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VARIATION OF ORE GRADE TRANSPORTED BY BELT CONVEYORS TO PROCESSING PLANTS

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Abstract: The paper presents result of comparison of Cu content variability in three industrial ore streams, that is on section and transfer conveyors as well as the feed for the processing plant. Comparisons were focused only on ore grade variability for consecutive shifts during one month. The samples were taken manually throughout the whole shift from the transfer conveyor and automatically from the conveyor which provides the ore to the concentration plant. The comparisons indicated that the smallest variability of Cu content can be observed for the feed to the processing plant with coefficient of variation (*cov*) equal to 5.33% and the biggest for the ore stream on the transfer conveyor with *cov* equals to 11.85%. The grade distribution for the transfer conveyor cannot be described by normal distribution, as it is the case for the ore going to the processing plant and the ore supplied onto the sections conveyors. The smallest variability in the feed to the concentration plant is a consequence of almost perfect ore mixing and averaging of the ore due to coming from different locations and bunkers. The mixing is only partial on the transfer conveyor because of smaller number of ore sources as well as time separation between following loads from the mining faces. This gives in effect larger, instead of smaller, spread between the minimum and maximum Cu content. The spread was 1.36% in comparison to 0.45% for the processing plant feed and 0.99% for the section conveyor. The distribution was not symmetric. The standard skewness for the transfer conveyor was 4.79 in comparison to 0.2 for the processing plant feed and 0.96 for the section conveyor.

Keyword: *belt conveyors, copper ore, concentration plant*

Introduction

One of important and difficult to maintain objectives of mineral industry is ore quality control at the feeding point for further processing (Tasdemir and Kowalczuk, 2014). It was shown by Jurdziak et al. (2016) that the present procedures of ore sampling from underground conveyors applied for instance by KGHM Polska Miedz SA is time consuming and is not accurate due to infrequent manual sampling and large size of ore lumps, in comparison to the samples mass. It is difficult, even roughly, to estimate

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sampling accuracy due to lack of an alternative verification method. Therefore, it is not uncommon that in financial accounting between KGHM Polska Miedz SA mines, despite regular sampling of the transported material, all sides have a feeling that the quality checking results do not represent real values. Frequently, there are also differences between estimates of the ore quality at working faces and transfer points as well as between estimates made by miners and by the staff of the Divisions of Concentrators (O/ZWR).

The problem of estimated ore grade accuracy via sampling from conveyor belt is not new (Jowett, 1952). Both the influence of the sampling interval (Marques and Costa, 2014), and the choice of the size of the sample mass (Gy, 1976) were the subject of numerous studies in the sampling developed by Pierre Gy and his co-workers (Esbensen, 2004). In the case of KGHM Polish Copper SA, both manual samples taken from the whole cross section area of the belt (Jurdziak et al, 2016), as well as from the whole falling stream of feed during automatic sampling in processing plant (Gy and Marin 1978; Cleary and Robinson, 2008) meet the conditions of representativeness, regardless of ore segregation effect on vibrating belts (Waters and Mikka, 1989). However, the frequency of sampling and the size of samples (their mass) require further research to determine the accuracy of the estimations (Holodnik et al, 2015) and its relationship to the variability of ore quality in loading points. Sometimes such variability, as in case of lignite, can even affect the accuracy of the work of on-line analysers in which those problems are not important (Galetakis and Pavloudakis, 2009).

Due to lack of quality data based on samples of the ore taken as it moves from the mining faces, through long and complicated conveying system with many runoff and flowing points and bunkers, to the concentration plant, it is difficult to compare quality of the transported material and notice grade changes. However, it is possible to compare the quality data for samples at different location and time moment of sampling, focusing on Cu content variation. Such a comparison is possible because variation of Cu content depends mostly on the quality of ore at the mined deposit.

Local grade variation, which occurs due to different geology of mined domains (Holodnik et al., 2015), can be reduced by ore mixing within the system of belt conveyors and bunkers. As a result, the variation of ore stream composition at the feeding points of the concentrating plant is stabilized (Drzymala and Kowalczuk, 2008).

Modelling of bulk material streams transported by belt conveyors was proposed by Jurdziak (2008 a,b). In other studies, the attention was paid to adjusting selection of equipment to random loading (Krol, 2013), estimating required power of conveyors drives (Gladysiewicz and Kawalec, 2006a), predicting durability of idlers under random load (Dworczynska et al, 2013) and selection of idlers spacing taking into account random stream of bulk material (Gladysiewicz et al., 2016). Most of research is usually performed for surface mine. However, there are some investigations devoted to copper ore mines (Gladysiewicz and Kawalec, 2006b). Some recent papers deal with the methods of improvement of production forecast with the help of novel sensor technology applied to on-line mineral grade recognition (Nienhaus et al., 2014), also used for real-time updating the resource block model (Wambeke and Benndorf, 2015).

Comparison of metal content on section conveyor at feeding point, transfer conveyor and feed sampling point

An assumption can be made that the run-of-mine stream composition, which is a time series of ore quantity and quality, determined in the feed, will be more stable than its counterpart from the analyzed conveyor, which may be considered as a transfer point on the route from the grizzly to the concentrating plant. This is so because the number of feeding points that contribute to the stream arriving at concentrating plant is significantly higher and the distance from ore extraction areas is greater, giving many opportunities for the run-of-mine material to be mixed on the way, which eventually leads to reduced grade variation.

The copper content variation analysis for one of three KGHM concentrating plants was performed by Drzymala and Kowalczuk (2010). Since then, the average copper grade has decreased and no information is available on whether the data regard the same concentrating plant that receives the ore from the analyzed conveyor. However, the analysis of variation of copper content in the feed to the concentrating plants allows to investigate the quantitative and qualitative character of the variations.

In this paper variations of copper contents were compared for three streams:

- the section conveyor (supplied through a feeding point directly from a mined face) for which the estimations were based on reconciliation of channel sampling,
- the transfer conveyor (on the conveyor route preceded by several section conveyors and ore bunkers),
- the feed for the concentrating plant, described by Drzymala and Kowalczuk (2010).

The first series of data included 104 values of variation for the section conveyor. The variations were from 1.527% to 2.5158% with the median value of 1.991%. The second series included 77 values in the range from 1.18% to 2.54% with median value of 1.62%. The third series for the feed to the processing plant included 93 variation values from 1.52% to 1.97% having median value at 1.73%.

The difference in the number of values results from the fact that the concentrating plants operate continuously on a 3-shift basis and the ore is delivered constantly, while the mine operates on a 4-shift basis. During weekends excavation is practically stopped. Clearly, variation range of Cu content in the ore stream as the feed for the concentration plant is the lowest (Fig. 1).

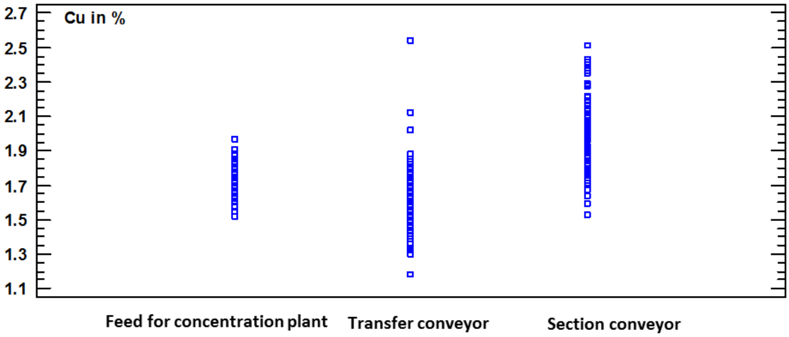

Fig. 1. Cu content in ore streams variation for each shift during one month for three places: feed for concentration plant, transfer conveyor and section conveyor

The selected statistics of Cu content in three ore streams were compared and presented in Table 1. The ANOVA test was used to check whether significant differences occur among the Cu content average values (Table 2). At 95% significance level, the differences proved to be significant, which is shown in the confidence interval graph for average values (Fig. 2). The kurtosis value out of +/- 2 range for the ore on transfer conveyor indicates a lack of normal distribution for this random variable.

Table 1. Summary statistics of Cu content for the analyzed ore streams

	Count	Average %	Standard deviation	Coeff. of variation, %	Minimum %	Maximum %	Range %	Stnd. skewness	Stnd. kurtosis
Concentration Plant	93	1.72581	0.0920459	5.3335	1.52	1.97	0.45	0.209964	-0.637583
Transfer conveyor	77	1.63149	0.193308	11.8485	1.18	2.54	1.36	4.78786	10.3165
Section conveyor	104	1.99808	0.20317	10.1683	1.527	2.516	0.989	0.955587	-0.426594
Total	274	1.80265	0.231636	12.8498	1.18	2.54	1.36	4.24484	1.83402

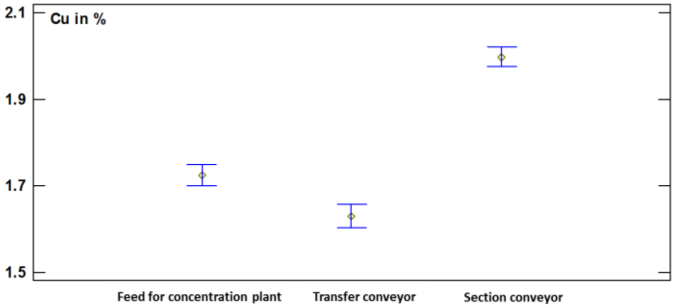

Fig. 2. Average values Cu content for three streams along with their 95% confidence intervals

Table 2. Table of ANOVA test for Cu content in analyzed ore streams

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	6.77677	2	3.38839	116.66	0.0000
Within groups	7.87106	271	0.0290445		
Total (Corr.)	14.6478	273			

Table 3. The average values of Cu content in ore streamsand their confidence intervals

	Count	Mean %	Stnd. error (pooled s)	Lower limit %	Upper limit %
Feed for Concentr. Plant	93	1.72581	0.0176722	1.7012	1.75041
Transfer conveyor	77	1.63149	0.0194217	1.60446	1.65853
Section conv.	104	1.99808	0.0167115	1.97481	2.02134
Total	274	1.80265			

The ANOVA table (Table 2) allows to split data variance into two components: variance between groups and variance within the group. The *F* indicator is the ratio of inter-group variance to intra-group variance. The *P* value represents the probability of type I error - incorrect rejection of a true null hypothesis. As *P* value of the *F* test is smaller than 0.05, statistically significant difference at the significance level of 5% exists between the average values for three variables representing Cu content in 3 analyzed copper ore streams.

Table 3 shows average value of Cu content in three ore streams for each column of data. The table also shows standard error of the average for each variable, which is a measure of variation in a sample. Standard error is obtained by dividing the total rolling standard deviation by the square root of the number of observations at each level. The table also shows the interval around each average value. The intervals are based on Fischer’s least significant difference (LSD). They are constructed so that if two average values are the same, then their intervals overlap for 95%. Multi-range tests show that each of the variables creates a homogeneous group (Table 4).

Table 4. Multi-range test results for the investigated average values of Cu content in ore streams

	Count	Mean in %	Homogeneous Groups
Transfer conveyor	77	1.63149	**X**
Feed for concentration plant	93	1.72581	**X**
Section conveyor	104	1.99808	**X**

Contrast	Sig.	Difference,%	+/- Limits, %
Feed for concentration plant - Transfer conveyor	*	**0,09431**	0,051697
Feed for concentration plant - Section conveyor	*	**-0,27227**	0,047885
Transfer conveyor - Section conv.	*	**-0,36658**	0,050443

* indicates a statistically significant difference (in bold)

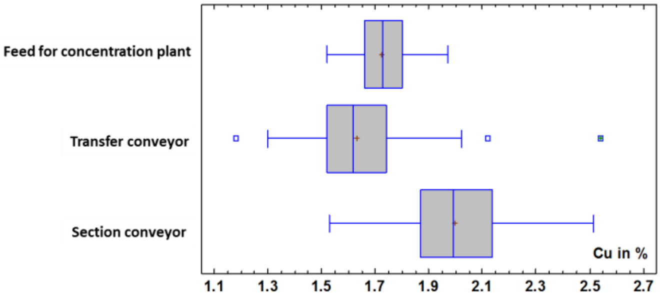

Fig. 3. Box and whisker graph for Cu contentin three analyzed ore streams in different location

Table 5. Variance test results for three Cu content variables

	Test	P value
Levene's	15.6761	**0.0000***

Comparison	Sigma1	Sigma 2	F Ratio	P Value
Feed for concentration plant / Transfer conveyor	0.0920459	0.193308	0.226731	**0.0000**
Feed for concentration plant / Section conveyor	0.0920459	0.20317	0.205253	**0.0000**
Transfer conveyor / Section conveyor	0.193308	0.20317	0.905271	0.6512

* bold font indicates significant and important results

The statistic displayed in Table 5 tests the null hypothesis that the standard deviations within each of the 3 data columns (containing Cu content in analyzed ore streams) are the same. Since the *P* value is less than 0.05, there is a statistically significant difference amongst the standard deviations at the 95.0% confidence level. This result violates one of the important assumptions underlying the analysis of variance and will invalidate most of the standard statistical tests.

The table also shows a comparison of the standard deviations for each pair of samples. The *P* values below 0.05, of which there are 2, indicate a statistically significant difference between the two sigma at the 5% significance level. As no differences occur between the transfer and the section conveyors, the average values between them may be compared using standard tests. The table also shows a comparison of standard deviations for each sample pair. The two *P* values below 0.05 indicate statistically significant differences between the two standard deviations at 5% significance level.

Due to variance variability, standard tests cannot be used to check the hypothesis that the average values are equal and therefore Mood's median test must be used (Table 6). The test allows to verify the hypothesis that the median values for all three samples are equal. The test consists of counting those observations whose positions in each group are on both sides of a common median. In this case it is 0.0176. As the *P* value for the chi-square test is below 0.05, sample medians are significantly different from each other at the significance level of 95%.

Table 6. Median test results of Cu content in three analyzed ore streams

Sample	Sample population	n<=	n>	Median %	95.0% lower lim. CL %	95.0% upper lim. CL %
Feed for concentration plant	93	64	29	1.73	1.69523	1.75
Transfer conveyor	77	63	14	1.63	1.66373	-20529.7
Section conveyor	104	11	93	1.984	1.94283	2.0879

Test statistics = 108.999, P-value = 0

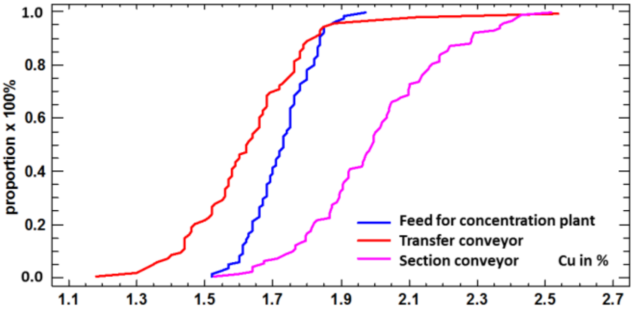

Fig. 4. Quantile graph for the histograms of Cu content in three ore streams

Figure 4 clearly shows the differences in the cumulative empirical distribution functions. Variability range and the inclination of the feed stream on the section conveyor and of the run-of-mine material on the transfer conveyor are similar (both the inclination and the range), but a significantly fatter distribution tail for the transfer conveyor in the upper values causes a significant difference. A clear, almost parallel offset can be observed into the area of lower metal content, of about 0.003 (0.3% of percentage point – about -15% as compared to output value). This fact can also be observed on histograms (Figs. 5 and 6) and on “box and whiskers” graphs (Fig.3).

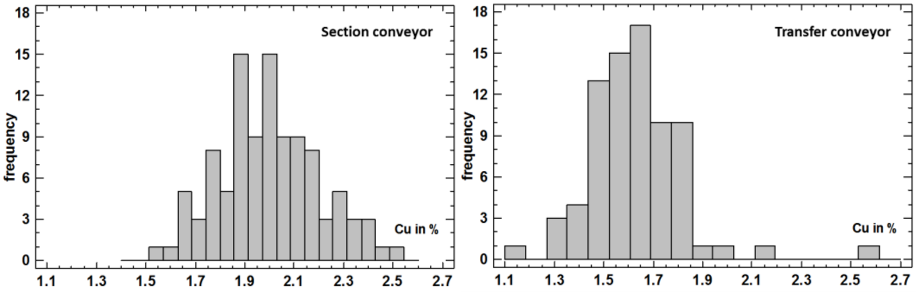

Fig. 5. Histogram of Cu content in ore streams from the deposit next to the section conveyor A (on the left) and on the transfer conveyor in September 2015

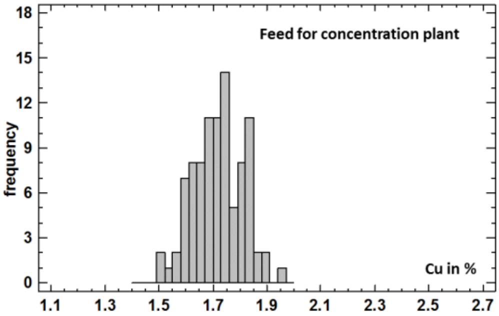

Fig. 6. Histogram of Cu content in feed for concentration plant
(based on Drzymala and Kowalczuk, 2010)

The most concentrated and symmetrical distribution can be observed for quality of the ore being the feed for processing plant. Drzymala and Kowalczuk (2010) were confident that the variation of Cu content in ore may be described by Gaussian distribution (Fig. 7).

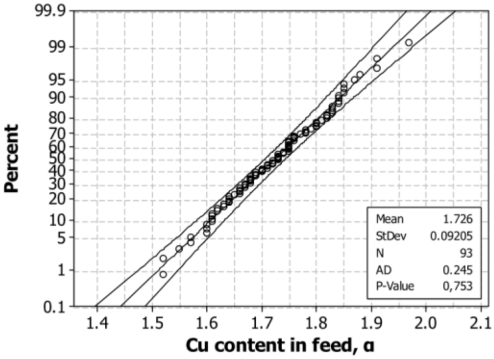

Fig. 7. Normality graph with 95% confidence intervals for time series data on Cu content
on a conveyor in feed for concentration plant (Drzymala and Kowalczuk, 2010)

The graphs indicate that mixing the run-of-mine material from different feeding points that supply ore of varying grades in the cumulative stream on the transfer conveyor (Fig. 8) does not lead to normal distribution. The deviations are visible especially in the “tail” on the right side. This fact may suggest insufficient ore mixing. Higher grades in the feed from the sections partially occurred on the transfer conveyor, although they should have been reduced due to mixing with lower grade ore from other feeding points. High Cu mineralization in the run-of-mine material (2.54% for shift no. 97) may be due to error. Possibly, the number of feeding points was insufficient as only 7 section conveyors fed to the gathering transfer conveyor from which samples were taken, and 3 conveyors: A, B, and C, dominated in terms of ore fed. A separate issue is whether feed mineralization levels in the sections supplying the run-of-mine material to the transfer conveyor can be treated as fully independent variables. Thus, the process of summing the values of independent random variables would meet the conditions of a limit theorem indicating normal distribution of such variations. The components of variability of Cu content in the deposit (in the ore fed to the conveyors upstream of the transfer conveyor) are normal, at least some most important ones (Fig. 9). The sum of those components does not show normal distribution, and this fact might imply either that the mixing process is not perfect or that dependent variables exist (spatial correlation of this parameter is actually used in geostatistics). The Cu content in the run-of-mine material fed to grizzlies located in proximity to each other may be correlated.

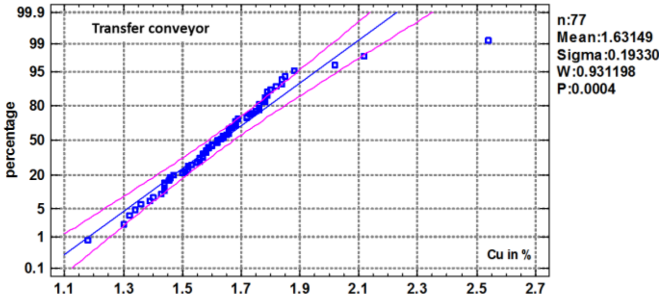

Fig. 8. Normality distribution graph with 95% confidence intervals for Cu content in ore on transfer conveyor between two mines

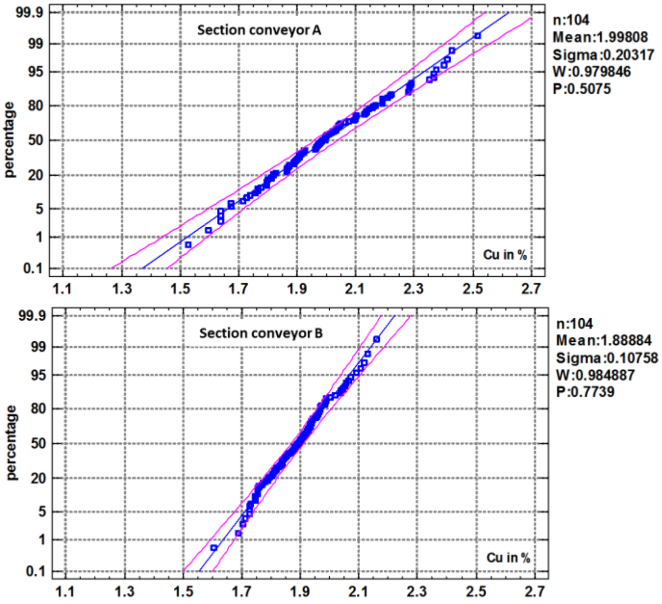

Fig. 9. Normality distribution with 95% confidence intervals for Cu content in the ore on section conveyors A and B feeding the transfer conveyor

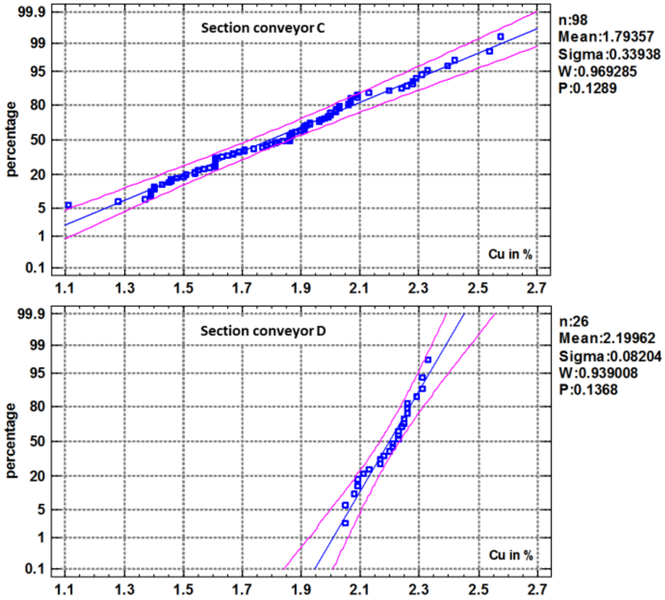

Fig. 10. Normality distribution with 95% confidence intervals for Cu content in the ore on conveyors C and D feeding to the transfer conveyor

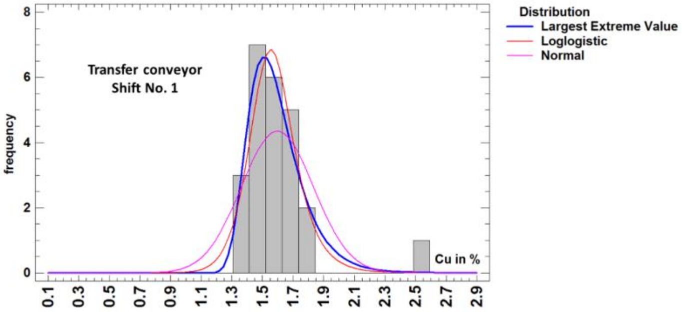

Fig. 11. Combined extreme (maximum) value distribution and normal distribution for Cu content during shift no. 1 on the gathering transfer conveyor

The frequency with which especially extreme Cu content values occur may thus deviate from normal distribution, as the same high values would occur simultaneously in several feeding points and are transferred to the cumulative stream. Hence, the mixing process does not allow to obtain sufficient average values. The best distribution for grade levels on the transfer conveyor during the 1st shift was maximum value distribution (Fig. 11), which might indicate that when samples are taken, maximum instantaneous mineralization value is recorded. This is impossible, however, due to randomly selected sample collection times. In addition, during other shifts the distribution is not the best fit. During shift no. 2 the distribution is uniform, during shift no. 3 it is inverse Gaussian and during shift no. 4 it is Weibull type. The best distribution for all shifts was logarithmic-logistic (Fig. 12).

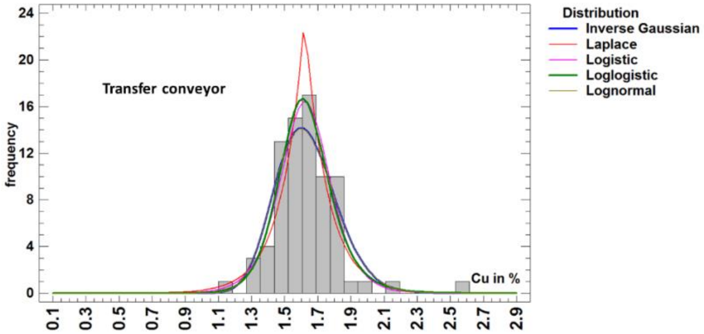

Fig. 12. Combined distributions for Cu content on the gathering transfer conveyor

The fact that in the analyzed period the normal distribution was not suitable for use in describing the variability of Cu content on the analyzed gathering transfer conveyor might be due to insufficient number of feeding points. As mentioned, the transfer conveyor was at that time supplied from a maximum of 7 conveyors (usually 3-4). It was not enough to achieve satisfactory convergence to normal distribution. A spatial correlation also exists of the quality of the run-of-mine material fed on the neighboring grizzlies. The range for this correlation may be determined using geostatistical methods and autocorrelation. The run-of-mine material may be insufficiently mixed. If the conveyors are fed sequentially, then the random samples might not represent many distributions, but instead only a small number of distributions and this can lead to the transfer of extreme values to the cumulative distribution. The averaging effect will not occur. Both the range and the variability will be similar to those at the feeding points on section conveyors.

Conclusions

Investigation of variation of Cu content in three copper ore streams at KGHM Polska Miedz SA, including the section conveyor, at the transfer point on the gathering conveyor, and on one of the conveyor transporting the feed for the concentrating plant, allowed to confirm the existence of variation of means and variances of Cu content in different ore streams.

Due to the lack of data of September 2015 the analysis of variation of Cu content in the stream of feed is of qualitative character, as the reference data were of 2010 and no information is available whether they are related to the same processing plant. Since then the average ore grade has significantly decreased, not allowing to make quantitative analysis of Cu content in ore.

From the Cu content analysis in three ore streams it can be seen that the smallest variability of Cu content can be observed in ore feed to the processing plant (coefficient of variation, *cov* = 5.33%) and the biggest in ore stream on the transfer conveyor (*cov* = 11.85%). The grade distribution on the transfer conveyor cannot be described by a normal distribution as for the case of ore directed to the processing plant and ore supplied onto the sections conveyors. The smallest variability in the feed to the concentration plant is the consequence of almost perfect mixing and averaging of ore from different locations in mining fields and bunkers. Mixing on the transfer conveyor is only partial due to smaller number of ore sources as well as time separation between following loads from mining faces. This gives in effect larger, instead of lower, spread between minimal and maximal Cu contents (range 1.36% Cu content in ore in comparison of 0.45% Cu for feed to processing plant and 0.99% Cu for the section conveyor) and asymmetric distribution. In this case the standard skewness is 4.79 in comparison to 0.2 for the feed to the processing plant and 0.96 for the section conveyor.

The findings of this work indicate that normal distribution may be used to describe the distribution of Cu content in the ore transported to the processing plants and on the section conveyors. The situation is different at the transfer conveyor. It may be a result of insufficient mixing and time separation between following loads coming from different locations and having different grade and feed to neighboring grizzlies or insufficient number of feeding points. There were only seven conveyors on the route from the farthest loading point and usually only three conveyors were loaded by the nearby mining sections. The capacity of the transfer conveyor was not fully utilized. Therefore, sometimes the following loads were not mixed with other loads at all. The averaging process was imperfect. In effect the Cu content distribution was best described by log-logistic or extreme value probabilistic distribution instead of normal. This can be expected in the case of perfect mixing ore streams coming from, independent from each other, sources as loading points are spread all over in the mine.

It is worth to compare three run-of-mine ore streams considering them as a random time series of consecutive values rather than random variables, to check if there are autocorelations between them (Tasdemir and Kowalczuk, 2014). It seems that due to the fact that consecutive excavation is continued in the very close area to the previous one, the average values should be correlated with next ones. Obviously it depends on the rate and scale of grade changes within the deposit. These should be recognised with the help of geological block model, developed and updated for the mined deposit.

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