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Multivariate data analysis of full-scale sludge dewatering

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ABSTRACT

A multivariate data analysis (MVDA) was conducted to identify operating parameters that affect the sludge dewatering efficiency in a Canadian pulp and paper mill. The sludge is a mixture of waste activated sludge (WAS) and three different types of primary sludge. The dewatering efficiency was defined by three target parameters: the cake solids content after dewatering, the solids capture efficiency, and the costs of dewatering aids (chemicals) used per ton of dewatered sludge solids. The results show that the most influential parameters affecting the dewatering efficiency are 1) the type and amount of primary sludge added to the sludge mix, 2) the operating parameters of the dewatering equipment and 3) the sludge solids throughput. A high proportion of fiber-rich primary sludge in the sludge mix substantially enhances dewaterability. Operating the screw press at a low torque and/or at a high screw press speed lowers the dewatering performance. The pH adjustment of the sludge prior to dewatering also significantly affects dewaterability. The effectiveness of the dewatering aids decreases notably when the pH is not within the target range. Besides the processes in the dewatering plant, the activated sludge process and the associated amount and quality of the WAS also affect the dewaterability of the sludge mix. In particular, the dewatering efficiency seems to be seasonal. The higher temperature during the summer produces less WAS, and thus increasing the proportion of primary sludge in the sludge mix and improving dewaterability. Also, WAS with high microbial activity and firm flocs, as well as a low sludge volume index enhances dewaterability.

1. Introduction

In pulp and paper producing countries, the amount of wastewater treatment sludge generated in all mills together can be much higher than that generated in all municipal plants combined. On average, the sludge produced in Canadian mills consists of 70 % primary sludge and 30 % WAS [1]. However, the fraction of WAS contributing to the sludge mix varies largely among the individual mills. Common sludge handling practice involves mixing of primary sludge and WAS, followed by pre-dewatering with rotary thickeners or gravity tables, and subsequent dewatering using belt or screw presses. In the majority of mills, the sludge is disposed of either by combustion or landfilling [2], both requiring cost-intensive thickening and dewatering, and in the latter case also transport and disposal costs. Approximately one-fifth of the sludge produced worldwide is used for some form of land application, including land spreading, utilization in agriculture and horticulture, and composting [2]. In order to diminish the costs for landfilling, mills either try to burn as much as possible sludge in their biomass boilers, or increase the final cake solids content of the dewatered sludge. If the sludge is incinerated, low solids content of the dewatered cake increases the energy required for the evaporation of sludge water. Burning moist sludge can also cause problems such as clogging of the sludge feeding system and deterioration of fluidization in fluidized bed biomass boilers.

Besides the cake solids content, the solids capture efficiency is another parameter used to describe the dewatering performance. The solids capture efficiency quantifies the fraction of solids of the raw sludge that is captured in the dewatered cake, as opposed to be lost in the dewatering filtrate and pressate. The filtrate/pressate is usually returned to the head of the treatment system. Costs for treatment of the filtrate/pressate and the additional sludge derived from that treatment can be 5–10% of the overall wastewater treatment costs. Therefore, the amounts of solids and chemical oxygen demand contained in the filtrate/pressate is of importance. Solids capture efficiency is commonly approximated by the equation:

$$C = \left(1 - \frac{S_f}{S_i}\right) \times 100$$

where C is the percentage solids capture, S_f is the percentage of the solids in the filtrate, and S_i is the percentage of the solids in the raw

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sludge prior to thickening. High solids capture efficiency not only decreases the treatment costs, but also diminishes the wear on the dewatering units and pumps, and reduces the amounts of particles with adverse dewatering properties. Particles in the filtrate/pressate are often made of filamentous bacteria, colloidal matter, and particles with poor surface charge that are difficult to flocculate [3].

Costs for dewatering chemicals at a mill range between a few hundred thousand dollars to a few million dollars per year. Therefore, the specific chemical costs, i.e. the costs of conditioner added per ton of sludge solids dewatered, are a significant economic factor in wastewater treatment.

Very few studies have applied multivariate data analysis methods to investigate sludge dewatering. Based on laboratory experiments with municipal sludge, Feng et al. [4] implemented a partial least squares (PLS) regression analysis to explore the importance of conditioner dose and applied pressure on the dewatering performance of a piston press. Kyllönen et al. [5] centrifuged WAS samples from various pulp and paper mills in a laboratory setting and implemented a MVDA to correlate physical and chemical properties of the sludge with its dewaterability. Accordingly, a high initial solids content and COD concentration as well as a high fiber content increases the cake solids. Only one study could be identified that has applied MVDA methods to full-scale sludge dewatering [6]. The sludge was dewatered by means of a centrifuge, and the goal was to determine the amount of dewatered biosolids that required landfill disposal, however investigating the dewatering performance was not part of the study. Laboratory studies on sludge dewatering can only investigate the sludge properties and the influence of polymer addition under controlled conditions, but not the impact of the operating conditions of the dewatering equipment and the activated sludge process. This work is the first to attempt to use MVDA to comprehensively investigate the performance of full-scale sludge dewatering by including parameters related to the type and properties of the sludge, the operating parameters of the dewatering equipment, and the activated sludge process, all at the same time. The approach makes it possible to rank these parameters in terms of their relative importance to the sludge dewatering performance.

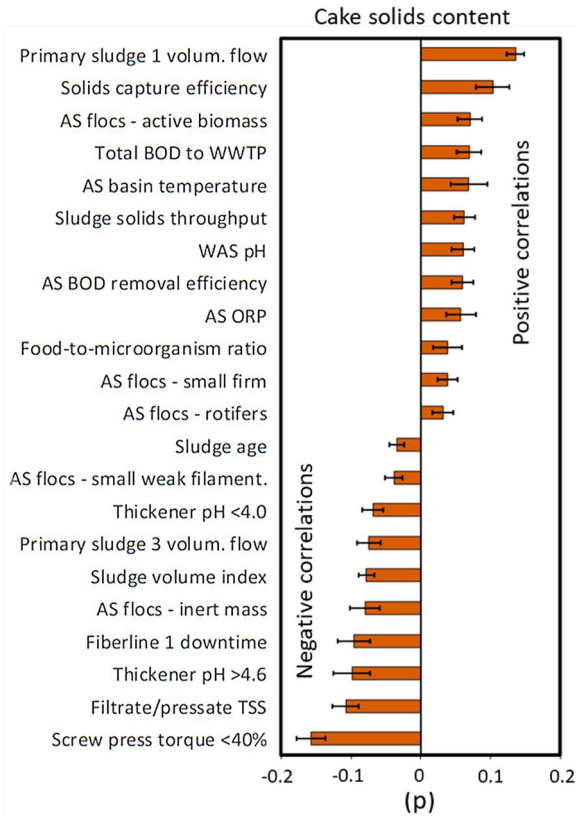


Fig. 1. Relationships between the operating parameters and the cake solids content (predictive component (p) of the X variation). Parameters right from the middle axis of the column chart (positive p-values) are positively correlated, and parameters to the left (negative p-values) are negatively correlated to the cake solids content. Longer bars mean stronger correlations. Results for the two screw presses and the two thickeners, respectively, are averaged. AS: activated sludge treatment.

2. Methods

2.1. Mill process data

Daily averaged data of 100+ operating parameters over a 6-year period were collected from the dewatering plant and the activated sludge process of a Canadian pulp and paper mill that produces chemical and mechanical pulp. Dewatering parameters include operating parameters from two gravity filtration units and two screw presses, properties and flow rates of the various types of sludge, the filtrate and pressate as a result of dewatering, the type and amounts of dewatering chemicals added, and others. The applied conditioners are a cationic polymer and a clay-based coagulant. Parameters from the activated sludge process include the food-to-microorganism (F-M) ratio, aeration basin temperature, sludge retention time, sludge age, oxidation-reduction potential, sludge volume index (SVI), parameters describing the physical and microbiological properties of the activated sludge flocs, and others.

2.2. Multivariate data analysis

The multivariate data analysis (MVDA) program SIMCA version 15 (MKS Umetrics, Umeå, Sweden) was used to perform an orthogonal partial least squares (OPLS) regression analysis. This software has been applied and described in detail in previous studies where operating data related to wastewater treatment and/or pulp and paper production were investigated [7–9].

MVDAs have been increasingly used to examine large datasets, identify patterns and correlations while considering all data simultaneously. During the analysis an empirical model is created based on measured process data (independent variables X), and by calculating latent variables that are orthogonal to each other. In the case of OPLS regression, these latent variables are selected to maximize their description of the output (dependent variables Y) variance [10]. The Y-parameter(s) are the target parameter(s), which in the case of this study are the cake solids content, the solids capture efficiency, and the specific chemical costs. The X-parameters are the plant operating parameters that may or may not correlate with the target parameters. OPLS regression analysis divides the systematic variation of the X-variables into two parts, one which is correlated to Y, and another part that is not correlated (orthogonal) to Y. OPLS regression analysis is particularly useful to investigate very complex systems that involve numerous, different and systematic parameter variations, such as wastewater treatment plants. In order to quantify and rank the relationships between the operating parameters (X-parameters) and the target parameters (Y-parameters), the so-called predictive component (p) of the variance in X was used, which is part of the software output. The higher the absolute value of (p), the stronger is generally the relationship between X and Y (Figs. 1–3).

The method is robust to variation in X and Y, and can handle correlations among variables, as well as missing data.

Prior to building the OPLS model the data were pre-processed, which involved the exclusion of unreasonable data such as those generated during shut-down events of wastewater treatment plant components. Also, all data were scaled to unit variance, and data related to several variables required transformation to logarithmic scale.

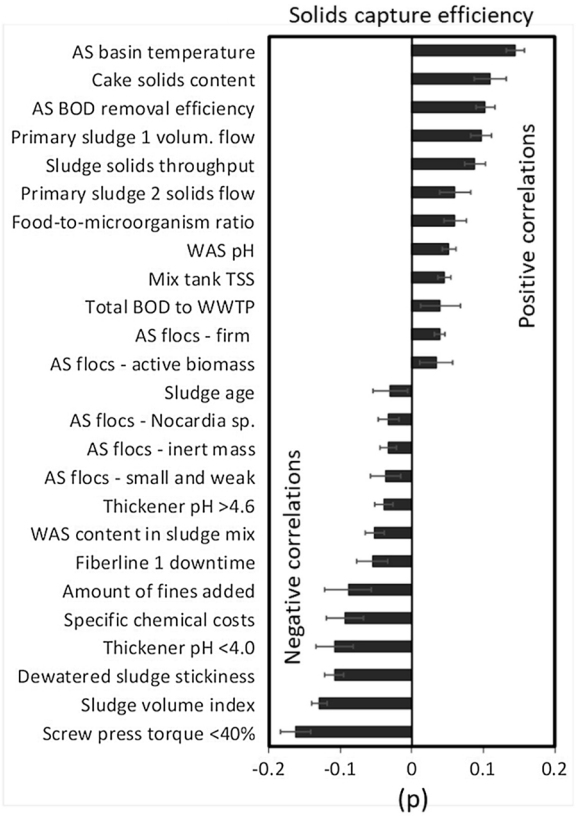


Fig. 2. Relationships between operating parameters and the solids capture efficiency (predictive component (p) of the X variation). Parameters on the right of the middle axis of the column chart (positive p-values) are positively correlated, and parameters on the left (negative p-values) are negatively correlated to the solids capture efficiency. Longer bars mean stronger correlations. Results from the two screw presses and the two thickeners, respectively, are averaged. AS: activated sludge treatment.

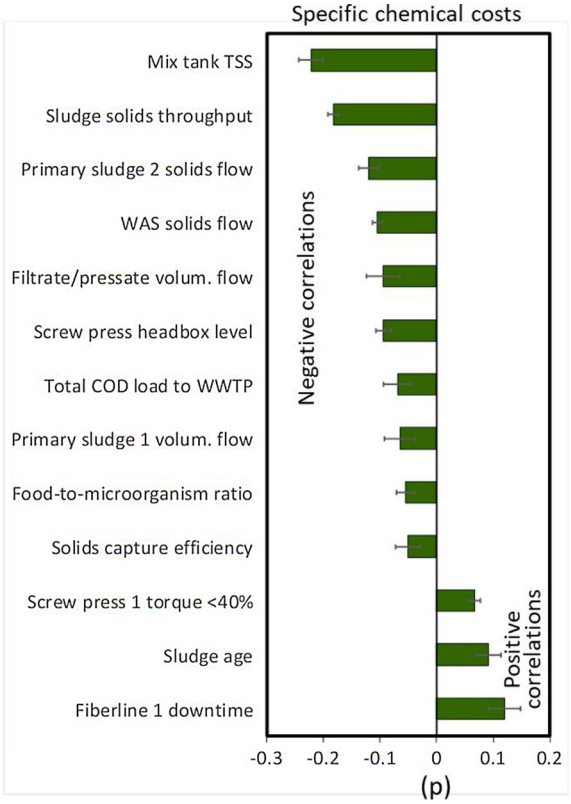


Fig. 3. Relationships between operating parameters and the specific chemical costs (predictive component (p) of the X variation). Parameters right from the middle axis of the column chart (positive p-values) are positively correlated, and parameters to the left (negative p-values) are negatively correlated to the specific chemical costs. Longer bars mean stronger correlations. AS: activated sludge treatment.

2.3. Target parameters

In order to implement a MVDA on the parameter importance, one or several target parameters are required that reflect the process performance. The overall costs for sludge dewatering and subsequent disposal are governed by i) the solids content of the dewatered cake, ii) the fraction of solids captured in the dewatered cake, and iii) the costs of chemicals (conditioners) added to the sludge per ton of dewatered sludge solids. These three parameters are therefore chosen as the target parameters in this study.

2.4. Sludge types

The sludge mix dewatered at the mill consists of three types of primary sludge and WAS (Table 1). Primary sludge 1 originates from a clarifier that receives effluent from mechanical pulping, and has a very high proportion of fiber. Primary sludge 2 receives the overflow of the mechanical pulping clarifier, as well as alkaline filtrate and evaporator condensate from chemical pulping, and has also a notably high fiber content. Primary sludge 3 receives a composite effluent including steam plant sewer, Thune press effluent, alkaline filtrate, and others, and has a relatively low fiber content [11].

3. Results and discussion

The results of four OPLS analyses are presented below. In the first three analyses only one target parameter at a time was assigned as Y-parameter, i.e. the cake solids content (Fig. 1), the solids capture efficiency (Fig. 2), and the specific chemical costs (Fig. 3). In the fourth analysis, all three target parameters were together assigned as Y-parameters (Fig. 4), in order to obtain a more comprehensive understanding of the correlation structure among the target parameters. In Figs. 1–3 only those process parameters were included that have a relatively strong relationship to the target parameter. The error bars in Figs. 1–3 indicate the jack-knifing uncertainty [12] with the confidence interval set to 95 %. According to definition, significance is provided when the error bar does not go through zero (Figs. 1–3). Sludge flows in Figs. 1–4 are presented in terms of sludge volumetric flow (m^3/hour), and sludge solids flow (tons/hour) on a dry solids basis.

Table 1
Total suspended solids concentration of the different types of sludge.

	Primary sludge 1	Primary sludge 2	Primary sludge 3	WAS
TSS	1 – 2 %	3 – 4 %	0.5 – 1 %	1 – 1.5 %

3.1. Cake solids content

Fig. 1 illustrates the relationship between the process operating parameters and the cake solids content. The results show that a large flow of the fiber-rich primary sludge 1 is most beneficial to the dewaterability of the sludge mix (Fig. 1). This type of sludge acts as a skeleton builder that maintains water permeability during sludge pressing by providing a porous and rigid structure [13]. The parameter "Fiberline 1 downtime" quantifies the number of minutes per day during which no primary sludge 1 was generated, and the dewatered sludge mix consisted only of WAS, primary sludge 2 and 3. The less downtime

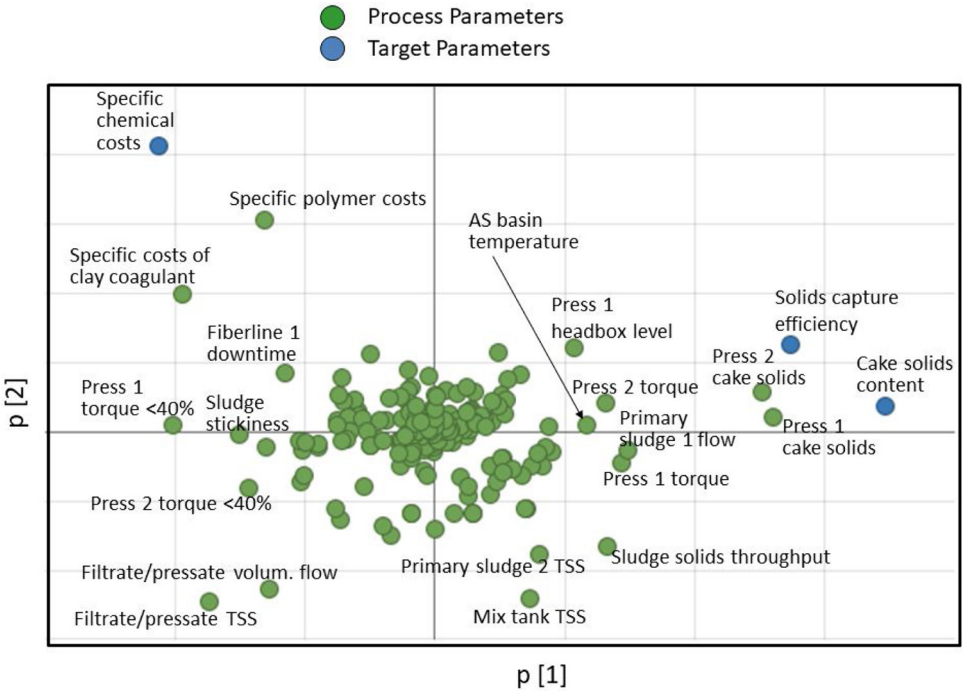


Fig. 4. Loadings plot comprising the first two components, p[1] versus p[2]. The p's are the predictive components that maximize the correlation between X-variables and Y-variables.

this production line experiences, the higher is the dewaterability in terms of cake solids content. Interestingly, a large fraction of the primary sludge 3 in the sludge mix is detrimental to the dewaterability. This type of sludge does not contain much fiber, and has a very low solids content (< 1 %).

Operating parameters of the dewatering equipment, and specifically the screw presses and gravity filtration thickeners, have also a high impact on the cake solids content. Operating the press at a low torque significantly decreases the cake solids content (Fig. 1). The screw press torque, which is the power required for rotating the screw, has a target range of operation. The parameter "Screw press torque < 40 %" quantifies the amount of time during which the screw press was operated at a torque below 40 %, which is the lower end of the target range. A torque that is too low does not provide sufficiently high pressure to squeeze enough water (pressate) through the filter screens. A too high torque, on the other hand, may lead to sludge clogging at the front end of the press. The applied torque is mainly related to the sludge solids throughput, because the larger the amount of sludge is in the screw press the more torque is required. The screw press speed is also important, i.e. a faster screw speed reduces retention time of the sludge in the press resulting in less dewatering or lower cake solids content. Thus, a large sludge solids throughput of especially fiber-rich sludge, combined with a low screw press speed would require a high torque.

Prior to screw press dewatering, the sludge is thickened on gravity filtration thickeners. Dewatering chemicals are added to the sludge before it enters the thickener. In addition, sulfuric acid is added to adjust the pH to between 4.0 and 4.6, a range in which the dewatering polymer is most effective. The parameter "Thickener pH > 4.6" refers to the amount of time during which the pH of the sludge mixture was above the target range. While operating the gravity thickeners at a pH outside of the target range notably decreases the cake solids content, the impact of a pH that is too high is stronger than that of a pH that is too low (Fig. 1).

The operation of the activated sludge process affects the amount and properties of the WAS, and hence the dewaterability of the sludge mix. Also, lower temperatures during the colder season causes the production of more extracellular polymeric substances (EPS), which leads to a deterioration in sludge dewaterability (Fig. 1) [14,15]. Lower temperatures also slow down endogenous respiration [16], which increases the net sludge yield in the activated sludge process. Larger amounts of WAS added to the sludge mix decrease the ratio primary sludge to WAS, which in turn deteriorates the dewaterability (Fig. 1).

The quality of the WAS flocs affects the dewaterability of the sludge mix. The proportions of inert mass and active biomass in the sludge flocs have the highest impact on dewaterability. The inert mass consists mostly of non-biodegradable particulate organics and inorganics that enter the process via the influent, whereas the active biomass refers to heterotrophic active microorganisms that are able to degrade organic material. Also, WAS with a high content of small, firm flocs, and a low content of small, weak and filamentous flocs, and an associated low sludge volume index is indicative of enhanced sludge dewaterability (Fig. 1).

Sludge age and feed-to-microorganism ratio (F:M ratio) are usually inversely related. A low F:M ratio and a high sludge age are correlated to low cake solids content in the dewatered sludge (Fig. 1). Older sludge, from operation at a high sludge age, contains more biological particles with weak electrical charges which limit the effectiveness of polymers. Therefore, those particles do not flocculate easily and hinder sludge dewaterability [17]. On the other hand, younger sludge is often associated with somewhat higher EPS concentration which can also diminish dewaterability [18]. Seemingly, the adverse effects on dewatering related to charge weakening of older sludge are stronger than those related to higher EPS content in younger sludge.

3.2. Solids capture efficiency

Fig. 2 shows parameters that have a strong relationship to the solids capture efficiency. There is a similarity between parameters related to cake solids content and those related to the solids capture efficiency, simply because both target parameters correlate well with each other. Similar to the cake solids content, operating parameters of the dewatering equipment greatly affect the solids capture efficiency. Operating the screw press torque below the target range (< 40 %) for extended periods of time substantially reduces the dewaterability (Figs. 1, 2).

Also, the pH adjustment of the sludge mix is of importance. However, contrary to the cake solids content, a pH above the target range has a much smaller impact on the solids capture efficiency than a pH below the target range (Fig. 2). The activated sludge process has also a large impact on the solids capture. A low sludge volume index is beneficial for the solids capture efficiency.

Higher temperatures during the summer have a strong positive effect for both the cake solids and the capture efficiency. Likewise, a sludge with a high fraction of firm flocs and active biomass promotes the solids capture rate, whereas high fractions of weak flocs and inert biomass have the opposite effect.

Also important are the types and amounts of sludge contributing to the sludge mix. As expected, primary sludge improves dewaterability. However, in contrast to the cake solids content, a large WAS content in the sludge mix and a high stickiness of the dewatered cake are associated with low solids capture efficiency (Fig. 2). The WAS content at the mill usually ranges between 20 % and 50 %, depending on the season, the sludge age, and many other variables. Within this range, the WAS content or the ratio between WAS and primary sludge is more important to the solids capture efficiency than to the cake solids content.

3.3. Specific chemical costs

Fig. 3 illustrates the correlation structure between the operating parameters and the specific chemical costs, i.e. the costs of chemicals added per ton of sludge solids dewatered. High specific chemical costs are related to low sludge solids throughput. As previously explained, low throughput deteriorates sludge dewaterability due to insufficient screw pressing (Figs. 1, 2). Therefore, during periods of low throughput operators add more conditioner, relative to the amount of sludge solids dewatered, in order to compensate for the poor dewatering. High specific chemical costs are also correlated to low TSS concentrations in the mix tank and in primary sludge 2.

The mix tank receives the primary sludges and WAS from the various clarifiers, and is located just upstream of the gravity thickeners. Because of its high TSS concentration (3–4%), primary sludge 2 is the largest contributor of solids to the sludge mix. The reason for this correlation is that it is difficult for operators to accurately adjust the conditioner flow to the variations in sludge solids throughput. Therefore, when the TSS in the mix tank and in the primary sludge 2 temporarily decreases, the specific chemical costs increase.

The influence of screw press and gravity thickener operation is of notably less influence to the specific chemical costs than it is to the other two target parameters. Only a very low torque in screw press 1 is negatively correlated to the specific chemical costs. High flows of primary sludge and WAS, a high COD load entering the wastewater treatment plant (WWTP), a high F-M ratio, and a low sludge age are all related to a high throughput of sludge in the dewatering plant, and therefore, low specific chemical costs.

3.4. Analysis including all three target parameters

As previously mentioned, the results presented in Figs. 1–3 are based on MVDAs in which each of the target parameters were investigated separately, i.e. only one target parameter at a time was assigned as Y-parameter, whereas all other parameters were assigned as X-parameter. The so-called “loadings plot” in Fig. 4 however, shows results of an analysis where all three target parameters were together assigned as Y-parameters, in order to gain more insight into the correlation structure between them. Parameters negatively correlated to each other can be found on opposite locations within the coordinate system of Fig. 4, and those positively correlated are close to each other. Parameters near the centre of the coordinate system have no impact on dewatering.

It can be seen that the parameters cake solids content and solids capture efficiency are located relatively close to each other, which means that they are positively correlated. At the same time, both parameters are to some extent negatively correlated to the target parameter specific chemical costs (Fig. 4). Therefore, there is a tendency that enhanced dewatering performance in terms of dry solids content and solids capture efficiency correlate with low specific chemical costs. An increase of the parameters located on the right side in Fig. 4 enhance the cake solids content and solids capture efficiency, whereas an increase of parameters on the left side has a detrimental effect. An increase of parameters located on the lower right quadrant is related to lower specific chemical costs. Fig. 4 illustrates that high dewatering performance can be achieved by operating the screw presses at sufficiently high torque, and by processing a sludge mix that consists to a large part of the fiber-rich primary sludge 1. It is worthwhile mentioning that fiber itself is a valuable resource at pulp mills and many mills strive to retain more fiber within the pulping process and thereby decreasing the amount of fiber that enters the wastewater treatment plant. Low specific chemical costs can be achieved mainly by maintaining high sludge solids throughput.

Fig. 4 shows two major correlation structures. One is the relationship between cake solids content, solids capture efficiency, filtrate/pressate TSS and screw press torque (upper right to lower left diagonal in Fig. 4). The other is the relationship between specific chemical costs, sludge solids throughput, primary sludge 2 concentration, and mix tank TSS (upper left to lower right diagonal in Fig. 4). Both correlation structures are governed by somewhat different mechanisms. Whereas the former is mostly governed by the type of sludge and the physical force applied during dewatering, the latter is largely governed by the amount and concentration of the incoming sludge solids.

The results of this study reveal potential opportunities for optimization of the dewatering process. Whereas the properties and the amounts of the various types of sludge are difficult to change, operating parameters of the dewatering equipment may be changed more easily. For example, periods of low sludge solids throughput and the associated poor dewatering performance may be addressed by operating the screw presses at a lower speed, or operating only one screw press at a time. Other potential changes are increasing the mix tank capacity upstream of the thickening units to help balancing out large fluctuations in sludge flow, or improving the adjustment of the sludge pH to keep the efficiency of the dewatering chemicals as high as possible. The costs for dewatering chemicals may be lowered by better aligning the conditioner flow with the varying sludge solids flow.

4. Conclusions

This work was the first to investigate the sludge dewatering performance using multivariate data analysis methods, and by including parameters related to the sludge type and properties, the press operating parameters, and the activated sludge process. The goal of the analysis was to determine the most important parameters for the dewatering performance at a pulp and paper mill. High dewatering performance in terms of cake solids content and solids capture efficiency can be accomplished by operating the screw presses at sufficiently high torque (> 40 %), which is related to high sludge throughput and/or low screw press speed. Also, important to the dewatering performance is maintaining the pH of the sludge mix within the target range in order for the dewatering polymer to be most effective. Finally, a sludge mix that is high in fiber-rich primary sludge and activated sludge of good quality, i.e. a high fraction of firm flocs and active biomass as well as a low sludge volume index, enhances dewaterability. Low specific chemical costs can be achieved by maintaining a high sludge throughput.

In summary, the factors that are most influential to full-scale screw press sludge dewatering are the operation of the screw presses and thickeners, the type and amount of primary sludge added to the sludge mix, as well as the operation of the activated sludge process and the associated quality and quantity of the WAS. Whereas there is a potential

to optimize parameters related to the operation of the dewatering equipment, the potential for changing the other parameters is rather limited. Since the properties of WAS and primary sludge, as well as the principles of sludge dewatering are similar among the treatment plants in the varying industries, this study provides insight into the factors that influence sludge dewatering not only in pulp and paper mills, but also in other industrial or municipal wastewater treatment plants. The results of this study enable process engineers and operators to assess the relative importance of all parameters that may potentially influence the dewatering performance, and to devise strategies for dewatering optimization.

CRediT authorship contribution statement

Torsten Meyer: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Adrew Barquin:** Validation, Resources, Writing - review & editing, Supervision. **Patrick Gionest:** Validation, Resources, Writing - review & editing, Supervision. **Honghi Tran:** Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

No competing financial interests exist.

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