A PERFORMANCE ANALYSIS OF KINETIC ENERGY AMMUNITION OPTIMISATION THROUGH EVOLUTIONARY METHODS

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Abstract. *The performance of Kinetic Energy munitions is usually measured by the penetration achieved when perpendicularly fired against a rolled homogeneous steel target. Much work has been done in the field but none looking into applying an evolutionary method as an optimisation tool. The problem is multi-variable with conflicting objectives, well-suited, in principle, for the application of Genetic Algorithms to improve performance. A method has been developed for such purpose but, despite the use of several penalisation strategies (including no penalisation at all), has not been able to find a unique global optimal set of parameters leading to the maximum possible penetration every time. However, results indicate that penetrations in excess of current existing munitions are possible to achieve, therefore the value of the method. This work introduces the method and presents a performance study in a high-performance, distributed memory environment.*

Keywords: *Kinetic Energy Ammunition, Long Rod Penetrator, Optimization, Genetic Algorithms, Impact*

1 INTRODUCTION

Historically, kinetic ammunition has been developed using *trial and error* and semi-empirical methods. The literature shows a variety of computational methods used to predict the performance of such munitions, but no method exists to help developing a new or to improve an existing long-rod shot. Motta & Ebecken (2014) presented a method, based on Genetic Algorithms (GA), for such purpose.

The method is based on the model proposed by Bennett (1998) and takes in consideration a selection of up to 15 relevant variables related to the penetrator, the sabot and the propellant charge. This set of variables is considered an *individual*, from the GA point-of-view. Extensive work has been carried out in the search for a global optimal *individual* but, so far, the method was not able to consistently *converge* to this set of parameters, using a range of penalisation functions or no penalisation at all.

It is estimated that this *lack of convergence to a global value* is due to the fact that the problem is actually a combination of three problems, following each other in time. The interior ballistics problem depends greatly in the parameters of the propellant and mass of the penetrator; the following exterior ballistics problem relies depends on the geometry of the penetrator; and the terminal ballistics problem depends on the material (density) of the penetrator and the ratio between its length and diameter (which defines the energy density upon impact).

The method, however, has allowed to achieve improvements in performance between 35 and 50 % when compared to a case selected as reference, herein referenced as the *standard case* (Bennett, 1998), proving its value. This work presents considerations of the application of the method; detailed information about the method itself can be found in Motta & Ebecken (2014).

The optimisations were executed in the Lobo Carneiro (a 504-CPUs SGI ICE-X machine) platform at the High-Performance Computing Centre, COPPE / Federal University of Rio de Janeiro. Coding was carried on locally using Intel® Parallel Studio XE Cluster Edition for Windows running on Microsoft® Visual Studio Enterprise 2015.

2 ARMOUR-PIERCING FIN-STABILISED DISCARDING SABOT MUNITION

Figure 1 shows a typical kinetic energy munition. Its purpose is to *pierce armour*, it is *fin-stabilised* (opposed to *spin-stabilised*) and it uses a *discardable* sabot to centre the penetrator in the bore and to obturate the volume behind the shot, thus containing the expanding gases resulting from the combustion of the propellant charge. It is comprised of a penetrator (in blue), a sabot (in orange) and a propellant charge. A metallic case is used to hold the parts and position them inside the gun upon loading.

The material of choice for the penetrator is depleted uranium because of its high density, pyrophoric property and failure mechanism under high strain rate loading. However, depleted uranium can be toxic for personnel (Briner, 2010), and other alloys with comparable properties have been researched for use in kinetic energy ammunition. Weerasooriya et al

(1992) discuss the failure behaviour of a heavy tungsten alloy under high strain rate loading conditions and compare it to depleted uranium. it is useful to point out that, upon high velocity impact, the ratio between the density of the striker and the target play a significant role in the penetration of the first in the last (Bennett, 1998).

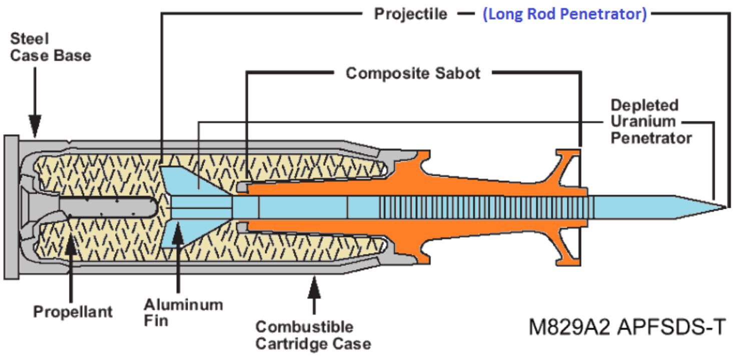

Figure 1: Schematics of Armour-Piercing Fin-Stabilised Discarding Sabot munition (Cooke, 2014)

The variables of interest in this work are listed in Table 1. The values under the heading *Bennett (1998)* are those considered *reference values*, constituting what is referred to, in this work (and in this work only), as *standard*. Results are compared to the penetration achieved using these values, 353mm.

Table 1: Data and limits for the selected variables of interest

#	Variable	Bennett (1998)	Minimum	Maximum
1	propellant/charge mass	6.700 kg	6.500 kg	7.200 kg
2	propellant/charge force constant	951,000 J/kg	940,000 J/kg	1,050,000 J/kg
3	propellant/charge burning index (α)	0.9930	0.9500	1.0000
4	propellant/charge burning rate (β)	1.680E-9	1.680E-9	1.680E-9
5	propellant/charge ballistic size	0.0015 m	0.0012 m	0.0018 m
6	propellant/charge form function	0.190	-0.050	0.200
7	propellant/charge shape	stick	stick	
8	propellant/charge density	1,167 kg/m^3	-	
9	propellant/charge specific heat ratio	1.26	-	
10	penetrator diameter	0.025 m	0.020 m	0.030 m
11	penetrator length-diameter ratio	16.0	12.0	20.0
12	penetrator density	16,500 kg/m^3	14,000 kg/m^3	18,600 kg/m^3
13	sabot / penetrator length ratio	0.760	0.500	0.850
14	sabot density	2,710 kg/m^3	2,000 kg/m^3	7,850 kg/m^3
15	sabot mean diam. / bore diam. ratio	0.500	0.500	0.850

Not all variables were used in the cases discussed in this work. It is possible to optimise all the 15 variables at once or some of them – or even others not considered by Bennett (1998) by simple modifications in the code. However, it was observed that including the remaining mentioned variables (charge force constant, charge burning index, Charge burning rate, charge ballistic size, charge form function, propellant shape, propellant density and propellant specific heat ratio) did not result in improved performance, not to mention that these variables are propellant-specific and could be considered in a dedicated study. The amount of propellant and the relevant dimensions of the penetrator and the sabot have shown to have a dominant impact in the resulting penetration.

3 CONSTRAINTS

Four constraints were considered in the problem, as per in Bennett (1998): the all-burnt position, the maximum pressure developed in the gun tube, the nominal shear stress in the sabot and the penetrator aspect (length/diameter ratio, the L/D ratio).

The first is the point at which the shot is when all propellant charge is considered fully burnt. Based on the literature and commonly acceptable values by the industry, the acceptable range was taken from 29 to 33% of the total shot travel in the bore. For values below 29 %, it was considered that the maximum pressure developed is too much thus requiring a more mechanically resistant barrel; for values above 33% of the shot travel, accuracy may be penalised due to excessive vibration of the gun barrel.

The second, the maximum internal pressure developed in the bore influences the hoop stress in the barrel, the load on the breech assembly and the shot resistance to compression. The maximum allowable value depends on the materials and/or thermal treatments used in the gun, the penetrator and the sabot. This value was set as 550 MPa, reasonable for a range of steels commonly used both in gun tubes and ammunition.

The nominal shear stress (τ_{sabot}) developed in the sabot, self-explanatory, depends on its mechanical properties and the internal pressure developed in the barrel. This value was set as 100 MPa. It will be shown that, in the problems herein included, the values of τ_{sabot} are well below this value.

Finally, the L/D ratio attempts to capture the possibility of buckling upon normal impact with undesirable effects on penetration.

4 IMPLEMENTATION, PENALISATION AND CONVERGENCE

The pseudocode subset representing the GA portion of the complete code is shown below. A high incidence of highly fit individuals with very short (and therefore unacceptable) all-burnt positions was verified hence a decision to replace these individuals for new, randomly generated ones, once zero fitness was observed.

Generate first (random) generation (distributed)
Calculate performance and fitness (distributed)
Gather on root
Rank population (root)
Repeat until criteria

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Scatter non-elite
Mono-point cross-over (distributed)
Mono-point mutation (distributed)
Calculate performance and fitness (distributed)
Replace individuals with zero fitness with new, random individuals (distributed)
Calculate performance and fitness now newly generated individuals (distributed)
Gather on root
Rank population (root)
Store best fit individual
Output results
Stop

Fortran double precision (64 bits) was used in the implemented code. Generational reproduction was applied to non-members of the elite (determined by a pre-selected portion of the whole population). A roulette wheel was used to determine whether each pair of individuals, tested sequentially in each node, was to be crossed. One of the variables in the individual and a position in the binary representation of this variable were also randomly selected using a roulette wheel where cross-over operations were to be carried on. After the cross-over operation, roulette wheels were used to determine whether mono-point mutation was to happen, at which variable in each individual and at which position in the variable (in its binary representation).

Several different static penalisation functions were tried in this work without noticeable impact in the convergence, understood as the desire of finding a universal maximum in the considered domain. However, it is important to not allow solutions with very short all-burnt positions, excessive high internal pressure and sabot shear stress or excessively long, thin penetrators to not go unpenalized for the reasons above. Although not ruled out, no other penalisation techniques (such as additive or adaptive) were attempted so far.

Linear and exponential functions were therefore adopted in the cases herein presented, generating multipliers which were smaller as the solution distanced from the acceptable limits for the constraints. For values within these limits, the multipliers were taken as the unit. The four multipliers were multiplied by the achieved penetration, resulting in a value of *fitness*, used to rank the individuals in the considered generation. These functions are shown in Figures 2, 3 and 4.

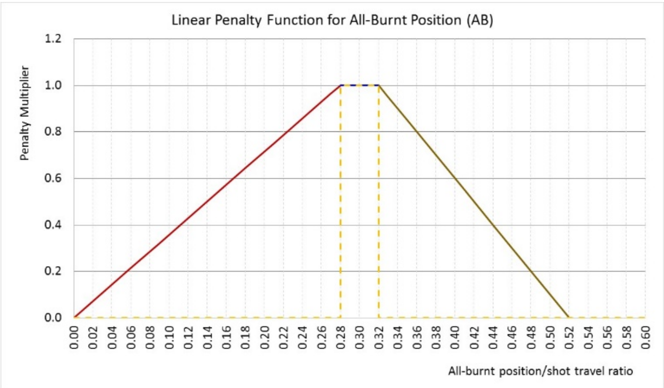

Figure 2: Linear penalisation for all-burnt position.

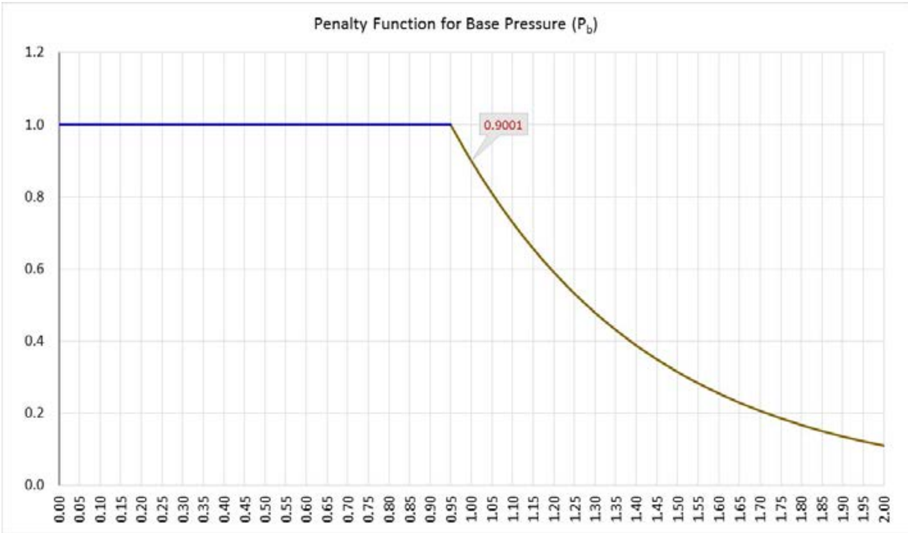

Figure 3: Linear-exponential penalisation for base pressure.

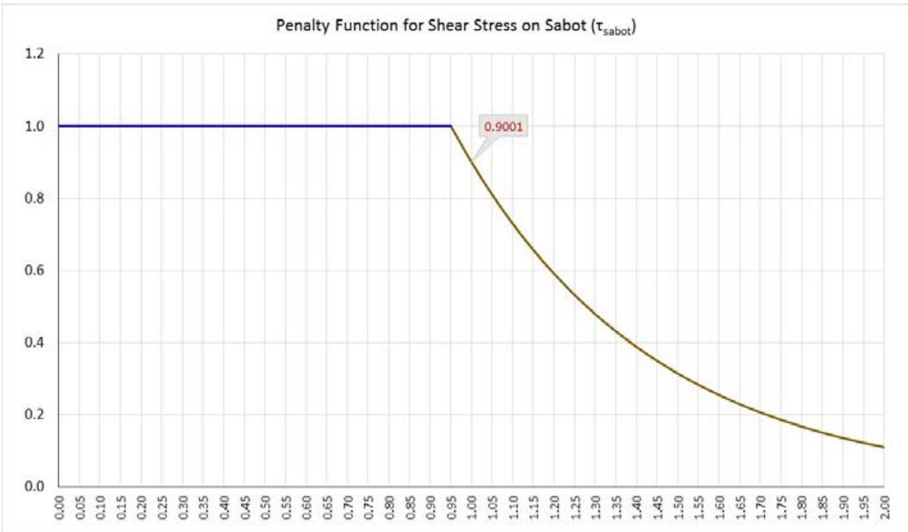

Figure 4: Linear-exponential penalisation for the shear stress on sabot.

It was observed that, if penalisation is not applied, solutions with very short all-burnt positions (between 15 and 20 %) are obtained. It is worth mentioning that more complex function led to no improvements in the results.

5 SELECTED CASES

Two cases were selected to be included in the present work. In the first, seven variables were selected for optimisation (variables 1 and 10-15: charge mass, penetrator diameter, penetrator length-diameter ratio, penetrator density, sabot / penetrator length ratio, sabot density and sabot mean diameter / bore diameter ratio); in the second, five variables were chosen (variables 1, 10, 11, 13 and 15: charge mass, penetrator diameter, penetrator length-diameter ratio, sabot / penetrator length ratio and sabot mean diameter / bore diameter ratio). It can be observed that the difference between these two cases is whether the densities of the penetrator and the sabot were included or not.

Table 2 presents the results for the first case (seven variables). The process was repeated 12 times with different values of cross-over and mutation rates (txc and txm, respectively). The elitism rate (txe) was fixed in 10 %, a fixed number of generations was selected (2,000) and all generations had a population of 3,600 individuals. The results for each execution are shown in the table. The values in blue are the average and the values in red, the standard deviation for each variable and are provided for information only. The usefulness of this information is in comparing an overall performance of the method with the selected reference, or *standard case*. As previously described, the value of *fitness* is obtained by multiplying the achieved penetration by the four penalisation multipliers.

Table 3 presents the corresponding all-burnt positions, the maximum pressure developed in the gun tube, the sabot’s nominal shear stress and the length-diameter (L/D) ratio of the penetrator. It is worth noticing that, despite of the penalisation policy, the L/D ratio (except in one case) is close to the upper limit in the range, an indication of the significance of the energy density on the penetration upon impact. The results indicate that no penalisation was applied for the sabot’s nominal shear stress since the values achieved were below the acceptable limit.

Table 4 presents the improvement in penetration when compared to the *standard case*. It can be noticed that the worst result is a 40.1 % improvement with respect to 353 mm, or 494.6 mm – the only result below 500 mm.

Table 2: Results for optimisation with seven variables

					Variable # →	1	10	11	12	13	14	15
				Fitness	**Penetration**	**Charge Mass**	**Diameter**	**L/d ratio**	**$\rho_{penetrator}$**	**Shot/Sabot LR**	**ρ_{sabot}**	**d_{sabot}/bore ratio**
					(lower limit →)	6.50000	0.02000	12.00000	14000.00	0.50000	2000.00	0.40000
					(upper limit →)	7.20000	0.03000	20.00000	18600.00	0.85000	7850.00	0.60000
#	txe	txc	txm	0.48472	0.50905	7.13193	0.02400	19.47900	17945.62	0.54141	2270.69	0.45606
				0.00697	0.00786	0.04363	0.00090	0.61611	521.82	0.03930	269.33	0.04781
1	0.10	0.90	0.00	**0.49912**	**0.52414**	7.11229	0.02499	19.63720	17826.50	0.50782	2042.82	0.41748
2	0.10	0.90	0.00	**0.48779**	**0.51330**	7.14699	0.02353	19.95090	17558.60	0.63392	2035.37	0.44580
3	0.10	0.50	0.50	**0.48306**	**0.50846**	7.18543	0.02240	19.99350	18547.00	0.56580	2289.90	0.54458
4	0.10	0.50	0.50	**0.49313**	**0.51903**	7.13855	0.02346	19.98490	18575.20	0.51213	2369.07	0.48733
5	0.10	0.90	0.50	**0.49050**	**0.51461**	7.19966	0.02344	19.49630	18139.40	0.55975	2155.09	0.49722
6	0.10	0.90	0.50	**0.47666**	**0.49457**	7.11955	0.02555	17.79250	18507.90	0.55495	2050.67	0.40318
7	0.10	0.00	1.00	**0.48153**	**0.50565**	7.06841	0.02466	19.63190	17199.90	0.50018	2452.76	0.41200
8	0.10	0.00	1.00	**0.47534**	**0.50660**	7.19350	0.02379	19.92690	17057.10	0.57115	2129.43	0.52730
9	0.10	0.90	0.00	**0.48093**	**0.50295**	7.10404	0.02512	19.00620	17584.50	0.54271	2011.92	0.45370
10	0.10	0.90	0.00	**0.48657**	**0.50984**	7.13674	0.02390	19.30140	17839.20	0.53961	2262.71	0.44025
11	0.10	0.50	0.50	**0.48219**	**0.50528**	7.10257	0.02389	19.31170	18115.50	0.50282	2515.37	0.43986
12	0.10	0.50	0.50	**0.47985**	**0.50416**	7.07545	0.02331	19.71460	18396.60	0.50608	2933.13	0.40402

Table 3: Constraints regarding the optimisation with seven variables

#	AB_{POS}	Pressure (Mpa)	τ_{SABOT} (Mpa)	L/D ratio
1	29.1%	99.4	19.8	19.637
2	31.9%	101.7	15.8	19.951
3	31.0%	101.7	17.8	19.994
4	29.6%	100.2	19.8	19.985
5	30.7%	101.7	18.3	19.496
6	29.0%	99.7	19.3	17.793
7	31.0%	99.6	19.5	19.632
8	28.6%	100.4	16.5	19.927
9	29.1%	99.5	18.4	19.006
10	32.5%	101.5	19.1	19.301
11	32.0%	100.7	20.4	19.312
12	32.3%	100.4	20.1	19.715

Table 4: Improvement in penetration with respect to the standard case (seven variables)

#	Pen (mm)	Pen/Std
1	524.1	148.5%
2	513.3	145.4%
3	508.5	144.0%
4	519.0	147.0%
5	514.6	145.8%
6	494.6	140.1%
7	505.7	143.2%
8	506.6	143.5%
9	503.0	142.5%
10	509.8	144.4%
11	505.3	143.1%
12	504.2	142.8%

Moving to the cases in which only five variables were considered, the corresponding results are shown in Table 5. It is similar to Table 2 and once more, 12 executions of the code with the same cross-over and mutation rates used before were chosen. It can be observed that, when the densities of the penetrator and the sabot were not used in the optimisation (reason why they appear in grey in the table), the improvement in penetration is consistently less – only one result was greater than 500 mm, in contrast with the previous cases.

Table 5: Results for optimisation with five variables

					Variable # →	1	10	11	12	13	14	15
				Fitness	**Penetration**	**Charge Mass**	**Diameter**	**L/d ratio**	$\rho_{penetrator}$	**Shot/Sabot LR**	ρ_{sabot}	**d_{sabot}/bore ratio**
					(lower limit →)	6.50000	0.02000	12.00000	14000.00	0.50000	2000.00	0.40000
					(upper limit →)	7.20000	0.03000	20.00000	18600.00	0.85000	7850.00	0.60000
#	**txe**	**txc**	**txm**	0.46870	0.49174	7.14985	0.02409	19.49378	16500.00	0.54369	2710.00	0.43138
				0.00617	0.00697	0.03166	0.00044	0.40272	0.00	0.03413	0.00	0.02710
1	0.10	0.90	0.00	**0.46523**	**0.48659**	7.18931	0.02411	19.02250	16500.00	0.51185	2710.00	0.47848
2	0.10	0.90	0.00	**0.45810**	**0.47966**	7.14751	0.02367	19.19080	16500.00	0.61077	2710.00	0.41583
3	0.10	0.50	0.50	**0.46724**	**0.49104**	7.13752	0.02372	19.75520	16500.00	0.52880	2710.00	0.46138
4	0.10	0.50	0.50	**0.46809**	**0.48801**	7.16638	0.02495	18.53350	16500.00	0.50823	2710.00	0.41090
5	0.10	0.90	0.50	**0.46543**	**0.48934**	7.12727	0.02339	19.81810	16500.00	0.56068	2710.00	0.43955
6	0.10	0.90	0.50	**0.47654**	**0.50036**	7.14232	0.02459	19.61680	16500.00	0.51372	2710.00	0.41578
7	0.10	0.00	1.00	**0.47129**	**0.49478**	7.19563	0.02362	19.59830	16500.00	0.55806	2710.00	0.43972
8	0.10	0.00	1.00	**0.47241**	**0.49633**	7.14613	0.02407	19.71100	16500.00	0.53029	2710.00	0.43238
9	0.10	0.90	0.00	**0.46655**	**0.48896**	7.17996	0.02413	19.33430	16500.00	0.60419	2710.00	0.40289
10	0.10	0.90	0.00	**0.46037**	**0.48404**	7.07637	0.02422	19.82350	16500.00	0.52215	2710.00	0.47152
11	0.10	0.50	0.50	**0.47727**	**0.50196**	7.14687	0.02432	19.87160	16500.00	0.54279	2710.00	0.40533
12	0.10	0.50	0.50	**0.47592**	**0.49982**	7.14296	0.02431	19.64980	16500.00	0.53277	2710.00	0.40277

Table 6: Constraints regarding the optimisation with five variables

#	**AB_{POS}**	**Pressure (Mpa)**	**τ_{SABOT} (Mpa)**	**L/D ratio**
1	30.3%	101.5	18.5	19.023
2	32.1%	101.6	15.5	19.191
3	31.3%	101.0	17.6	19.755
4	30.7%	101.3	19.1	18.534
5	32.9%	101.6	16.8	19.818
6	29.4%	99.9	18.1	19.617
7	31.1%	101.9	16.9	19.598
8	30.6%	100.9	17.6	19.711
9	29.4%	100.9	15.4	19.334
10	29.3%	99.2	17.3	19.824
11	29.5%	100.0	17.0	19.872
12	30.6%	100.7	17.7	19.650

Similarly, Tables 6 and 7 show the considered constraints and the resulting penetration for each case.

By comparing Tables 3 and 6, no relevant, significant differences are noticed. The comparison between Tables 4 and 7, however, allows to observe the difference in improvement in the performance in more detail; with an average enhancement in the penetration below 140 %, in contrast with the previous case, above 140 %.

Table 7: Improvement in penetration with respect to the standard case (five variables)

#	Pen (mm)	Pen/Std
1	486.6	137.8%
2	479.7	135.9%
3	491.0	139.1%
4	488.0	138.2%
5	489.3	138.6%
6	500.4	141.7%
7	494.8	140.2%
8	496.3	140.6%
9	489.0	138.5%
10	484.0	137.1%
11	502.0	142.2%
12	499.8	141.6%

6 BRIEF DISCUSSION

Comparing Tables 3 and 4 allows to speculate if the relatively low penetration achieved in case 6 (Table 4) could be related to the smaller L/D ratio. The relevance of this ratio in the penetration can be observed that, despite of the penalisation imposed to L/D ratios bigger than the average value, all results are near the maximum value in the range.

Considering the densities of the penetrator and the sabot led to improved results, although not significantly. Whether this difference is relevant is a consideration for the designers to make.

Single-point cross-over and single-point mutation operations applied to a binary representation of the variables was used in this work, as presented by the authors (2014). The effect of different rates was not noticeable.

As stated in item 5, relatively large populations were used (3,600 individuals) in the included cases, combined with a fixed number of generations (2,000). The use of relatively large populations is an advantage in parallel environments and may allow to achieve the desired result quickly, thus reducing the need of a large number of generations. It was noticed that the use of small populations (100, 200 and 500 individuals) did not produce similar results as the obtained with larger populations. It was also noticed that, regardless of the size of the population, a large number of generations did not lead to improvement in the result neither.

The model presented by Bennett (1998), simple and yet complete, can be easily replaced by other models, providing flexibility and allowing the method to be tailored to specific needs, or even applied to other types of ammunition.

The work herein presented was produced whilst trying to understand why a global convergence was not achieved. It has been considered using Lagrange multipliers but the inherent difficulty of having three different, independent sequential problems prevented further investigations successfully using them so far.

7 CONCLUSION

The method in reference has been shown to be a useful tool in the design of new or in the improvement of existing kinetic energy munitions with significant gain in performance.

The impact of cross-over and mutation rates in the optimisation could not be verified since results with different rates were similar. Although global convergence might not be achievable, results provide valuable insights on the study of this class of problems and can be used to suggest design modifications to improve performance. Executions with smaller populations may provide further insights on this.

Finally, as before (2014), the authors suggest that the adoption of improved, more complex models, the incorporation of artificial intelligence and machine learning, as well as adaptive penalisation, might lead to improvements in the results.

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