**63.1**	**75.4**	**126.4**
	GEA SD (HBW)	**16.4**	**9.8**	**0.8**	**2.0**	**4.2**
General results for fired bullet	**GENERAL Mean (HBW)**	**118.5**	**128.7**	**64.8**	**77.1**	**127.5**
	GENERAL SD (HBW)	**21.7**	**13.0**	**4.8**	**2.5**	**3.2**

(ff) - Condition of the test: Tip: 1mm, Load: 10kgf, F/D^2: 10 kgf/mm^2.

APPENDIX D: DETAIL OF AMMUNITIONS EMPLOYED ON THIS RESEARCH

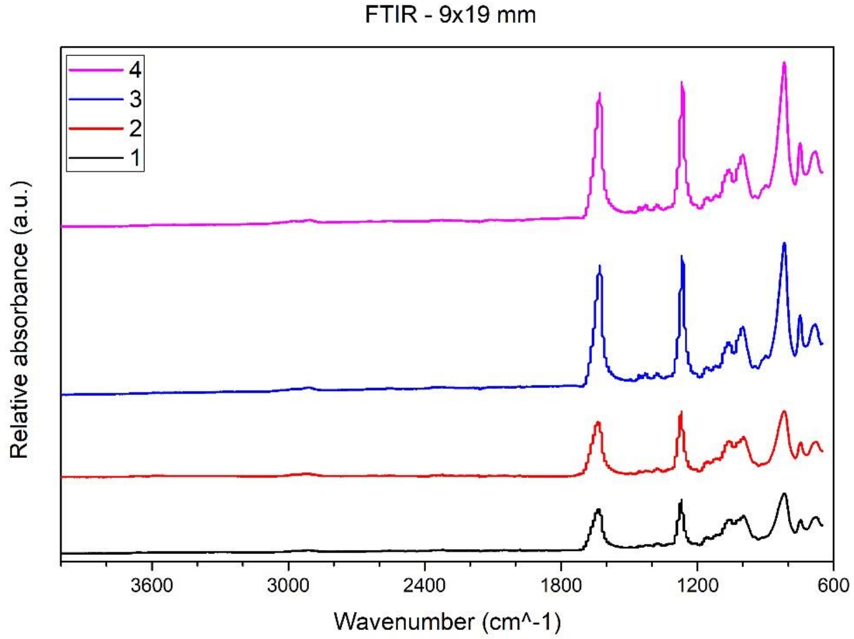
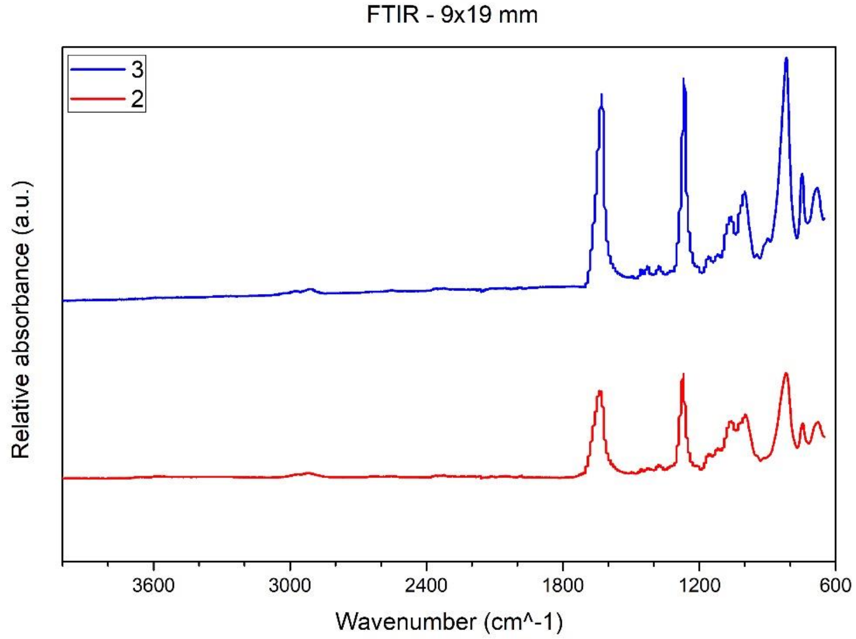
Table 40 – Determination of the propellant mass of each type of ammunition of the study.

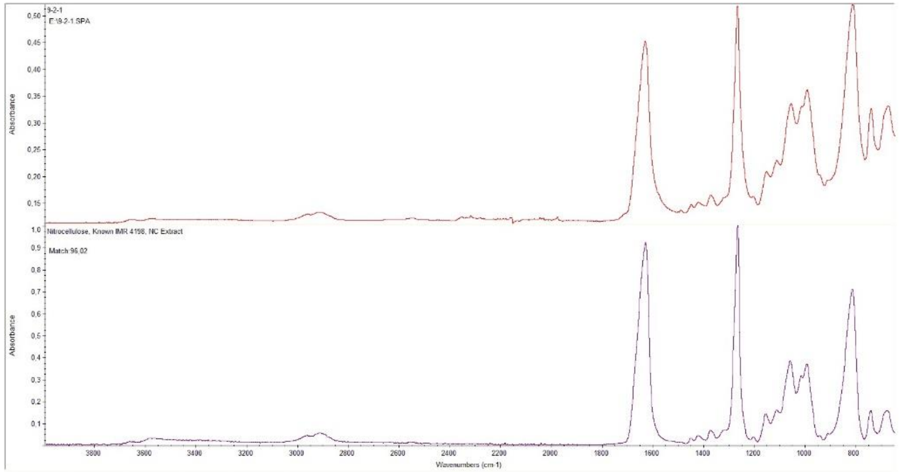
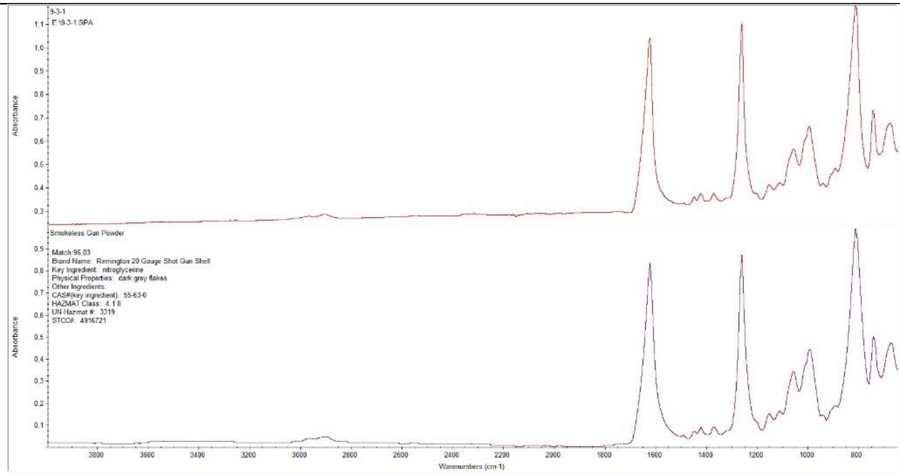
Ammunition (Symbol)	Cartridge mass (g)	Cartridge - Propellant mass (g)	Propellant mass (g)	Average 1 (g)	Container mass (g)	Container + Propellant mass (g)	Propellant mass (g)	Average 2 (g)	Average (g)	Propellant mass SD (g)	Propellant composition by ATR-FTIR
.38 SPL TFB 1	15.373	15.193	0.180	0.248	3.888	4.121	0.233	0.242	0.245	0.004	single-base
	15.333	15.085	0.248		3.801	4.048	0.247				
	15.439	15.126	0.313		3.794	4.036	0.242				
.38 SPL TFB 2	15.179	14.833	0.346	0.337	3.745	4.079	0.334	0.334	0.336	0.002	single-base
	15.159	14.822	0.337		3.902	4.236	0.334				
	15.147	14.811	0.336		3.882	4.217	0.335				
.38 SPL TFB 3	15.344	14.981	0.363	0.341	3.732	4.091	0.359	0.359	0.350	0.013	double-base
	15.348	15.029	0.319		3.786	4.147	0.361				
	-	-	-		3.846	4.199	0.353				
.38 SPL TFB 4	13.341	12.933	0.408	0.408	3.766	4.159	0.393	0.393	0.401	0.011	double-base
	13.499	13.088	0.411		3.726	4.122	0.396				
	13.268	12.868	0.400		3.834	4.211	0.377				

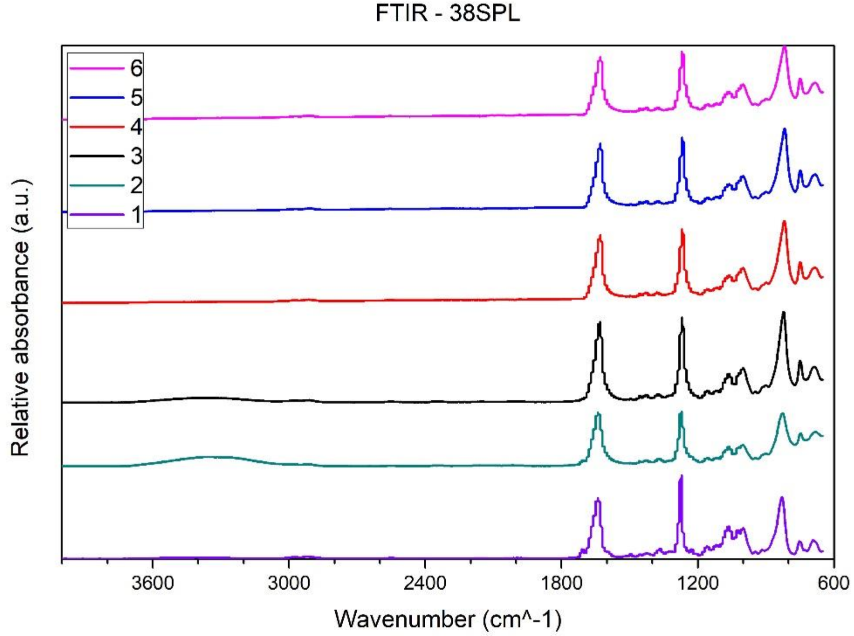
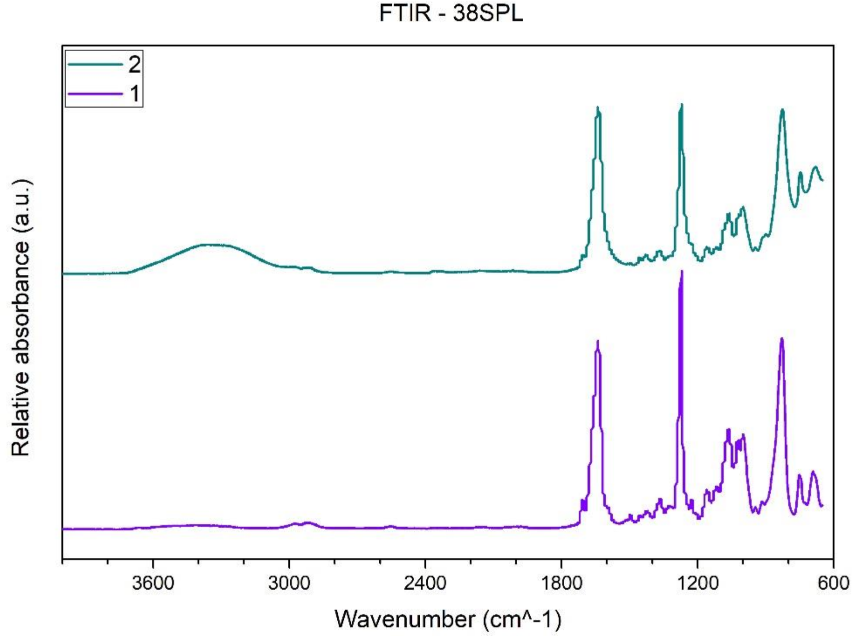
.38 SPL TFB 5	13.132	12.730	0.402	0.402	3.788	4.178	0.390	0.390	0.396	0.008	double-base
	13.126	12.720	0.406		3.859	4.249	0.390				
	13.116	12.723	0.393		3.745	4.127	0.382				
.38 SPL TFB 6	13.141	12.734	0.407	0.413	3.797	4.187	0.390	0.408	0.411	0.004	double-base
	13.167	12.752	0.415		3.809	4.217	0.408				
	13.176	12.763	0.413		3.756	4.165	0.409				
9mm TFB 1	11.831	11.484	0.347	0.349	3.800	4.141	0.341	0.343	0.346	0.004	single-base
	12.468	12.113	0.355		3.747	4.099	0.352				
	11.861	11.512	0.349		3.691	4.034	0.343				
9mm TFB 2	11.891	11.464	0.427	0.427	3.799	4.199	0.400	0.411	0.419	0.011	single-base
	12.057	11.635	0.422		3.781	4.195	0.414				
	11.874	11.445	0.429		3.787	4.198	0.411				
9mm TFB 3	11.895	11.483	0.412	0.402	4.073	4.463	0.390	0.388	0.395	0.010	double-base
	11.863	11.461	0.402		3.758	4.146	0.388				
	11.940	11.538	0.402		3.810	4.198	0.388				

9mm TFB 4	10.378	10.003	0.375	0.375	3.801	4.164	0.363	0.363	0.369	0.008	double-base
	10.330	9.958	0.372		4.036	4.397	0.361				
	10.362	9.968	0.394		3.781	4.167	0.386				
40SW TFB 1	17.056	16.605	0.451	0.452	3.727	4.168	0.441	0.442	0.447	0.007	single-base
	17.080	16.625	0.455		3.850	4.293	0.443				
	17.064	16.612	0.452		-	-	-				
40SW TFB 2	15.385	14.900	0.485	0.485	3.751	4.223	0.472	0.463	0.474	0.016	double-base
	15.409	14.924	0.485		3.917	4.380	0.463				
	15.411	14.942	0.469		4.086	4.547	0.461				
40SW TFB 3	13.832	13.371	0.461	0.456	3.723	4.171	0.448	0.444	0.450	0.008	double-base
	13.850	13.400	0.450		3.812	4.251	0.439				

Table 41 – FTIR spectra obtained for the propellants of the ammunition used on this study.

	
Results: 9x19mm type 1 and 2 same composition, and type 3 and 4 same composition	Results: 9x19mm type 2 and 3 different compositions

	
Results: 9x19mm type 2 spectra in good agreement with single-base (nitrocellulose) powder	Results: 9x19mm type 3 spectra in good agreement with double-base (nitrocellulose + nitroglycerine) powder

	
Results: .38SPL types 3, 4 ,5, 6 and 7 same composition (compatible with double-base powder), while type 1 and 2 compatible with single-base powder.	Results: .38SPL types 1 and 2 same composition (compatible with single-base powder).

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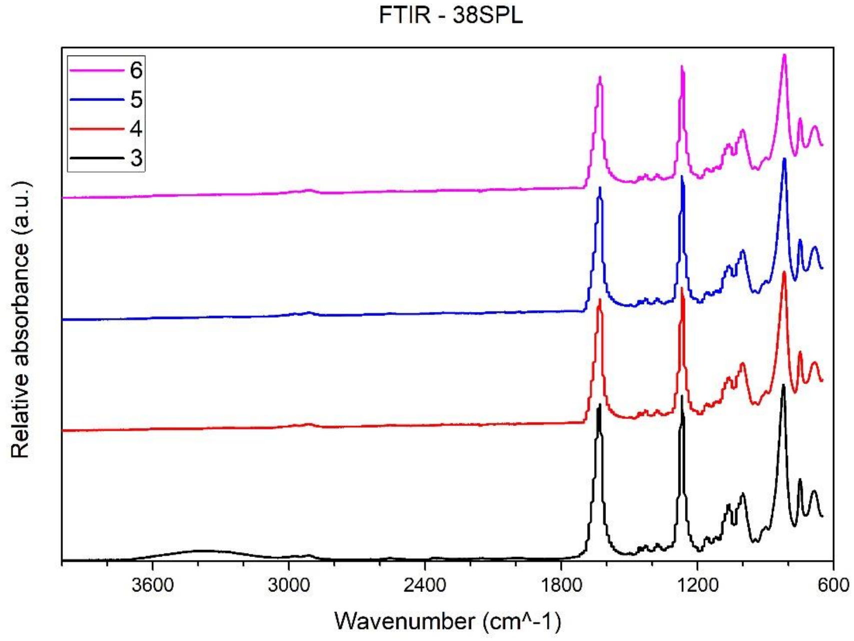

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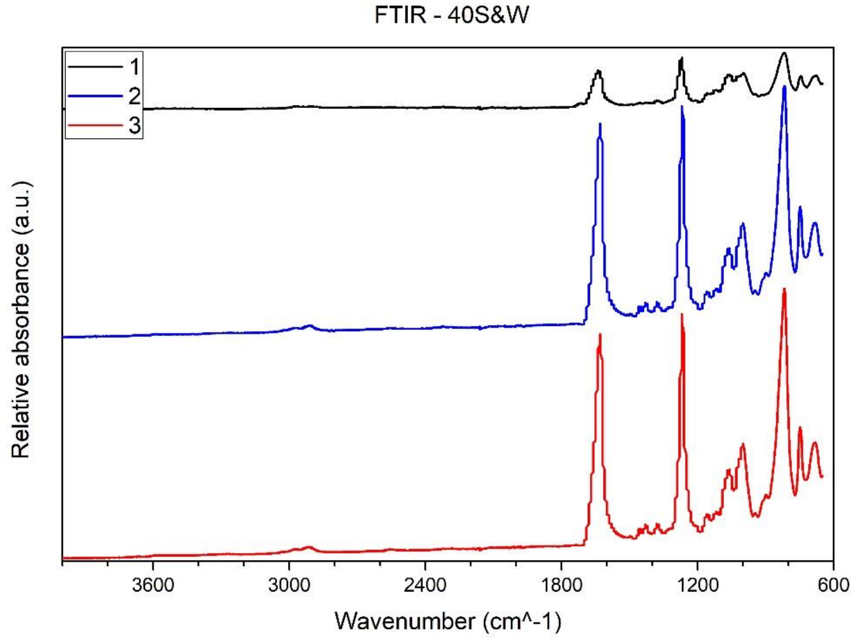

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<tr>
<td>Results: .38SPL types 3, 4, 5 and 6 same composition (compatible with double-base powder).</td>
<td>Results: .40S&W type 2 and 3 same composition (compatible with double-base powder), while type 1 compatible with single-base powder.</td>
</tr>
</table>

ATTACHMENT A: Cartridge and Chamber .38SPL SAAMI Drawning

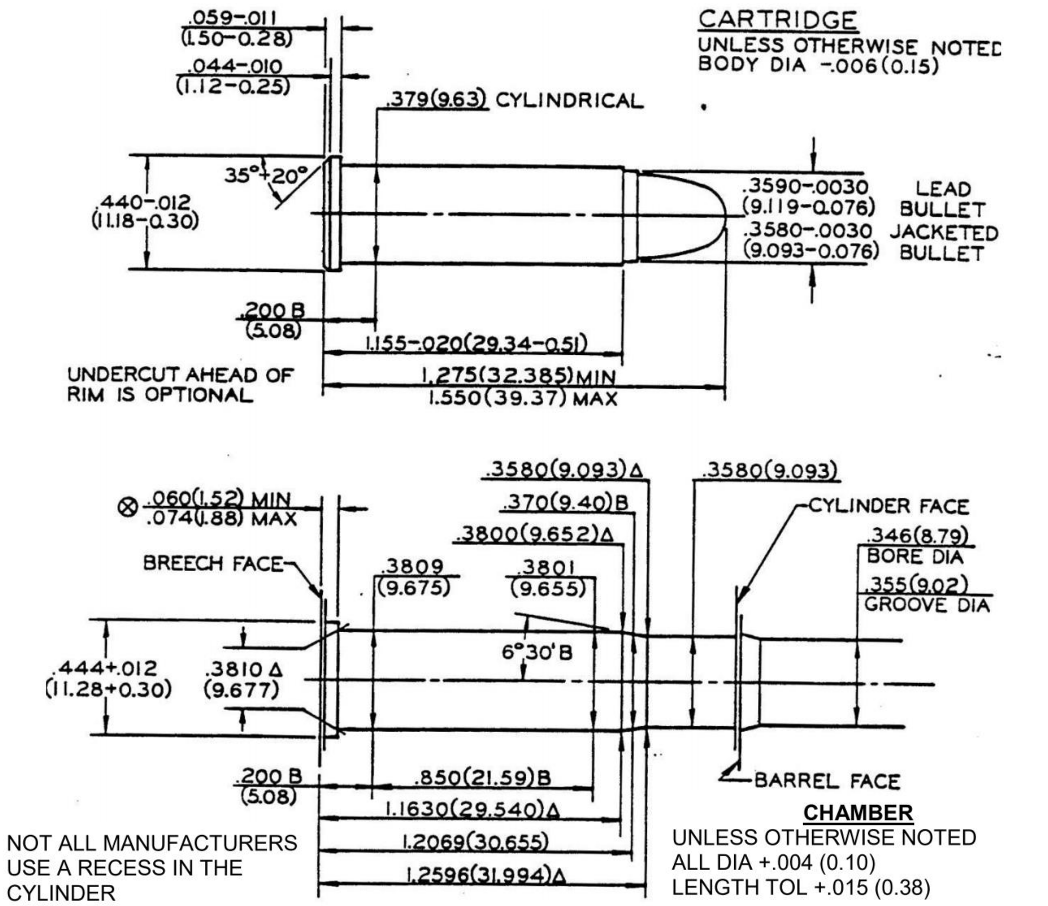
SECTION I – CHARACTERISTICS
CENTERFIRE PISTOL & REVOLVER
SAAMI VOLUNTARY PERFORMANCE STANDARDS

CARTRIDGE AND CHAMBER DRAWING
38 SPECIAL / 38 SPECIAL +P

NOTICE: This drawing is subject to change. Current version is available at www.saami.org.

MAXIMUM CARTRIDGE / MINIMUM CHAMBER

38 SPECIAL / 38 SPECIAL +P



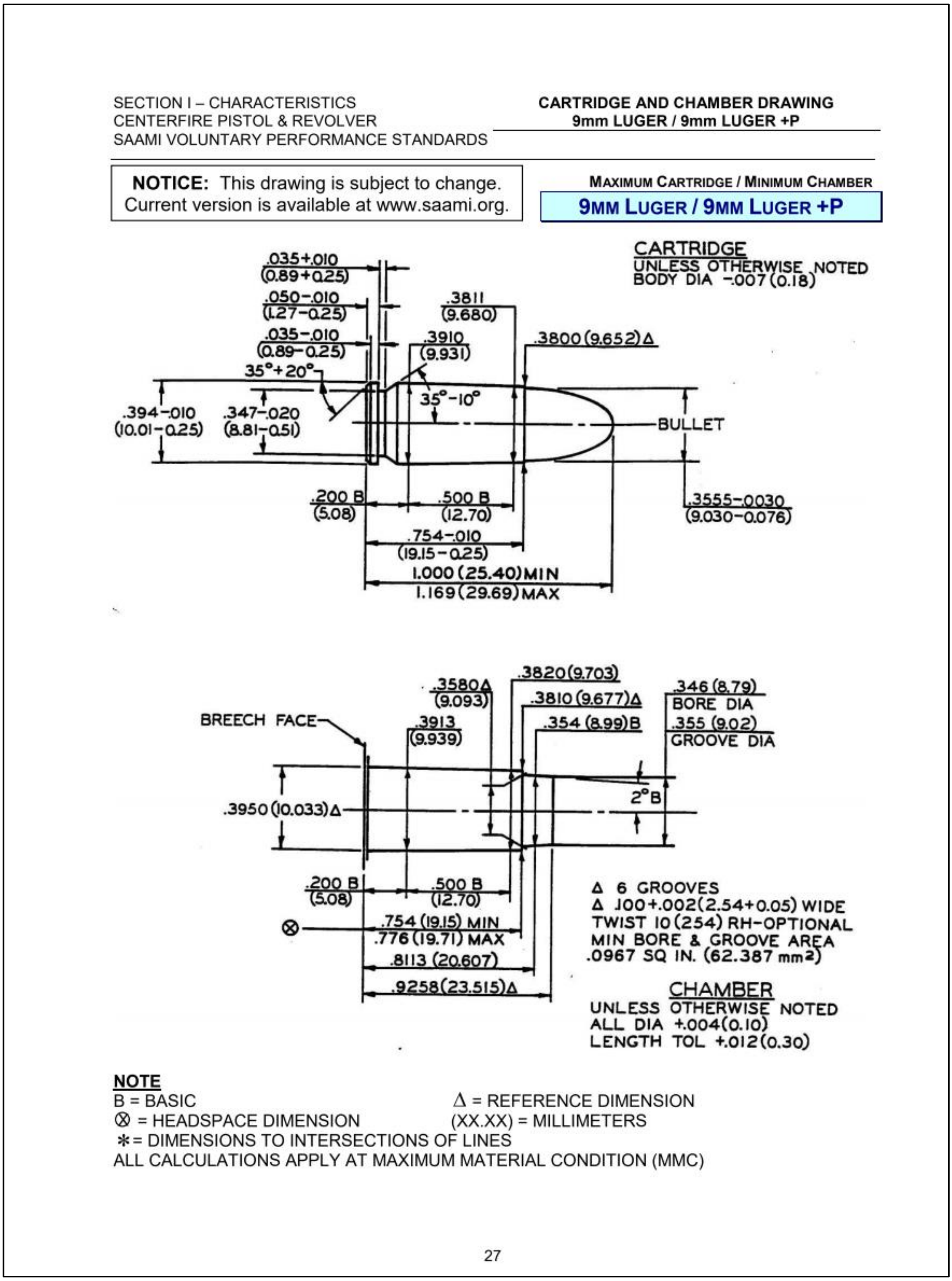
Δ 6 GROOVES
Δ .105+.002 (2.67+0.05) WIDE
TWIST 18.75 (476.3) RH – OPTIONAL
MIN. BORE & GROOVE AREA:
.0969 IN^2 (62.516 mm^2)

NOTE
B = BASIC
Δ = REFERENCE DIMENSION
⊗ = HEADSPACE DIMENSION
(XX.XX) = MILLIMETERS
∗= DIMENSIONS TO INTERSECTIONS OF LINES
ALL CALCULATIONS APPLY AT MAXIMUM MATERIAL CONDITION (MMC)

47

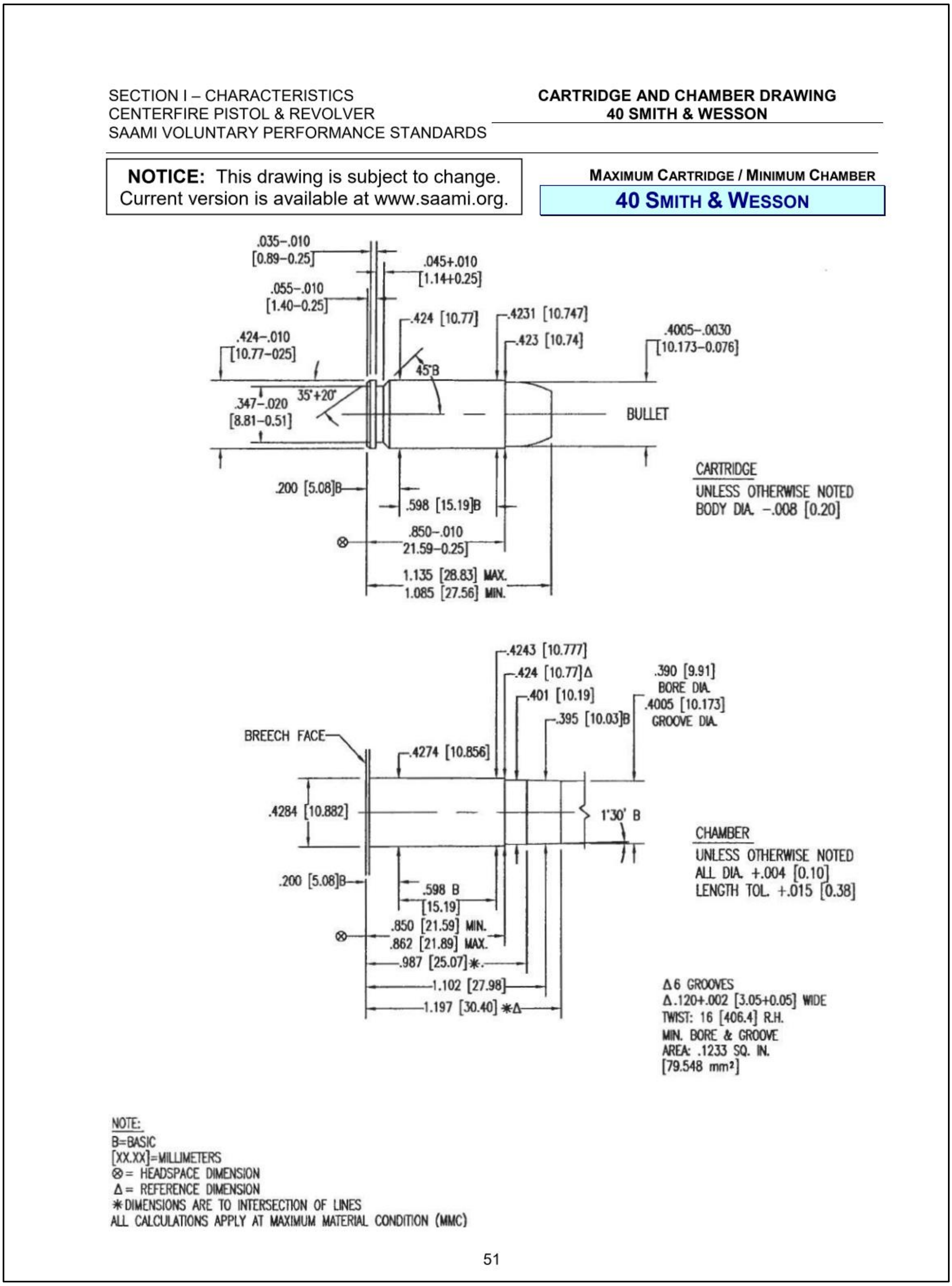
Source: ANSI / SAAMI, 2015, p. 47.

ATTACHMENT B: Cartridge and Chamber 9x19mm SAAMI Drawning



Source: ANSI / SAAMI, 2015, p. 27.

ATTACHMENT C: Cartridge and Chamber .40S&W SAAMI Drawning



Source: ANSI / SAAMI, 2015, p. 51.

ATTACHMENT D : LOAD FACTORS FOR DIFFERENT TEST CONDITIONS IN BRINELL HARDNESS TESTS

Hardness simbol	Indenter diameter D mm	Relation Force load-diameter $0.102xF/D^2$ N/mm^2	Nominal force load F	
HBW 10/3000	10	30	29,42	KN
HBW 10/1500	10	15	14,71	KN
HBW 10/1000	10	10	9,807	KN
HBW 10/500	10	5	4,903	KN
HBW 10/250	10	2,5	2,452	KN
HBW 10/100	10	1	980.7	N
HBW 5/750	5	30	7,355	KN
HBW 5/250	5	10	2,452	KN
HBW 5/125	5	5	1,226	KN
HBW 5/62,5	5	2,5	612,9	N
HBW 5/25	5	1	245,2	N
HBW 2,5/187,5	2,5	30	1,839	KN
HBW 2,5/62,5	2,5	10	612,9	N
HBW 2,5/31,25	2,5	5	306,5	N
HBW 2,5/15,625	2,5	2,5	153,2	N
HBW 2,5/6,25	2,5	1	61,29	N
HBW 1/30	1	30	294,2	N
HBW 1/10	1	10	98,07	N
HBW 1/5	1	5	49,03	N
HBW 1/2,5	1	2,5	24,52	N
HBW 1/1	1	1	9,807	N

Source: NBR ISO 6506-1:2010, p. 6.