Quantitative Estimation of Logging Residues by Line-Intersect Method

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Abstract

Line intersect sampling (LIS) is a method used for quantifying forest residues after logging operations. In conventional LIS theory, forest residues are considered as separate pieces of cylindrical shape, they occur horizontally, and are randomly orientated and randomly distributed. In the case of cut-to-length (CTL) logging operation, forest residues represent separate clusters, consisting of pieces of branches, twigs, tips, etc. So the application of the conventional LIS theory for quantifying forest residues after CTL logging is difficult. The purpose of the article was to assess the accuracy of the modified LIS method for quantifying forest residues after CTL logging. The studies were conducted by computer simulations. In the models, the forest residues are represented as clusters in the form of circles. The laws of distribution of the radius of the clusters and their position in the plot were determined by field measurements. In the simulations, 4 types of clusters were considered:

- ⇒ *type 1 – clusters uniformly distributed within the entire cutting area (Fig. 7)*
- ⇒ *type 2 – clusters uniformly distributed along the X-axis and five stripes on the Y-axis (Fig. 8)*
- ⇒ *type 3 – clusters uniformly distributed along the X-axis and three stripes on the Y-axis (Fig. 9)*
- ⇒ *type 4 – clusters uniformly distributed along the X-axis and one stripes on the Y-axis (Fig. 10)*

It was determined through simulation that the formula of the modified LIS method estimated appropriately forest residues after CTL logging. According to the results of simulation experiments, it was found that when the location of the lines of sample are across the area of Fig. 7, 8 (across the stripes with clusters), the results are in good agreement with the theoretical formulas. Differences are within error of 20%.

Key words: Line intersect sampling (LIS), cut-to-length logging (CTL), simulation model, logging residues, clusters of logging residues, sample line

1. Introduction

In recent years, forest residues are increasingly used in various industries, particularly in bioenergy industry. The choice of efficient technologies for collecting and processing of logging residuals are based on information about their quantity and quality. For quantifying forest residues, indirect assessment methods can be used as well as direct measurement in the cutting area.

Indirect methods (regulatory, balance sheet and regulatory balance sheet) are used for quantitative estimation of logging residues based on the number of branches and tops of the plants. According to the Russian Guidelines, the volume of logging residues can be calculated by the formula (Guidelines 1985):

$$Q = \frac{V \times N}{100} \qquad (1)$$

Where:

Q volume of logging residues, m^3

V volume of raw materials, m^3

N norm of wood waste generation, %

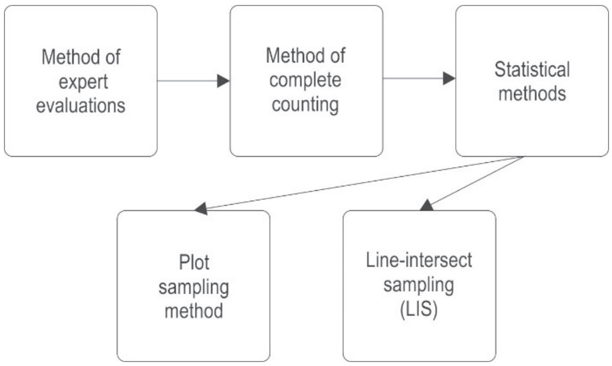

Fig. 1 Methods of estimation of logging residues

The norm of wood waste generation N depends on the technology of logging operations and growing conditions of the forest. So the indirect methods are not accurate and require field inspection of the cutting area.

Methods of quantitative estimation of logging residues by direct measurements on the cutting area can be divided into the following groups (Fig. 1):

⇒ method of expert evaluations
⇒ method of complete counting
⇒ statistical methods.

All the above estimation methods were tested by the authors in practice, for assessing logging residues, windfalls, sunken logs, etc.

The method of expert evaluations, the Delphi Method (Dalkey and Olaf 1963), was applied by the authors of the article to assess the sunken logs in rivers. The method included groups of highly skilled professionals with experience in logging and timber rafting. For each river, where there were sunken logs, a group of experts of 7 to 9 people was selected.

The comparison of the experimental data on the number of sunken logs with the data obtained by the method of expert estimates showed difference of about 100%. For this reason, this method cannot be applied in practice.

The method of complete counting assumes a continuous recalculation of the whole wood. Complete counting consumes more time, but can be effective in the use of modern technologies, for example, using aerial and satellite images.

Statistical methods are best suited to assess the quantity and quality of logging residues. The accuracy and complexity of statistical methods depends on the volume of the sample.

The authors have used the following statistical methods:

⇒ plot sampling method
⇒ line-intersect sampling (LIS).

The plot sampling is mostly used for estimating plants in the forest, animal nests, soil fauna, etc. According to this method, every item is counted within each plot (plants, nests, etc). This method may also be used for sampling logging residuals (Ghaffariyan et al. 2012, Ghaffariyan 2013). In this case, the estimated volume of wood W (m^3/m^2) in a cutting area:

$$W = \frac{Q}{S} \qquad (2)$$

Where:

S total area of the sample plot, m^2
Q volume of wood on the sample plot, m^3

The line intersect sample (LIS) was originally described by Warren and Olsen (Warren and Olsen 1964). Since then, the LIS method has been extensively used for the quantity estimation of logging residues (Van Wagner 1968, Van Wagner and Wilson 1976, Van Wagner 1982, Bailey 1969, Bailey 1970, Bailey and Lefebvre 1971, Howard and Ward 1972, De Vries 1973, De Vries 1974, Brown and Roussopoulos 1974, Brown 1974, Van Wagner 1976, Pickford and Hazard 1978, Pickford and Hazard 1986, Harmon et al. 1986, Karpachev 2008a, Karpachev 2008b, Karpachev and Scherbakov 1990, Karpachev and Scherbakov 2009, Karpachev and Scherbakov 2013, Karpachev et al. 2010, Linnel Nemec and Davis 2002, O'Hehir and Leech 1997, Woldendorp et al. 2004, Bate et al. 2009, Bell et al. 1996).

The LIS method allows obtaining sufficiently accurate results, and the time for sampling is reduced, as compared with the plot sampling method, by about 60–70%. However, it was noted that the accuracy of the estimations is significantly affected by the concentration of the logging residuals per unit area. In recent years, the LIS method has probably been one of the most common techniques for the assessment of forest residuals.

According to the LIS method, logs and their pieces that are crossed by a sample line are selected into a sample (Fig. 2). The volume of all wood on the cutting area is estimated by the sample logs and their pieces.

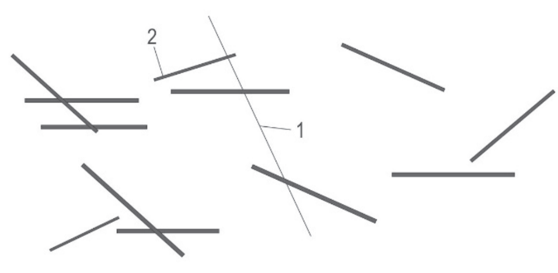

Fig. 2 A graphical explanation of the LIS method (1 – sample line, 2 – intersected log)

The theory of the LIS method was the subject of numerous scientific papers (De Vries 1973, Marshall et al. 2000, De Vries, 1979, De Vries 1986, Hazard and Pickford 1984, De Vries 1974, Van Wagner 1976, Karpachev and Scherbakov 2013).

It should be noted that much of the published literature on LIS theory and its application in practice falls under the topic of estimation of logging residues in the form of separate logs and their pieces distributed across the area (Fig. 2). Such characteristics of forest residuals are typical for whole-tree logging (Feller buncher + skidder technology).

In the case of cut-to-length (CTL) logging operation, forest residues look like separate heaps (Fig. 3), consisting of pieces of branches, twigs, tips, etc. So the application of the conventional LIS theory for quantifying forest residues after CTL logging is difficult.

In recent years, theoretical and field studies on the application of the LIS method for estimating logging residues after CTL logging have been carried out. (Karpachev et al. 2010, Karpachev and Scherbakov 2013).

The purpose of this paper is to provide information on LIS method for estimating logging residues in the form of separate heaps (it will be called clusters of logging residues or simply – clusters) after CTL logging.

This paper:

⇒ explains the theory underlying LIS for estimating clusters

⇒ provides basic formulas for estimating the number of clusters

⇒ provides simulation models of the heaps with different statistical characteristics and LIS field procedures for estimating the number of clusters

⇒ provides basic results of computer simulation of LIS method for estimating the number of clusters

⇒ briefly describes the field-sampling requirements for LIS.

Fig. 3 The clusters after CTL logging (author's photo)

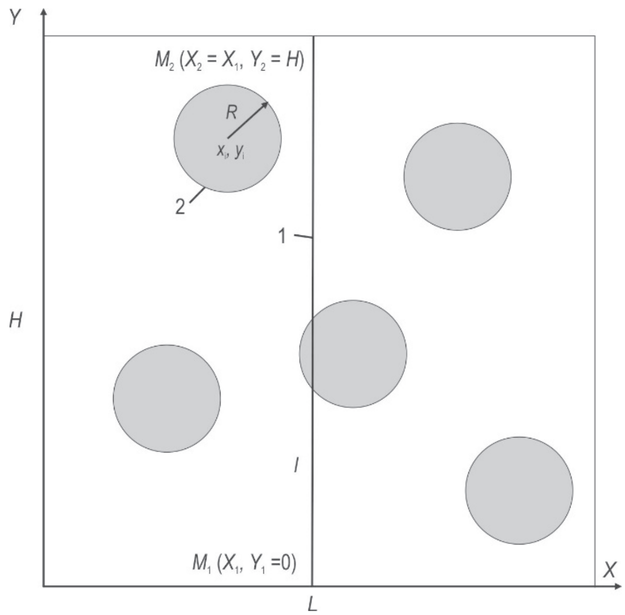

Fig. 4 Scheme of clusters on the cutting area (1 – sample line, 2 – clusters of logging residues)

2. Theoretical Approach

As defined before, this paper deals with forest residues after CTL logging. These forest residuals are clusters consisting of branches, twigs, tips, etc. (Fig. 3).

When considering a plane rectangular cutting area of size L_xH, the area contains n clusters (Fig. 4) and all the clusters have the shape of a circle of radius R.

The sample line of length l passes through the cluster area. The sample line is parallel to the ordinate axis. The sample line will be equal to the width of the area: $l = H$. The coordinates of the beginning of the line will be $M_1(X_1, Y_1 = 0)$. Coordinates of the end of the sample line will be equal to M_2 ($X_2 = X_1$, $Y_2 = H$).

The number of clusters on the cutting area of size $L \times N$ can be defined by the formula:

$$N = \frac{M,[\mathrm{m}]}{p} \qquad (3)$$

Where:

$M,[\mathrm{m}]$ mathematical expectation of the number of intersections between the sample line and clusters

P probability that the sample line will intersect the cluster.

In practice, the value M, [m] can be estimated by the average number of clusters that intersects with n lines. If it is defined that all sample lines have the same length l, which is convenient in practice, then the mean will be equal to:

$$m = \frac{\sum_{j=1}^{n} m_j}{n} \tag{4}$$

Estimation of the number of clusters on the cutting area can be defined by the formula:

$$N \approx \tilde{N} = \frac{m}{p} \tag{5}$$

The probability that the sample line will intersect the cluster of radius R, will be equal to:

$$p = \frac{\Omega_+}{\Omega} \tag{6}$$

Where:

Ω_+ event that will bring the sample line to intersect the cluster

Ω all position of clusters on the cutting area, i.e. a complete system of events.

The coordinates of the centers of the clusters x_i, y_i are defined as a uniform distribution on the interval [0, L] [0, H]. Then the probability that the sample line with the length $l > 2R$ on an area of the size $L \times H$ will intersect the cluster with the radius R, will be equal to (Karpachev and Scherbakov 2013).

Assuming the condition: $l >> 2R$, then (Eq. 7) is transformed as follows:

$$p = \frac{2 \times R \times l}{L \times H} \tag{8}$$

If the sample line is parallel to the ordinate axis and equal to the width of the cutting area $l = H$, then the formula (Eq. 8) can be represented in the form:

$$p = \frac{2 \times R}{L} \tag{9}$$

If there are n sample lines, then, in this case, the estimate of the number of clusters is equal to:

$$N \approx \tilde{N} = \frac{1}{n} \times \frac{L}{2 \times R} \times \sum_{i=1}^{n} m_i \tag{10}$$

The required number of sample lines can be defined according to the known formula:

$$N = \left[\frac{V \cdot t}{P}\right]^2 \tag{11}$$

Where:

t confidence factor
P accuracy rate, %
V coefficient of variation, %.

In theoretical studies, some assumptions are accepted:

⇒ the radius of all clusters are the same and equal to R
⇒ the coordinates of the cluster centers x_i,y_i on the cutting area are defined according to a uniform distribution law
⇒ the length of all sample lines are the same $l = H$ and $l >>R$.

Because of the accepted assumptions, the theoretical formula may not be accurate enough in practice. In particular, a number of questions arise:

⇒ What will be the effect of variability of the radius of clusters on the accuracy of the estimate?
⇒ What will be the effect of variability of the radius of clusters on sampling?
⇒ What will be the effect of the law of distribution of coordinates of the cluster centers x_i, y_i on the accuracy of the estimate?

3. Methods

In theoretical studies, we have accepted a number of assumptions about the characteristics of clusters. It was decided to covnduct simulation experiments with

$$p = \frac{\pi^2 \cdot R^2 + 4\pi\left(\frac{R^2}{2}\left(\frac{l}{2R} - \mathrm{arctg}\frac{l}{2R}\right) + \frac{l^2}{8}\arcsin\frac{1}{\sqrt{1+\left(\frac{l}{2R}\right)^2}}\right)}{\pi \cdot L \cdot H} + \frac{4\pi\int_{R^*}^{R_c} r \cdot \frac{\sqrt{R^2 - \frac{\left[R^2 - \left(\frac{l}{2}\right)^2 + r^2\right]^2}{4 \cdot r^2}}}{\frac{l}{2}} \cdot dr}{\pi \cdot L \cdot H} \tag{7}$$

mathematical models using the actual characteristics of clusters.

Simulation studies on LIS were carried out by various authors (Pickford and Hazard 1978, Pickford and Hazard 1986, Karpachev 1990). All these studies had different purposes but all papers considered the logging residues in the form of separate logs and their pieces distributed across the area.

In this paper, the main task was to develop stochastic mathematical models that adequately describe the process of quantifying clusters by the LIS method. Also, it was decided to undertake studies of accuracy of LIS method in order to estimate clusters in a wide range of variation of their characteristics. In these models, we used the statistical characteristics of the clusters obtained in field measurements in the central regions of Russia. (Karpachev et al. 2010).

Based on the field measurement data, the following assumptions were accepted and used in the model:

⇒ shape of the clusters is a correct circle with variable radius R_j

⇒ variation of radius of the clusters is described by the normal distribution law.

In theoretical studies, the distribution of the cluster's centers coordinates x_i, y_i on the cutting area was defined as uniform. Field measurements showed that the distance between the clusters was in accordance with uniform distribution law (Karpachev et al. 2010). However, the location of the clusters is determined by the technology of the harvester and may differ from the uniform law. Usually clusters are located in accordance with the technology traffic lane (strip) of the harvester. Because of this, the distribution law of the cluster's coordinates on the cutting area may be different from the uniform law.

In the model, two types of distribution of the cluster's coordinates x_i, y_i were considered:

⇒ uniform distribution within the entire cutting area (Fig. 4)

⇒ uniform distribution within the technological strips of width b (Fig. 5).

According to (Eq. 10), it would be necessary to know the number of clusters to estimate the number of clusters that intersected with the sample lines.

The fact of intersection of the cluster with the sample lines was determined in the model by the following algorithm:

⇒ each sample line was represented by the equation of a straight line on the area and was defined by the point of its beginning $M_{1j}(X_{1j}, Y_{1j} = 0)$:

$$X = X_{ij} \qquad (12)$$

⇒ each cluster was defined as a circle with center $C_i(x_i, y_i)$ and variable radius R_i

⇒ event of intersection of the j^{th} sample line with the i^{th} cluster was determined as (Fig. 4):

$$(x_i + R_i) \geq X_{ij} \geq (x_i + R_i) \qquad (13)$$

The model should simulate the LIS process of quantifying clusters. To implement this process, the model was composed of two blocks (Fig. 6):

⇒ generation block of clusters on the cutting area with the specified characteristics

⇒ generation block of sample lines on the cutting area with the specified characteristics.

The model contains three procedures:

⇒ procedure of counting the actual number of clusters on the cutting area

⇒ procedure of LIS method for the clusters and estimation of their number

⇒ procedure of comparison between the estimated number and the actual number of clusters.

The modeling principles and algorithms of these programs were taken into consideration.

Characteristics of clusters in the model were assigned according to the following algorithm:

⇒ the number of clusters n on the cutting area was specified in the primary source data

⇒ the radii R_i of clusters was generated according to the normal distribution law.

The coordinates of the cluster's center x_i, y_i were generated in the intervals [0, L] [0, H]. In the model, two cases of distribution of the cluster's coordinates on the cutting area were considered:

⇒ uniform distribution

⇒ distribution by stripes.

In the latter case, the coordinates of the center of clusters x_i were generated by the uniform distribution on the interval [0, L], and the coordinates y_i were generated by the normal distribution law in the interval [0, H] with the mean in the centers of the strips b (Fig. 5).

The model generated the sample lines with a set of specified characteristics. The main characteristics of the sample line were:

⇒ length of the sample line l

⇒ coordinates of the sample line on the cutting area X_j, $Y_j = 0$.

Characteristics of the sample lines in the model were assigned according to the following algorithm:

⇒ the beginning of coordinate Y_{1j} of each sample line was $Y_{1j} = 0$

⇒ the beginning of coordinate X_{1j} of the sample line was generated by the uniform distribution law in the interval [0, L], so that the line passed across the whole cutting area

⇒ length of each sample line was equal to the width of cutting area H.

Examples of generating the clusters with specified characteristics are presented in Fig. 7 and Fig. 8. Fig. 7 shows only one sample line.

The coordinates of the center of clusters x_i, y_i were generated in accordance with the following laws:

⇒ Fig. 7 – uniform law

⇒ Fig. 8 – distribution by strips.

The specified characteristics of clusters (x_i, y_i, R_i) were generated by means of Excel software. 4 types of clusters were considered in the experiments:

⇒ type 1 – clusters uniformly distributed within the entire cutting area (Fig. 7)

⇒ type 2 – clusters uniformly distributed along the X-axis and within five stripes on the Y-axis (Fig. 8)

⇒ type 3 – clusters uniformly distributed along the X-axis and within three stripes on the Y-axis (Fig. 9)

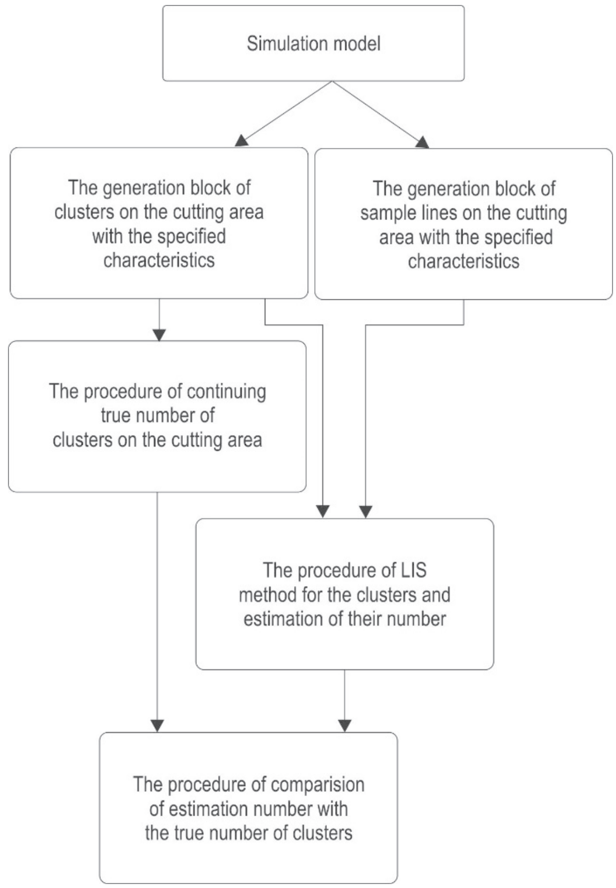

Fig. 6 Structural diagram of a simulation model

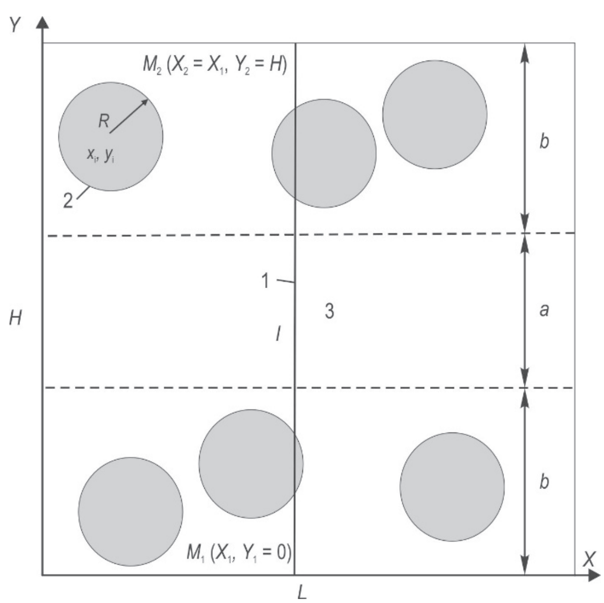

Fig. 5 Location scheme of cluster stripes on the cutting area (1 – sample line, 2 – clusters, *a* – harvester movement technology corridor, *b* – technology stripes of clusters)

⇒ type 4 – clusters uniformly distributed along the X-axis and within one stripes on the Y-axis (Fig. 10).

The generation of various types of clusters was saved as database for the simulation experiments.

The number of clusters in the model varied in each type of clusters from 10 to 170 pieces in increments of 40 pieces.

The specified characteristics of the clusters were tested for compliance with the above mentioned laws of distribution and their statistical characteristics were

Table 1 Example of statistical characteristics of the clusters (Fig. 7)

Statistical characteristic	Value		
	x_1	y_1	R
Mean	51.45	53.90	3.11
Variance	867.56	740.05	2.96
Standard deviation	29.45	27.20	1.72

Table 2 Example of statistical characteristics of the clusters (Fig. 8)

Statistical characteristic	Value										
	Strip 1		Strip 2		Strip 3		Strip 4		Strip 5		R
	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4	x_5	y_5	
Mean	52.27	7.43	49.03	27.46	49.73	47.71	49.07	67.44	51.58	87.47	2.95
Variance	1032.42	2.45	749.38	2.11	814.22	2.13	799.88	2.03	913.34	1.71	3.46
Standard deviation	32.13	1.57	27.37	1.45	28.53	1.46	28.28	1.43	30.22	1.31	1.86

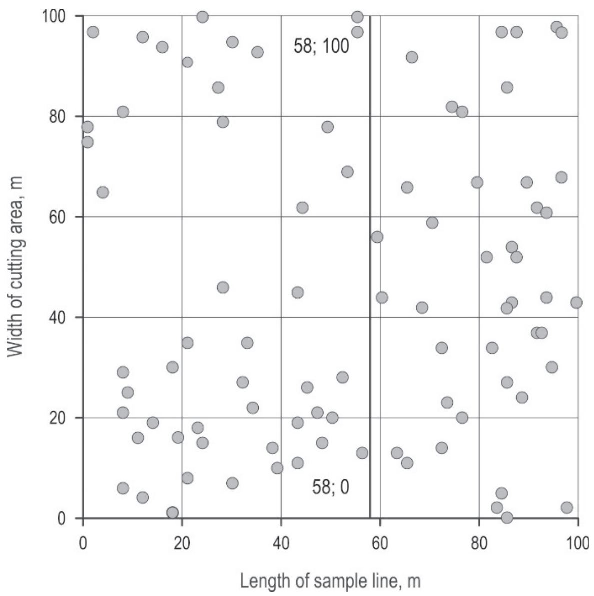

Fig. 7 An example of generation of 90 clusters with the uniform distribution (one sample line and its coordinates are demonstrated)

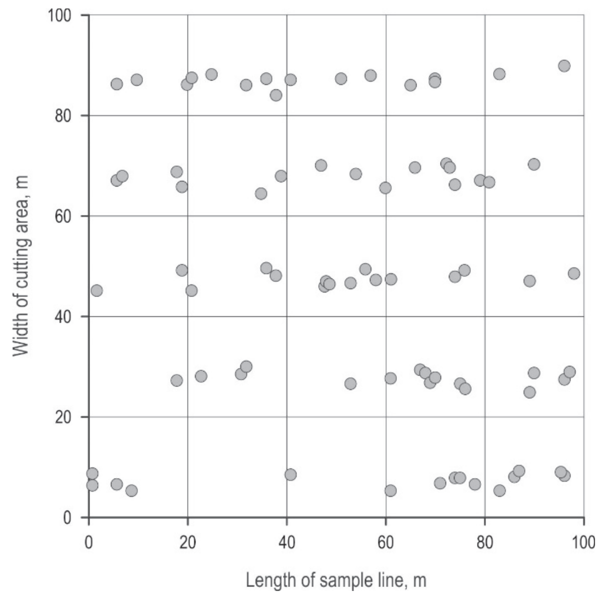

Fig. 8 An example of generation of 90 clusters within five stripes

calculated. Examples of the estimated statistical characteristics of the clusters are given in Table 1 and Table 2. After generation of the characteristics of clusters, they were saved in Excel tables.

The sample lines on the cutting area were set as follows:

⇒ for 1st type of clusters – along the Y-axis (case 1, Table 3)

⇒ for 2nd type of clusters – along the Y-axis (case 2, Table 4) and along the X-axis (case 3, Table 4)

⇒ for 3th type of clusters – along the X-axis (case 4, Table 5)

⇒ for 4th type of clusters – along the X-axis (case 5, Table 6).

The required numbers of sample lines for estimation of the number of clusters were defined according to the formula (Eq. 11).

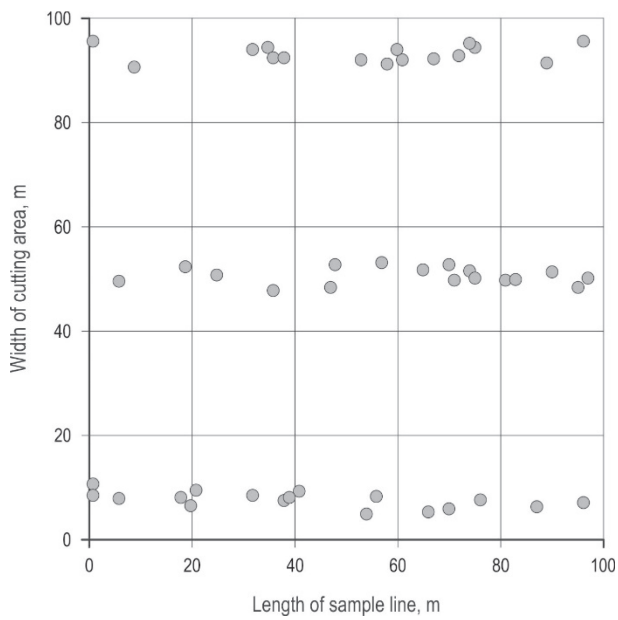

Fig. 9 An example of generation of 50 clusters within three stripes

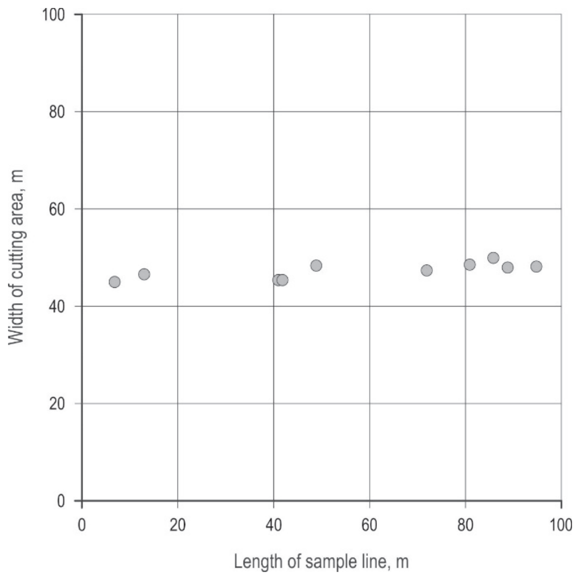

Fig. 10 An example of generation of 10 clusters within one stripe

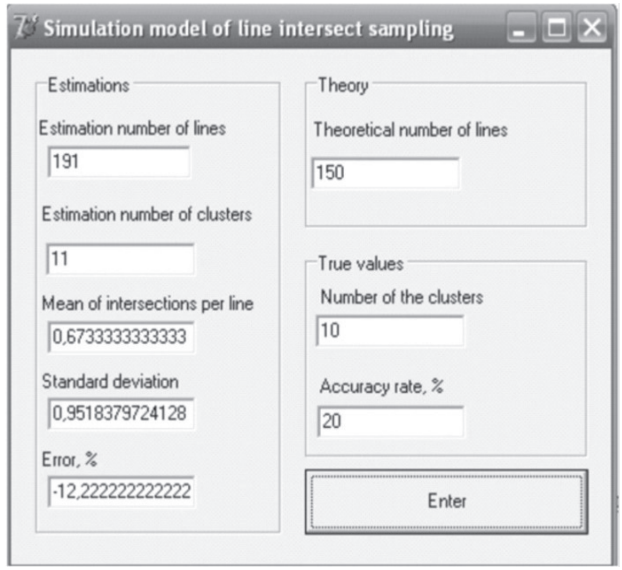

Fig. 11 Program's interface for estimation of clusters by LIS method

Estimation of the number of clusters was conducted using the algorithm described above. Estimation procedures were implemented in Delphi 7 program. The program's interface of the estimation of clusters by LIS method is shown in Fig. 11. In the experiments, the accuracy rate was assumed to be 20%.

4. Results and Discussion

Examples of LIS simulation results are displayed in Tables 3 – 7.

The results of simulation experiments (Table 3 – case 1, Table 4 – case 2) with the clusters on cutting

Table 3 Example of results of LIS simulation (case 1)

True number of clusters	Theoretical number of lines	Estimation number of lines	Estimation number of clusters	Mean number of intersections per line	Standard deviation	Error %
10	150	188	8	0.48	0.672	20
50	30	29	43	2.633	1.449	12.22
90	16	16	95	5.75	2.352	–6.48
130	11	7	139	8.363	2.377	–7.22
170	8	13	138	11	4.14	–7.84

Table 4 Example of results of LIS simulation (case 2)

True number of clusters	Theoretical number of lines	Estimation number of lines	Estimation number of clusters	Mean number of intersections per line	Standard deviation	Error %
10	150	126	12	0.733	0.84	–22.22
50	30	24	48	2.9	1.47	3.33
90	16	6	84	5.062	1.34	6.25
130	11	11	137	8.272	2.831	–6.06
170	8	3	193	11.625	2.326	–13.97

Table 5 Example of results of LIS simulation (case 3)

True number of clusters	Theoretical number of lines	Estimation number of lines	Estimation number of clusters	Mean number of intersections per line	Standard deviation	Error %
10	150	121	12	0.733	0.824	–22.22
50	30	124	46	2.8	3.188	6.66
90	16	83	84	5.062	4.711	6.25
130	11	96	148	8.909	8.938	–14.21
170	8	68	241	14.5	12.247	–42.15

Table 6 Example of the results of LIS simulation (case 4)

True number of clusters	Theoretical number of lines	Estimation number of lines	Estimation number of clusters	Mean number of intersections per line	Standard deviation	Error %
10	150	586	7	0.433	1.07	27.77
50	30	220	41	2.466	3.739	17.77
90	16	164	105	6.312	8.268	–16.89
130	11	346	80	4.818	4.818	38.22
170	8	250	202	12.125	19.577	–18.87

Table 7 Example of results of LIS simulation (case 5)

True number of clusters	Theoretical number of lines	Estimation number of lines	Estimation number of clusters	Mean number of intersections per line	Standard deviation	Error %
10	150	883	8	0.493	1.496	17.77
50	30	532	81	4.866	11.458	–62.22
90	16	816	101	6.062	17.68	–12.268
130	11	476	287	17.272	38.471	–121.44
170	8	559	60	3.625	8.749	64.46

areas (Fig. 7, Fig. 8) were plotted in Fig. 12 as markers. For comparison, Fig. 12 shows the theoretical curve obtained from the equation (Eq. 11).

As follows from the graph in Fig. 12, the discrepancy between the theoretical and experimental results has exceeded the error of 20% in only one case. It should be emphasized that the sample lines in these cases were directed across the cutting area (along Y axis). The X coordinate of the lines were determined according to the uniform distribution law.

It is logical to assume that if the sample lines are drawn along the cutting area (Fig. 8, 9, 10) (along the X-axis and along the stripes of the clusters), then the variance of the average number of intersection of clusters with the lines will be increased with a decrease of the number of stripes. This should increase the required number of sample lines. Simulation experiments (Fig. 8, 9, 10) have confirmed this hypothesis. This is also shown in Table 5, 6, 7 and the graph in Fig. 13. For example, for the cutting area with one stripe with 50 clusters on the area (Fig. 10 and Table 7), the theoretical numbers of sample lines are 30 lines. The number of sample lines, calculated by the results of the experiments, amounted to 532 lines.

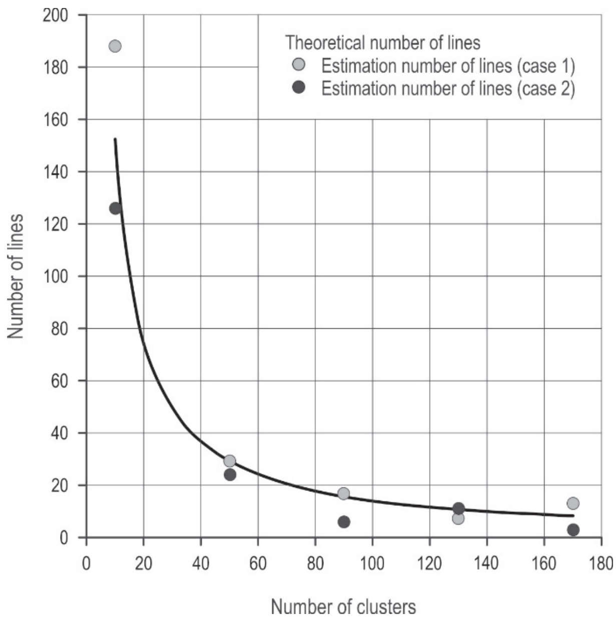

Fig. 12 Dependence of the required number of sample lines on the number of clusters

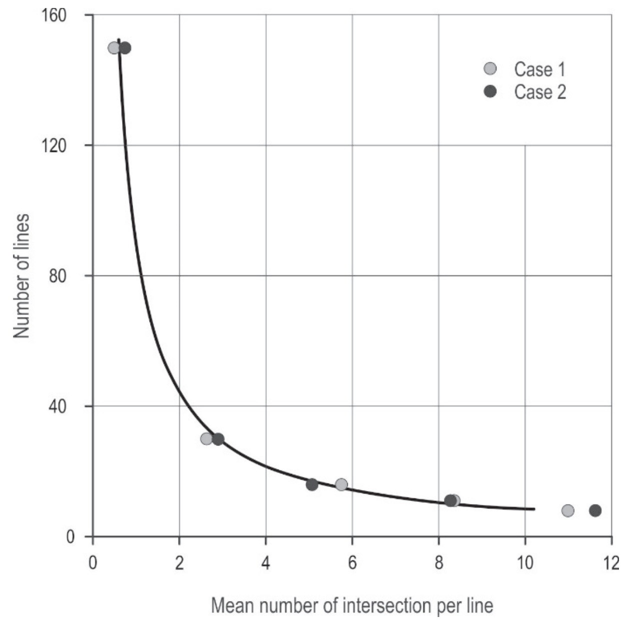

Fig. 14 Dependence of the required number of sample lines on the mean number of intersections of clusters with sample line

In order to estimate the variance (standard deviation) of the number of clusters intersected with the lines, an additional simulation experiment was carried out with clusters located on one stripe (Fig. 10).

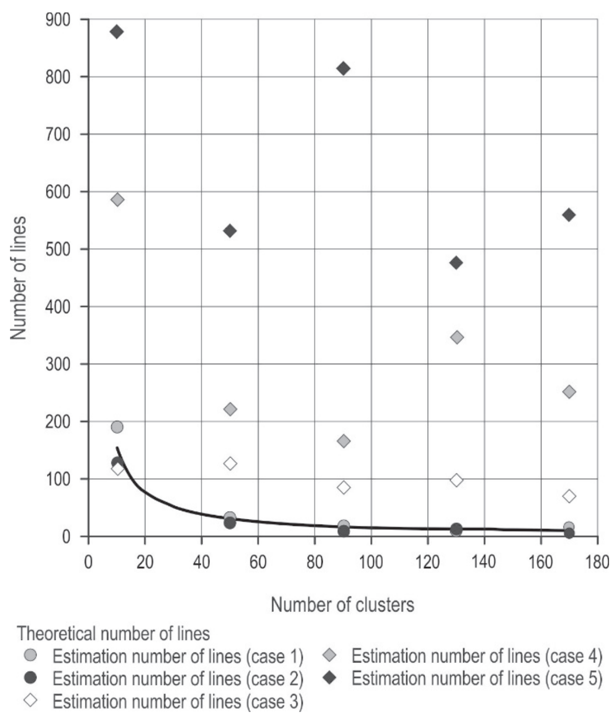

Fig. 13 Dependence of the required number of sample lines on the number of clusters for different types of clusters

In a simulation model carried out to estimate the number of clusters, 1000 sample lines were generated for each cutting area. The results are displayed in Table 8. The table shows that the sample lines should be located across the area (along *Y* axis). In this case, the required number of sample lines is close to the theoretical number. Correspondingly, 20 and 16 lines are required. In comparison to the lines drawn along the area (along the *X*-axis), the required number of sample lines is very different from the theoretical one. Correspondingly, 823 and 16 lines are required. This can be explained by large differences in standard deviation (16.168 and 2453, Table 8).

From a practical point of view, the graph in Fig. 14 is very interesting. The graph shows the dependence of the required number of sample lines on the average number of intersections of clusters with the sample line.

5. Conclusions and Practical Recommendations

Estimation of the number of clusters on the cutting area of a rectangular shape can be made according to the formula (Eq. 5).

If the sample lines cross the cutting area (parallel to the *Y*-axis) and are equal to the width of the area, then the probability that the sample line will intersect the cluster can be determined by the equation (Eq. 9).

Table 8 Results of estimation of clusters by 1000 sample lines (case 5)

Direction of line	True number of clusters	Theoretical number of lines	Estimation number of lines	Estimation number of clusters	Mean number of intersections per line	Standard deviation	Error %
0*Y*	90	16	20	88	5.315	2.453	1.574
0*X*	90	16	823	92	5.522	16.168	–2.259

Estimation of the number of clusters should be done according to the results of the intersections of the clusters with n sample lines according to the formula (Eq. 10). The required number of sample lines can be determined according to the known formula (Eq. 11).

Simulation experiments were carried out for 4 types of clusters as shown in graphs in Fig. 7, 8, 9, 10.

The results of simulation demonstrated that, when the location of the sample lines are across the area as shown in Fig. 7, 8 (across the stripes with clusters), the results are in good agreement with the theoretical formulas. Differences are within the error of 20%. This is due to the fact that, in this case, the estimation is only affected by the x-coordinate of the clusters.

When the location of the sample lines are along the plot (along the strips with clusters, Fig. 8, 9, 10), the results disagreed with the theoretical formulas. The differences can exceed the error of 100%, for example as shown in Table 7. A significant discrepancy is explained by the fact that, in this case, the assessment is only affected by the y-position of the center of cluster, which is distributed within the stripe. Part of the sample lines go through the stripes with a large number of intersections with the clusters, but another part of the lines get between the strips, where there will be no intersections between the lines and clusters. It is clear that this will lead to an increase of the variance (or standard deviation), which will correspondingly increase the required number of sample lines.

For clusters with coordinates x, y distributed by the uniform law through the cutting area, it is possible to carry out a sample line across the area and along the area. In this case, in practice, it makes no difference how to draw the sample lines (along or across the cutting area).

For clusters, which are distributed in the cutting area inside the stripes, the sample lines should pass across the stripes. The required number of the sample lines can be pre-determined according to the formula (Eq. 11) and can be clarified during the field measurement process using the graph (Fig. 10).

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