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ELABORATION OF A MATHEMATICAL MODEL FOR DESIGNING ATTRIBUTE ACCEPTANCE PLANS

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Professional paper

In this article, attribute acceptance plans are explained and elaborated, together with their design by using standards and nomograms. The elaboration of a mathematical model for designing specific acceptance plans is also presented as well as the implementation of these models in a software application. Their possible application in specific cases is shown on several examples. The results obtained by using a software application are compared with the standards and are presented with adequate curves.

Keywords: *AQL, attribute acceptance plans, HRN ISO 2859-1:1989, Larson nomogram, operating characteristic curve of the acceptance plan, sampling, statistical quality control*

Razrada matematičkog modela za izradu atributivnih planova prijema

Stručni članak

U ovome radu obrađeni su i pojašnjeni planovi prijema za atributne karakteristike proizvoda pomoću normi i nomograma, te razrađen matematički model za izradu specifičnih planova prijema koji je prilagođen računalnoj aplikaciji. Na nekoliko primjera prikazani su mogući načini primjene u konkretnim slučajevima. Rezultati dobiveni pomoću računalne aplikacije uspoređeni su s normama i prikazani s pripadajućim krivuljama.

Ključne riječi: *AQL, HRN ISO 2859-1:1989, Larsonov nomogram, operativna krivulja plana prijema, planovi prijema za atributivne karakteristike, statistička kontrola kvalitete, uzorkovanje*

1 Introduction
Uvod

Quality is a notion that has always been present in nature and can be simply described as the survival of the fittest. In today's sense, quality control has existed since the day men started making things. It evolved with time in order to satisfy larger production of goods, to cut expenses, and to satisfy market demand for higher quality. One of the definitions of quality is: "Quality is the level at which a set of distinctive characteristics satisfies requirements." [1]

In order to satisfy the above mentioned definition, it is necessary to determine the mode and control parameters.

Two basic types of control offer themselves:

- 100 % control
- Statistical control.

100 % control is a type of inspection applied to certain characteristics of all products or materials in a group to determine whether a product meets imposed requirements. The main disadvantage of the 100 % method is that each element needs to be inspected separately, which results in high costs of this inspection type. Moreover, it is impossible to apply control during which the object of control gets destroyed.

Statistical control presents a set of methods and procedures for gathering, processing, analysis, and interpretation of data to ensure the quality of a product, process and service. It can be divided into control during a process (control charts) and control after the finished process (acceptance plans). Acceptance plans can be further divided depending on the controlled characteristics into variable acceptance plans and attribute acceptance plans. The advantage of statistical control presents significantly smaller control volume in the form of element numbers which need to be controlled. Tests are simpler and a large number of objects can be controlled in a relatively short time. Acceptance plans present an only possibility in case the control is destroying an object.

2 Attribute acceptance plans
Planovi prijema za atributivne karakteristike

An acceptance plan (sampling plan) presents a set of regulations which determine the size of a sample (or samples, when it is a matter of double or multiple systems), which needs to select acceptance or rejection numbers from the basic lot. [2, 8]

Within the system of sample selection, one or more samples are selected from the delivery by using any procedure which ensures randomness or adequate representative quality of the whole delivery. If the subject are smaller parts or parts packaged in a loose condition (e.g. screws, nuts, and similar), it is enough to randomly select from the container as many pieces as necessary according to the received size of the sample. In case the subject are parts which are separately packaged or placed in separate containers, after labeling each piece in any numerical order, random numbers are used for choosing representative pieces [7].

Acceptance plans can be further divided into single (Fig. 1), double (Fig. 2), and multiple (Fig. 3). The decision on the choice of an acceptance plan is usually based on economic and administrative factors. Double and multiple acceptance plans enable the use of smaller sample size than the size used with single acceptance plans. However, administrative difficulties and the price per unit in a sample are usually smaller with single acceptance plans. With multiple acceptance plans, the procedure is repeated until the right condition for acceptance or rejection of the shipment is achieved. The main advantage here is that the lot is sorted out during the inspection process.

Acceptance number (Ac or c) is the maximum number of defective units which can be tolerated in a sample to consider the basic lot satisfying.

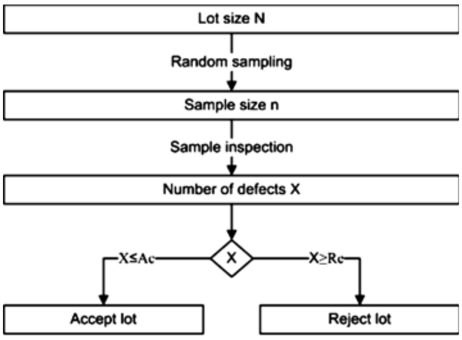


Figure 1 Single acceptance plan
Slika 1. *Jednostruki plan prijema*

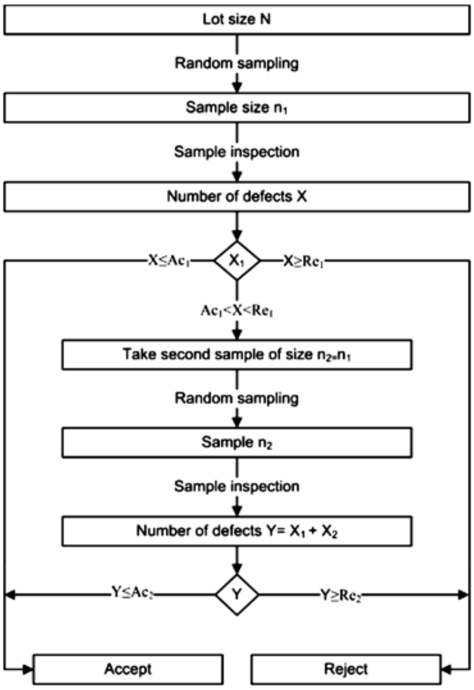


Figure 2 Double acceptance plan
Slika 2. *Dvostruki plan prijema*

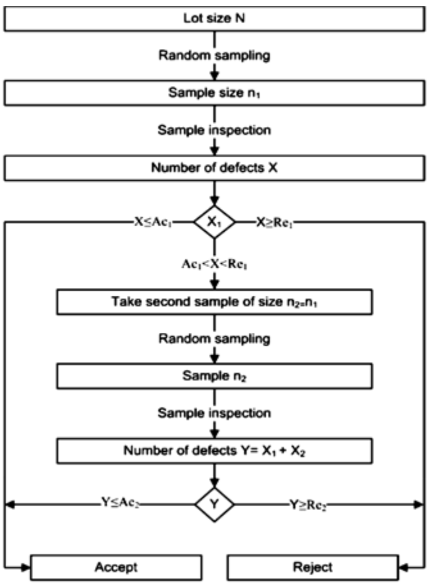


Figure 3 Multiple acceptance plan
Slika 3. *Višestruki plan prijema*

2.1 Operating characteristic curve of an acceptance plan
Operativna krivulja plana prijema

Operating characteristic curve represents the probability of accepting the sample *Pa* depending on the fraction of defects in sample *p* (Fig. 4).

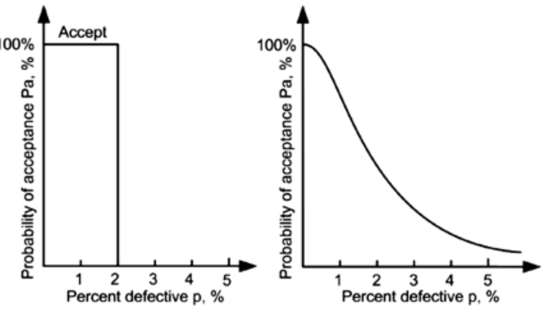


Figure 4 Operating characteristic curve
Slika 4. *Operativna krivulja*

When it comes to 100 % control, operating characteristic curve represents an ideal case (Fig. 4, left). This means that each lot that has a lower quality level (the quality level represents the percentage of defectiveness, what means lower is better) from the acceptable level ($p<p_a$) will be accepted with the probability of 100 %, while every shipment with a quality level higher than the acceptable ($p>p_a$) will be rejected. The borderline case ($p=p_a$) requires an agreed upon procedure.

When it comes to sampling (Fig. 4, right), the situation changes since there is no more 100 % certainty for acceptance or rejection of the shipment, depending on the fraction of defects in the sample. Operating characteristic curve in that case presents the probability that a lot of certain quality level is accepted or rejected. Depending on the acceptance plan parameters there is a certain probability for a good lot to be rejected or for a bad lot to be accepted. These values are defined by using α and β risks for the predetermined percentage of defective parts [9, 10].

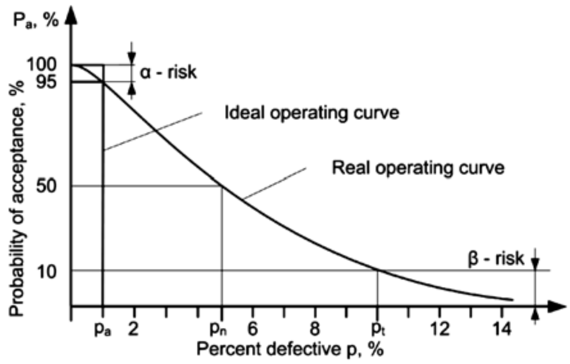


Figure 5 Operating characteristic curve in the sampling case
Slika 5. *Operativna krivulja u slučaju uzorkovanja*

p_a=AQL presents the acceptable quality level for which there is so called α producer's risk that a delivery of good quality is rejected (as a rule 5 %). AQL presents the highest tolerated percent defective to consider the shipment satisfying.

p_t=RQL presents the tolerated quality level for which there is so called β consumer's risk that a delivery of a significantly worse quality is accepted (as a rule 10 %).

p_n is neutral quality or % of a lot discard for which there is a 50 % probability that a good delivery is rejected or a bad delivery accepted.

2.2 Average outgoing quality curve
Krivulja prosječne izlazne kvalitete

Average Outgoing Quality (AOQ) is a percent defective at the entrance warehouse. (After applying the sampling, the deliveries are taken to the entrance warehouse.) AOQ can be taken into consideration when the production is stable and the number of deliveries is large enough. The value of average outgoing quality can be obtained by using the equation (1), and when the basic lot size N is much bigger than sample n it can be simplified and calculated by using the equation (2), by inserting in the equation the data with units as shown in Fig. 6, where p_i equals the percent defective and P_{ai} the probability of acceptance at a specific point.

$$AOQ = \frac{P_{ai} \cdot p_i \cdot (N - n)}{N}, \tag{1}$$

$$AOQ_i = p_i \cdot P_{ai} = F_i. \tag{2}$$

The average outgoing quality curve presents the graph of dependence of average outgoing quality in relation to the percent defective. The value AOQL is the maximum value of average quality of an outgoing product (AOQ) for every possible quality tolerated according to the given acceptance plan. Fig. 6 presents the operating characteristic curve (up) and the curve of average outgoing quality (down). It can be seen in the graphs that for the presented acceptance plan and alpha risk of 5 % AQL equals 1 %, while the maximum amount of average outgoing quality according to the given acceptance plan amounts approximately to 1,25 %.

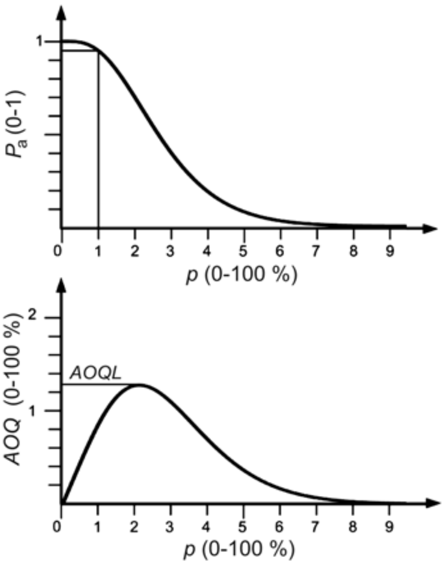


***Figure 6**. Average outgoing quality curve*
***Slika 6**. Krivulja prosječne izlazne kvalitete*

2.3 HRN ISO 2859-1:1989
HRN ISO 2859-1:1989

Standard HRN ISO 2859-1:1989 specifies sampling plans and procedures for the inspection of discrete elements according to the attributes. The sampling plans in this standard are indexed according to the values of acceptable quality level AQL. [3]

The purpose of this standard is to affect the supplier by putting economic and psychological pressure on him with not accepting the delivery in order to maintain the process average at least on the level of specified quality of AQL, at the same time giving the consumer upper border for the risk of occasionally accepting a defective lot.

Application:

- Final products
- Components and raw materials
- Procedures
- Materials in process
- Warehouse stocks
- Maintenance procedures
- Data or records
- Administrative procedures.

Fig. 7 shows the process of acceptance plan design by using the standard.

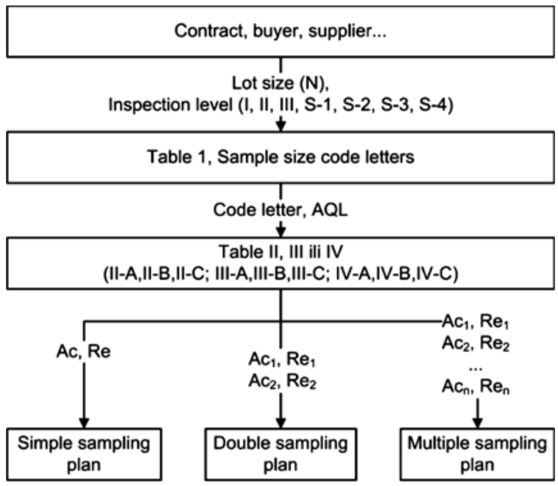


***Figure** 7 Choosing an acceptance plan by using the standard*
***Slika 7.** Odabir plana prijema pomoću norme*

3 Statistical bases
Statističke osnove

Standard HRN ISO 2859-1:1989 is focused on the protection of a producer and the acceptance of shipments whose quality level is the same as *AQL*, while the buyer's need to identify a bad shipment is put in a position of secondary importance (alpha risk is always higher than beta risk). In order to develop a mathematical model which enables arbitrary choice of sampling parameters, it is necessary to study data distribution.

For the elaboration of attribute acceptance plans discontinuous distributions are used (Hypergeometric, Binomial and Poisson), while for the making of variable acceptance plans continuous distributions are used (Normal, Student's-t, χ^2, Fisher)[11].

3.1 Hypergeometric distribution
Hipergeometrijska razdioba

In the sample of N elements there are M elements with attribute A (□) and N-M elements with attribute Ā (o), as shown in Fig. 8. If a random sample is selected from n pieces, there will be d elements in it with attribute A (□)and n-d elements with attribute Ā (o) [7, 8, 11].

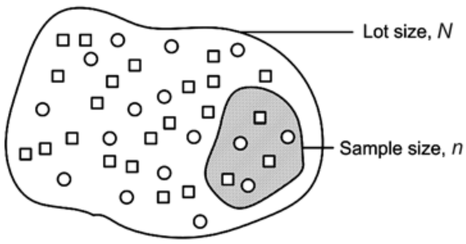


Figure 8 *Lots of hypergeometric distribution*
Slika 8. *Skupovi hipergeometrijske razdiobe*

Hypergeometric distribution presents the probability of appearance of certain elements with attribute A in a random sample size n selected from the basic lot size N.

The distribution function is given in equation (3) and it presents the probability of appearance of exactly d elements with attribute A in a representative sample of size n which is randomly selected from lot N.

$$H(d,N,M,n)=\frac{\binom{M}{d}\cdot\binom{N-M}{n-d}}{\binom{N}{n}}. \tag{3}$$

Cumulative distribution function is given in equation (4) and it presents the probability of selecting c or less elements with attribute A in a representative sample of size n which is randomly selected from lot N.

$$P_r(d\le c)=\sum_{i=0}^{c}\frac{\binom{M}{i}\cdot\binom{N-M}{n-i}}{\binom{N}{n}}. \tag{4}$$

Hypergeometric distribution is applied for isolated shipments when the basic lot is small, and by selecting samples proportions of good and bad parts in the basic lot are changed.

3.2 Binomial distribution
Binomna razdioba

For easier understanding of binomial distribution it is necessary to explain the binomial experiment which satisfies these conditions:

- The experiment consists of n trials
- Each trial can result in only two possible outcomes which can be called success or failure
- The probability of success p is the same in each trial (the probability of failure q=1–p)
- The trials are independent, which means the outcome of one trial does not affect the outcome of the other.

In case all the abovementioned points are satisfied, the probability of success is given in equation (5) which presents the distribution function of binomial distribution.

$$P_r(d\le c)=\sum_{i=0}^{c}\binom{n}{i}\cdot p^i\cdot q^{n-i}. \tag{5}$$

Cumulative distribution function of binomial distribution is given in equation (6) and it presents the probability c or less success realized in n trials, when in the sample there is a fraction of defective parts given in p.

$$P_r(d\le c)=\sum_{i=0}^{c}\binom{n}{i}\cdot p^i\cdot q^{n-i}. \tag{6}$$

In case the basic lot N is big in relation to the sample n, so that selecting the sample from the basic lot does not significantly change the rest of the basic lot, independently on how many defects there are in the basic lot, the defect distribution can be considered binomial with parameters n and p [7, 8].

3.2.1 Larson nomogram
Larsonov nomogram

Nomograms are considered to be an out-of-date technology and are mostly replaced with standards and software, but there are cases where they present a fast and elegant solution. Fig. 9 shows the Larson nomogram which presents a graphic illustration of cumulative distribution function of binomial distribution.

On the basis of the following example, the way of designing an acceptance plan by using the Larson nomogram is explained:

It is necessary to create such a sampling plan which accepts 95 % of samples containing 2 % of defective lots and accepts only 5 % of samples containing 9 % of defective lots.

1. Determine the allowed fraction of defective lots p_α to consider the shipment satisfying: p_α= 2 % (0,02)
2. Determine the probability needed for the acceptance of a good shipment: $P_\alpha = 1-\alpha = 95$ % (0,95)
3. Determine the size of fraction p_β of defective lots to consider the shipment unsatisfying: p_β = 9 % (0,09)
4. Determine the probability for accepting a bad shipment with P_β which can be tolerated: P_β = 5 % (0,05)
5. Connect the points p_α and P_α=1– α with a straight line
6. Connect the points p_β and P_β= β with a straight line
7. Read the values n and c in the nomogram.

It can be seen in Fig. 10 that the solution of this problem presents acceptance plan given with parameters n = 100 and c = 4.

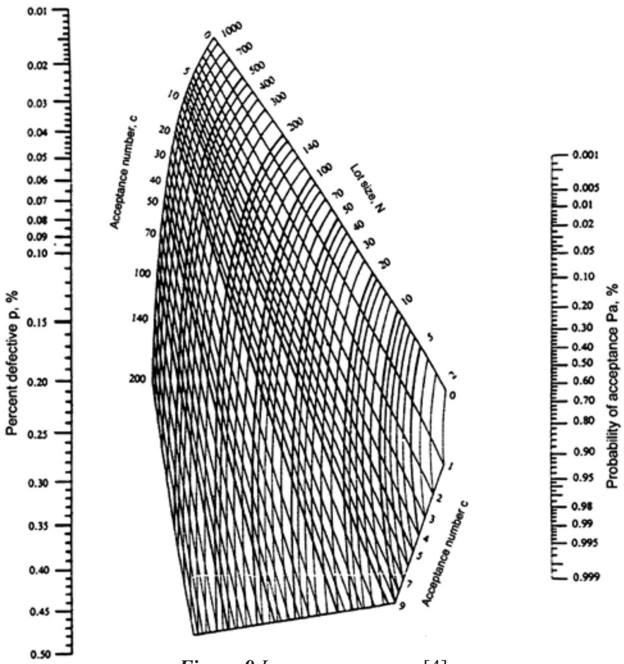


Figure 9 *Larson nomogram* [4]
Slika 9. *Larsonov nomogram* [4]

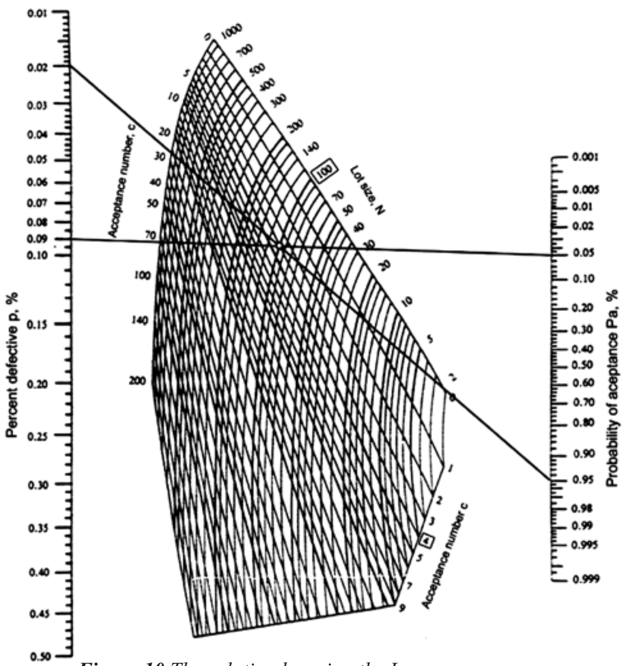


Figure 10 *The solution by using the Larson nomogram*
Slika 10. *Rješenje pomoću Larsonovog nomograma*

3.3 Poisson distribution
Poissonova razdioba

Poisson distribution can be seen as a borderline case of binomial with parameters n and p, in case the number of trials approaches infinity ($n\to\infty$) while p approaches zero ($p\to 0$) where $\lambda = n\cdot p$ =const.

A discrete random variable has the Poisson distribution with parameter λ if its distribution function is given in equation (7).

$$P_r(d \le c;\lambda) = \sum_{i=0}^{c} \frac{\lambda^i}{i!} \cdot \mathrm{e}^{-\lambda},$$

$$P(d;\lambda) = \frac{\lambda^Q}{x!} \cdot \mathrm{e}^{-\lambda}. \tag{7}$$

Cumulative distribution function of the Poisson distribution is given in equation (8).

$$P_r(d \le c;\lambda) = \sum_{i=0}^{c} \frac{\lambda^i}{i!} \cdot \mathrm{e}^{-\lambda}. \tag{8}$$

The Poisson distribution is used for approximating the binomial with parameters n and p when n is big and p is small, e.g. $n \ge 20$ and $p \le 5$ and excellent overlap for $n \ge 100$ and $n\cdot p \le 10$.

4 The elaboration of mathematical model
Razrada matematičkog modela

For an easier understanding of mathematical formulation for the sampling plans design, it is necessary to remember operating characteristic of an acceptance plan. The graph of operating characteristic curve presents the probability of accepting a delivery with a certain percentage of defective parts for the mentioned sampling plan.

Given that the size of delivery N is big in relation to the sample size n, and that selecting a sample n from the delivery does not significantly change the average structure of the rest of the delivery (independently on how many defective lots there are in the sample), the distribution of defects d in a random sample n is binomial with parameters n and p, where p presents the fraction of defects per delivery.

The probability of observing exactly d effects according to the binomial formula is given in equation (5).

The probability of acceptance is the probability at which the number of defects found in a sample d is smaller or equal to the acceptance number c and for the binomial distribution is given in equation (6).

In order to design a sampling plan with associated operating characteristic curve two points are needed. The first point presents the probability of acceptance $P_\alpha = 1-\alpha$ for deliveries with the fraction of defects $p_1 = AQL$. The other point can be called P_β, where the fraction of defects is $p_2 = RQL$. [5]

Given that the binomial distribution is adequate, parameters n and c can be obtained by solving nonlinear system of equations obtained in (6):

$$1-\alpha = B(d,c;n,p_1) = \sum_{d=0}^{c} \binom{n}{d} \cdot p_1^d \cdot q^{n-d}, \tag{9}$$

$$\beta = B(d,c;n,p_2) = \sum_{d=0}^{c} \binom{n}{d} \cdot p_2^d \cdot q^{n-d}. \tag{10}$$

Equations (9) (binomial acceptance probability of a good shipment) and (10) (binomial acceptance probability of a shipment of significantly worse quality) present nonlinear system of equations, which means a direct solution does not exist. There are several iterative methods for solving this system, thus for the design of the acceptance plan a computer is essential. Equivalently to the equation systems (9) and (10) it is possible, with minor changes, to use the systems obtained by using equation (4) both for hypergeometric or by using equation (8) for the Poisson distribution.

4.1 Integration of the mathematical model in software application
Integracija matematičkog modela u računalnu aplikaciju

In 1969, W. C. Guenthier found appropriate algorithm for searching the solution for the system of equations (9) and (10). One of the forms of this algorithm applicable in programming in software applications is given in the flow chart shown in Fig. 11 [6]. The example of integration of the mathematical model for binomial distribution by using m-file in MATLAB is shown in Fig. 12. On the basis of the code in Fig. 12, a user interface is created for easier input and printout of results and curves, which is shown in Fig. 13.

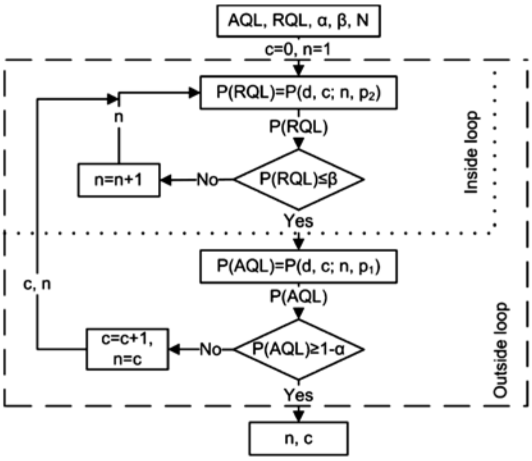


Figure 11 Chart flow of the algorithm for iterative solution finding
Slika 11. Dijagram toka algoritma za iterativno traženje rješenja

```
%SIMPLE SAMPLING PLANS USING BINOMIAL DISTRIBUTION
%=====> Input data <==============================
AQL = 2;          %Acceptable Quality level, %
RQL = 9;          %Rejectable Quality level, %
alfa = 5;         %Alfa risk, %
beta = 5;         %Beta risk, %
%=====> End of input <============================
%=====> Start program <===========================
%==========> Units calculation <==================
p1=AQL/100;, p2=RQL/100;, alfa=alfa/100;
beta=beta/100;, Pa=1-alfa;
%==========> Marginal conditions setting <========
c=0;, n=1;, Pa_calc=0;,     betarisk=1;
%==========> Outside loop start <=================
while Pa_calc<=Pa
    betarisk=1;
    while betarisk >= beta%> Inside loop start <=
              betarisk = binocdf(c,n,p2);
        if betarisk >= beta
            n=n+1;
        end
    end%======================> Inside loop end <=
    Pa_calc = binocdf(c,n,p1);
    if Pa_calc<=Pa
        c=c+1; n=c;
    end
end%=======> Outside loop end <==================
n, c%======> Print results <=====================
%==========> Plot OC curve <======================
p=0:0.01:1;            % => Set plot area <=========
Pa_calc = binocdf(c,n,p); %Probability calculation
plot(p*100,Pa_calc*100);  %Plot graph
%==========> Plot labels on graph <===============
xlabel('Percent defective p [%]');
ylabel('Probability of acceptance Pa [%]');
title('Operating characteristic Curve');
```

Figure 12 The example of algorithm adaptation for implementation in Matlab
Slika 12. Primjer prilagodbe algoritma za izvođenje u Matlabu

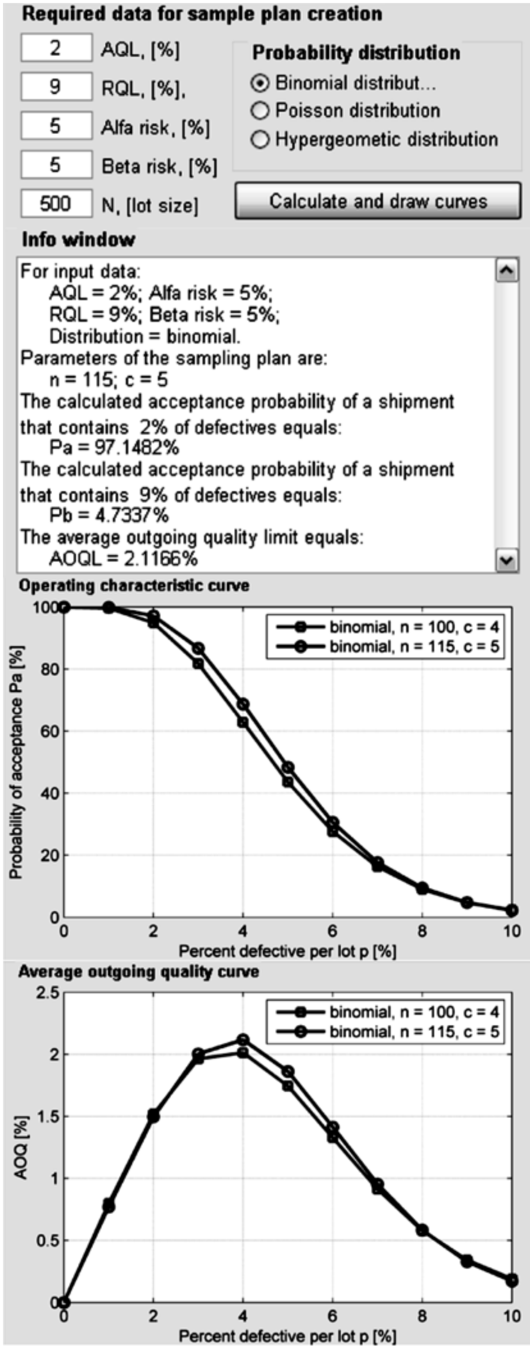


Figure 13 The example of user interface designed in Matlab
Slika 13. Primjer korisničkog sučelja izrađenog u Matlabu

5 Application
Primjena

In this chapter, on the basis of examples, classic examples of usage and comparison with the Larson nomogram and standard are presented. Since the copying of Croatian standards or their parts is prohibited, tables from the cancelled American military standard MIL STD-105E will be used for comparison, together with the name of analogue table from the HRN ISO 2859-1:1989 standard (standard HRN ISO 2859-1:1989 derived from the American standard MIL STD-105, with cosmetic changes so the tables and results correspond).

5.1
Comparison with the Larson Nomogram
Usporedba s Larsonovim nomogramom

It is necessary to create such a sampling plan which accepts 95 % of samples containing 2 % of defective lots and accepts only 5 % of samples containing 9 % of defective lots.

Since the task is analogue to the former example solved with the Larson nomogram, following conclusions can be drawn, based on Fig. 13:

- Operating characteristic curve derived from the data in the Larson nomogram (curve marked with circles in Fig. 13) is placed below the curve derived by using the mathematical model for the input data (curve marked with squares in Fig. 13), which means that it will result in stricter criteria for acceptance with the same percentage of defective lots
- The average outgoing quality curve for the data from the Larson nomogram can also be found below the outgoing quality curve for the input data, which means that after a number of shipments big enough at the entrance warehouse would be less defective lots for the acceptance plan derived from the Larson nomogram.

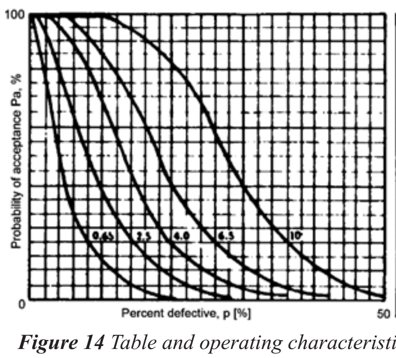
5.2
Comparison with the standard ISO HRN 2859-1:1989
Usporedba s normom ISO HRN 2859-1:1989

In order to make the comparison with standards, it is necessary to find input data for the software application first. Since in the standard only *AQL* and the level of review are defined, it is necessary to inspect carefully the tables and operating characteristic curves for the appropriate code letter and take out the needed data.

As an example, a code letter F is chosen:
HRN ISO 2859-1:1989, graph F, Table X-F-1,
MIL STD-105E, graph F, table X-F-1,
Sample size 91-150, $AQL = 4$, n=20, c=2,
shown in Fig. 14.

The following data can be read from the diagram and the table in Fig. 14:

$AQL = 4\ \%$; $\alpha \approx 5\ \%$
$RQL = 24{,}5\ \%$ for $\beta = 10\ \%$.



Pa, %	AQL, % 0.65	2.5	4.0
	p, %		
99.0	0.050	0.75	2.25
95.0	0.256	1.80	4.22
90.0	0.525	2.69	5.64
75.0	1.43	4.81	8.70
50.0	3.41	8.25	13.1
25.0	6.70	12.9	18.7
10.0	10.9	18.1	24.5
5.0	13.9	21.6	28.3
1.0	20.6	28.9	35.6

Figure 14 *Table and operating characteristic curve with code letter F*
Slika 14. *Tabela i operativna krivulja kodnog slova F*

When this data is inserted into the application, obtained results are shown in Fig. 15. The sample size N when using binomial distribution does not play any part during the design of sampling plans, but it is necessary to insert the number which describes the size of the basic lot for the calculation necessary for the printout of the AOQ curve.

Obtained sampling plan has parameters $n = 20$ and $c = 2$ which correspond to the data in the standard (Fig. 15).

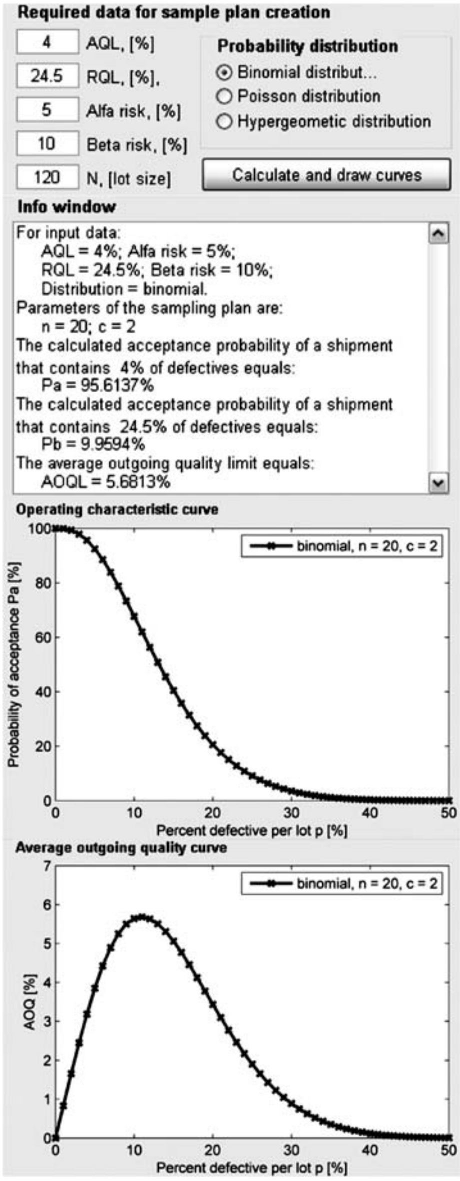


Figure 15 *Printout of the results for the code letter F*
Slika 15. *Ispis rezultata za kodno slovo F*

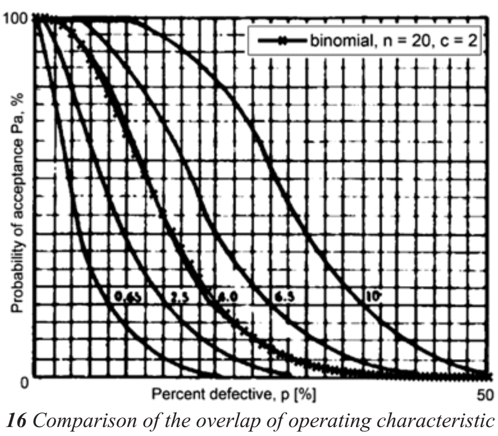


Figure 16 *Comparison of the overlap of operating characteristic curves*
Slika 16. *Usporedba poklapanja operativnih krivulja*

When the operating characteristic curve from Fig. 15 is copied onto the graph in Fig. 14, it is visible that the overlap of the curves is more than satisfying (Fig. 16).

Based on the procedure presented in the previous example, it is necessary to design sampling plans for the data given in Tab. 1.

Table 1 *Input data for comparison*
Tablica 1. *Ulazni podaci za usporedbu*

Ord. numb.	Code letter	Sample size	AQL	α	RQL	β
1	D	26-50	10	4	58	10
2	G	151-280	2,5	5	15,8	10
3	J	501-1200	1	5	6,25	10
4	L	3201-10000	0,25	10	1,94	10

Table 2 *Compared solutions by using the standard and software application*
Tablica 2. *Usporedna rješenja pomoću norme i računalne aplikacije*

Ord. numb.	Standard	Application
1	n=8, c=2	B: n=8, c=2
		P: n=12, c=3
		H: n=7, c=2
2	n=32, c=2	B: n=32, c=2
		P: n=43, c=3
		H: n=32; c=2
3	n=80, c=2	B: n=80, c=2
		P: n=103, c=3
		H: n=79, c=2
4	n=200, c=1	B: n=200, c=1
		P: n=201, c=1
		H: n=197, c=1

B – Binomial distribution, P – Poisson distribution,
H – Hypergeometric distribution

It is visible from Tab. 2 that the application gives results which correspond to the standard. It is also visible that the Poisson distribution approximates well the binomial for large samples and smaller probabilities.

6 Conclusion
Zaključak

Standard HRN ISO 2859-1:1989 is created with the aim to enable a simple and reliable system for the design of sampling plans. The main problem presents the fact that it is formed around the acceptable level of quality AQL and is stern when it comes to the choice of other parameters for the design of acceptance plans.

Larson nomogram presents a fast and simple way for the design of acceptance plans, which is with parameters adapted to the specific case. However, because of the network distribution, some discrepancy of parameters is possible, which results in insufficiently critical or overly critical acceptance plan.

As opposed to the mentioned standard, statistical approach enables the design of mathematical models which correspond to specific situations, but it presents a problem since there is extensive and slow calculation of cumulative distribution functions in relation to data distribution.

This paper presents an overview of one of the possible ways of development and implementation of mathematical model in a software application which is not limited with sampling parameters or with the volume of mathematical calculation and it presents a simple and fast way for the design of acceptance plans adapted for the use in concrete situations. The emphasis is put on design of optimal acceptance plans which ensure that the obtained parameters and operating characteristic curves faithfully follow requirements (AQL, RQL, alpha and beta risks, and sample sizes) and by that favor both the producer and the consumer.

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