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„One Shot Items Impact onto Systems Reliability“

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***Summary**: This article deals with modelling and analysis of the reliability of complex systems that use one-shot items during their operation. It includes an analysis of the impact of the reliability of used one-shot items on the resulting reliability of the system as a whole. Practical application of theoretical knowledge is demonstrated on an example of a model of reliability of an aircraft gun that was used for optimization of the gun's design during its development and design. The analysed gun uses two types of one-shot items – rounds intended for conducting of fire and special pyrotechnic cartridges designed for re-charging a gun after a possible failure of the round.*

1. Introduction

This contribution is supposed to contribute to a solution of dependability qualities of the complex (in this case) weapon system as an observed object. I would like to show one of the ways how to specify a value of single dependability measures of a set. The aim of our paper is to verify the suggested solution in relation to some functional elements which influence fulfilment of a required function in a very significant manner. [1]; [3]

A weapon set is a complex mechatronics system which is designed and constructed for military purposes. We are talking about a barrel shooting gun – a fast shooting two-barrel cannon. It is going to be implemented in military air force in particular.

Generally speaking the set consists of mechanical parts, electric, power and manipulation parts, electronic parts and ammunition. For the purpose of use in our paper we are going to deal with isolated functional blocks and ammunition only. In this case we view the ammunition as recommended standardised rounds and pyrotechnic cartridges.

Single parts of the set can be described with qualitative and most importantly quantitative indices which present their quality. In my paper I am dealing especially with quality in terms of dependability characteristics. We are working first and foremost with probability values which characterize single indices, and which describe functional range and required functional abilities of the set. We focus on the part handling rounds and pyrotechnic cartridges which are crucial for this case. In order to continue our work it is necessary to define all terms and specify every function.

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2. Esential Terms and Definitions

We are always talking about an object in terms of reliability analyses. The definition for object is the same as the used in IEC 60500 (191/50). Consequently we need to describe the basic object's measures. [2];

Object's function:

The main function: The main function of the object is putting into effect a fire from a gun using standard ammunition.

The step function: Manipulation with ammunition, its charging, initiation, detection and indication of ammunition failure during initiation, initiation of backup system used for re-charging of a failed cartridge.

It is expected that the object will be able to work under different operating conditions especially in different temperature spectra, under the influence of varied static, kinetic and dynamic effects, in various zones of atmospheric and weather conditions.

In this case we will not take into account any of the operating conditions mentioned above. However, their influence might be important while considering successful mission completion.

One of the main terms we are going to develop is:

Mission: It is an ability to complete a regarded mission by an object in specified time, under given conditions and in a required quality.

In our contribution it is a case of cannon ability to put into effect a fire in a required amount – in a number of shot ammunition at a target in required time, and under given operating and environmental conditions.

As it follows from the definition of a mission it is a case of a set of various conditions which have to be fulfilled all at once in a way to satisfy us completely. Our object is supposed to be able to shoot a required amount of ammunition which has to hit the target with required accuracy (probability). We will not take into consideration circumstances relating to evaluation of shooting results, weapon aiming, internal and external ballistics, weather conditions and others. We will focus only on an ability of an object to shoot. [4]

As we have stated above we will deal with isolated function blocks only. We are presuming that these blocks act according to required and determined boundary conditions. In order to understand functional links fully we introduce our way of dividing an object.

We are talking about the following block:

- manipulation with ammunition, its charging, initiation, failure detection and indication during initiation, initiation of a backup system in order to recharge a failed cartridge, all mechanical parts, all electric and electronic parts, interface elements with a carrying device - Block A;
- ammunition – Block B;
- pyrotechnic cartridges – Block C.

3. Description of the Process

The process as a whole can be described this way:

From a mathematical and technical point of view it is a fulfilling of requirements´ quee which gradually comes into the service place of a chamber. The requirements´ quee is a countable rounds´ chain where the rounds wait for their turn and are transported from the line where they wait in to a service place (fulfilment of a requirement) of a chamber and there they are initiated. After the initiation the requirement is fulfilled. An empty shell (one of the essential parts of a round) leaves a chamber taking a different way than a complete round. When the requirement is fulfilled, another system which is an integral part of a set detects process of fulfilling the requirement. The process is detected and indicated on the basis of interconnected reaction processes. In this case fulfilling the requirement is understood as a movement of a barrel breech going backwards. Both fulfilling the requirement and its detection are functionally connected with transport of another round waiting in a line to go into a chamber.

Let’s presume that rounds are placed in an ammunition feed belt of an exactly defined length. A maximum number of rounds which could be placed in a belt is limited by the length then. The length is given either by construction limitations or by tactical and technical requirements for a weapon set. Let’s presume that despite different lengths of an ammunition belt, this will be always filled with rounds from the beginning to the end. Let’s also assume that the rounds are not non-standard and are designed for the set.

The process of fulfilling the requirement is monitored all the time by another system which is able to differentiate if it is fulfilled or not. The fulfilment itself means that a round is transported into a chamber, it is initiated, shot, and finally an empty shell leaves a chamber according to a required principle. If the process is completed in a required sequence, the system detects it as a right one.

Because of unreliability of rounds the whole system is designed in the way to be able to detect situations in which the requirement is not fulfilled in a demanded sequence and that is why it is detected as faulty.

Although a round is transported into a chamber and is initiated, it is not fired. A function which is essential for a round to leave a chamber is not provided either, and therefore another round waiting in line cannot be transported into a chamber. That is the reason why fulfilling of the requirement is not detected.

The system is designed and constructed in such a way that it is able to detect an event like this and takes appropriate countermeasures. A redundant system which has been partly described above is initiated. After a round is initiated and the other steps don’t carry out (non-fire, non-movement of a barrel breech backwards, non-detection of fulfilling the requirement, non-leaving of a chamber by an empty shell, and non-transport of another round into a chamber) a system of pyrotechnic cartridges is initiated. It is functionally connected with all the system providing mission completion. A pyrotechnic cartridge is initiated and owing to this a failed round is supposed to leave a chamber. A failed functional link is established and another round waiting in line is transported into a chamber.

In order to restore the main function we use a certain number of backup pyrotechnic cartridges. Our task is to find out a minimum number which is essential for completing the mission successfully.

4. Mathematical Model

To meet the needs of our requirements we are going to use a mathematical way which helps us to express successful completing the mission. We know that the number of rounds n in an ammunition belt is final. We also know that an event-failure of a round $\overline{B}$ (ammunition block – B) can occur with a probability p_n. All the requirements and specifications mentioned above will be used in further steps.

Because it is about a stream of rounds of a number n which wait in line to meet the requirement, and each of them has a potential quality p_n, a number of failed rounds has a binomial distribution (*Bi)* of a an event occurrence. The distribution is specified by the parameters n and p_n: $Bi(n,p_n)$. A number of occurrences X_n of an event $\overline{B}$ follows the distribution in Bernouli´s row n of independent experiments, and probability of event occurrence $P(\overline{B}) = p_n$. A number p_n is the same in every experiment. [5]; [6]

Because there is an occurrence of a number of events in an observed file we are talking about a counting distribution of an observed random variable. A random variable is in this case a number of failed rounds. A probability function of a binomial distribution can be put that way:

$$P(X_n = x) = \binom{n}{x} p_n^{\,x} (1 - p_n)^{n-x} \text{ ; } x \in \{0,1,2,...,n\} \quad (1)$$

Qualities of binomial distribution like a mean value $E(X_n)$ and dispersion $D(X_n)$ are obtained by calculating the formula:

$$E(X_n) = n \,.\, p_n \quad (2)$$

$$D(X_n) = n \,.\, p_n \,.\, (1- p_n) \quad (3)$$

A number of failed rounds follows a binomial distribution with parameters n – a number of rounds and p_n – failure occurrence probability of a round.

In order to specify a mean number of possible failures in an ammunition belt of a given length (there is a certain amount of rounds) we quantify the formula (2) and replace n by a real number of rounds in an ammunition belt.

On the basis of construction, technical and technical requirements we can have ammunition belts of different length at a given moment, and consequently we have a different number of rounds. Only a maximum number of rounds in an ammunition belt is considered in another calculation. The ammunition belt is supposed to be of a maximum length which is able to fit a loading device

In case a round fails initiation of a backup system for function restoration occurs according to a mechanism described above. It is a case of successive initiation of pyrotechnic cartridges (in a system of pyrotechnic cartridges) which are supposed to guarantee restoring of a required broken chain of function. A number of pyrotechnic cartridges in a backup system is m. Pyrotechnic cartridges have also a probability p_m of a failure occurrence which unables their initiation. Pyrotechnic cartridges too are placed in line waiting for meeting the requirement which results from their function. In case of a failure of the first pyrotechnic cartridge the next one is initiated up to the moment when either a function is restored or all pyrotechnic cartridges are used up.

On the basis of the facts mentioned above it is obvious that the process of fulfilling the requirements follows geometrical distribution (*Ge*). It means that the process of fulfilling the requirements repeats so often until it meets them in terms of reversion of all the process to an operational state. It is a case of an observed discreet random variable. Pyrotechnic cartridges also have failure rate p_m (failure probability) and there is a limited number of them. It means that a failure can occur up to *m-times*. A geometrical distribution $Ge(p_m)$ generally follows this outline.

We are going to assess the succession of independent attempts, and probability of an observed event occurrence equals the same number p_m in each attempt. The quantity X_m is a serial number of the first success which means that a required event occurs. The event here means a function of a block C, and a probability p_m means an event occurrence $\overline{C}$. Characteristics of the process are as follow. A probability function:

$$P(X_m=x) = p_m^{x-1}(1-p_m); \qquad x\in\{1,2,3,\ldots,m\} \tag{4}$$

It is a special case of a geometrical distribution when a probability of an event occurrence (a pyrotechnic cartridge failure) does not depend on a number of previous unsuccessful attempts of a value 0. Characteristics of a geometrical distributions, for example mean value $E(X_m)$ (a mean number of pyrotechnic cartridges necessary for removing one failed round) and dispersion $D(X_m)$ are obtained by a calculation of a formula:

$$E(X_m) = \sum_{x=0}^{\infty} x.Pr(X_m = x) = \frac{1}{1-p_m} \tag{5}$$

While completing the mission during either training or a real deployment a few scenarios can occur, and the course of them depends on single functional blocks. To complete the mission M successfully single blocks are expected to be failure free as stated above. The function of the blocks mentioned above are designated as *A*, *B*, *C*, the opposite is $\overline{A}$; $\overline{B}$; $\overline{C}$. The relation can be expressed by using events this way:

$$M = A \cap (B \cup C) \tag{6}$$

Using probability expression we talk about probability of mission completion M. We can put it that way:

$$P(M) = P(A) . [P(B) + P(C) - P(B \cap C)] \tag{7}$$

5. Description of Scenarios

Description of the scenarios which can occur during completing or defaulting the mission relate only to an ammunition block and to a redundant mechatronics system with pyrotechnic cartridges.

The mission is completed. In the first case there can be a situation when all the ammunition of a certain amount which is placed in an ammunition belt is used up and a round failure occurs or it is used up and a round failure does not occur. In this case a backup system of pyrotechnic cartridges is able to reverse a system into an operational state. Using up can be single, successive in small bursts with breaks between different bursts, or it might be mass using one burst. Shooting is failure free or there is a round failure occurrence *n.* In case a round failure occurs, a system which restores a function of pyrotechnic cartridges is initiated. There are two scenarios too – a system restoring a pyrotechnic cartridges function is failure free, or a pyrotechnic cartridge fails. If a function of pyrotechnic cartridges is applied, it can remove a failure *m-times*. So a number of restorations of the function is the same as the number of available pyrotechnic cartridges. In order to complete the mission successfully we need a higher amount of pyrotechnic cartridges *m*, or in the worst case the number of pyrotechnic cartridges should be equal to a number of failures. Another alternative is the situation that a round fails and in this case a pyrotechnic cartridge fails too. A different pyrotechnic cartridge is initiated and it restores the function. This must satisfy the requirements that an amount of all round failures *n* is lower or at least equal to a number of operational (undamaged) pyrotechnic cartridges *m*. The mission is completed in all the cases mentioned above and when following a required level of readiness of a block A.

The mission is not completed. In the second case the shooting is carried out one at a time, in small bursts or in one burst, and during the shooting there will be *n* round failures. At the time the failure occurs a backup system for restoring the function will be initiated. Unlike the previous situation there will be *m* pyrotechnic cartridges´ failures and a total number of pyrotechnic cartridges´ failures equals at least a number of round failures, and is equal to a number of implemented pyrotechnic cartridges M at the most. It might happen in this case that restoring of the function does not take place and the mission is not completed at the same time because there are not enough implemented pyrotechnic cartridges.

The relation of transition among the states can be expressed by the theory of Markov chains.

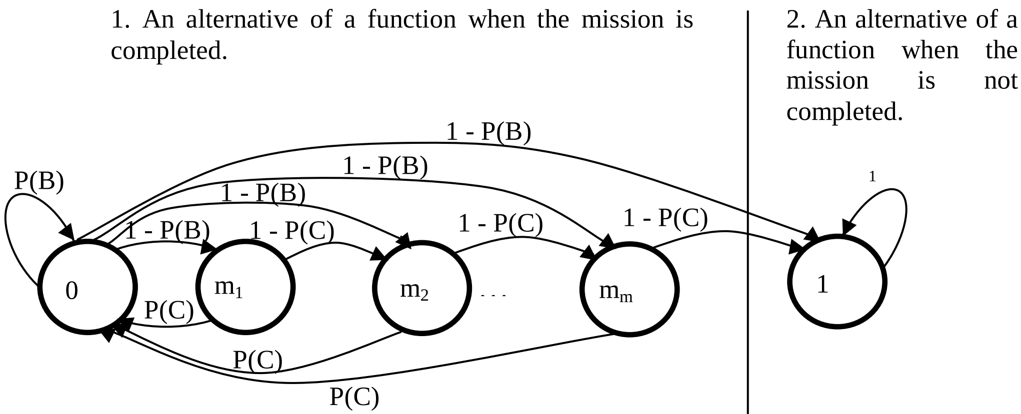

Figure 1. Description of transitions among the states

Characteristics of the states:

0 state: An initial state of an object until a round failure occurs with a probability function of a round P(B). It is also a state an object can get with a pyrotechnic cartridge probability P(C) in case a round failure occurs $P(\overline{B}) = 1 - P(B)$,

or $P(C|\overline{B}) = \dfrac{P(C \cap \overline{B})}{P(\overline{B})}$.

$m_1 \dots m_m$ state: A state an object can get while completing the mission. Either a round failure occurs in probability $P(\overline{B}) = 1 - P(B)$, or there is a pyrotechnic cartridge failure in probability $P(\overline{C}) = 1 - P(C)$.

1 state: A state an object can get while completing the mission. It is so called an absorption state. Transition to the state is described as probability $P(\overline{C}) = 1 - P(C)$ of a failure of last pyrotechnic cartridge as long as an object was in a state „k_n" before this state, or it can be described as probability of a round failure occurrence $P(\overline{B}) = 1 - P(B)$ as long as an object was in a state 0 before this state and all pyrotechnic cartridges are eliminated from the possibility to be used.

Transitions among different states as well as absolute probability might be put in the following formulae:

$$P(0) = P(B) + P(C_{k_1 0}) + P(C_{k_2 0}) + \ldots + P(C_{k_{1n} 0}) \quad (8)$$

$$P(m_1) = 1 - P(B) \quad (9)$$

$$P(m_m) = (1 - P(B)) + (1 - P(C)) \quad (10)$$

$$P(1) = 1 \quad (11)$$

We suggest the subsequent steps for all the scenarios mentioned above. Following the mathematical formula (1) it is possible to find out probability of a number of round failures´ occurrences in an ammunition belt of a length *n*. Following the equation (2) we can specify an expected mean value of a mean number of round failures in an ammunition belt of a given length.

The mean value result is recommended to be used for a maximum length of an ammunition belt (a maximum number of rounds) which could be implemented into a weapon set concerning construction as well as tactical and technical views. The result informs us of a minimum number of pyrotechnic cartridges which are to be applied for a successful completing the mission.

In this case there is a threat of a pyrotechnic cartridge failure which could cause a system failure (as far as a number of round failures is higher than a number of available pyrotechnic cartridges). In this case we would not complete the mission.

In order to assess dependability of a shooting function it is necessary to know a number of pyrotechnic cartridges and, depending on this, probability of completing the mission. To fulfil the requirements I suggest three steps:

1) To determine a required number of pyrotechnic cartridges;
2) To quantify generally probabilities of completing the mission;
3) To quantify exactly probabilities of completing the mission

Following the steps mentioned above we suggest this method.

Ad 1) To determine a required number of pyrotechnic cartridges

When we calculate a mean number of failed rounds $E(X_n)$ which is determined from a maximum number of rounds *n* in a ammunition belt (see above) and probability of a round failure occurrence p_n, see the formula (2), we get a minimum recommended number of pyrotechnic cartridges which are supposed to guarantee completing the mission in case a round fails.

The calculation would be successful in case a pyrotechnic cartridge failure does not occur. However, even a system of pyrotechnic cartridges concerning a failure occurrence depends on counting distribution of a discreet random variable which is specified in our case by a geometrical distribution. (Because the system is activated so long until the observed and required event occurs – in terms of repairing the failure.) We suggest calculating a mean number of pyrotechnic cartridges´ failures following the formula (5). For the calculation we will need only pyrotechnic cartridge failure probability p_m. On the basis of this calculation we get an average number of pyrotechnic cartridges required to repair a failure of one round.

In order to complete the mission a number of available (operational) pyrotechnic cartridges should be at least the same as a number of failed rounds. When we multiply the mean values we obtain a total number of pyrotechnic cartridges M which will guarantee completing the mission (even in the situation when besides failed rounds there are failed pyrotechnic cartridges too).

$$\mathrm{M} = \mathrm{E}(X_n)\ .\ \mathrm{E}(X_m) = \frac{n.p_n}{1-p_m} \tag{12}$$

Logically a number of pyrotechnic cartridges which are essential for completing the mission successfully is continually proportioned to a number of rounds n and to probability of their failure p_n, and inversely proportioned to probability of pyrotechnic cartridge "success" $1\text{-}p_m$. The figure 2 shows a typical course of dependability $M\ (p_n;p_m)$, it means a invariant M which depends on variables p_n a p_m. This way might be the first of the alternatives how to solve the problem. It suggests a total number of pyrotechnic cartridges which are essential for completing the mission but it does not show the way how to quantify probability of mission completion.

While recording distribution parameters we are going to use an equivalent m standing for a value M.

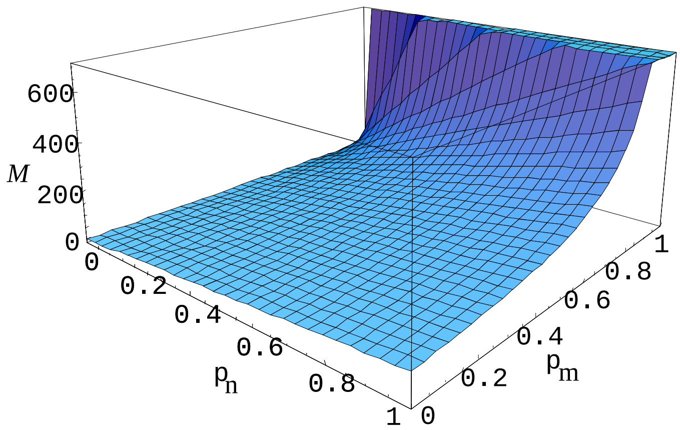

Figure 2. Course of dependability of a number of pyrotechnic cartridges M on variables p_n and p_m

Ad 2) To quantify generally probability of completing the mission

In this case we follow the solution which has been stated in the part Ad 1. We take into account that there is a number of pyrotechnic cartridges required for completing the mission. So, we determine an α fractile which provides an upper limit of a number of rounds which fail in probability α. After we specify β fractile which provides an upper limit of pyrotechnic cartridges which fail in probability β.

While working with fractiles we follow the general information. 100% fractile of a random variable X is a number x_p, and a probability p where $0<p<1$ is denoted by

$$P(X \le x_p) \ge p \tag{13}$$

and

$$\lim_{x \to x_p^-} P(x) \le p \tag{14}$$

The fractile of an observed random variable we are working with is expressed by

$$p_n = \sum_{n=0}^{x_\alpha} P(X_\alpha = n) \tag{15}$$

We put it into words this way – occurrence probability n of a number of events is specified by a sum of probabilities for the occurrence of all events from 0 to n.

In our case we take into account that round failures´ distribution is binomial $B_i=(n;p_n)$ and a fractile determining an upper limit of a number of rounds which might fail in probability α will be designated as x_α. We put it that way

$$P(X_n \le x_\alpha) = \alpha \tag{16}$$

We suppose that a general distribution of a pyrotechnic cartridge follows a binomial distribution too $Bi(m;p_m)$. A fractile providing an upper limit of a number of pyrotechnic cartridges which fail in probability β is denoted by y_β. Thus

$$P(Y_m \le y_\beta) = \beta \tag{17}$$

The equation can be put in a different way as

$$Pr(m - Y_m \ge m - y_\beta) = \beta \tag{18}$$

The following interpretation of a fractile y_β is useful for other steps – at least $m - y_\beta$ of pyrotechnic cartridges will be available with probability β.

As it was stated before we are supposed to know a total number of pyrotechnic cartridges M which are essential for completing the mission. The requirement is shown in the following equation:

$$(M - y_\beta) \ge x_\alpha \tag{19}$$

The equation shows that a number of available pyrotechnic cartridges (we obtain it when we subtract failed pyrotechnic cartridges from a total amount of all applied pyrotechnic cartridges) will be at least the same (it would be better to have a higher number) as a number of failed rounds. If this assumption is fulfilled, we can expect that the mission will be completed in probability p_{mis}. Probability of completing the mission can be put that way.

$$p_{mis} = \alpha \,.\, \beta \tag{20}$$

The formula can be described like this – probability of completing the mission equals a multiplication of probabilities $\alpha;\beta \in (0;1)$ which provide us an upper limit of failed rounds and an upper limit of failed pyrotechnic cartridges for required levels of fractiles.

If the level of mission completion probability is known in advance, e.g. it is specified by technical requirements for a set, we can put it in the formula which is based on an assumption that the mission will be completed in case a number of available pyrotechnic cartridges is at least the same as rounds which are supposed to fail.

$$x_{\alpha} \leq m - y_{\beta} \tag{21}$$

If it goes this way, the mission will be completed in probability expressed in the formula (20).

If we have the values α, n, β, p_{mis}, we may find a value *m (M)* using quantitative methods. At the end of my contribution there is an example of this solution.

Ad 3) To quantify exactly probabilities of completing the mission

In the last step we are going to examine how to quantify an exact value of mission completion probability p_{mis}. On the basis of the assumption described above we know that probability of completing the mission depends on reliability of two key blocks. It is an ammunition block (B) and a pyrotechnic cartridges´ block (C). Following the last two alternatives we might specify both a required total number of pyrotechnic cartridges which is essential to complete the mission (in case all conditions are met), and a general value of mission completion probability in case general conditions are followed. This solution might satisfy us under certain circumstances but it is not always like that. Therefore we suggest the last way how to quantify probability of completing the mission based on more exact method.

It is necessary to define indices and quantities which effect directly probability of completing the mission p_{mis}. These are a number of rounds n, probability of a round failure occurrence p_n, a number of pyrotechnic cartridges m, and probability of a pyrotechnic cartridge failure occurrence p_m. A general function of mission completion probability and its variables is put that way:

$$p_{mis}(n,p_n,m,p_m) \tag{22}$$

Further steps follow well known assumptions. The function of a rounds´ failure takes form of a binomial distribution with parameters n and p_n – $Bi(n,p_n)$, and the rounds which may fail can be marked with k where $k \in \{0;1;2;\ldots;n\}$. Moreover, we introduce functions of a pyrotechnic cartridges´ failure Y_k where $k \in \{0;1;2;\ldots;m\}$. They show us possibility of a pyrotechnic cartridge failure while shooting as soon as it is necessary to remove a failed round. Let us assume that a sum of functions of a pyrotechnic cartridges´ failure will be lower than a number of available pyrotechnic cartridges used for removing a failed round. We put it in the following formula:

$$\sum_{k=0}^{m} Y_k \leq m \approx Y_0 + Y_1 + \ldots\ldots Y_k \leq m \tag{23}$$

Following the assumption mentioned above we consider the case that the first available pyrotechnic cartridge follows geometrical distribution of a function of its activity $Ge(p_m)$

during the failure of the *k-th* round Y_k. The function p_m means probability of pyrotechnic cartridge failure occurrence. It can be described as:

$$Y_k \sim Ge(p_m) \tag{24}$$

The equation showing probability of completing the mission is put that way:

$$P(n, p_n, m, p_m) = \sum_{k=0}^{n} P(X = k).P(Y_0 + Y_1 + ... + Y_k \le m) \tag{25}$$

where in case $k=0$ (it reflects a situation where there is no round failure) a function would be specified additionally provided that $P(Y_1+....Y_k \le m)=1$. And in order to solve a probability value of completing the mission we would use so called completing the formula taking advantage of forming functions. From a mathematical point of view this is much more demanding but it offers a very exact value expressing probability of completing the mission p_{mis} while using a variation of function factors. On its basis it is easy to prove a dependability of a total number of used pyrotechnic cartridges on a level of mission completion probability p_{mis}.

An example of a possible solution:

Given: p_n = 0,000 1 - round failure probability;
n = 200 - maximum rounds´ number during one process;
p_m = 0,01 - pyrotechnic cartridge failure probability;
p_{mis} = 0,99 - probability of mission success.

Solution according to "Ad 1)": We are looking for a sufficient number of pyrotechnic cartridges used for removing a possible failure.

$$M = \frac{n.\alpha}{1-\beta} = \frac{200.0{,}0001}{1-0{,}01} \cong 0{,}02$$

The formula shows us that having at least one pyrotechnic cartridge is enough to complete the mission successfully. However, we cannot quantify probability for completing the mission.

Solution according to "Ad 2)": We are looking for a level of mission completion probability p_{mis} as well as a required number of pyrotechnic cartridges. We follow the values described above. The solution is put in the table.

Table 1. Results of example

α	x_α	$\beta = \frac{p_{mis}}{\alpha}$	m
0,991	1	0,998991	2
0,992	1	0,997984	2
0,993	1	0,996979	2
0,994	1	0,995976	2
0,995	1	0,994975	2
0,996	1	0,993976	2
0,997	1	0,992979	2
0,998	1	0,991984	2
0,999	1	0,990991	2

If we take into account this solution and starting marginal conditions, two pyrotechnic cartridges will be enough to complete the mission successfully in 0,99 probability.

6. Conclusions

This contribution is supposed to serve as one of the alternatives (for other possible solution see [7]) solving the problems connected with providing a function of an object whose function is redundant (backed up) because its failure is important to complete the mission. In order to solve the problem we chose the methods which are supposed to be the most suitable for it. Other ways are also likely to be used in order to reach the aim but it is not the intention of this contribution.

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