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An Ordnance Reliability and Life Model for the Estimation of the Component Kits in Preventive Replacement in Terms of Production and Operating Costs

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Abstract. This paper presents an outline of a method of optimising the service life of aircraft guns at the stage of design engineering and retrofitting. The essence of this method is a selection of service lives and quantities of preventively replaced components and the service parts of non-reconditionable components resulting in an overall reduction of gun production and operating costs (including the costs of replacement parts stocks) with an improvement of the service life of the whole gun assembly. The method assumes that the service lives to be selected must meet a criterion of predefined reliability, maximum service availability when installed aboard a combat platform (i.e. an aircraft) and the minimum time to re-use.

It is pointed out that in the design engineering of preventive component replacement and the assessment of the gun selection, a criterion of total gun cost reduction shall apply; the total gun cost is construed as the cost of production/purchase and maintenance applicable to the operating mode (with the costs and time to provide replacement parts). The total gun cost should be decisive in the definition of service lives and the number of components in preventive replacement. To analyse and select the service life and the MTBR (*Mean Time Between Replacements*), examples of reliability and life models of guns were developed in reference to the applicable operating standards and changes in total costs. This was followed by a demonstration of an innovative model of mapping gun (production/purchase and operating) costs with a complex number plane. The method presented herein facilitates analysing and assessing the feasibility for improvement of a gun's availability in combat field and training operations.

Keywords: design and retrofitting of aircraft guns, operation, life estimation, service life, high fire rate guns, reliability, ordnance, replacement parts stocks, ordnance availability

1. INTRODUCTION

Selection of service life for ordnance components subject [3, 11, 27] to preventive replacement is a significant stage in system design [9, 19, 30]. A good selection of service life facilitates maximised usage of the life [19] of components and assemblies with the longest life duration and qualified as non-replaceable [3, 7, 13, 16, 17, 18, 20, 25]. Given the variety of criteria in the design engineering of objects (such as mass reduction, retention of a designed reliability level or availability level, etc.), some parts/components/assemblies of ordnance require preventive replacement of these items with due consideration of cost optimisation and the preventive MTBR/service life [13, 19, 25]. To determine the service life of an object only with the results of the object's change of life vs. reliability [10, 21, 24] is an overt simplification if the costs and variability of maintenance quality and the operating environment. Hence a reliability and life model applicable to aircraft guns and being a plot of reliability vs. time to failure of gun components within a population of the same guns (Fig. 1) is a simplest model which facilitates the analysis and selection of component service life and MTBR. When reliability is specified, the service life (in units of time or operating cycles) can be determined for a component. However, already at the stage of design engineering of an object, the service lives of object components should be determined with consideration of the object's time to failure, compliance with the life of the whole object, compliance with the scheduled maintenance times of the system in which the object operates, and the operating cycles of the object (use, maintenance, and standby for maintenance or use).

Note that 'service life' as construed by common consent in Polish scientific papers is "resurs" and hails from the jargon used in Polish military technical operations.

Hence, in Polish reality, ‘service life’ (PL: resurs) (*R*), which in English is also known as ‘useful life’ ‘calendar life’ or ‘operating life’ [5, 14] may denote: operating life, life, operating life, fitness for use, or working life (expressed in operating cycles or mileage) of an object with predefined operating and maintenance conditions. The factor *R* in Polish and foreign references is investigated mainly for the selection of *R* for machine parts (components) or complete objects at the stages of object design engineering and operating implementation carried out by engineering object manufacturers. The factor *R* value [26] of a specific object is, as a rule of thumb, usually determined by the manufacturing plant from applicable test results and applies to the projected (average) period or operating cycles of the object. Manufacturers usually reduce the maximum permitted *R* of an object to its working life within which ageing factors are still not predominant. [3] defines the operating life of a technical object as the operating life between each two maintenance cycles. [4] provides a concept of ‘functional resources’ of elements and technical objects which result from the performance capabilities that are generated once an element or a technical object is manufactured.

The author of [4] disclosed that the consumption of the functional resource of an object is not a property of the object; it is dependent on the operation of the object. Many works [e.g. 6, 15, 19, 20] investigate modern methods for the assessment of health of technical objects and relate the methods with the in-operation statistical data to forecast the life (and extend the operating time) and reliability of the objects in their operating systems. However, certain time is necessary to acquire the statistical data, which are only reliable when applied to the same or similar operating conditions. A critical problem here is the selection of service life whenever an object’s load is changed, the operating process of an object is upgraded, or the whole object’s service life is extended by extension of the service life of its primary component. An example applicable to an airplane would be its airframe. It is critical to differentiate the approach to the determination of service life of the components of an object, a gun, or a machine considering the adopted optimisation criteria, which may include: retention of the required levels of reliability, life (durability), availability of materials, production time, cost minimisation, and achievement of a balanced reliability structure, when ordnance is considered. Some of the problems discussed in this paper have been proven useful in the improvement of the efficiency ordnance design engineering, production and operation [9, 12, 18, 25]. However, the existing reference literature lacks the holistic approach presented herein.

The focus of the author’s works so far [7, 8, 10, 11, 25] was placed on the determination of service life and required quantities of components, both in theory [8, 10, 25] and from operating databases [7, 11].

Optimisation of component quantities in component kits and the times between their preventive replacement were the focus of this author during his work on the retrofitting of the aircraft gun types NR-30 and NS-23 (in collaboration with Air Force Institute of Technology, Warsaw, Poland), and resulting in the implementation of Service Bulletins U/4902/E/06 and U/4988/E/07 in the operations of the Polish Air Force.

Aircraft guns, the maintenance system of which features frequent periodic maintenance tasks imposed by the necessary cleaning and preservation (following each fire mission, e.g. a flight day), do not require a long life of their easily replaceable components. What is sufficient to be secured is the long life of the fixtures of easily replaceable components which form the gun assembly (which is usually the gun frame) and which provide attachment to the aircraft hardpoints. This approach is well met by powered rotary machine guns, a Polish example of which is the latest four-barrel 12.7 mm machine gun, manufacturer's designation WLKM [11]. The replacement of an entire gun assembly contributes to the problems with maintenance (especially under combat mission conditions), since it requires test firing to align the firing line of the barrel with the LOS of the targeting systems of the weapon. It is then prudent to include the criterion of maximum ordinance availability as installed aboard an aircraft and the criterion of ordinance operating cost minimisation in the process of ordinance design engineering (i.e. the selection of life and reliability levels of the complete ordinance and its components).

2. OBJECTIVE AND ASSUMPTIONS FOR THE ESTIMATION OF AUTOMATIC AIRCRAFT GUN COMPONENT KITS

The objective of this paper was to develop an outline of a method applied to optimise the selection of service lives and quantities of preventively replaced components and the service parts of non-reconditionable components resulting in an overall reduction of gun production and operating costs (including the costs of replacement parts stocks) with an improvement of the service life of the whole gun assembly. This method is based on reliability and life models of ordinance and components thereof, the reliability structure of technical objects, a proposed method for determination of total ordinance costs, and a scheme for component service life optimisation by applying the total ordinance (gun) cost model. It was assumed that the selected service life must meet the criterion of minimising the time to reuse the ordnance. Given the practical experience to date, the proposed outline concerns a method based on reliability and life models (N-T), ordnance reliability structures (S_NO), and a purpose-designed (within a complex number space) total cost model (K_{Co}), which results from the production costs (K_P) and the operating costs (K_E) for the purpose of determining the service life (R_o) of components subject to preventive replacement.

The operating specifics (i.e. the use and maintenance combined) and the wear rate of gun components (imposed by the requirements for air combat, i.e. maximised fire rate with a minimum deadweight of a gun) applicable to aircraft guns is (in certain aspects) very different from same-calibre automatic ordnance installed on combat ground vehicles, air defence systems, or immobile platforms. Note that the wear rate of a gun depends greatly on the calibre, power rating, and projectile propellant type; example: desensitization of the propellant in a cartridge helps extend the service life by 100% for JakB 12.7. It is then critical to include all possible and major contributors to the service life of ordnance (guns) and components thereof.

2.1. Assumptions for the required conditions of implementation of components under preventive replacement

The process of estimation of replacement parts of guns and gun populations includes: estimation of components under preventive replacement (which depends on the number of shots fired), estimation of components prone to failure by random (and sporadic) overload and material defects, and estimation of components eligible for replacement after a specified operating time. A high reliability level of a gun is not always cost-effective by maximizing the life (durability) of gun components, which under certain conditions is also infeasible (due to design engineering limitations on volume and weight). The decisive issue here is the costs of production and operation of an object, and the required tactical and technical guidelines of the object. For aircraft guns, the guidelines include: minimised weight, maximised fire rate (due to the extremely short effective firing times during air combat), maximised gun service life, and simplification of preventive replacement of those components which are not cost effective (or simply impossible) to increase the life of up to the target life of the whole gun assembly. It is assumed that gun components are qualified for preventive replacement if:

- the components do not require complex replacement processes, and the replacement can be completed during periodic gun maintenance;
- a functional model of the gun components can be developed (and from which a structural model of replacement can be derived) with the structural modularity of the gun, where each component can be preventively replaced or form a base module by which the life of the whole gun is determined;
- an explicit selection of reliability, life and other criteria is approved for a gun and its components;
- it is feasible to build a serial reliability structure (S_NO) of a gun given its modular structure and the pre-design number of necessary preventive replacements which transform the gun’s serial structure into a serial-parallel structure, in which the parallel structural elements define the necessary numbers of preventive replacement;

- it is feasible to build (upon the data from the manufacturer or the operation of the same or similar guns) *N-T* models for the individual elements of the serial reliability structure of a gun and for the entire gun (with a module qualified as non-replaceable, which is usually the frame for the remaining components, or an element permanently attached to the frame);
- an analysis was completed on the selection of preventive replacement times against the periodic maintenance times of a gun and its operating system, and the number of maintenance tasks which involve disassembly of the gun for preventive maintenance was approved;
- the required quantities of components/modules will be calculated for the specific gun component types and the gun population;
- preventive replacement component kits will be defined with the replacements following random failures, where the component kits will be kits of individual components and component groups;
- the foregoing assumptions will be verified against the characteristic standards of operation of a gun (checks, training firing and combat firing);
- schemes of preventive replacement rescheduling will be developed by applying a differentiated process of gun use;
- whenever cost effective, an operating strategy based on the technical health will be applied, or a post-maintenance service life will be established;
- it is feasible to develop and implement a hard-copy or computer-based support system for the management of in-operation preventive replacement of gun components.

2.2. Method assumptions

The assumptions for the preliminary method design stage applicable at the stages of gun design, retrofitting and operation include:

- an aircraft gun service life can be extended by a correct selection of service lives and the number of gun component preventive replacements;
- the essence of the method is to select service lives and quantities of preventively replaced components and the service parts of non-reconditionable components to achieve an overall reduction of gun production and operating costs (including the costs of replacement parts stocks) with an improvement of the service life of the whole gun assembly;
- the service lives shall be selected to meet the criterion of predefined reliability, maximum service availability during a combat mission and the minimum time to re-use;
- the main criterion for the selection of component service lives and component preventive replacement intervals is to minimise the total gun costs as estimated by the costs of production/purchase and maintenance/use of the gun;

- the requirement of understanding the reliability and life models of the gun with respect to the gun's operating standards and changes in the total gun cost;
- a new model must be proposed for mapping the gun (production and operating) costs, where such a model can be developed with complex numbers, for example;
- the improvement of gun availability in operation in combat and training, which is an essential criterion decisive for the gun service life extension.

3. DEVELOPMENT OF *N-T* AND *S*N*O* MODELS FOR AIRCRAFT GUNS

The development of *N-T* and S_NO models for aircraft guns is essential for the estimation of preventive replacement component kits as applied herein. A standard aircraft gun *N-T* model is shown in Fig. 1 (and Fig. 2 shows the same for the components); the applicable S_NO model is shown in Fig. 4. To choose an optimum selection of preventive replacements, the costs of components and preventive replacement execution must be considered. If the cost of an additional replacement exceeds the cost of the component being replaced, the preventive replacement interval of the component must be reduced, and vice versa (Fig. 2). With the reliability criterion, the component life must be reduced by applying more frequent preventive replacements. If a non-replaceable component has a longer life in actual operation than designed, the analysis shall focus on all other components, since they cannot have their service lives automatically and proportionally increased. The simplest solution here is to assess the reliability of components with the data on their failure rate in operation (if the data is available). Whenever actual reliability significantly exceeds the design reliability, the component service life shall be extended proportionally to the extended life of the primary component (which is non-repairable and non-replaceable). Whenever the actual reliability of a component is equal to or less than the design reliability, more preventive replacements shall be determined (applicable examples include rubber parts, such as gaskets). If no modifications are made to such component's production, its service life shall not be extended; hence, additional preventive replacements shall be designed. The S_NO must include four component groups:

- primary components, which are non-replaceable and non-repairable;
- components with the reliability and life levels significantly above those of the primary component, and the failure rate is a result of excessive loads which may only occur at random (e.g. material defects, outcomes of accumulated random loads);
- components with normal wear that depends on the operating intensity of the gun, and these components are eligible for preventive replacement by design (e.g. springs, latches, etc.);

- ageing components, with the main contributor of the ageing being;
- the progression of time (e.g. rubber gaskets).

For each of these groups, the service lives shall be determined according to the actual methods in use. Hence, for an aircraft gun *N*-*T* mode, each of the groups features a different method of determination of component service life and preventive replacement number.

In certain types of aircraft guns, disassembly of a gun may result in a condition under which the components must be realigned during every reassembly; the increasing number of disassembly and reassembly cycles increase the wear rate. Here, another criterion is applicable: minimisation of the number of gun disassembly maintenance tasks. The number of preventive replacements during these maintenance tasks shall be minimised by harmonising the preventive replacements with the minimum number of gun disassembly cycles. Hence, every optimisation criterion imposes specific preconditions to the *N*-*T* model. The preconditions follow:

- minimise the weight at the design stage at the expense of life, if:
  - the replacement cost is low and does not affect the gun life;
  - the preventive replacements do not exceed the scheduled periodic maintenance which results from the gun operation (e.g. cleaning after a fire mission);
  - the component is not primary or complex;
  - the production of components is simple to process, and replacement component stocks are not difficult in terms of logistical processing;
  - the replacements do not require experienced operators or complex/expensive tooling (and can be completed during periodic maintenance and with standard work tools).
- at the production stage:
  - the manufacturing processes are simple and generally available (manufacturability exists in any production plant which makes similar components);
  - the materials are highly available;
  - the production launch does not require a complex pre-production process.
- at the operating stage:
  - the replacement of components does not require high personnel qualifications or complex tooling;
  - high operating reliability is required;
  - short preventive replacement time is required after use and to prepare the gun for re-use.

3.1. *N-T* model

The *N-T* model is a function of reliability. The probability of correct operation (or the function of reliability) $R(t)$ expresses the probability at which an aircraft gun, which starts operating at time $t_0 \geq 0$ will not fail before time t and will continue to work properly within an interval (t_0, t_0+t). Relationship (1) includes three parameters: reliability (R), life (T) and health check/inspection time (t). The parameters can be selected relative to each other for a gun and its components to achieve a gun design optimised for a specific combat mission under specific conditions of maintenance and operation.

$$R(t)=P\{T>t\} \tag{1}$$

with:

$R(t)$ – expected / designed (limit / acceptable) reliability at time T;

T – time to which the gun remains fit for use at the designed reliability level; this parameter is the gun's reliability or the determined service life of the gun or its specific component;

t – the time of testing the fitness of the gun for use.

3.1.1. *N-T* model for an aircraft gun (30 mm calibre)

This example shows an *N-T* model (see Fig. 1) for a 30 mm calibre aircraft gun (and based on the definition of wear in [7]) used with the following firing bursts: 1 – single shots, 2 – one burst in training, 3 – more than one burst in training, 4 – one burst in combat, 5 – more than one burst in combat, 6 – one full ammunition loadout.

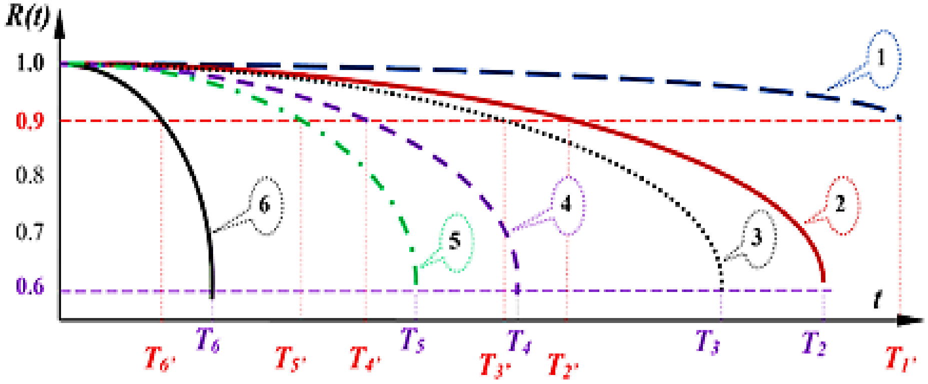

Fig. 1. *N-T* model of a 30 mm gun barrel / aircraft gun used with the following firing bursts: 1 – single shots, 2 – one burst in training, 3 – more than one burst in training, 4 – one burst in combat, 5 – more than one burst in combat, 6 – one full ammunition loadout, $R(t)$ – reliability, T – life

The *N-T* model (Fig. 1) shows that the life/service life of the aircraft gun / barrel is the following at the gun reliability of 0.6: T_6 – when firing with a single ammunition loadout, T_5 – when firing in more than one combat bursts, T_4 – when firing in one combat burst, T_3 – when firing in more than one training burst, T_2 – when firing in one training burst. The life / service life of the aircraft gun / barrel is the following at the gun reliability of 0.9: $T_{6'}$ – when firing with a single ammunition loadout, $T_{5'}$ – when firing in more than one combat bursts, $T_{4'}$ – when firing in one combat burst, $T_{3'}$ – when firing in more than one training burst, $T_{2'}$ – when firing in one training burst, $T_{1'}$ – when firing single shots. It is evident that the increase of the designed gun reliability and the increase in the firing intensity reduces the life of the whole gun and its components. Application of the maximum reliability with the maximum use standards of the gun markedly changes its life, and thus the operating life.

3.1.2. *N-T* model of an aircraft gun/component with increased or reduced production and operating costs

The example of an *N-T* model of an aircraft gun/component with increased or reduced production and operating costs with shown in Fig. 2.

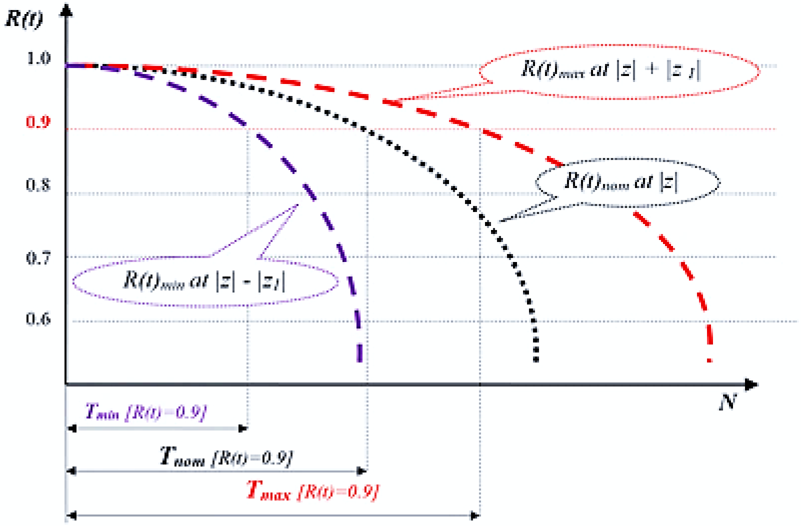

Fig. 2. Gun/component *N-T* model which includes the costs (|**z**| = x + i y) of production (x) and operation (y): $R(t)$ – reliability, T – life, $R(t)_{min}$ at |**z**| - |z_1| – reliability of a less expensive gun/component, $R(t)_{\mathrm{miax}}$ at |**z**| + |z_1| – reliability of a more expensive gun/component, $R(t)_{\mathrm{nom}}$ at |**z** |– reliability at the nominal gun/component costs

Each reduction of production costs by application of less expensive materials, sub-par technologies and poorer quality control causes an accelerated emergence of failure in the affected gun components.

However, as already explained, this is not necessarily mean negative results if preventive replacement of the affected components is provided at the reliability levels required for the components.

The *N*-*T* model (Fig. 2) shows that the life/service life of the aircraft gun/component is the following at the gun reliability of 0.9: $T_{\min(R(t)=0.9)}$ – with lower costs of gun/component production and operation, $T_{\mathrm{nom}(R(t)=0.9)}$ – with the nominal costs of gun/component production and operation, $T_{\max(R(t)=0.9)}$ – with higher costs of gun/component production and operation.

3.2. *SNO* model

For the kit of primary modules/components (without an ammunition belt and a firing control system) shown in Fig. 3, a reliability structure can be built as shown in Fig. 4.

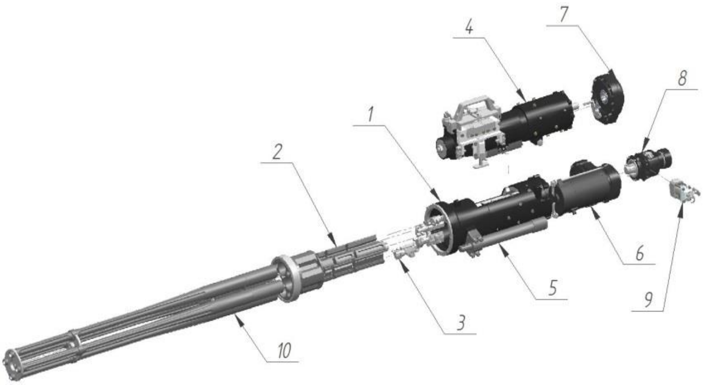

Fig. 3. Breakdown of the gun modules/components selected for the reliability structure: 1 – frame, 2 – rotor, 3 – breeches, 4 – ammunition feeding system, 5 – shocks, 6 – electric motor barrel rotation drive, 7 – ammunition feeding system drive gear, 8 – ammunition feeding system power switch, 9 – power switch safety latch, 10 – gun barrels [11]

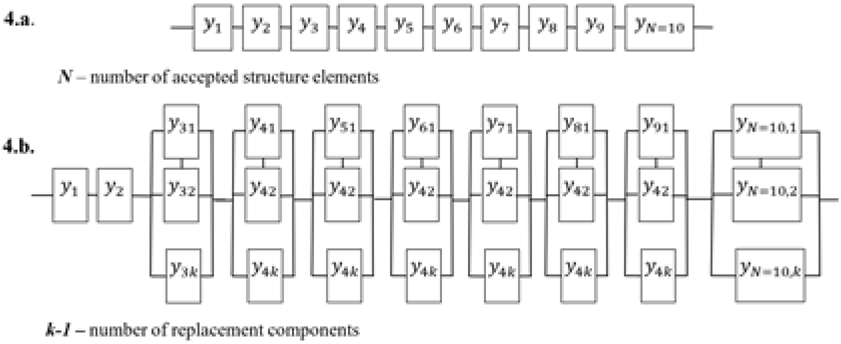

Fig. 4. Gun reliability structure: 4.a. serial structure; 4.b. serial-parallel structure (based on [11])

It is assumed that the elements of the serial structure (Fig. 4a) are independent of one another in terms of failure rate. The reliability of the system is the product of reliability of its components, and the system life is determined by its component/assembly with the lowest reliability. Life can be improved by improving the reliability of the weakest components. This is done by upgrading them in the design engineering process, or by preventive replacement.

In this structure, the non-replaceable components are the frame (y_1) and the rotor (y_2). Other components can be repaired by replacement with new counterparts. Figure 4b shows a serial-parallel structure which includes components replaced preventively or following a failure.

The replacement component kits for preventive and failure replacement are designed from:

- the analysis of operating data derived from the existing solutions which use components similar in design or analogical to the components of JakB-12.7 (e.g. the barrel);
- theoretical analysis and reliability and life testing of function-critical components and assemblies (e.g. firing pin, breech, and cut-off system);
- expert assessments completed for the components with a low theoretical failure and wear probabilities and for which the design calculations provide a high surplus strength (e.g. the frame and the rotor), and the life of which is critical to the maximum service life of the complete gun.

3.3. Structure of preventive replacement times in existing periodic maintenance

Operation of aircraft incurs little problems in adjusting the preventive replacement times to the periodic maintenance schedules. Aircraft guns require frequent cleaning, involving complete disassembly. It is problematic, however, to track the required time of replacement the components of a specific gun and to reliably record the number of shots fired from the specific guns, followed by reliable processing of this data into the scheduling of the maintenance times. The problem would seem to be simple to solve for anyone who has not participated in training or combat missions; in reality, it is not simple at all.

One solution involved recording the component replacement schedules on wall boards (Fig. 5) at maintenance facilities; a more modern approach replaces the wall board logging with mobile applications. The specific nature of live fire training with aircraft guns and the related extension of gun service life require an analysis of adequacy between the existing replacement component kits and the kits required under the specific operating conditions where training fire missions prevail. The statistical data for training fire missions reveals that there is a group of surplus components with shortages of some other components.

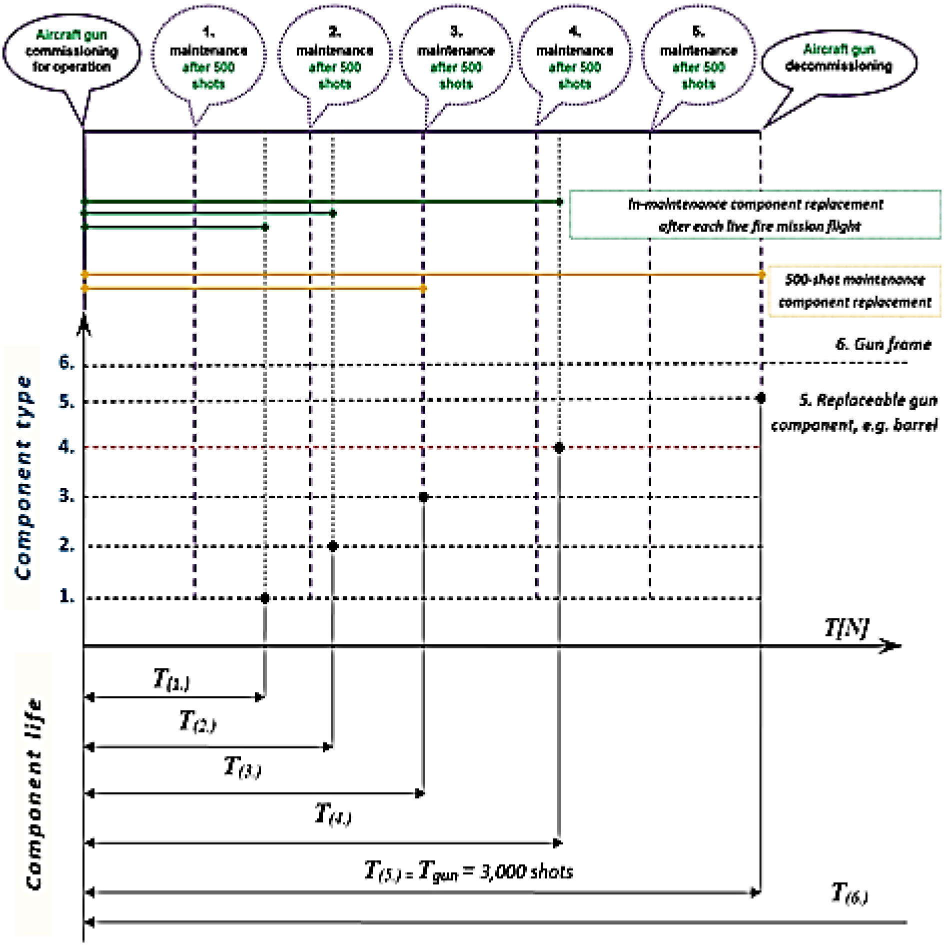

Fig. 5. Model of a structure for preventive component replacement times: *N* – number of shots fired, *T[N]* – component life expressed as the maximum number of shots fired

The reason is simple: manufacturers develop replacement component kits for wartime combat specifications, which vary from training specifications, and do not consider extended gun service life.

The analysis of adequacy conducted on the existing replacement part stocks must consider the specific nature of aircraft guns, which is:

- the point of interest related to an aircraft gun is to maintain the required reliability during actual use;
- the component replacement duration must not be longer than the maintenance cycle duration, and each replacement must be completed during scheduled periodic maintenance;

- it must be known which components suffer critical failure and the contributors of critical failure; the replacement of critically failed components must be scheduled;
- it is not possible to design a piece of ordnance which does not suffer from failure and component wear;
- gun jamming remedied by reloading a round is insignificant.

3.4. Mathematical model of production and operating costs for the optimisation of preventive replacement component service life

It is critical to map the production costs of an object and its components replaced at the operating stage. However, when a user purchases or orders the production of a specific ordnance type, it must consider the operating costs of the ordnance, which include: costs related to the qualifications of ordnance maintenance technicians, the required replacement facilities and tools, the projected ordnance non-service time for the duration of maintenance, the number of additional maintenance tasks, the ordnance availability as installed aboard an aircraft, etc. A critical aspect is to map these costs with the service life they can provide, and this service life is a measure of the capital expenditure committed.

Financial analyses of these aspects are most likely carried out; however, no comprehensive representation of them has been found. Hence, an ordnance designer cannot use such financial analysis for a fast or preliminary verification of the cost optimisation of its solution and/or to compare the solution with other weapon systems in different operating systems. This paper proposes an innovative method for modelling the costs and mapping them to the service life outcomes. The innovation of the method consists in the application of complex numbers, by which the total gun cost separates the production costs from the operating costs. The proposed potential cost model (P_K) helps determine a numerical index of the total gun costs expressed as K_{Co} and mapping the index to the gun service life (R_o). This approach significantly simplifies ROI/profitability analyses and demonstrates very well the dependence (and its magnitude) of ordnance service life on specific costs.

3.4.1. Object potential costs model (P_K) in a set of complex numbers

The mathematical form of the P_K model is represented by relationship (2) and illustrated in Fig. 6. The mathematical model of numerical indicator P_K allows mapping the production costs (K_P) and operating costs (K_E) of an object, resulting in a single numerical value of the potential production and operating costs of the object/component.

$$P_K = (K_P)_i + \mathrm{i}(K_E)_j \tag{2}$$

with:

P_K – complex number, defining the potential production and operating costs of an object/component;

K_P – real part of complex number P_K, defining the object / component production costs;

K_E – imaginary part of complex number P_K, defining K_E – the object/ component operating costs;

i – value number i of costs K_P within an interval $0 – i_{gr}$;

j – value number j of costs K_E within an interval $0 – j_{gr}$;

i_{gr} – maximum (limit) value of the production costs;

j_{gr} – maximum (limit) value of the operating costs.

The potential production and operating costs (P_K) of an object/component are expressed (2) with the value of complex number $z = a_i + \mathrm{i}b_i$ the components of the real part (a conventional inherent resource of the costs) of which are the production costs ($a_i = K_P$) and the components of the imaginary part (a conventional inherent resource of the costs) of which are the operating costs ($b_i = K_E$). Fig. 6 illustrates the numerical indices P_K.

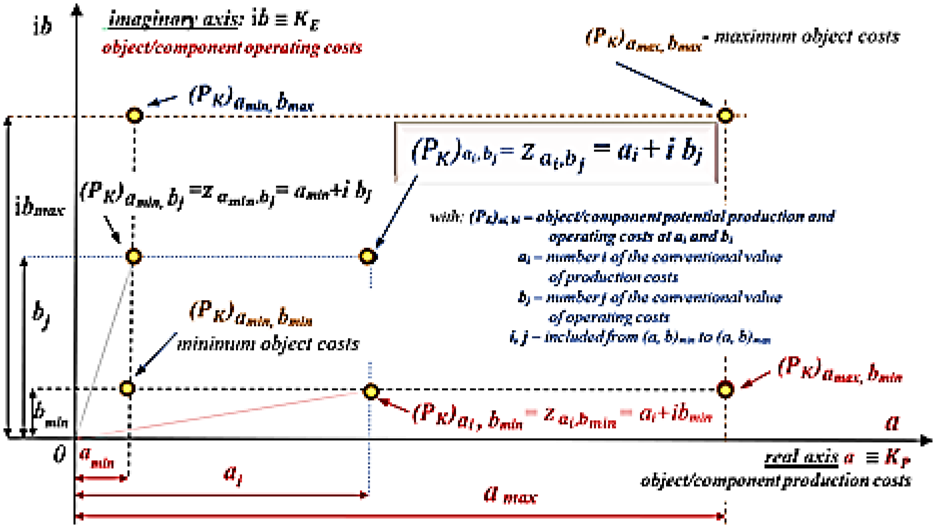

Fig. 6. Object potential costs model (P_K) in the 1st quadrant of the complex number plane

This shows the overall reduction of value P_K described with relationship (3)

$$(P_K)_{a_i,b_j} = (K_P)_{a_i} + \mathrm{i}(K_E)_{b_j} = z_{\,a_i,b_j} = a_i + \mathrm{i}b_j \tag{3}$$

and special cases of P_K, including:

- $(P_K)_{a_{max},b_{max}}$ – at the assumed maximum values of K_P and K_E;
- $(P_K)_{a_{min},b_{min}}$ – at the assumed minimum values of K_P and K_E
- $(P_K)_{a_{min},b_j}$ – at the minimum value of K_P,
- $(P_K)_{a_i,b_{min}}$ – at the minimum value of K_E.

The illustrations of P_K in Fig. 6 allow a conclusion that when the value of $b_i = K_E$ is changed or the value of $a_i = K_P$ is changed (or both are changed at the same time), the value of P_K changes. This means that every change in the performance conductions, e.g. the wear rate (a – change in use standards), or a change in the maintenance quality (ib) results in a change of P_K, and this a change in the location of complex number P_K in the complex number plane. A comparison (with inequalities) between two P_K values, represented by two complex numbers, is not possible, since field $\mathbb{C}$ (of complex numbers) is not organised. The non-organisation of $\mathbb{C}$ make inequalities of complex numbers, like $z_1 > z_2$ (with $P_{K1} > P_{K2}$ in the discussed example) pointless, unless they apply to real numbers. An ordering relation exists for two complex numbers, like the following one (7):

$$a_1 + i\,b_1 \geq a_2 + i\,b_2 \Leftrightarrow a_1 \geq a_2 \; or \; a_1 = a_2 \; i \; b_1 \geq b_2 \tag{7}$$

but it is difficult to correlate it with arithmetic and derive a numerical value sensible to the entire complex number, and not just to its components. The relation defines the change of a complex number represented by the point the complex number defines on the complex number plane. This change alone facilitates an estimation of which primary resource types should be changed or has changed since the last time the value of P_K was determined. However, the modelling proposed here which involves the application of the complex number for the mapping of P_K in a function of K_P, K_E facilitates using the P_K value defined so to calculate the total object costs K_{Co} (see Section 3.4.2). Given this, Section 3.4.3 is a proposal of a model for the determination of gun (ordnance) service life, R_o, from K_{Co}.

3.4.2. Mathematical model of K_{Co} in a set of complex numbers

While the value of complex number P_K does not satisfy arithmetic requirements, its modulus does so. The modulus was axiomatically mapped (with the method proposed here) as the value of K_{Co}. Expression $|Z_1| > |Z_2)|$ (which reads $|P_{K1}| > |P_{K2})|$ in this example) is perfectly feasible because of (4), and the real numbers form an organised body.

$$|Z_1| > |Z_2)| \in \boldsymbol{R}; \; |P_{K1}| > |P_{K2})| \in \boldsymbol{R} \tag{4}$$

A geometric interpretation of P_K modulus on a complex number plane is the distance of the complex number point (representative of P_K) from the origin of the coordinate system. Hence the modulus, or the absolute value of $z \epsilon \mathbb{C}$ is expressed as (5)

$$|z| = |a_i + \ i\ b_i\ | = \sqrt{a_i{}^2 + \ b_i{}^2} \text{ to } K_o = |P_K| = \sqrt{(K_P)^2 + \ K_E{}^2} \qquad (5)$$

Figure 7 shows three cases of characteristics pairs of values K_P, K_E, from which $(P_K)_{1,1}$; $(P_K)_{2,min}$; $(P_K)_{min,2}$ are derived with the same value of K_{Co}, i.e. $K_{Co(1,1)} = K_{Co(2,min)} = K_{Co(min,2)}$, as expressed with a set of equations (6)

$$K_{Co_{min,2}} = \left|(P_K)_{min,2}\right| = \sqrt{x_{min}^2 + y_2^2}\ ; \qquad K_{Co_{1,1}} = \left|(P_K)_{1,1}\right| = \sqrt{x_1^2 + y_1^2}$$

$$K_{Co_{2,min}} = \left|(P_K)_{2,min}\right| = \sqrt{x_2^2 + \ y_{min}^2}\ ;\ K_{Co_{o_{1,1}}} = K_{Co_{min,2}} = K_{Co_{2,min}} \qquad (6)$$

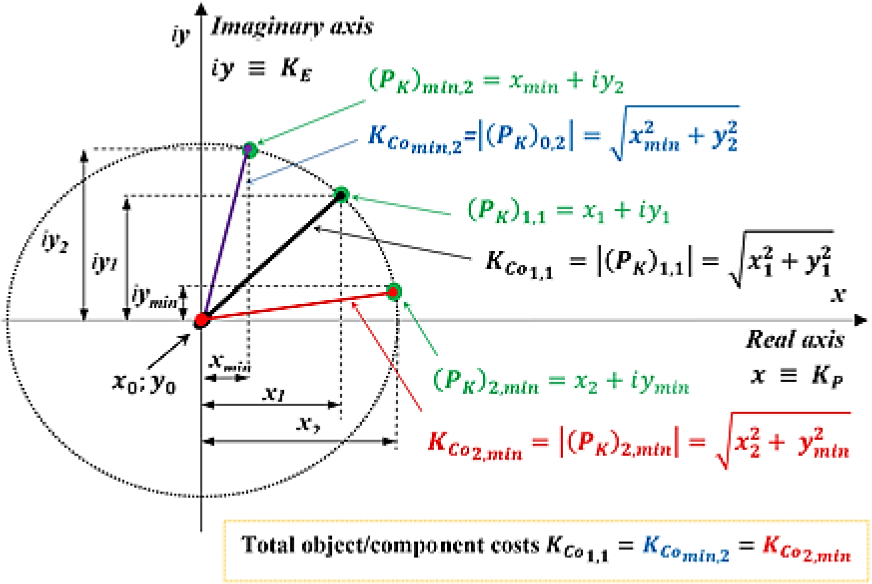

Fig. 7. Model of K_{Co} determination in the 1st quadrant of the complex number plane

Figure 8 shows three cases of characteristics values K_P, K_E, from which $(P_K)_{1,1}$; $(P_K)_{2,3}$; $(P_K)_{3,2}$ are derived with different values of K_{Co} and where the total object costs are $K_{Co(3,2)} > K_{Co(2,3)} > K_{Co(1,1)}$, as expressed with a set of equations (7)

$$K_{Co_{2,3}}=\left|P_{K_{2,3}}\right| = \sqrt{x_2^2 + y_3^2}\ ; \quad K_{Co_{3,2}} = \left|P_{K_{3,2}}\right| = \sqrt{x_3^2 + y_2^2}$$
$$K_{Co_{1,1}} = \left|P_{K_{1,1}}\right| = \sqrt{x_1^2 + y_1^2}\ ;\ K_{Co\,o_{3,2}} > K_{Co_{2,3}} > K_{Co_{1,1}} \tag{7}$$

Based on the illustrated mapping between K_{Co} and P_{K} with various sets of values for K_{P}, K_{E} shown in Fig. 7 and Fig. 8, the object/component manager/ operator can immediately, yet roughly estimate the changes in K_{Co} which may occur in the object/component when K_{P} and/or K_{E} is changed, and what reserve/deficiency there is for K_{P} and K_{E} for the object at the required productivity value of K_{Co}.

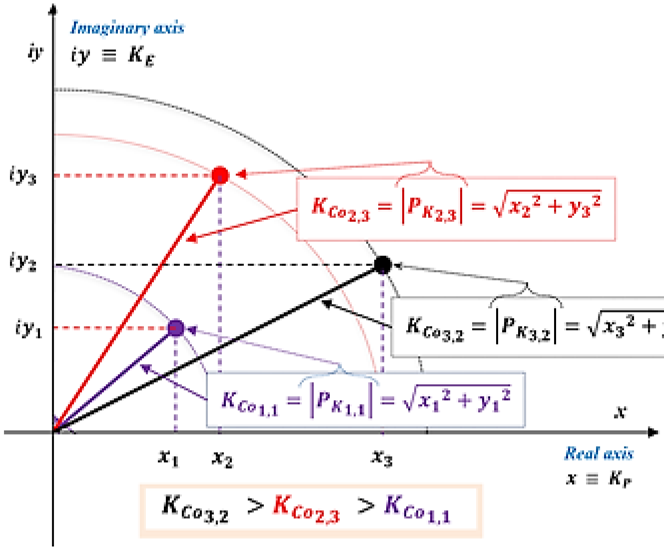

Fig. 8. Illustration of the increase / reduction of K_{Co} caused by changing the operating costs (K_{E}; $y_1 < y_2 < y_3$) and changing the production costs (K_{P}; $x_1 < x_2 < x_3$)

Understating the existing or forecast the level of operating personnel's technical proficiency, technical culture (in the form of the K_{E} values assigned), the retrofitting conditions of objects and the environmental conditions (in the form of the K_{P} values assigned), reasonable choices of gun service life (R_{o}) and the replacement component kits can be made, given K_{Co}, as shown in Section 3.4.3.

3.4.3. Mathematical model of R_o in a set of complex numbers

If, provided that corresponding conventional conversion factors are applied, an increase or reduction of K_{Co} is directly translated into an increase or reduction of the service life of an object (or a component or an assembly) (R_{o}), the model expressed with relationship (5) is converted into (8).

The service life ($R_{\mathrm{a_i,b_j}}$) of an object is defined here as a modulus of complex number $(P_{\mathrm{K}})_{\mathrm{a_i,b_j}}$ with the complex number components being the conventional object production cost $(uK_{\mathrm{P}})_{\mathrm{a_i}}$ at a value of a_{i} and the conventional object production cost $(uK_{\mathrm{E}})_{\mathrm{b_j}}$ at a value of b_{j} (8).

The term ‘conventional’ includes all the cost matches within a group of contributors which improve/reduce the life of an object in production, and within a group of contributors which improve/reduce the usage of the produced life of an object in operation.

Regarding expert knowledge, anyone can intuitively prove the argument that a reasonable increase of investment into an object in production (by applying better materials, processes and quality controls) results in an improved life (and an improved service life) of the object. By analogy, if capital expenditure is increased on the operating process (with better and more expensive maintenance tooling, use of advanced diagnostic systems, employment of highly professional maintenance technicians and operators), it favours an improve usage of the operating potential (the maximum life) of an object. Conversely, if the production costs are cut at the expense finished product quality (life) and the operating costs are cut by reducing the usage of the existing life of an object, then, in statistical terms, the service life of the object has to be reduced to retain the required operating reliability of the object. The reductions can be functionally related to lower total object costs, K_{Co}. These assumptions are adopted axiomatically.

Investigating a special case of value $K_{\mathrm{P}} = x_1$ and $K_{\mathrm{E}} = y_1$, the module of complex number $(P_{\mathrm{K}})_{1,1}$ can be expressed as $R_{\mathrm{o}1,1}$.This is shown in Fig. 9, where complex number $(P_{\mathrm{K}})_{1,1}$ enables the determination of service life $R_{\mathrm{o}1,1}$ of an object with formula (8). Relationship (8) can already be applied in a data acquisition system of a computer-aided operating management (machine maintenance) system [9, 27, 30, 31].

$$R_{o_{1,1}} = \left|(P_K)_{1,1}\right| = \left.\sqrt{(a_i)^2 + \left(b_j\right)^2}\right|_{\substack{i=1\\ j=1}} = \sqrt{(x_1)^2 + (y_1)^2} \tag{8}$$

with:

$R_{\mathrm{o}\,1,1}$ – production (servicing) service life of an object at $(P_{\mathrm{K}})_{1,1}$

$(P_{\mathrm{K}})_{1,1}$ – potential production and operating costs of an object/component at $uK_{\mathrm{p}} = x_1$ and $uK_{\mathrm{E}} = y_1$

x_1 – value uK_{p}, y_1– value uK_{E}

i – is $0, 1, 2 \ldots i \ldots i_{gr}$, j – is $0, 1, 2 \ldots j \ldots j_{gr}$.

Fig. 9 illustrates special cases of a complex number expressed as $(P_K)_{\min,2}$ and $(P_K)_{2,\min}$, and the resulting values of R_o, such as: $R_{o_{\min,2}}$ – at the zero value of $uK_p = x_{\min}$ – described with expression (9) and $R_{o_{2,\min}}$ – at the zero value of $uK_E = y_{\min}$ – described with expression (10). The two extreme cases highlighted in Fig. 9 could be interpreted as follows:

- If $R_o \cong R_{o\ \min,2}$ (if $R_{\min,2} \to x_{\min}$) which means that the object has a low post-production value. Only if the maintenance / control costs are high can the object achieve the assumed value of $R_o \cong R_{o\ 2,\min}$ (9).
- In the second case, if $R_o \cong R_{o\ 2,\min}$ (if $R_{o\ 2,\min} \to y_{\min}$) means that the maintenance costs of an object are low, it is so technically perfect that little maintenance and control is required within the assumed value R_o (10).

$$(P_K)_{min,2} = x_{min} + iy_2 \Rightarrow R_{o_{min,2}} = |(P_K)_{min,2}| \tag{9}$$

$$(P_K)_{2,min} = x_2 + iy_{min} \Rightarrow R_{o_{2,min}} = |(P_K)_{2,min}| \tag{10}$$

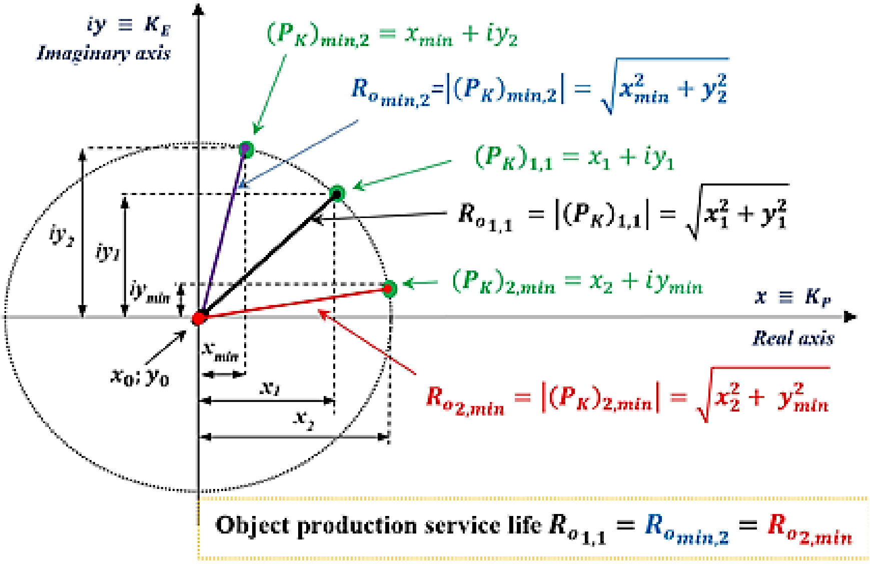

Fig. 9. Model of the determination of object production service live ($R_{o\ 1,1}$) in the 1st quadrant of the complex number plane

4. ESTIMATION OF THE COMPONENT KITS IN PREVENTIVE REPLACEMENT

By applying the *N-T* model (Fig. 1 and 2) and the S_NO model (Fig. 4 and 10) with the scheme of component replacement times (Fig. 5), the necessary number of preventive replacement components can be determined.

However, a sufficient rationale for this choice lacks any reference to the process of operation an object is intended for. The type of the operating strategy applied for a system in which the object will be placed, and the type of the operating strategy applied for the object in the same system will define the selection of the service lives of the modules/assemblies and of the elements/components, and thus the number of required replacement components, including the preventive replacement components/assemblies[1] (Fig. 5).

For aircraft cannons, yet another problem is relevant and related to the feasibility of various use standards during in-flight firing. This generated a great variance in the wear rate of gun barrels (as shown in Fig. 2). Replacement component kits are usually built for gun operating loads which occur during firing in long bursts, which are common in combat mission scenarios. Hence if an aircraft gun is predominantly fired in training mission scenarios (in short bursts, which impose lower loads while extending the operating life of the ordnance beyond the manufacturer's design), a certain number of spare parts (which depends on the operating life or actuation cycles during maintenance) will be insufficient, and this must be considered.

When analysing the maintenance times of a system formed by an aircraft, where the engine or engines is or are critical, it is impossible to harmonize the times of periodic and overhaul maintenance of aircraft guns with the maintenance of the entire aircraft. Therefore, an analysis of maintenance times of an aircraft gun should only be based on the periodic maintenance of its platform (the aircraft).

A method for estimating ordnance service life is shown in [11]. Based on this example and the proposed modification of the reliability structure (Fig. 10) of the ordnance, and according to the approach rationalized in this paper, the total aircraft gun service life was determined in Section 4.1. The essential resource of preventive replacement components for the aircraft gun was determined in Section 4.2.

In the reliability structure shown in Fig. 10: 10c. and relative to the structure shown in Fig. 10: 10b., the life of the frame (y_1), the rotor (y_2) and the shock absorbers (y_5) were increased, and one kit of each was added: the breeches (y_3) and the barrels (y_{10}).

While the production cost of the finished aircraft gun (K_P) with the new reliability structure will most likely be increased, the operating cost (K_P, K_E) of the aircraft gun should be markedly reduced, resulting in a significant reduction of the total aircraft gun costs (K_{Co}) in relation to the achieved service life.

---

[1] This terminology (Polish: 'część / zespół', respectively), is common in ordnance maintenance manuals.

This would also provide an additional deliverable (and a very important one) consisting in an extended operating life of the aircraft gun in a combat theatre, without the need for periodic maintenance, since there would be no need for aircraft gun replacement as frequent as before, and no need for test firing for alignment. If the aircraft gun is intended for sale, a great advantage in bidding for a sales contract would be the total service life, a critical commercial criterion.

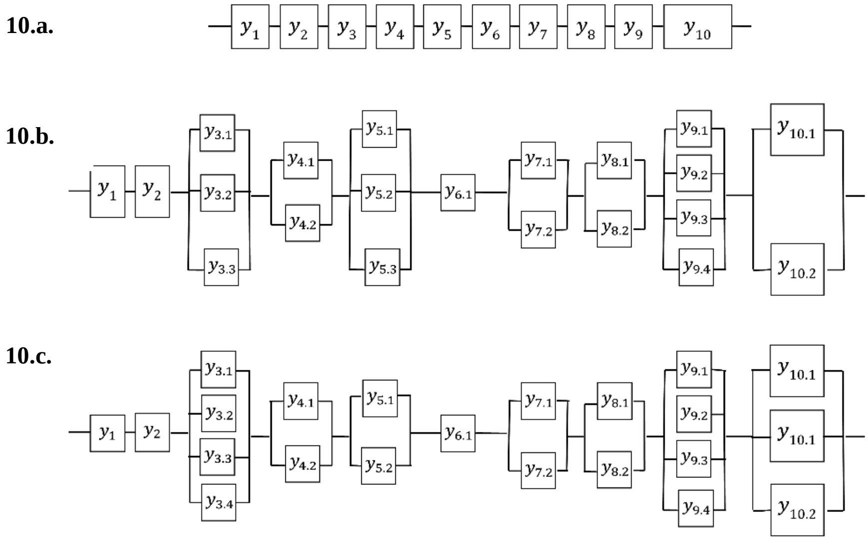

Fig. 10. Model of the aircraft gun reliability structure shown in Fig. 3: 10.a. – serial reliability structure; 10.b. – serial-parallel reliability structure, which includes preventive replacement of components prior to the design modification resulting from the cost analysis; 10.c. – serial-parallel reliability structure, which includes preventive replacement of components after the design modification resulting from the optimisation of aircraft gun production and operating costs

4.1. Simplified method of service life estimation

The aircraft gun serial-parallel reliability structure shown in Fig. 10b. was proposed as an outcome of an expert analysis of the structure shown in Fig. 10b.

The changes in the number of preventive replacements of specific components proposed following a preliminary cost analysis are designed to provide better reliability of the aircraft gun. By applying the design modification proposed following an expert analysis of the aircraft gun production and operating costs, the structure was converted into the form shown in 10c.

The simplified method of service life estimation for the structures (shown in Fig. 10b. and 10c) is based on the following assumptions:

- the aircraft gun service life is calculated from the combat service life of the barrels;
- the gun frame and the rotor are qualified as components with a high surplus strength, which is verified during periodic maintenance by inspection for crack development, and this does not limit the life of the aircraft gun;
- the barrel has a verified life of 3,000 rounds fired;
- for all other components of the aircraft gun, individual component kits are prepared for periodic replacement and component group kits are prepared for post-failure replacement so that each of the kits forms a system with a life longer than the barrel life;
- the firing follows the adopted firing cycle. Each round fired in excess of the firing cycle reduces the aircraft gun service life, and the value of reduction can be calculated with the method presented in [2].

With the foregoing assumptions, the aircraft gun service life is calculated by the service life of its barrels:

- aircraft gun reliability serial-parallel structure, shown in Fig. 10b.;

(4 barrels, 3,000 shots each) + post-replacement (4 barrels, 3,000 shots each)
= 12 000 + 12 000 = 24 000 rounds fired;

- aircraft gun reliability serial-parallel structure, shown in Fig. 10c.;

(4 barrels, 3,000 shots each) + post-replacement (4 barrels, 3,000 shots each) + post-replacement (4 barrels, 3,000 shots each)
= 12 000 + 12 000 + 12 000 = 36 000 rounds fired.

Considering the firing in training conditions only (in short bursts, as shown in Fig. 1), the expert knowledge (i.e. the live firing testing of 23 and 30 mm calibre aircraft gun life) suggests that the barrel wear rate is much lower; hence, given the assumed extremely high reliability factor of the aircraft gun, its service life can be extended by 50%. This means that the total aircraft gun service life, which applies to the structure in Fig. 10c., should be approximately 54 000 rounds.

4.2. Simplified method for estimating a preventive replacement component kit

Given the aircraft gun service life estimated in Section 4.1, the necessary numerical values of the individual replacement parts were determined and shown in Table 1.

The results provided herein reveal that a cursory expert evaluation already enabled insightful conclusions which facilitate an optimised design of technical and tactical specifications for ordnance by beginner weapon designers

Table 1. Preventive replacement component kit, 1:1 (1 kit per 1 gun)

Aircraft gun reliability structure option	shown in Fig. 10 b	shown in Fig. 10 c
Gun component	[pcs.]	[pcs.]
y_1 - Frame	0	0
y_2 - Rotor	0	0
y_3 - Breeches	2 × 4 = 8	3 × 4 = 12
y_4 - Ammunition feeding system	1	1
y_5 - Shock absorbers	2 × 2 = 4	1 × 2= 2
y_6 – Power unit with an electric motor	0	0
y_7 - Ammo feeding system drive gear	1	1
y_8 - Ammunition feeding system switch	1	1
y_9 - Switch latch	3	3
y_{10} - Barrels	1 × 4 = 4	2 × 4 = 8

5. CONCLUSION

The problems presented in this paper were considered to be important with the developed analytical method and the model of determination of K_{Co} form P_{K} was found to be useful in the following:

- a fast-numerical analysis of relationships between ordnance service life and the production and operating costs the ordnance service life requires; the analysis is useful for:
  - the development of tactical and technical specifications for ordnance and its operation;
  - the assessment of costs when selecting ordnance types in bids;
  - the selection of ordnance design solutions at the design engineering and upgrade stages, and when adapting legacy ordnance to different operating systems;
- improvement of ordnance availability for use both in combat and training scenarios;
- ROI / profitability assessment of the design and purchase of new ordnance.

It is also assumed that the scheme of analysis with the application of this outline of the method for estimation of ordnance component service life and estimation of replaceable component stocks (especially for preventive replacement) will help design engineers and operators (and other actors) to rationalize and direct the decisions made at the design stage and concerning the selection of materials readily available in wartime conditions, the application of a technology to facilitate easy production launch across manufacturing sites, the simplification of ordnance design and maintenance – to minimise the time to train staff and repair the ordnance and streamline the implementation of preventive replacement components [11] in the object reliability structure – and forecast the operating reliability and operating capabilities of ordnance.

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Model niezawodnościowo-trwałościowy broni w szacowaniu zestawów części wymienianych profilaktycznie w ujęciu kosztów produkcji i eksploatacji

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Streszczenie. W artykule opracowano zarys metody optymalizacji resursu lotniczej broni lufowej (w skrócie broni) w etapie jej projektowania i modernizacji. Istotą metody jest taki dobór resursów i liczby części wymienianych profilaktycznie oraz resursów części nieodnawialnych, by uzyskać sumaryczne zmniejszenie kosztów produkcji i kosztów eksploatacji broni (w tym zapasów części zamiennych) przy jednoczesnym zwiększeniu resursu całej broni. W metodzie przyjęto, że dobór resursów musi spełniać kryterium zachowania założonej niezawodności, maksymalnej dyspozycyjności na platformie bojowej (np. statku powietrznym) oraz minimalnego czasu przygotowania do powtórnego użycia. Wskazano, że przy projektowaniu profilaktycznych wymian i ocenie wyboru broni należy stosować kryterium minimalizacji kosztu całkowitego broni, tj. koszt produkcji/zakupu, jak i koszt procedur obsługowych stosowanych w danym typie eksploatacji (w tym koszt i czas pozyskiwania części zamiennych). Zakłada się, że koszt ten powinien odgrywać decydującą rolę w określeniu zarówno resursów, jak i liczby części wymienianych profilaktycznie. Do analizy i doboru resursu oraz okresów wymian opracowano przykładowe modele niezawodnościowo-trwałościowe broni w odniesieniu do ich norm użytkowania i zmiany kosztów całkowitych. Następnie pokazano innowacyjny model powiązania kosztów broni (produkcyjnych/zakupu i eksploatacyjnych) na płaszczyźnie liczb zespolonych. Zaprezentowana w artykule metoda umożliwia analizę i ocenę możliwości zwiększania dyspozycyjności broni w trakcie jej użytkowania zarówno na polu walki, jak i w procesie szkolenia.

Słowa kluczowe: projektowanie i modernizacja lotniczej broni lufowej, eksploatacja, szacowanie trwałości, resurs, armaty szybkostrzelne, niezawodność, uzbrojenie, zapasy części zamiennych, dyspozycyjność broni