Proceedings of the 9th International Symposium on
Dynamics and Control of Process Systems (DYCOPS 2010),
Leuven, Belgium, July 5-7, 2010
Mayuresh Kothare, Moses Tade, Alain Vande Wouwer, Ilse Smets (Eds.)

MODELING OF THE FOULING PROBABILITY OF AN ACTIVATED SLUDGE DRYER

B. Peeters [*] **R. Dewil** [**, ***] **J.F. Van Impe** [***] **I.Y. Smets** [***c]

[*] Monsanto Europe N.V., *Environmental Dept.,*
Haven 627, Scheldelaan 460, B-2040 Antwerp, Belgium
[**] Campus De Nayer, *Dept. of Chemical Engineering,*
J. De Nayerlaan 5, B-2860 Sint-Katelijne-Waver, Belgium.
[***] BioTeC, *Dept. of Chemical Engineering, K.U. Leuven,*
W. de Croylaan 46, B-3001 Leuven, Belgium
[c] *Corresponding author*

Abstract: Better understanding (and so better control) of the stickiness phenomenon of drying sludge is critical for proper operation of a variety of industrial dryers, as is the case for the combined centrifuge-dryer system used on the Monsanto Europe site in Antwerp, Belgium. In this paper a binary logistic regression analysis is performed on a 4-years data base, which resulted in an empirical model for the evaluation of the dryer fouling probability as function of changes in the Sludge Volume Index (SVI) and the dosing of clay additive and tertiary (flotation) sludge to the main secondary (biological) sludge feed to the system. According to the research results, a decreasing SVI increases the probability of obtaining fouling in the dryer. Furthermore, in periods of low SVI, the fouling probability can be reduced significantly by reducing the clay dosing. This extended analysis confirms the hypothesis formulated earlier (Peeters *et al.*, 2009a) that a wetter cake (induced by high SVI and low clay dosing) at the beginning of the drying stage of this system is better to avoid drying sludge fouling the dryer wall.

Keywords: activated sludge, SVI, dewatering, drying, sticky phase, fouling, binary logistic regression.

1. INTRODUCTION

It is well known that thermal drying of activated sludges, most often the one-before-last step in treating waste activated sludge, is an energy intensive and, hence, costly process. Reduction of the sludge volume by mechanical dewatering before thermal drying is, therefore, of prime importance (Chen *et al.*, 2002; Kudra and Mujumdar, 2009). On the Monsanto Europe site in Antwerp, Belgium, a unique combined centrifuge-dryer (Centridry®) system is used for handling this waste stream.

What makes the drying of activated sludge rather cumbersome is the stickiness phenomenon of this material: when partially dried it has such a consistency that it tends to stick to dryer walls causing operational problems. Previous research with data of the system from April 2005 till April 2006 indicated that sludge characterised by an excellent settleability and dewaterability represents a higher chance of fouling risk in the sludge dryer, and as a consequence the hypothesis was formulated that very dry sludge at the beginning of the drying stage caused this problem (Peeters *et al.*, 2009a). Reduction of the clay additive to the biological sludge feed towards the centrifuge was recommended to verify this hypothesis, because a lower clay addition in bench scale studies yielded a wetter cake after centrifugal compaction.

The aim of this research was to develop a statistics based model to further substantiate the abovementioned hypothesis by quantifying the effect of clay dosing and of flotation sludge addition on the activated sludge dryer fouling. To this end, an extended data base was compiled covering almost 4 years of operational experience with the Centridry® system on site.

2. WASTEWATER TREATMENT AND CHANGING SLUDGE QUALITY

The wastewater treatment plant (WWTP) at the Monsanto Europe site in Antwerp, Belgium, is a conventional activated sludge process (Figure 1). Suspended aggregates of micro-organisms convert the dissolved organic matter into carbon dioxide and new biomass. The biomass is separated from the water in the clarifier by simple gravity settling and recycled to the beginning of the aeration basin (Recycle Activated Sludge, RAS). Part of this stream is sent as excess sludge (Waste Activated Sludge, WAS) to the Centridry® system to be reduced in volume. Fine sludge flocs which do not settle in the clarifier are removed in the flotation unit (Dissolved Air Flotation, DAF) with addition of coagulant (PolyAluminiumChloride, PAC) and an anionic polymer as flocculant. The sludge removed from this flotation unit is also sent to the Centridry® system.

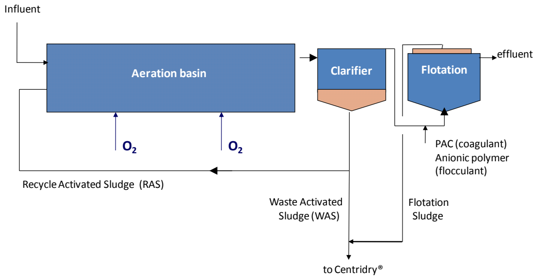


Fig. 1 Flow scheme of Monsanto Antwerp WWTP.

Previous research (Peeters and Herman, 2007) on this WWTP has revealed that changing cation balances, and in particular changes in the Ca^{2+} concentration, in this wastewater result in significant changes in the Sludge Volume Index (SVI), a key sludge characteristic for activated sludge processes. The SVI is a long established measure of sludge settling ability (Gray, 2004) and is the volume (in mL) that one gram of sludge takes after 30 minutes of settling in a lab sedimentation cylinder. A high SVI indicates a poor settling sludge and *vice versa*. The SVI at this WWTP varies between 20 and 120 mL/g.

The sludge inorganic fraction, varying between 10 to 40 wt% correlates well with the SVI, with a higher inorganic fraction corresponding with a lower SVI as shown in Figure 2. At higher inorganic fractions, enmeshment of solids within the floc structure (by precipitating Ca^{2+} products) yields a heavier floc that settles extremely well, whereas at lower inorganic fractions changes in SVI can be explained by cation exchange on the sludge flocs (Peeters and Herman, 2007), in accordance with the Divalent Cation Bridging Theory (DCBT).

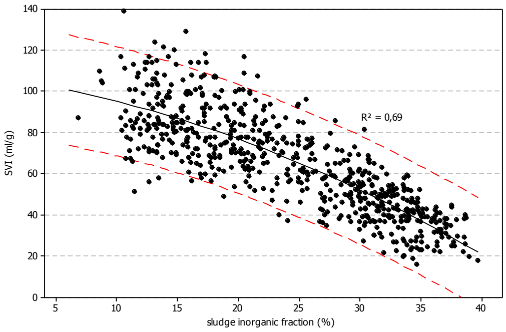


Fig. 2 Sludge Volume Index and inorganic fraction from July 2003 till August 2009.

3. CENTRIDRY®: COMBINED CENTRIFUGE-DRYER APPARATUS

The Centridry® process (Figure 3) combines conventional centrifugation of sludge with hot-gas flash drying, both treatment stages taking place in one single piece of equipment. What makes this technology unique is that it does not require any intermediate storage or conveying of dewatered or dried product, while most of the dewatering–drying technologies used in industry rely on a separate dewatering step and then feeding a stand-alone drying unit (Chen, 2002). Special feature of the Centridry® technology is that a high-solids decanter centrifuge has been modified to include a thermal stage directly following the mechanical dewatering stage, by means of an insulated cyclone chamber around the centrifuge into which the centrifugated solids are discharged to instantly begin drying. The technology was developed in the 1990's by Baker Process (Schilp *et al.*, 2000), is now marketed in the UK by Euroby Ltd. and has been installed worldwide in about 18 installations (O'Conner *et al.,* 2004; Denuell and Godwin, 2005). Euroby is a specialist in sludge treatment, dewatering and drying.

Dewatering stage

As depicted in Figure 1, the feed towards the centrifuge-dryer system consists of a mixture of the waste activated sludge (WAS) and flotation sludge. Clay is added to this sludge feed to improve sludge dewatering, shown to be effective during earlier research by means of capillary suction time (CST) measurements (Peeters and Herman, 2007) and spin tube tests (Peeters *et al.*, 2009a). Once the sludge-clay mixture is pumped into the centrifuge, a cationic polymer is added to enhance flocculation, this way improving the settling of the solids in the cylindrical section of the bowl under influence of centrifugal force (clarification). During transport of the settled solids by the internal Archimedian screw conveyor, interstitial water is squeezed out of the solids structure under the centrifugal force (compaction) referred to as expression (Leung, 1998). The solids residence time in the centrifuge is typically in the order of 10 minutes (Leung, 1998; Peeters *et al*., 2009b).

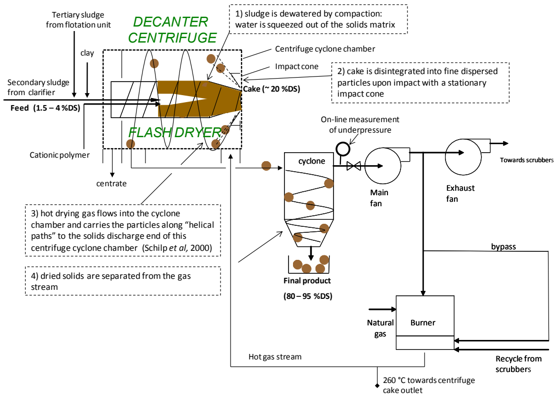


Fig. 3 Flow scheme of the Centridry® combined centrifuge-dryer technology used at the Monsanto Antwerp WWTP.

Drying stage

The mechanically dewatered cake is ejected from the centrifuge through the cake discharge ports (Figure 4). The wet solids are dispersed in finely granular form and change their flight path upon impact with the stationary impact cone inside the casing of the centrifuge (Schilp *et al.*, 2000). This solid spray is immediately entrained in a hot drying sweep gas stream from typically 250-260 °C which carries the particles along *helical paths* (Schilp *et al.*, 2000) to the solids discharge end of the casing as illustrated in Figure 3. Thanks to the high specific surface area of the particles, drying rates are extremely high and within a few seconds residence time in the flash dryer (O'Connor *et al.*, 2004) the product has reached its final moisture content. The dried solids at a temperature of 50-60 °C are finally separated from the gas stream in the cyclone, before being discharged to the stockpile via the rotary valve.

The sweep gas is drawn through the system by the main ventilator fan. Part of the used drying gas is re-heated in the hot gas generator (natural gas burner) which supplies the hot gas stream to the beginning of the centrifuge cyclone chamber. Excess vapours are drawn off the system by a small exhaust fan and sent to a series of two scrubbers before discharge to the atmosphere.

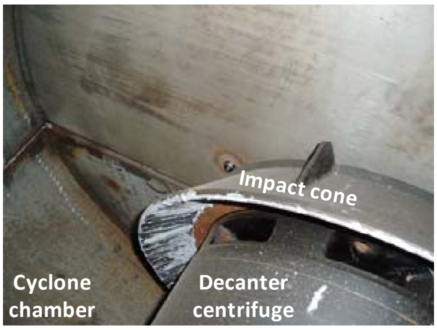


Fig 4. Detail of the centrifuge cake discharge ports (2 ports shown) and the impact cone, yielding a fine-grained spray of solid particles entering the beginning of the cyclone chamber (Courtesy of Euroby Ltd.).

4. FOULING PHENOMENON

Sticky phase of drying sludge

During the drying stage, the physical state of sludge changes successively from liquid to plastic and crumbly material, to finally dry-dust solids (Gray, 2004). Sludge comes in the highly cohesive plastic phase when being partially dried and its consistency is at that moment comparable to sticky rubber, reason why in literature this phase is called the *sticky phase*. The sticky phase is characterised by high cohesion and adhesion, respectively an internal material property and an interfacial property, which causes serious operational problems in many types of dryers as described by Papadakis and Bahu (1992), and Kudra (2003). Stickiness is a complex phenomenon that represents the tendency of the drying materials to stick to contact surfaces when being in its sticky phase, and is of general concern for many industrial dryers because uncontrolled clinging of material on the dryer walls can alter the hydrodynamics and so cause severe quality and/or operational issues.

The problems related to the stickiness phenomenon are also experienced in the processing of food products as described by Adhikari *et al*. (2001).

Fouling of the centrifuge-dryer system

Solids build-up (fouling) in the flash dryer is monitored by the on-line underpressure measurement after the cyclone (Figure 3). A decrease of this underpressure indicates that solids sticking to the dryer wall cause a reduction of the internal diameter for the solids/sweep gas to flow through. Typical time trends of this underpressure in periods of fouling can be found in earlier published work (Peeters, 2010; Peeters *et al.*, 2009a). In case the underpressure is lower than a pre-determined setting, the sludge feed towards the Centridry® is stopped by which no additional cake is ejected in the flash dryer. When the built-up solids layer (lump) in the dryer has totally been dried up (with the sweep gas still entering the dryer, but at a lower 200 °C), this fouling comes loose from the dryer wall and sludge feeding can start again. It is evident that these feeding stops have to be reduced to a minimum.

5. BINARY LOGISTIC REGRESSION

The fouling phenomenon is a binary variable since fouling does appear (1) or does not appear (0) during a one-day operation. Purpose of this study was to find a model that predicts the probability or proportion (P) of the fouling in the flash dryer as function of the SVI, clay dosing and flotation addition (last two being categorical data).

In contrast to a straight relationship between a continuous response (Y) and continuous predictor (X) found with linear regression, the relationship between an event (fouling) probability (P) and a predictor (X) is usually an S-shaped curved with asymptotes at 0 and 1 as visualised in Figure 5 (Mader, 2006; Sharma, 1996).

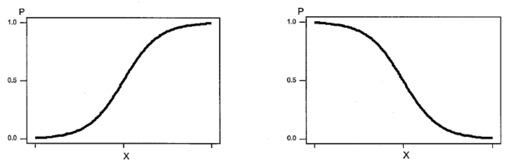


Fig. 5 S-shaped curve between an event probability P and a continuous X predictor.

In logistic regression, the Logit transformation

$$Logit\ (P) = \ln\left(\frac{P}{1-P}\right)$$

is used on P which straightens the relationship between P and X (Figure 6), so adjusting for the curved nature of the response (logistic regression gets its name from this Logit transformation). The ratio of P/(1-P), the ratio of the proportions for the two possible outcomes, is called *the odds*. Next, the log odds are modeled as a linear function of the explanatory variable X:

$$Logit\ (P) = b_0 + b_1X$$

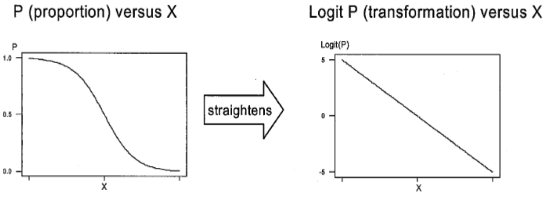


Fig. 6 The Logit transformation straightens the S-shaped relationship between an event probability and a predictor X.

The coefficient b_1 indicates the direction of the curve. A positive value of b_1 indicates an increasing probability with increasing X, while a negative value of b_1 indicates a decreasing probability with higher X-values like the one in Figure 6. Finally, with a back-transformation the desired probability P can be found:

$$Logit\ (P) = b_0 + b_1X \longrightarrow \frac{P}{1-P} = e^{b_0+b_1X}$$

$$\longrightarrow P = \frac{e^{b_0+b_1X}}{1+e^{b_0+b_1X}}$$

$$\longrightarrow P = \frac{1}{1+e^{-(b_0+b_1X)}}$$

It must be mentioned that logistic regression analysis does not make any assumptions regarding the distribution of the independent variables. Therefore, it is preferred to discriminant analysis when the independent variables are a combination of categorical and continuous (like in this case study) because in such cases the multivariate normality assumption is violated (Sharma, 1996).

The statistical analysis in this study was performed with the MINITAB® software package (Minitab Inc., 2003).

6. DATA BASE

An extended data base was compiled covering the period from April 2005 till August 2009. Taking into account shutdown periods of the Centridry® this resulted in a data base of 1425 days. For every day, it was tabulated if fouling/no fouling had occurred together with the SVI (Figure 7), the applied clay dosing (high/medium/low) and the addition of flotation sludge (no addition/addition/ PAC direct in feed). The high, medium and low clay dosing correspond respectively with an average clay-to-biosolids ratio of 0,42; 0,25 and 0,10 kg clay/kg biosolids.

The direct addition of PAC in the feed to the centrifuge was applied in the last 1,5 month of the period considered (middle of July 2009 – August 2009) after some first short trials in the weeks before. The dosing of PAC was at the same level as normally added as coagulant to the flotation unit.

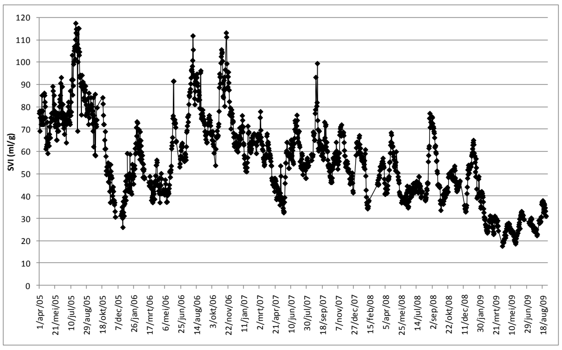


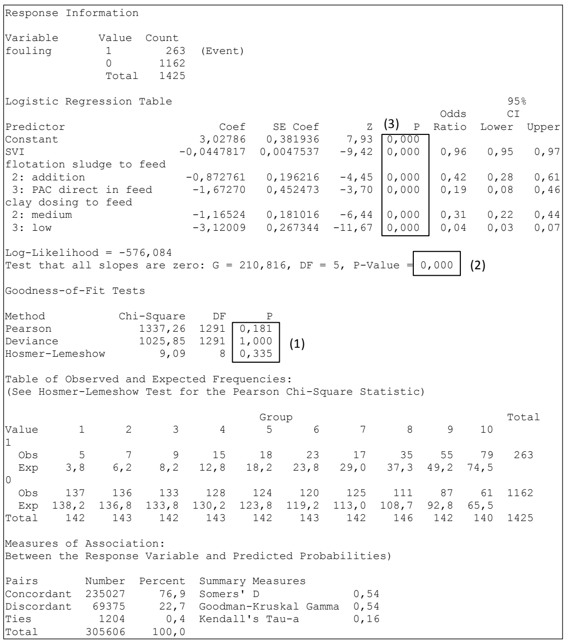
Fig. 7 Sludge Volume Index (SVI) in the period under study (April 2005 till August 2009).

7. RESULTS AND DISCUSSION

Initial model checks

(Mader, 2006).

Before starting to interpret the obtained model (parameters), some model checks are performed of which the outcome is presented in the MINITAB (boxed) output of Figure 8. First of all, analysis showed no multicollinearity existing between the independent variables indicated by a Variance Inflation Factor (VIF) of maximum 1,3 after coding the categorical X's to numeric. Furthermore, (1) the p-values of the three methods to evaluate the goodness-of-fit (p>0,05) show that the model adequately describes the observed data; (2) the p-value of 0,00 for the test that all slopes are zero indicates that at least one of the regression coefficients does not equal zero; (3) the p-values of 0,00 for the individual regression coefficients show significant effects of the predictors on the fouling frequency.



```
Response Information

Variable      Value  Count
fouling        1       263  (Event)
               0      1162
               Total  1425

Logistic Regression Table                                                 95%
                                                               Odds        CI
Predictor                     Coef     SE Coef        Z (3)  P  Ratio  Lower  Upper
Constant                   3,02786    0,381936     7,93  0,000
SVI                     -0,0447817   0,0047537    -9,42  0,000   0,96   0,95   0,97
flotation sludge to feed
 2: addition             -0,872761    0,196216    -4,45  0,000   0,42   0,28   0,61
 3: PAC direct in feed    -1,67270    0,452473    -3,70  0,000   0,19   0,08   0,46
clay dosing to feed
 2: medium                -1,16524    0,181016    -6,44  0,000   0,31   0,22   0,44
 3: low                   -3,12009    0,267344   -11,67  0,000   0,04   0,03   0,07

Log-Likelihood = -576,084
Test that all slopes are zero: G = 210,816, DF = 5, P-Value = 0,000  (2)

Goodness-of-Fit Tests

Method           Chi-Square    DF      P
Pearson             1337,26  1291  0,181
Deviance            1025,85  1291  1,000  (1)
Hosmer-Lemeshow        9,09     8  0,335

Table of Observed and Expected Frequencies:
(See Hosmer-Lemeshow Test for the Pearson Chi-Square Statistic)

                                      Group                                   Total
Value      1      2      3      4      5      6      7      8     9    10
1
  Obs      5      7      9     15     18     23     17     35    55    79    263
  Exp    3,8    6,2    8,2   12,8   18,2   23,8   29,0   37,3  49,2  74,5
0
  Obs    137    136    133    128    124    120    125    111    87    61   1162
  Exp  138,2  136,8  133,8  130,2  123,8  119,2  113,0  108,7  92,8  65,5
Total    142    143    142    143    142    143    142    146   142   140   1425

Measures of Association:
Between the Response Variable and Predicted Probabilities)

Pairs       Number  Percent  Summary Measures
Concordant  235027     76,9  Somers' D              0,54
Discordant   69375     22,7  Goodman-Kruskal Gamma  0,54
Ties          1204      0,4  Kendall's Tau-a        0,16
Total       305606    100,0
```

Fig. 8 MINITAB® output of the binary logistic regression.

Model (parameter) evaluation

The estimated coefficient b_1 of the model equals -0.0448, whereas the constant b_0 depends on the level of clay dosing and flotation sludge (table 1). For example, in case no flotation sludge is added to the sludge feed and a high clay dosing is applied, the model to estimate the fouling probability as function of the SVI equals:

$$P = \frac{1}{1 + e^{-(3{,}028 - 0{,}0448 * SVI)}}$$

According to this model, for different SVI's the following fouling probabilities are found:

SVI of 120: $$P = \frac{1}{1 + e^{-(3{,}028 - 0{,}0448 * 120)}} = 0.087 = 8.7\%$$

SVI of 60: $$P = \frac{1}{1 + e^{-(3{,}028 - 0{,}0448 * 60)}} = 0.584 = 58.4\%$$

SVI of 20: $$P = \frac{1}{1 + e^{-(3{,}028 - 0{,}0448 * 20)}} = 0.894 = 89.4\%$$

The model equations for the other combinations are found accordingly.

Table 1. Values of constant b_0 in the model.

model constant b_0	flotation sludge to feed		
clay dosing to feed	no addition	addition	PAC direct in feed
high	3,028	2,155	1,355
medium	1,863	0,990	0,190
low	-0,0922	-0,965	-1,765

Visualisation of the model

The model is visualised in Figure 9 and clearly shows the effect of the different independent variables on the fouling probability. The chance of obtaining fouling issues in the dryer is highest in case of a low SVI, confirming the conclusion of earlier research (Peeters *et al.*, 2009a). When the sludge is characterised by a low SVI, the fouling probability can be reduced again by lowering the clay dosing from high to low, according to the statistical analysis. This corrective action, lowering clay dosing in case of low SVI, is in operation since December 2007.

The present long-term analysis confirms the hypothesis that was formulated after the former statistical analysis with data only from April 2005 till April 2006; at that time the system was operated always at high clay dosing. Based on lab spin tube tests simulating centrifugal compaction of the sludge (Peeters *et al.*, 2009b) it was shown that sludge with a low SVI dewaters better than sludge with a high SVI; by lowering the clay dosing, again wetter cake can be obtained (Peeters *et al.*, 2009a). The combination of both observations, that is sludge with a low SVI (high inorganic fraction) (1) corresponds with a higher chance of getting fouling in the dryer and (2) yields a higher sludge dryness after centrifugal compaction has led to the hypothesis that *too dry cake entering the flash dryer causes fouling*. To verify this hypothesis, the clay dosing was reduced from standard 35 kg/h to 10 kg/h in case of low SVI's. The obtained model (Figure 9) now confirms the positive effect of the reduced clay dosing in case of a low SVI.

Further, a positive effect of the presence of flotation sludge in the centrifuge feed is shown on the fouling phenomenon. This tertiary sludge contains

PAC and anionic polymer. The separate effect of direct PAC addition into the centrifuge feed during 1,5 month has revealed that PAC addition yields a lower fouling probability in case of extremely low SVI's. A possible explanation could be found in the charge repulsion as result of the added Al^{3+} ions to the sludge and in addition the cationic polymer dosed in the centrifuge itself, resulting in again wetter cake leaving the centrifuge. Ongoing research focuses on verifying this hypothesis.

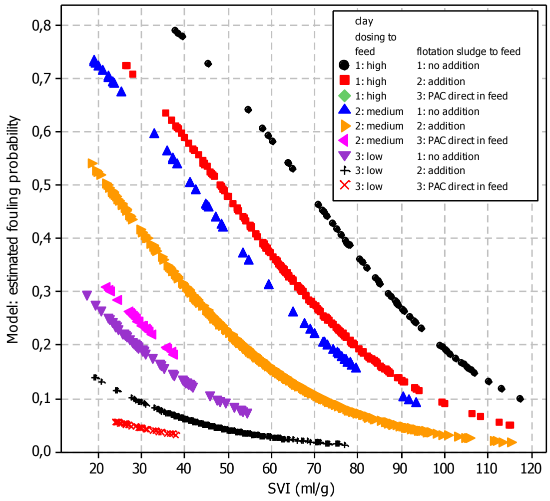


Fig. 9 Visualisation of the model predicting the fouling probability as function of SVI, clay and flotation addition into the sludge feed.

8. CONCLUSIONS

Binary logistic regression is an ideal statistical tool when a prediction has to be made about the presence/absence of a certain parameter, like the fouling (not) appearing in a sludge dryer, based on the values of a set of independent variables.

In conclusion, from this analysis (and previous work) follows that control of the sludge solids dryness at the early stage of the flash dryer under study is critical to avoid drying sludge sticking to the dryer wall. By controlling the sludge dryness at the early stage of the dryer, e.g. by changing the clay dosing, one controls the place where the sludge goes through the sticky phase in the dryer.

ACKNOWLEDGMENTS

J. Van Impe holds the chair Safety Engineering sponsored by the Belgian chemistry and life sciences federation essenscia.

REFERENCES

Adhikari, B., T. Howes, B.R. Bhandari and V. Truong (2001). Stickiness in foods: A review of mechanisms and test methods. *International J. Food Properties* **4**(1), 1-33.

Chen G., P.L. Yue and A.S. Mujumdar (2002). Sludge dewatering and drying. *Drying Technology* **20**(4), 883-916.

Denuell M. and P. Godwin (2005). CENTRIDRY® - A technology for the future. In *Proceedings of the 10th European Biosolids and Biowastes Conference*, Wakefield, UK, November 13-16, Session 12, Paper 39 (CD-rom).

Gray, N.F. (2004). *Biology of wastewater treatment* Series on Environmental Science and Management, Volume 4, 2nd ed., Imperial College Press, London.

Kudra, T. (2003). Sticky region in drying – Definition and identification. *Drying Technology* **21**(8), 1457-1469.

Kudra, T. and A.S. Mujumdar (2009). *Advanced Drying Technologies*, CRC Press, Taylor&Francis Group, New York.

Leung, W.W.-F. (1998). *Industrial Centrifugation Technology*, McGraw-Hill, New York.

Mader, D. (2006). *SigmaPro Master Black Belt Participants Guide, Module 18 – Categorical Data Analysis*, SigmaPro Inc., Fort Collins, Colorado.

Minitab Inc. (2003). *MINITAB Statistical Software, Release 14 for Windows*, State College, Pennsylvania. MINITAB® is a registered trademark of Minitab Inc.

O'Connor, J., S. Tilley and R. Edgington (2004). Operational experiences with direct, flash drying technology for raw sewage sludge. In *Proceedings of the 9th European Biosolids and Biowastes Conference*, Wakefield, UK, November 14-17, Session 22, Paper 66 (CD-rom).

Papadakis S. E. and R. Bahu (1992). The sticky issues of drying. *Drying Technology* **10**(4), 817-837.

Peeters, B. (2010). Mechanical dewatering and thermal drying of sludge in a single apparatus. *Drying Technology* **28**(4), IN PRESS.

Peeters, B. and S. Herman (2007). Monitor cations in CPI wastewater for better performance. *Chemical Engineering* **114**(5), 56-62.

Peeters, B., L. Vernimmen and W. Meeusen (2009a). Changing wastewater sludge characteristics affecting the fouling of a single stage mechanical dewatering and thermal drying process. *Filtration* **9**(1), 52-62.

Peeters, B., L. Vernimmen and W. Meeusen (2009b). Lab protocol for a spin tube test, simulating centrifugal compaction of activated sludge. *Filtration* **9**(3), 205-217.

Schilp, R., W.W.-F. Leung, S. Hegarty, M. Ismar and R. Kluge (2000). Continuous slurry dewatering and drying – all in one machine. *Fluid/Particle Separation* **13**(1), 85-96.

Sharma, S. (1996). *Applied multivariate techniques*. John Wiley & Sons, Inc.