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Practical use of variographics to identify losses and evaluate investment profitability in industrial processes

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This work illustrates variographic analysis applied to industrial production processes to identify and reduce adverse production deviations (over-specification, loss) and evaluate profitability. A first example concerns production of light-weight expanded clay aggregates (Exclay), produced in cement-like rotary kilns. Clay raw material is heated to 1150 °C to be expanded. An adverse periodicity was observed in a specific plant cooler manifested as fluctuations in the material volume (height level) causing a periodic variance in the production output from the kiln. This problem must be resolved by instigating a more stable cooler, which could in fact be engineered by a very small investment of about 5,000 Euro. A variogram characterization was carried out to evaluate the amplitude of the periodicity, and the quantities involved (losses), which information was used to calculate the investment pay-back time. From the variogram it was observed that the reduced kiln output volume was at least 0.7%. During one year with improved cooler level control, this translates into savings of about 100,000 Euro, i.e. a pay-back time will be less than one month. A second example is from a LRM-project (Loss and Reduction Model) at a plant producing bagged pre-mixed mortars, in which the variance of the weight of the produced bags was found to be consistently too large. A pilot variographic analysis was applied with an aim to identify the root causes of this problem (three filling stations at the same line were investigated, all with identical filling systems and scales): Two stations were found to have a total material loss of 1.2%, while the third was running perfectly well (low V(0) and low sill), but with a too high set point. The technical resolution shows that it is possible to reduce material loss with existing equipment by improved monitoring/recording routines but no need to acquire new expensive belt scales a.o. For two of the stations V(0) (MPE) was in fact at a level almost identical to the sill making it structurally impossible to keep bag weight within specifications. Recurrent monitoring of V(0) and moving average smoothing should be evaluated at the very many similar production lines in the multinational corporation involved to gain improved process control to reduce overfilling. While relatively small on the basis of an individual filling line, the potential accumulated corporate savings take on a quite different economic significance. Variographic analysis is a powerful tool for industrial technicians and process engineers to improve processes – and in the present cases for industrial managers as well for evaluating ultimate investment profitability in industrial processes.

Introduction

To illustrate systematic application of variographic analysis in process industry, two examples from the multi-national Saint-Gobain Weber corporation are presented. The first example, from production of expanded clay aggregate building material, shows how variografic analysis can be used to calculate investment pay-back time with better accuracy than by use of standard statistical methods. The other example concerns bagging of premixed mortars are in fact typical for a variety of industrial bagging processes in general. This example shows how variographic analysis can be used to identify the main reasons for adverse product variances (here bag weight) and how to reduce such deviations and thereby reduce production costs.

Example from Exclay industry

The first example concerns production of light-weight expanded clay aggregates (Exclay), produced in cement-like rotary kilns. Clay raw material is heated to 1150ºC to be expanded. A periodicity was observed in a specific plant cooler regarding fluctuations in the material level. This influences the amount of air passing through the cooler and thereby amount of air and the pressure in the kiln. Periodicities in the pressure in the kiln cause periodicities in the level of expansion and thereby in the output from the kiln. A lower expansion means a smaller volume produced from the same amount of raw material, i.e. higher production costs (sales are valued by m3 produced). There is a lower limit to an acceptable product density. Also, if the temperature/pressure is raised too high, a point will be reached where the material will sinter and sizable lumps in the kiln will cause severe problems. The operators always try to burn as hard as possible to optimise the m3 output from the kiln. However the maximum level of hard burning is limited by the material with lowest densities, if a cyclic short term periodicity is manifested. Periodicities in the densities will then reduce the output of the kiln.

The unstable level in the cooler could be improved by a small investment of about 5,000 Euro. Earlier the level in the cooler has been measured by use of a radioactive isotopes. This has been found not to be precise enough however (besides being a serious environmental issue). By replacing this approach with a modern radar measurement system, the precision is increased satisfactorily. Variographic analysis was carried out to evaluate the pay-back time of the investment. Figure 1 shows a photo and schematic drawings of the Niems cooler used at the plant.

Example from pre-mix industry

The other example is from a LRM-project (Loss and Reduction Model) at a plant producing pre-mixed mortars. LRM enables manufactures to evaluate four modules: material, machine, distribution and maintenance, that each may require improvement. The losses in each module are identified by breaking down the process in its part elements, allowing a simplified, focused improvement

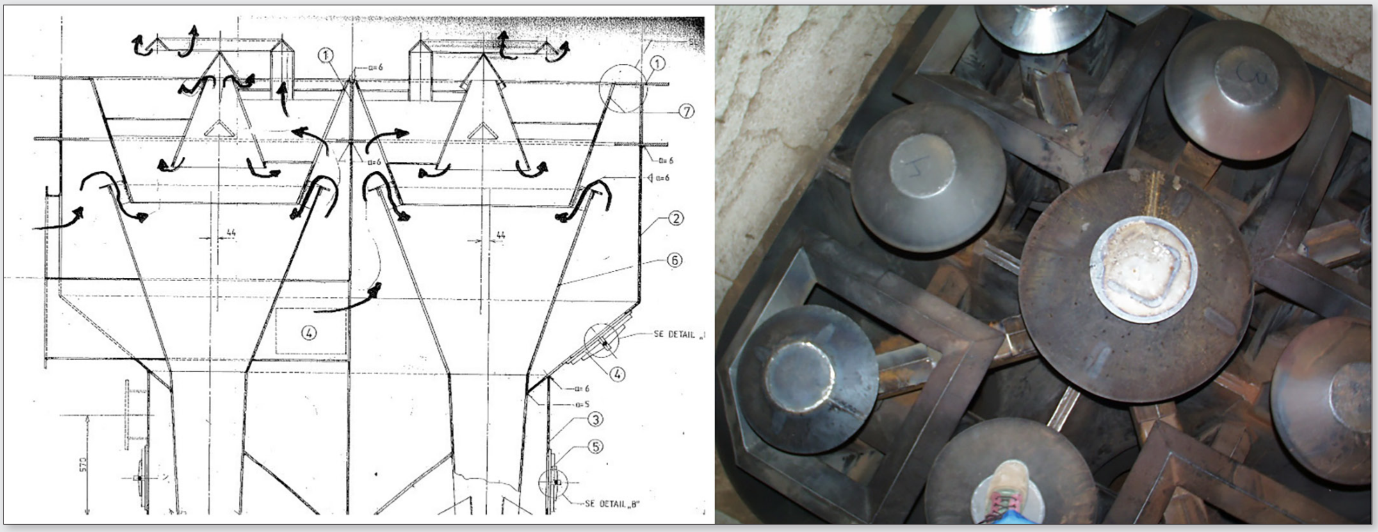

Figure 1. Schematic drawing and photo of a Niems shaft cooler. Material falls from the kiln head into the top of the cooler. Cooling air is blown in from below as shown in the drawing (left).

approach. Variographic analysis is not included in LRM today, but the present contribution suggests how this may be introduced with significant advantage.

The LRM project identified a material loss by weighing pallets of bagged material. The bags on the pallet originated from three filling stations at a specific line as a pilot study. The bags shall have a nominal weight of 25 kg. The lower and upper acceptance limits are stipulated to 24.5 and 25.5 respectively. The pallets were too heavy and indicated material losses. Variographic analysis together with traditional statistics was used to try to identify the root causes and suggestions for further progress on reduction of material losses. Variographic analysis has earlier shown to be a powerful tool to separate the different potential factors contributing to this variance[2]. Investment caution rules the day, e.g. it would be futile to invest in new expensive equipment to level the filling degree, if the main problem f.ex. turned out to be caused by inaccurate scale measurements.

The bags are filled by using air-pressure from two nozzles into a transportation air-tube. One of the nozzles sets the packing chamber under pressure to force the material through an opening, with a connecting tube that leads into the filling-bag. The second nozzle delivers the conducting airstream. Adjustment of the differential air-pressure between these two streams controls the filling of the bags. The nozzles get their regulatory input from the scales, which are stipulated to operate according to a specification of 25 ± 0.5 kg. Outside these limits the filling station is stopped. The scales are normally put on 'auto-correct' which is able to perform corrections with a magnitude of ±0.1–0.2 kg. If the weight of a particular bag is registered as above 25 kg, the weight of the next bag is reduced with 0.1 kg – and conversely if the weight is below 25 kg, the weight of the next bag is increased with 0.1 kg.

Methodology

A variogram can be used to break down the contributing elements together making up the overall variance into their separate component sources. This is of critical interest in industrial processes. The variogram can be divided into three different components[1]:

$$V(j) = V_1(j) + V_2(j) + V_3(j) \qquad (1)$$ [1]

Where:

$V(j)$ is the overall variance (total observed process variance), i.e. the variogram

$V_1(j)$ is the short-range random, discontinuous contribution

$V_2(j)$ is the long-range, non-random continuous contribution (trend errors)

$V_3(j)$ is the periodic continuous contribution (periodic error)

j – is the sampling inter-distance, aka the lag

$V_1(j = 1)$ describes the overall variance contribution reflecting the uncertainty introduced because measurements are only made at discrete intervals[1]. This is of course always of interest, but even more interesting is $V_1(j = 0)$. This is a back-extrapolation made from the variogram indicating the variance to be obtained, if one would be able to sample at the exact same location twice (repeated sampling). This estimate (the 'nugget effect') quantifies the quality of the total sampling and measuring systems used. Thus V(0) includes all the correct and incorrect sampling errors (CSE + ISE) in addition to TAE. For this reason V(0) is also termed the Minimum Possible Error (MPE) for a process monitoring system. V(0) will never be zero due to Fundamental Sampling Errors (FSE), but in the practical industrial use V(0) is never dominated by FSE alone, but will always be significantly higher. Thus a high V(0) usually indicates significant contributions from the Incorrect Sampling Errors and or GSE. A significantly high V(0) (with respect to the sill) is a critical warning of a serious total measurement system problem, which must be rectified. If V(0) is too high in this sense, it will not be possible to control the process in a satisfactory way, since this disallows insight into the real process variations. The closer V(0) is to the sill the more the real process variation signals are drowned out by a structurally flawed measurement system, a situation which will unavoidably lead to faulty decisions and actions.

$V_2(j)$ reflects underlying process trends, important in any industrial production process, but easily spotted already in the raw time series process monitoring data. It is preferable to deal with this type of process deviations before applying variographic analysis.

$V_3(j)$ reflects cyclic process behaviours, of critical interest in production and manufacturing process. A variogram will easily detect a periodicity and its apparent amplitude, indicating how much it contributes to the overall variance. The associated costs can thereby also be estimated with relative ease. This is an area that requires some insight and experience.

The overall variance V(j) at high j (large sampling distances) reflects the total process variance beyond the range, i.e. the sill.

It has been found useful to relate the magnitude of V(0), the process measurement system error (MPE), to the level of the sill, as a%-age, and to use this as a *quality index* for the total process measurement system[6]. The higher this index w.r.t. its maximum value (100% – at which level it would be equal to the sill), the worse the performance of the measurement system. Indices over 50% run a severe risk of deceiving process monitoring proper; in general this index should be below 33% or so to be acceptable *ibid*.

Estimation of cyclic amplitudes

Considering a sine curve, $h_x(T)$, with an amplitude h_3 and a period T, one can calculate the corresponding variogram

$$h_{3t} = h_3 \sin\left(\frac{2\pi t}{T}\right) \qquad (2)^1$$

$$V_3(j) = (h_3^2)/2(1 - cos(2\pi j / T)) \qquad (3)^1$$

Thus the amplitude of a cyclic variogram is:

$$V_3(j) = \frac{h_3^2}{2} \qquad (4)^1$$

i.e. half the distance from minimum to maximum in the relevant cyclic part variogram[1].

The amplitude of the cycle h_3 can thus be calcualted as follows:

$$h_3^2 = 2 \times V_3(j) \qquad (5)$$

Leading to:

$$h_3 = \sqrt{2 \times V_3(j)} \qquad (6)$$

i.e the square root of the cyclic contribution variance estimated from the variogram.The amplitude of a cyclic periodicity is found by first defining V(0). Thereafter is a line drawn from the minimum in the cycle to V(0) on the y-axes (see Figure 6). A parallel line is drawn from the maximum point to the y-axis (see Figure 6). The value of the cyclic contribution of the variance is read/measured/calculated by subtracting the minimum value of crossing from the maximum value. This furthers a basis for estimating cost savings from reducing or eliminating a cyclic contribution.

Exclay industry

Samples for loose bulk density measurements were taken after the cooler unit every 90 seconds for close to two hours. The samples were taken from a falling stream with a customized collector. See Figure 2. This sampling equipment is not in full accordance with Theory of Sampling (TOS), but has earlier been evaluated to be fit-for-purpose[3]. This earlier work also concluded that loose bulk density is an informative parameter regarding instability control in the production process[3]. Density measurements were carried out continuously by a Thaulow bucket in accordance with EN1097-3[4].

Figure 2. Sampling equipment for loose bulk density measurements (while not 100% TOS compliant, the manual cross-stream sampler at least covers the entire width of the falling stream).

Pre-mix industry

Since bag weights are not recorded in the present plant setup, a continuous film recording was made of the bagging line showing the display of all three filling lines. The weights were extracted from this documentation variographic analysis was carried out on this basis.

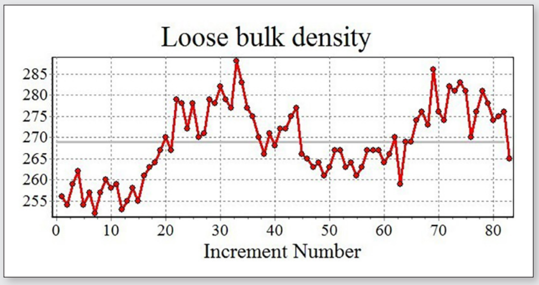

Figure 3. All 83 single measurements from the Exclay experimental campaign.

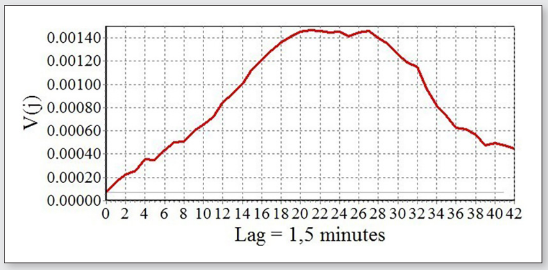

Figure 4. Variogram of the 83 measurements in Fig. 3.

Results and discussion

Exclay industry

All 83 single measurements of the loose bulk densities and the corresponding variogram are shown in Figures 3 and 4.

A major long term periodicity is observed, showing an unstable production period, interpreted as probably caused by changes in clay and/or coal feeding. It is important to follow up on this variance contribution[3,5], but this is not a part of the present study. In order to assess the contribution from the level in the cooler better, the long term periodicity has to be eliminated from the variogram. The first part of the period measured is from a period with an increasing trend and unstable production. This part is not included in the final analysis. In addition there is a dip in the densities between measurements 45 and 65 of about 10 kg/m^3. This is typically what happens when the operator adjust the coal feeding to the burner. These densities are therefore increased by 10 kg/m^3 to eliminate this long term contribution. One outlier (measurement no 63) was also adjusted.

The adjusted measurements and the corresponding variogram are shown in Figures 5 and 6.

After these process-experience dependent adjustments, a periodicity with a frequency of lag = 5 emerges, i.e. 7.5 minutes. This corresponds well with the experience of seasoned process operators. This strong periodicity makes it difficult to estimate V(0), but from Figure 6 it can be seen that the V(0) probably lies between 0.000067 and 0.00010. A conservative estimate of the contribution to the variance from the cyclic periodicity, would therefore be ~0.00005 (see Figure 6). The amplitude of the recorded data is then calculated from equation 6 to be 0.0071 or 0.71%. With an average density of 276 kg/m^3 this equals 2.0 kg/m^3. This may appear as but a small effect, but when accumulated equals savings of approximately 100,000 Euro per year. On this bases pay-back time of the investment of 5,000 Euro will be less than one month. It will likely even be shorter since short term cycles often confuse operators to decide to take action where they in fact should have remained passive.

Pre-mix industry

For each filling station 23 (24) bags are included in the analysis. This is absolutely at the lower end to give a fully satisfactory data base upon which to arrive at fully credible conclusions, but the results may still point to real-world problems and may certainly help to illustrate how variografic analysis can be used to identify root causes and to propose an action plan at a bagging line.

Figures 7– 9 show the results of the three filling stations of the bagging line investigated. Figures 10–12 show the corresponding variograms. It is easily seen that the three filling stations behave very different at the pilot study campaign time.

The overall overfilling was 1.2% in the period analysed, i.e. 1.2% unnecessarily increased raw material costs.

Bagging station 1 was found to be the one best tuned. The overall variance (sill) is low, and almost the whole contribution to

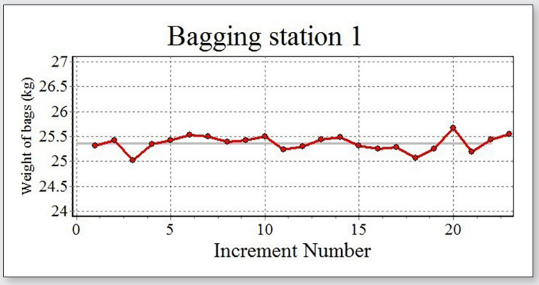

Figure 7. Weight measurements at bagging station 1.

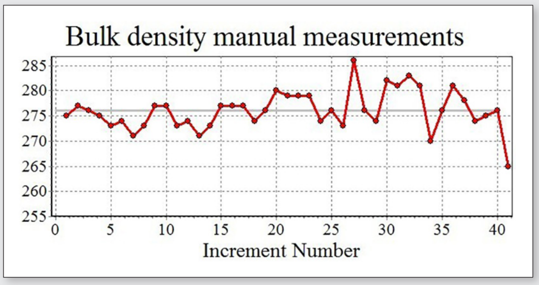

Figure 5. Single measurements of loose bulk density (see text for details)

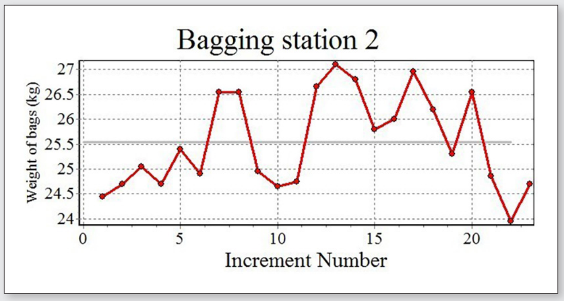

Figure 8. Weight measurements at bagging station 2.

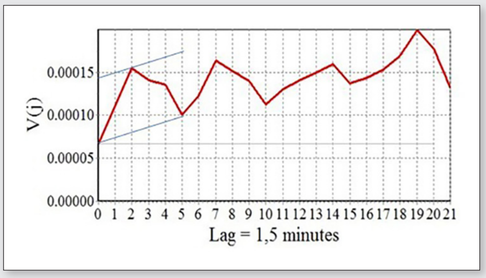

Figure 6. Variogram of the last part of the measured period (see text for details).

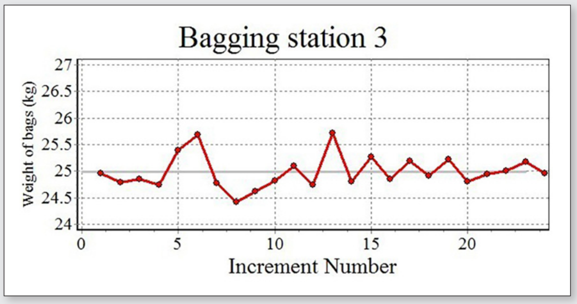

Figure 9. Weight measurements at bagging station 3.

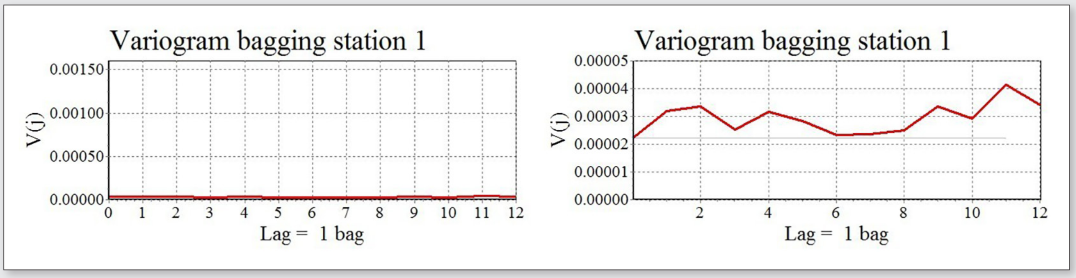

Figure 10. Variogram of data from bagging station 1, (left) for comparison of all stations; (right) for close-up evaluation.

the variance comes from V(0). This means that most of the variance observed stems the measurement system. The variance of the bags from this station is well inside the limits of ±0.5 kg from the average. There was one notable issue however; the average is 25.36, i.e. an overconsumption of 1.5% of raw material. This will of course increase the production costs. The explanation for the high average was probably that the autocorrect of the weight was found to be turned off, in combination with slightly too high pressure.

Bagging station 2 has a serious problem, displaying extremely high variations. The sill (overall variance) is 100 times higher than for bagging station 1. One bag is even above 27 kg. The average weight is 25.55 kg which corresponds to an overconsumption of 2.2%. V(0) is higher than for bagging station 1. The different bagging lines are using the same type of scale, but there could be other factors contributing to the higher V(0) value, such as vibrations, dust on the scales etc. V(0) is presently at the limit to give bag weights just within the ±0.5 kg specifications. Two STD (95% confidence level) interval around V(0) is 0.44 kg, meaning that the scales will measure 5% of the bags above 25.44 kg or below 24.56 kg – even if all bags had a weight of 25 kg on statistical average. This will make it very difficult to adjust the filling to 25 kg when the remaining part of the variance is also considered. The tolerance limit has probably been *increased* by the plant personal to avoid an uncomfortably high occurrence rate in the production. In addition the high variance indicates an air-leakage influencing the filling. Could it be that the air-leakage influences the scale causing a high V(0) as well as a high overall variance due to bad filling control? If this is the case the air-leakage simply doubles-up the problems, in practise making it virtually impossible to control the process. The last ‘explanations’ are only speculative at the present, but show how detailed interpretation of experimental variograms is of great help for process control in pointing out both problems as well as possible solutions.

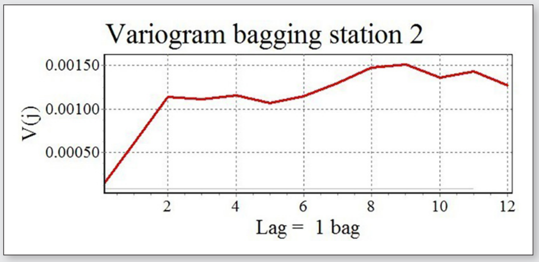

Figure 11. Variogram of data from bagging station 2; same Y-axis variance units as Fig. 10 (left).

Bagging station 3 has an accurate, correct set point; 24.99 kg, but both the sill (total variance) and V(0) is significantly higher compared to bagging station 1, bagging station 3: 0.00015 compared with 0.00003 for bagging station 1. The difference is more or less explained by higher V(0) and a contribution from a strong cyclic periodicity with lag = 2. V(0) is again at the limit to deliver the bags within the spec of ±0.5 kg. The two STD (95% confidence level) around the V(0) is here 0.43 kg. By a similar argument as above, this means that the scales will measure 5% of the bags above 25.43 kg or below 24.57 kg solely as a function of the quality of the measurement system. Combined with the cyclic periodicity, this gives 3 bags out of spec, even if the material consumption is perfect. The cyclic periodicity again comes from the auto-correction facility. This is deemed acceptable, but a high v(0) will probably cause the auto-correction occasionally to go in the wrong direction, and again make it almost impossible to keep all the bags inside the limits of ±0.5 kg. Investigations will be carried out as to why the scale has such a high variance. It also must be pointed out that the periodicity makes the estimation of V(0) difficult.

It is important to realise that a high V(0) is a function of an inferior (TSE + TAE), which will occasionally indicate bags out of spec, which are in fact not. Such a measurement system is not acceptable in the industrial practise as it disturbs proper process control.

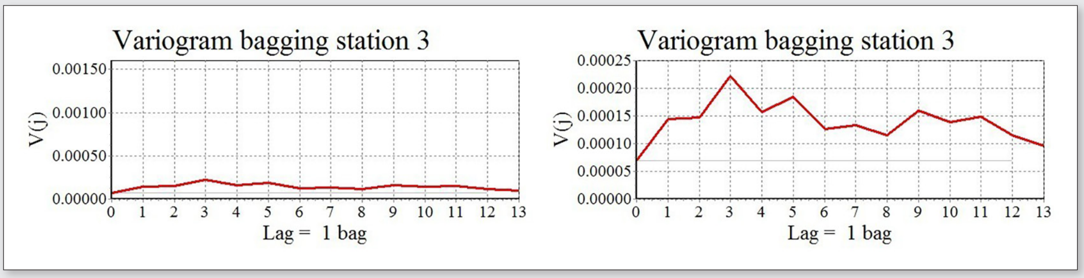

Figure 12. Variogram of data from bagging station 3, (left) for comparison of all stations; (right) for close-up evaluation.

To reduce material losses at the production line, the first step should be to evaluate the weight measurement system. This will make it much easier to eliminate or to reduce real losses. It will be important to monitor and keep V(0) low. Bagging line 1 had an acceptable V(0), and since all the station use the same system it should be possible to achieve the same system quality at the other two stations as well. Further analysis to find the root causes of the differences has to be carried out, e.g. is there influencing dust contamination, air-flow or other, not yet identified agents? Can operator adjustment influence V(0)?

As an important aside, it is worthy of considerable note (and concern) that all scales were newly calibrated before this experiment.

It is likely that operators have been under time pressure during the experimental campaign, possibly substantiated in their choice to increase the specification limits instead of stopping the bagging equipment to solve the problems. There is always a balance between the costs (and time pressure) of non-production time and the costs of increased raw material consumption. On-line recording using moving average smoothing and V (0) monitoring could ease the decision of when to stop or not. Specific routines of when to take action, related to specific limits could be worked out depending of type of product and raw material costs. Even if the producer chooses to continue without correction, for example due to high demand, they will now be fully aware of the potential costs of doing so.

Conclusions

A periodicity with a frequency of lag equal 5, i.e. 7.5 minutes arises from cooler level fluctuations in the case of production of Exclay. This corresponds to a conservative estimate of a loss of 0.71% of output of the kiln, leading to a yearly loss of 100,000 Euro. An investment of 5,000 Euro will have a pay-back time of less than 1 month. This is but a modest economic result but shows the power of variografic analysis as a strong strategic tool for industry in general.

Bag overfilling in the analysed period was 1.2%, originating from two stations with an overfilling of 1.5 and 2.2% respectively and one perfectly run station. It seems that the plant focus has been on time and not on costs, since an auto-correction facility was deliberately turned off on one of the weighing stations and the specification limits of another were manually increased – leading to weights far off from the ±0.5 kg specification. The existing equipment used to fill and weigh the bags is likely good enough, based on the fact that the acceptable filling station shows completely acceptable levels of V(0) and sill, resulting in bags well within the limit of ±0.5 kg . It is necessary to pay more attention and awareness to the costs of overfilling – at the very least, data from the scales must be recorded. On-line moving average smoothing with set limits of action depending on product should also be introduced. On-line monitoring of V(0) is also a new feature to be implemented, since two of the bagging stations show such a high V(0) that it is in practise structurally impossible to keep the measured weight of the bags within the stipulated specifications. By the unavoidable addition of even small process variances, e.g. periodicity stemming from the auto-correction, the whole process monitoring is bound to get out of control. At all times a special focus must be on keeping V(0) low, indicated the need, and the significant return from, proper education of the plant operators/supervisors. This example shows the usefulness of variographic analysis in industrial LRM analysis.

The power of using variograms to untangle and separate different contributors to the total process and measurement system variances in industry is 'priceless' in more ways than one.

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