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INTELLIGENT CONTROL SYSTEM FOR LOW EMISSIONS AND HEAT LOSS WITH MAXIMIUM LIME KILN PRODUCTION

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ABSTRACT

In this paper, the major results of a field study with special attention being paid to TRS emissions, carried out at UPM-Kymmene's Wisaforest pulp mill in western Finland, are first summarized. The structure and main functions of an intelligent supervisory-level control system which was designed on the basis of acquired process expertise for ensuring a low level of emissions and heat losses while maximizing kiln production, are described. Finally, the test results of the system, which has been successfully operated over extended periods at the mill, are presented and discussed.

INTRODUCTION

Environmental issues in general, and especially the reduction of flue gas emissions have received increasing attention in recent years (Walburga, Loogyam & Dorothy, 1996). The major substances of environmental interest in the case of the lime kilns are the total reduced sulfur (TRS) emissions (Caron, 1989; Pinkerton, 1999). In fact, during the past decade the significance of TRS emissions from lime kilns has increased as a result of the elimination of the earlier major emission sources from pulp mills by means of comprehensive collection and efficient treatment systems (Järvensivu, Saari & Jämsä-Jounela, 2000). Accordingly, the limits on the emissions have become more stringent. (Blackwell, 1996; Meadows, 1996). Although it has been possible to reduce emissions through new designs, and the special chemicals used in lime mud filters and flue gas treatment, TRS emissions at many well-managed mills even tend to sporadically exceed the limits set by the authorities (Ford, 1994; Trauffer, 1995; Diercks & Robinson, 1996). Further reduction of these emissions will therefore be among the major challenges facing the pulp and paper industry in the future.

In practice, however, process conditions that are the most desirable from the environment protection point of view are not necessarily the most energy efficient ones (Davey and Hsieh, 1989; Gullichsen, 1999). Enhanced process control can therefore be readily justified as a feasible mean of avoiding the generation of preventable emissions, while operating the process at the highest attainable production rate and heat energy efficiency. Furthermore, improvements related to high-level control can often be carried out at a reasonably low level of investments and subsequent maintenance costs and, at the same time, avoiding long process downtimes. This is not necessarily the case when new equipments, retrofits and/or end-of-pipe treatments are employed.

DOMAIN KNOWLEDGE ACQUISITION

Background and objects

The prime motivation of this research was the ecologically aware work carried out at the Wisaforest pulp mill in the field of TRS-emission reduction. In addition to substantial investments in odor abatement systems, a field survey of the entire pulp mill's TRS emissions has recently been performed at the mill (Järvensivu, Saari & Jämsä-Jounela, 2000). A field study on the operation of the lime reburning process, which comprised both statistical analysis of the process operations and implementation of process experiments with special attention paid to emissions, was subsequently carried out at the mill (Järvensivu, Kivivasara & Saari, 1999). The results of the field study showed that, in addition to considerable enhancement potential in the overall performance of the process, improved control is a feasible means of reducing emissions from the kiln which account for a marked proportion of the TRS emissions from the pulp mill.

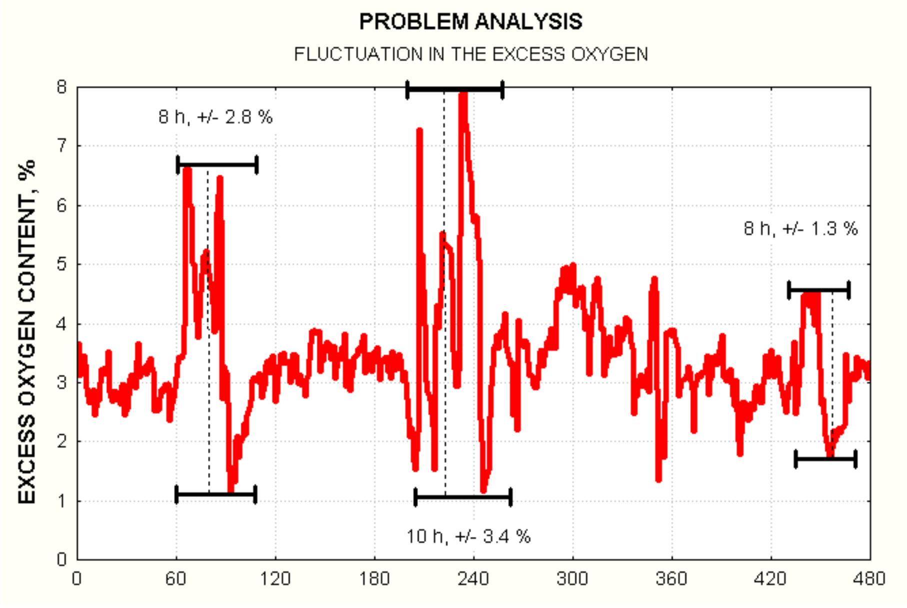
This research was also a continuation of the work done concurrently at the mill in the field of lime kiln control (Penttinen, 1994; Juuso, Ahola & Leiviskä 1996). The primary objective of the research work has therefore been to develop, on the basis of the acquired knowledge, an intelligent control system for the lime reburning process. The objects set by the mill management for the project were to ensure low flue gas emission levels and heat losses while, at the same time maximizing production and reducing the variation in burnt lime quality. The previous version of the system and the main results obtained during an extended testing period are described in more details in Järvensivu, Saari & Jämsä-Jounela (2001).

2.2 Problem analysis

The major results of the field study that are related especially to the reduction of TRS emissions and/or potential enhancements in high-level process control are summarized below.

- Lime kiln #2 has to be operated for most of the time above the designed capacity and hence close to the maximum sustainable production rate. Mud storages prior the kiln have however a tendency to accumulate slowly and subsequently become full. Therefore, after every second or third week, old kiln #1, which is considerably less energy efficient than newer kiln #2, has to be taken into operation. The old kiln burns non-renewable fossil fuel, i.e. fuel oil, while the less expensive and renewable biomass is used as the primary fuel in kiln #2. Furthermore, both the dust and TRS emissions from the old kiln are considerably greater than those from kiln #2, which is equipped with an efficient flue gas treatment system.

- Unnecessary large changes are repeatedly made by the operators to the production rate in order to balance out increasing or decreasing levels of mud storage. Pending production rate changes tend to cause considerable fluctuations in the kiln process. Large changes in production also considerably increase the risk of TRS emissions. **Figure 1** shows clearly identifiable examples of fluctuations in the excess oxygen content and cold-end temperature after three production rate changes. **Figure 2** indicates a marked increase in emissions during the first production rate change shown in Figure 1. In addition, adverse short-term disturbances frequently occur in the mass flow of lime mud pumped to the filters due to an uncontrollable decline in the suspended solids of the incoming mud.



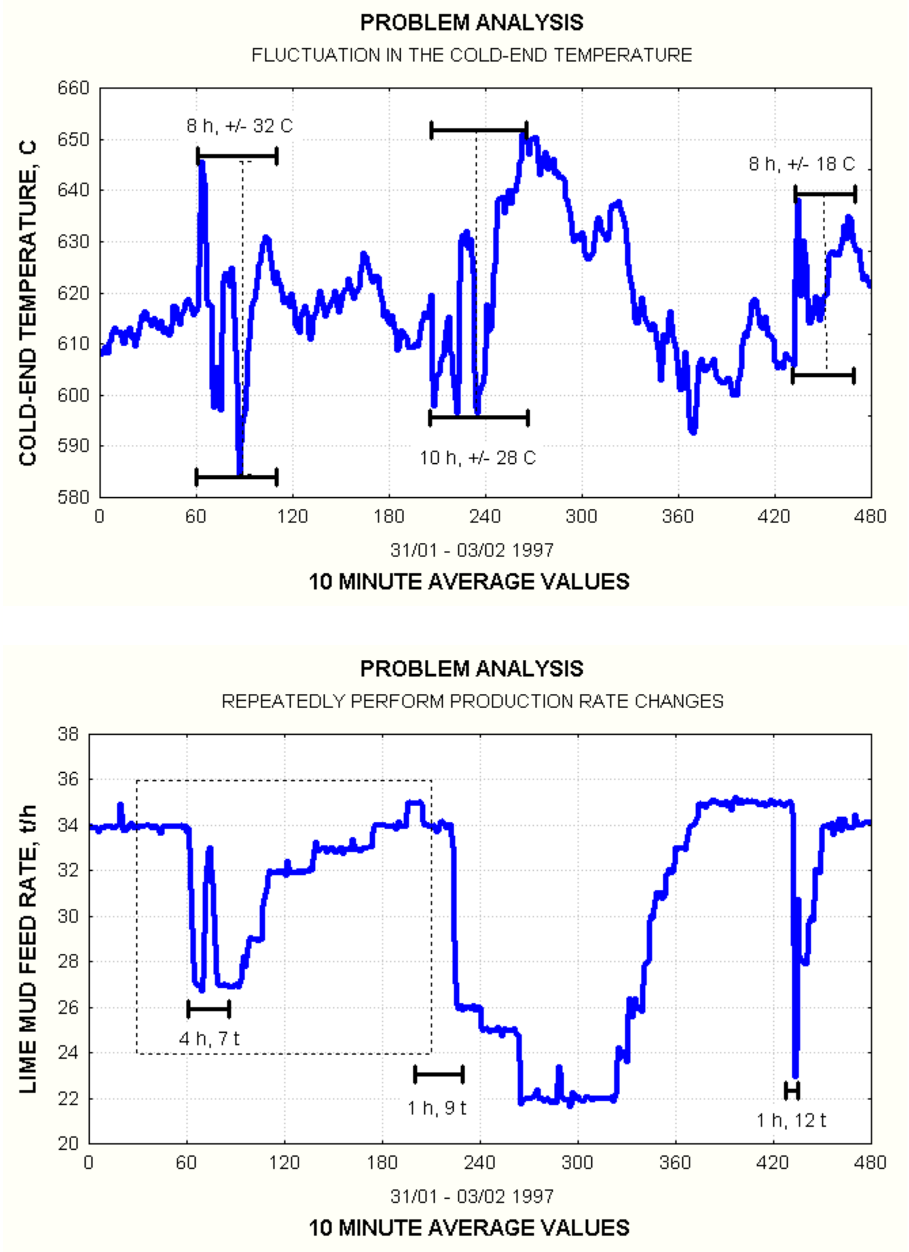


Figure 1. Examples of severe fluctuations in the excess oxygen content and cold-end temperature after three large production rate changes.

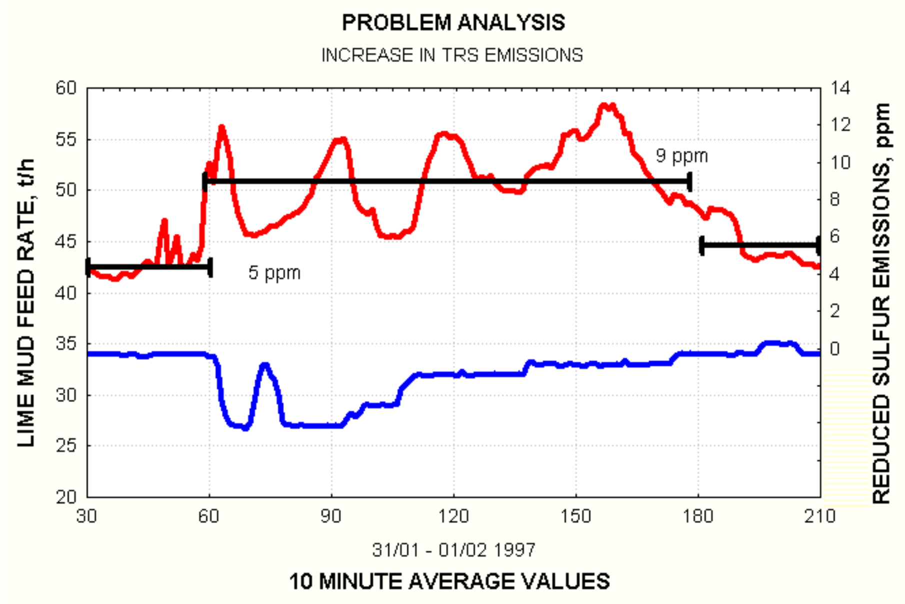


Figure 2. Example of an increase in TRS emissions during a pending production rate change (indicated with a dashed line box in the Figure 1).

- Irregular variation in the filtration properties of the mud induces oscillations in the dry solids content of the mud. Gradual deterioration in the shape of the filter, which mainly occurs as a result of filter cloth blocking, reduces the attainable dry solids content of the lime mud. A decline in the dry solids content is closely related to an increase in the amount of sodium sulfide (Na_2S) fed into the kiln, which causes a corresponding increase in the formation of H_2S during mud drying. An example of the gradual deterioration of the operating conditions of the lime mud filter is shown in **Figure 3** as a decline in the filter pressure and in the dry solids content during long-term operation.

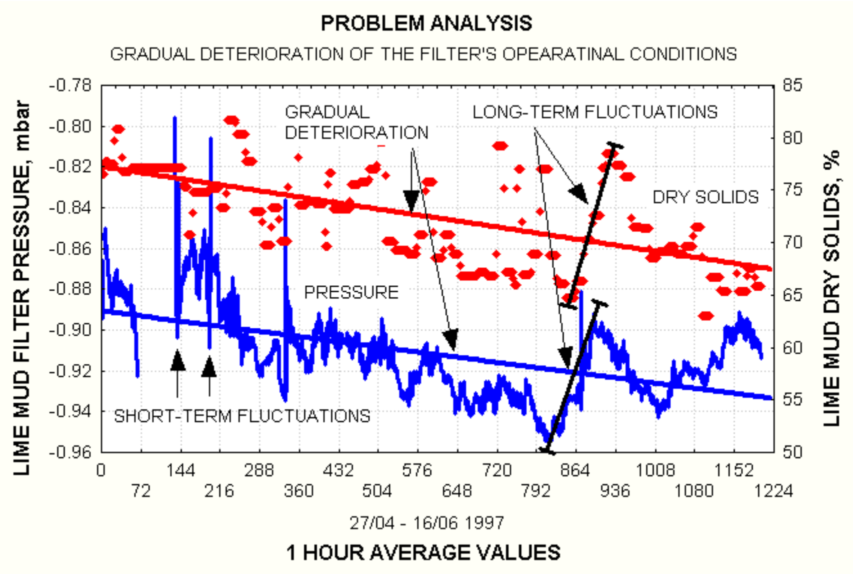


Figure 3. Example of the gradual deterioration of the shape of the filter over a period of one and a half months.

- Operating the kiln with a higher excess burning air level than is necessary for optimal combustion is a common practice. The resulting relatively high excess oxygen level is, however, an obvious indication of avoidable flue gas heat losses. In addition, it results in an increase in the flue gas velocity, and subsequently also in the amount of dust escaping from the kiln which, in turn, reduces the attainable maximum throughput of the kiln. An example of a considerable reduction potential in the excess oxygen content is illustrated in **Figure 4**. On the other hand, the reasonably large variation in the excess oxygen content, as shown in Figure 4, occasionally brings about insufficient excess oxygen during mud drying, which instantaneously generates a marked peak in TRS emissions.

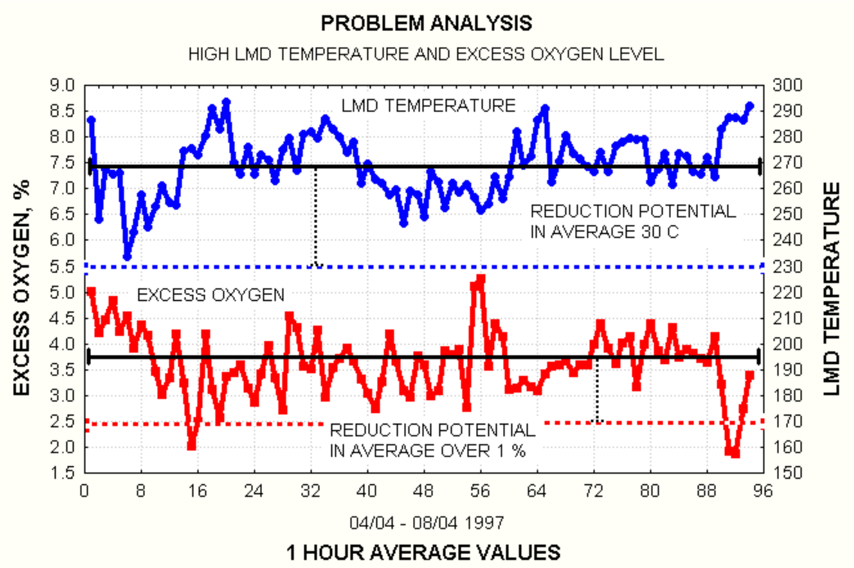


Figure 4. Example of the reduction potential in the excess oxygen content of the flue gas.

INTELLIGENT SUPERVISION AND CONTROL SYSTEM

Functional requirements of the system

The following functional requirements were applied in designing the supervisory-level control system for the lime reburning process. First of all, the frequent disturbances in the mass flow of mud pumped into the filters have to be eliminated. Furthermore, when the production rate needs to be altered, stepwise changes have to be made by the system over an extended time period with small increments or decrements. Moreover, the major regulatory level control loops in the lime mud filtration and kiln process need to be adjusted in a feedforward (FF) manner during the pending production rate changes. A FF control structure is required in order to ensure smooth operation of the process during transient conditions, in spite of long time delays before the effect of the change can be seen in the process outputs.

Furthermore, the temperature and excess oxygen content need to be controlled in a closed loop manner by means of small corrections to the setpoint of the draught fan speed. A high-level feedback (FB) control structure with reasonable slow responses is required to moderate the flue gas heat losses that would otherwise occur due to the surplus burning air fed into the kiln. In addition to, the FB controller, a routine for reasonably large stepwise corrections is also a needed in order to be able to eliminate the TRS emissions peaks caused by insufficient excess oxygen or inadequate temperatures during mud drying after severe disturbances.

In addition, the performance of the kiln process has to be supervised during long-term operation. The target values for the temperature and excess oxygen need to be adapted by the system with reference to the actual state of the process. This is a prerequisite for the consistent operation of the process over the entire production rate range. It is also required in order to ensure a low level of emissions and heat losses while the process operation is optimized with respect to production efficiency.

Proposed control scheme

The proposed overall control scheme combines hierarchically structured and inter-related modules of the feedforward control models, stabilizing controllers and constraints handling, as illustrated in **Figure 5**.

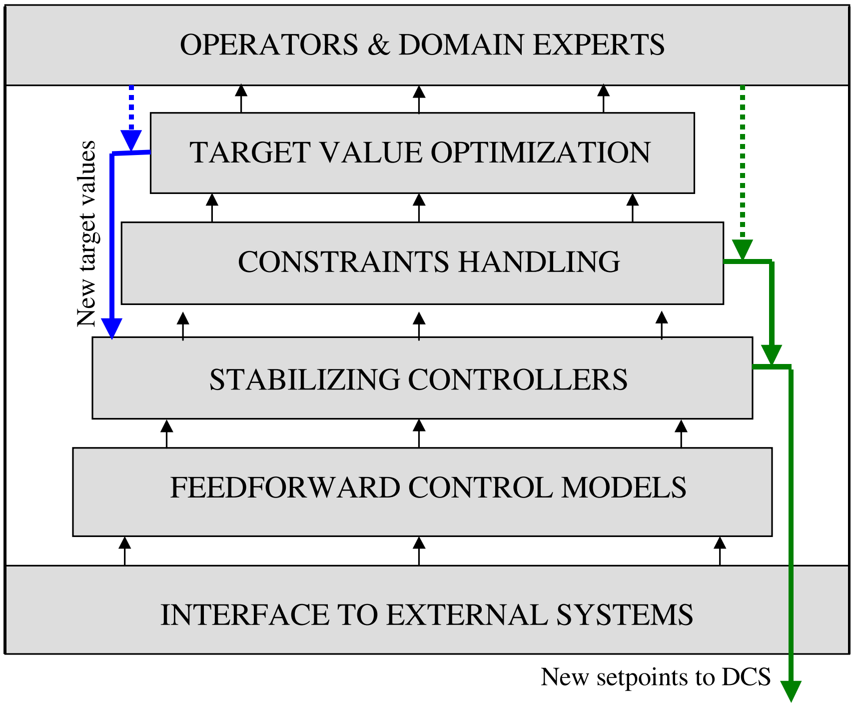


Figure 5. Schematic presentation of the inter-related and hierarchically structured functional modules.

The main purpose of the *feedforward control models* (FFMs) module is to ensure smooth operation of the filters and the kiln during the pending production rate change, i.e. a major load disturbance in the entire lime reburning process. The FFMs module relies on the predetermined relationships that have primarily been obtained from the large amount of historical data. In practice, the module manages the production rate changes by means of appropriate adjustments made to the setpoint (SPs) of all the basic-level control loops in the lime reburning process. These models also take into account some other quantifiable changes occurring in the operational conditions that have a predictable influence on process behavior.

The primary purpose of the *high-level stabilizing controllers* (SCs) module is to maintain controlled variables close to their target values by means of small FB corrections in the SPs, despite unmeasured disturbances and gradual changes that occurs frequently either in the mud filtration or in the kiln process. It also provides adaptation in case of inaccuracy in the FF control models during the pending production rate changes. On top of the SCs module, the *constraints handling* (CH) module is activated to protect personnel, equipment and the environment when preset and/or dynamic constraints are exceeded, e.g. in the case of severe disturbances and/or abnormal process conditions. The CP module is also used to tackle large deviations from the target values by means of stepwise changes in the SPs. Both the SCs and CH modules rely for the most part on the practical expertise of the process behavior, and the real-time inference of the actual state of the process with respect to the desired conditions and existing constraints.

Control of the lime mud filters

At the time when this project was started, the filters (#21 & #22) were controlled manually by the operators. In a very early stage of the project the ratio controllers were implemented in the basic automation system in order to maintain the wash water rate and rotational speed of the filter at a certain ratio with respect to the incoming lime mud flow (l/s). However, these ratio controllers were replaced already in the beta version of the system by neural network (NN) models. These models, with some modifications, were also used in the pilot version of the system.

In the current version of the system, however, NN models have been replaced by the non-linear SISO type of FF models based on the linguistic equations (LEs) approach (see Appendix A). The input applied in all the LE models is the 30-minute moving average of the lime mud (tons/hour) fed into the filter. As a consequence, operation of the filtration process is controlled in a FF manner in accordance with the filter's production. **Figure 6** illustrates how the SP for the lime mud density, filter's vat level, wash water rate and rotational speed are increased inline with an increase in the production, i.e. in the amount of lime mud to be washed and de-watered. The wash water rate is, for instance, increased from 3.0 l/s up to 4.8 l/s as the filter's production increases. This is done in order to facilitate displacement of the increased volume of residual white liquor containing soluble alkaline and sodium sulfide with the unsoiled water. The rotational speed of the filter drum is accordingly increased as the production increases. Increasing the speed is intended to maintain the thickness of the mud cake within an appropriate range with reference to the moisture removal, which is adversely affected as the thickness of the cake increases. Furthermore, the SPs for both the lime mud density and the filter vat level are altered in accordance with the production. This is done primarily in order to prevent the density and level regulators from becoming saturated, i.e. the valve becoming fully opened or closed.

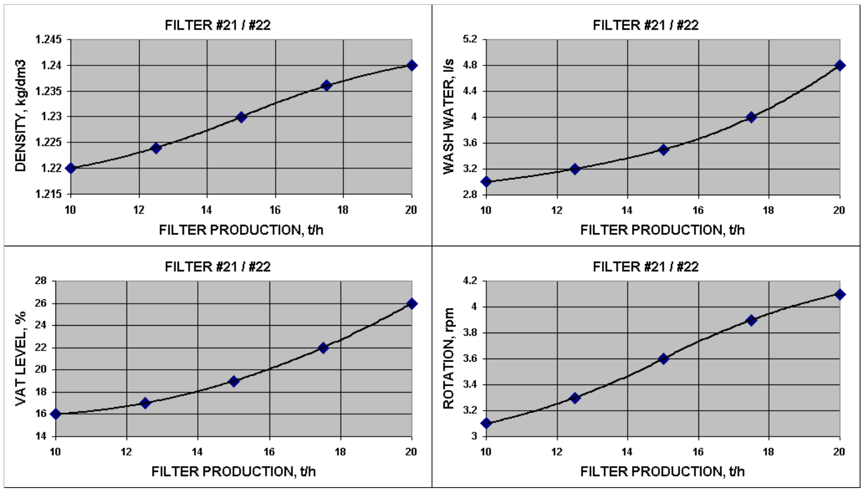


Figure 6. Outputs of the non-linear SISO type of LE model applied for FF control of the lime mud filters as a function of the filter production.

Control of the draught fan speed
Feedforward control model

Prior to this project, the draught fan was controlled manually except for certain short periods at the end of 1993 and beginning of 1994 when a draught fan speed controller based on the rule base and fuzzy logic were developed and tested at the mill (Penttinen, 1994). The draught fan has, however, a considerable influence on the operation of the kiln process, and especially on the rate of emissions and heat losses. A FF controller, based on the neural network (NN) model developed on the basis of historical data collected during the field survey period, was therefore implemented in the beta version of the system (Järvensivu, 1998). An updated version of the model was then applied in the pilot version of the system (Järvensivu, Saari & Jämsä-Jounela, 1999).

In the current version of the system the NN model is however replaced by a MISO type of LE model (see Appendix A). The first input of the model that has a predominant influence on the output is the 60-minute moving average of the production rate. The second input is the 8-hour moving average of the cold-end pressure, which is updated at a one-hour scan interval. A moving average over an extended time period is used for the cold-end pressure in order to avoid rises and falls in the output due to the regular and reasonable large fluctuations in the pressure. The pressure is, however, used in the model in order to indirectly indicate ring build-up, which causes an abnormally higher draft in the cold-end of the kiln with this production rate.

The continuous curve, in **Figure 7** shows how the SP of the draught fan speed is altered in order to induce more secondary burning air into the kiln when the production rate is increased. The dashed lines above and below the nominal curve, also show how an increase or decrease in the pressure is taken into account by adjusting the draught fan speed. For instance, if the under-pressure increases, the draught fan speed is correspondingly increased in order to compensate at least partially the restrictive influence of the existing ring on the flue gas flow, and hence also on the heat transfer from the hot- into the cold-end of the kiln. A 5 tons/hour increase in the production rate from 30 tons/hour up to 35 tons/hour results in an increase of about 90 rpm in the draft fan speed if the cold-end pressure simultaneously follows its nominal curve. A decline in the cold-end pressure from -2.0 mbar to -3.2 mbar results in an increase of about 20 rpm in the draught fan speed at a production rate of 30 tons/hour. The low and high limits, which are set in accordance with the mechanical constraints of the draught fan motor, are 700 rpm and 980 rpm, respectively.

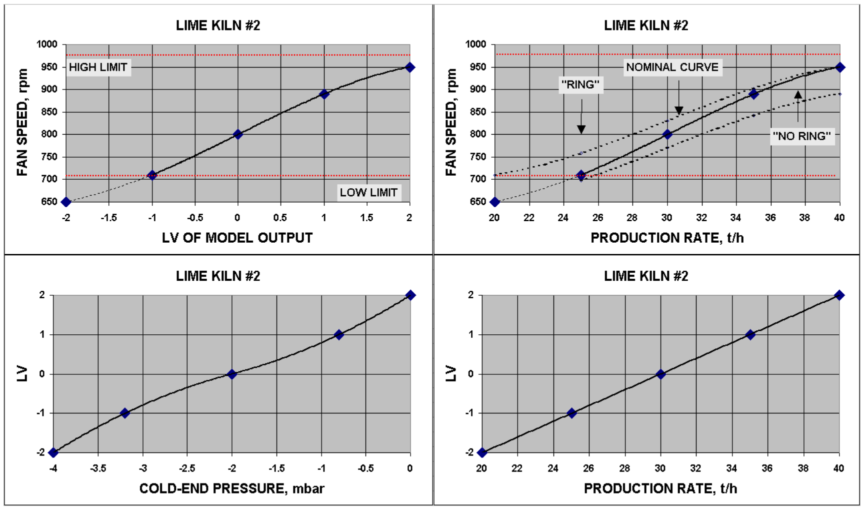


Figure 7. Model applied for FF control of the draught fan speed (rpm).

High-level feedback controller

In addition to the above-described FF model, the draught fan speed is corrected in a FB manner on the basis of the excess oxygen content of the flue gas, and the temperature profile along the length of the kiln. However, an appropriate corrective control action to the draught fan speed is frequently a compromise between unequal and even contradictory corrections that are required to bring each of the controlled variable, i.e. the excess oxygen content, and the cold- and hot-end temperature, closer to their target values. An increase in the draught fan speed is first and foremost used to increase the excess oxygen content of the flue gas, and vice-versa. In addition to the excess oxygen, the draught fan speed also influence the rate of the flue gas flowing through the kiln, and hence also the heat balance between the cold- and hot-end of the kiln. For instance, if the draught fan speed is increased more heat will be transferred from the hot- to cold-end of the kiln, which raises the cold-end temperature and correspondingly lowers the temperature in the hot-end of the kiln.

In the current version of the system, a MISO type of LE controller is applied at a 10-minute scan interval in order to determine small corrections to the SP of the draught fan speed. The arithmetics of the LE controller and the tuning-parameter values applied are described in more detail in Appendix A. The LE controller replaces a corresponding controller based on the fuzzy logic approach, which was applied in the former beta and pilot versions of the system (Järvensivu, Saari & Jämsä-Jounela, 1999). The inputs used in the LE controller are the 10-minute moving average of the excess oxygen content of the flue gas, and the 30-minute moving average of the cold- and hot-end temperature, all of which are updated at a 2-minute scan interval.

Figure 8 illustrates the influence of both the error in the excess oxygen content and the derivative of the error on the correction of the draught fan speed. As shown in the figure, the correction ranges from about -3 rpm to nearly 5 rpm. As a general rule, larger corrections are carried out when the excess oxygen content is below the target than in the reverse case. Larger corrections are used on the positive side, because the consequences of oxygen deficiency, i.e. an increase in emissions and, in the most severe case, also incomplete burning of the fuel, are more critical than the additional energy consumption associated with burning air in excess. For the same reason, the 10-minute moving average of the excess oxygen content is used as the first input into the LE controller, while the moving average value over the last 30 minutes is applied for both the cold- and hot-end temperature. Furthermore, the influence of a relative small negative error in the excess oxygen content is set to be dominant compared to even relatively large errors in either the cold- or hot-end temperature. The excess oxygen content therefore needs to be near the target value or slightly above it before the controller implements corrections to the draught fan speed on the basis of the temperature profile in the kiln.

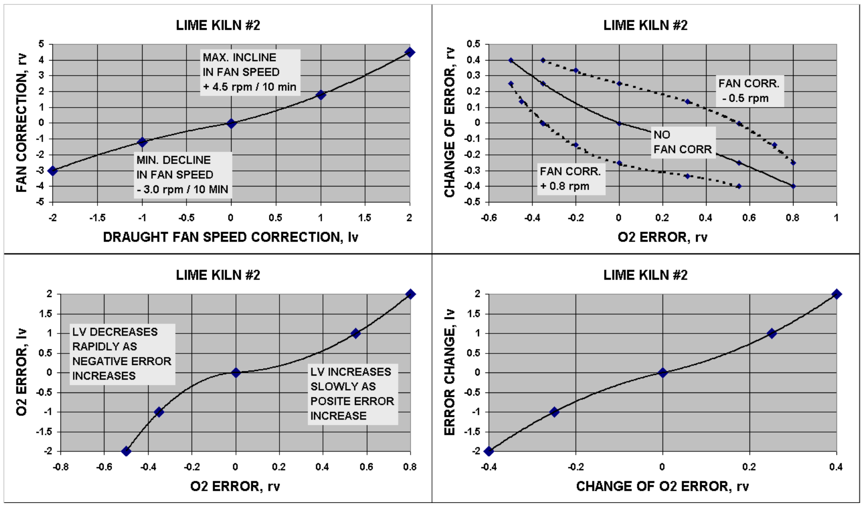


Figure 8. Draught fan speed correction calculated by means of the LE controller as a function of the error in the excess oxygen and change in the error.

Constraints handling

On top of the LE controller, procedural reasoning in conjunction with structured natural language rules is used to check at 2-minute scan intervals whether the excess oxygen content and the temperature of the flue gas after the LMD are in between both dynamically calculated low and high boundaries and the preset limits. The primary reason for setting a low limit for both the excess oxygen content and the LMD temperature is that the TRS emissions will drastically rise, producing a marked short-term emission peak, if the excess oxygen content and/or the temperature of the flue gas is, even for a short period of time, at too low a level during mud drying. Furthermore, it is essential to maintain the temperature above the low limit in order to prevent the formation of acid condensates in the flue gas channel. In contrast, the high limit for the LMD temperature is applied in order to protect the flue gas treatment system against excessively high temperatures, especially during severe disturbances. It is also used, in combination with the high limit for the excess oxygen, to reduce preventable flue gas heat losses.

If either the excess oxygen content or the LMD temperature drops below the low limit or rises above the high limit, the SP of the draught fan speed is immediately altered by means of a stepwise change. The size of the step is calculated on the basis of the degree of limits violation. In general, stepwise changes carried out by the CH module are about 5 - 10 times larger than the corrections made by means of the LE controller. Reasonably large changes, i.e. changes in the range of -10 rpm - +15 rpm, are used in order to return the process immediately to the safe operating range. After each step change the module is blocked for a specific time period, the length of which depends on the cumulative magnitude of the change carried out by the module during the last few hours. This ensures that the process has time to become stable after relatively large control actions.

Optimization of the operation of the kiln process

The improved stability of the kiln process obtained with the modules described above allows the process to be operated closer to the constraints, and therefore also closer to the optimum conditions. In order to realize the benefits of the reduced variability, the target values of the controlled variables need, however, to be shifted closer to their constraints. Control of the process within a narrower safety margin in the presence of gradual changes necessitates certain adaptive features in the system. For instance, the amount of impurities in the mud may change and/or the shape of the filters may deteriorate, e.g. due to the filter fabric fouling or the cake blocking. The operating conditions in the kiln may also change, e.g. due to ring formation or diminution. Hence, the operation of the process needs to be supervised over an extended period, and the production rate and the target values of the controlled variables adjusted correspondingly. The adjustments that are required in order to avoid unsafe operating conditions, and to ensure low emission levels while the process is maintained close to the most optimal state from the economical point of view, are carried out by means of the modules described in more detail below.

Production rate maximization

The target value for production is determined by means of the production rate maximization module. The state of the mud storage is first evaluated on the basis of the current level of storage, and the derivative of the level over the last 2 hours. A small correction is then calculated for the production rate on the basis of the state of the storage and the current loading state of the process. Accordingly, if the storage level decreases below the low level, or if it is to some extent above it but decreasing rapidly, the production rate is decreased in order to avoid depleting the lime mud supply. On the other hand, as soon as the storage level starts building up, the production rate is gradually increased up to the rate at which the level rise stabilizes, or either the preset high limit or the maximum sustainable production is reached.

The maximum rate of production that the kiln process can sustain is determined by checking several indications of the loading state of the kiln. The temperature of the flue gas after the LMD, the draft in the cold-end of the kiln and the torque of the kiln drive are used to indicate ring buildup, which significantly limits the maximum rate of production. The draught fan speed is used, in conjunction with the excess oxygen content, to check whether the amount of burning air induced into kiln can be increased. An increase in the amount of burning air will be a direct consequence of an increase in production and a subsequent rise in the energy supply to the kiln. In addition, the level of TRS emissions is checked in order to ensure that the environment is protected in all situations.

Analysis of the maximum sustainable production rate is not crisp, but has to be performed by combining linguistic values of the variables used to indicate the loading state of the process. The mean of the linguistic values is used to scale the correction determined primarily on the basis of the state of the mud storage. For instance, when the maximum sustainable production rate is approached, upward corrections are diminished and correspondingly downward corrections are enlarged. The target value for the production rate is, however, reduced if one of the variables reaches an intolerable high level, i.e. a linguistic value over 1.5. Furthermore, if the hot-end temperature or the excess oxygen content is below the target value, corrections that increase the target value are scaled down. In addition, if the deviation of the hot-end temperature or the excess oxygen content of the flue gas reaches -25 °C or -1.2 %, respectively, rising corrections on the production rate are avoided in order to ensure that the kiln process is not overloaded.

The target value for the production is set in accordance with the above principles every second hour. However, before the target values are actually changed, the current production of the filters is checked with respect to the target value. The target value is not changed further away from the obtained production, if for some reason or other, the filters cannot reach the previous target. The balance between the filters is also checked, and if an imbalance is detected, the proposed change in the production rate is carried out so that it balances out the difference. The actual change in the production rate is then implemented by means of small, stepwise increments or decrements at a 5-minute scan interval into the SPs of the mud feed rate controllers in the automation system. The maximum rate of change is limited to ± 0.25 tons per hour for each filter. The low and high limits, that are set in order to safeguard the operations in case of instrument or system failures, are 10 tons/hour and 20 tons/hour, respectively.

Environmental protection and energy efficiency

The target value for both the temperature in the cold-end of the kiln and the excess oxygen content, i.e. the most advantageous conditions for mud drying in respect to the environmental protection and energy efficiency, are determined by a module, that is schematically represented in **Figure 9**.

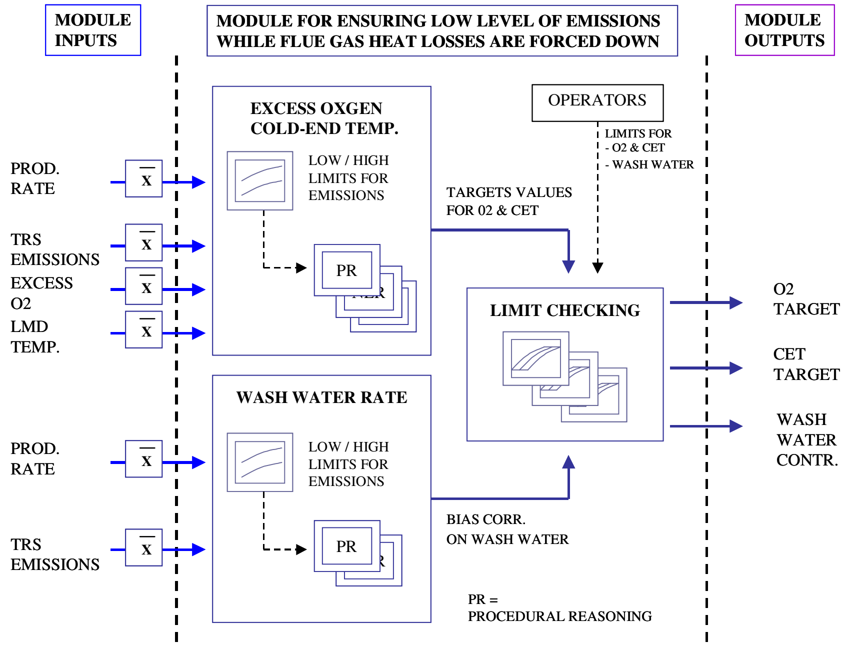


Figure 9. Module for ensuring low flue gas emissions while forcing down heat losses.

The purpose of the module is to ensure, despite conflicting objectives that the emissions are maintained at a tolerable level while forcing down the flue gas heat losses. In order to reduce the heat losses caused by hot flue gases leaving the kiln, the module supervises the mud drying, and subsequently lowers with relatively small steps the target values for the excess oxygen content and the cold-end temperature, if the emissions are low enough and the temperature after the LMD is not already below the low limit. In the opposite case, the target values are stepwise increased in order to avoid adverse environmental impacts. However, before the new target values are adopted by the high-level control module, they are checked with respect to the range for the acceptable target values. The low and high boundaries for the target value of the excess oxygen are 2.2% and 3.8%, respectively. The corresponding values for the cold-end temperature are 620° C and 660° C.

The module also adjusts the bias correction of the models used for FF control of the wash water rate. If the TRS emissions are below the low boundary, the bias is reduced with small steps in order to achieve a high dry solids content of the mud fed into the kiln and, at the same time, to improve the energy efficiency of the process. Consequently, the magnitude of the wash water rate is raised in order to achieve better washing of the mud if the emission rises above the high boundary. The low and high boundaries for TRS emissions are calculated on the basis of the current production rate.

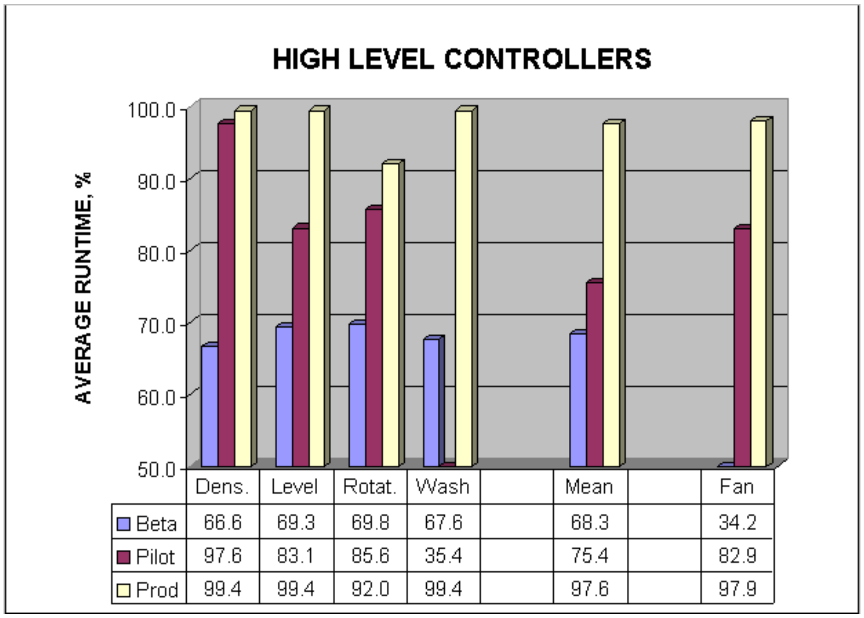
RESULTS AND DISCUSSIONS

The results presented in this paper are related to four different time periods. The first 15-month period represents the reference state, i.e. manual operation of the process (12/96–2/98). The next 11-month period corresponds to the incremental development phase of the system (03/98–01/99). The third five-month period represents the first extended testing period of the system (2/99–6/99). After the testing comprehensive analyze of the results and system performance were carried out (see Järvensivu, Saari & Jämsä-Jounela, 2000). The fourth two-month period represents the auditing period of the production version of the system (9/00–10/00). The production system, which is also described in this paper, was connected on-line at the mill for first time at the beginning of May 2000, after a design, development and encoding phase that lasted about five months.

UTILIZATION OF THE SYSTEM

The average running of the high-level controllers for the lime mud density, filter vat level, drum rotation and wash water rate during the three periods, i.e. the incremental development phase (Beta), testing of the pilot system (Pilot) and the auditing of the production system (Prod) are illustrated in **Figure 10**. During the auditing the average utilization rate of the system was over 97%. Figure 10 also illustrates the utilization of the high-level controllers applied for the draught fan speed. The average running time of the draught fan controller in the closed loop mode was in the region of 98%. The longest continuous runtime span of the controller in the closed loop mode during the auditing was over 300 hours.

Optimization of the target value for the major controlled variable from the point of view of emissions, i.e. the excess oxygen content, reached an utilization rate of over 99%. Whereas, optimization of the target value for the cold-end temperature, which is more related to the heat balance in the kiln, reached an utilization rate of approx. 66 %. The earlier version of the target value optimization was implemented already in the beta version of the system, but comparable utilization statistics are not available. The production rate maximization module, which was implemented in the system during the testing and fine-tuning phase of the production system (June–August 2000), reached over 90% utilization during the auditing of the system that started shortly after the module was connected on-line for first time.



	Dens.	Level	Rotat.	Wash		Mean		Fan
■ Beta	66.6	69.3	69.8	67.6		68.3		34.2
■ Pilot	97.6	83.1	85.6	35.4		75.4		82.9
□ Prod	99.4	99.4	92.0	99.4		97.6		97.9

Figure 10. Average run time (%) of the controllers.

Process behavior under closed loop control

Figure 11 presents (upper chart) the production rate and level of the lime storage at the one-hour average level during a four-day runtime span in closed loop mode (10/13/00-10/17/00). The corresponding excess oxygen content and TRS emissions are shown in the lower chart in Figure 11. The charts demonstrates the ability of the system to maintain the excess oxygen content relatively close to the target value, despite the gradual changes in the production rate that were implemented by the system due to a fast decline or raise in the storage level, and even in the event of a considerable load disturbance. During the period the emissions also remained well below the level of 9 ppm (~20 mg H_2S/Nm^3), which is the limit set by the regulators*, except for one emission peak. The reason for the emission peak was the severe disturbance caused by the unscheduled repair of filter #21. Filter #21 was stopped, and the production of the other filter (#22) was increased from about 16.5 tons/hour up to 25 tons/hour, i.e. the kiln production was reduced from about 35 tons/hour down to about 28 tons/hour.

**TRS emissions have to be below 20 mg H_2S/Nm^3 for 90 % of the time on a monthly basis.*

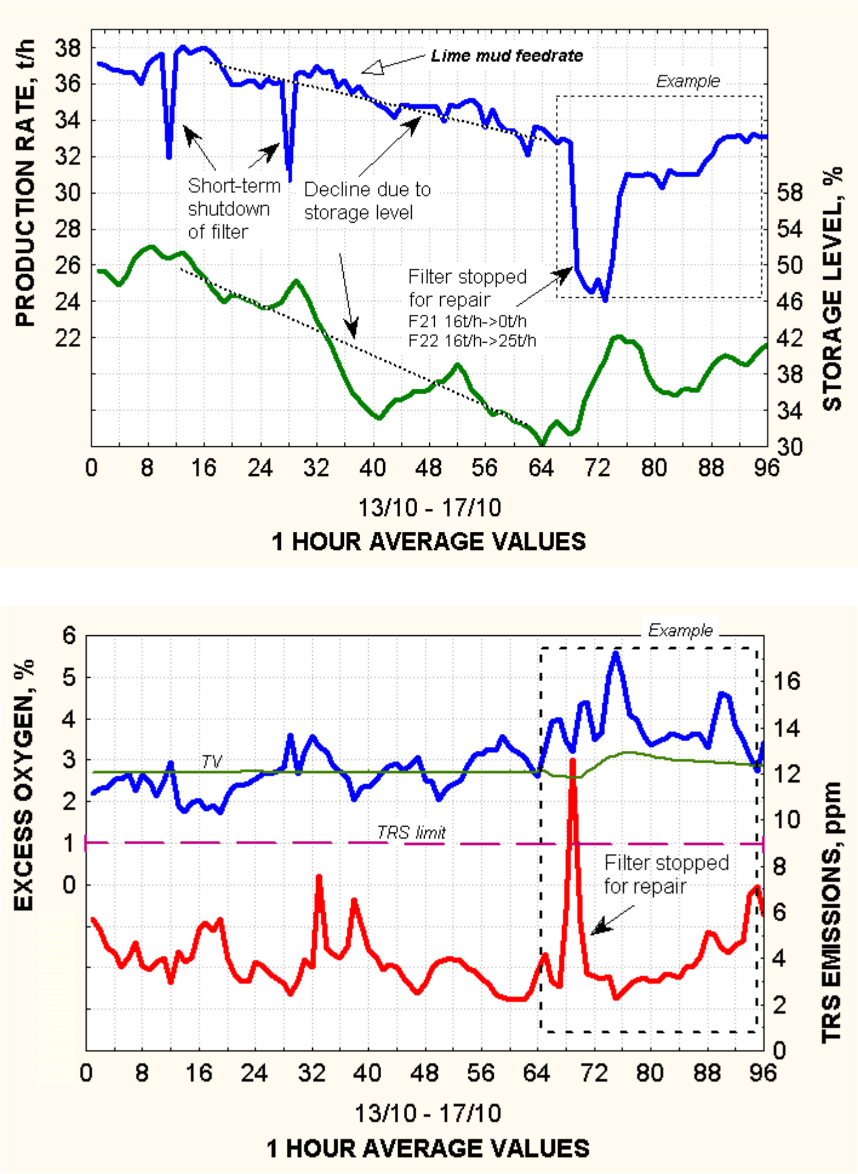


Figure 11. Example of the dynamic performance during a 4-day period (above; production rate and storage level, below; excess oxygen and TRS emissions).

In order to obtain a more detailed view of the system performance during the pending production rate changes especially, a ca. 30-hour period, marked with a dashed line in Figure11, was selected for further analysis. The period includes, at the beginning, an almost 8 tons/hour drop in the production rate (implemented by the operators due to the repair of filter #21), followed by the kiln operating at a very low production rate for about 6 hours. It also includes two periods with a gradual rise in production, the first effected manually by the operators (average change rate of about 0.8 tons/hour) and the second carried out by the system (average change rate of about 0.2 tons/hour). Two periods when the kiln was operating at a constant production rate also occurred during the period. The production rate and draught fan speed are presented in the lower chart, while the excess oxygen content and the cold-end temperature are shown in the upper chart. The offset in the temperature with respect to the target value is due to the fact that the excess oxygen content has been above the target value that limits the system in increasing the draft fan speed. Overall, the charts in **Figure 12** demonstrate the ability of the system to handle large changes in production. The charts also apparently illustrate the importance of small increments (or decrements) when the production rate needs to be changed.

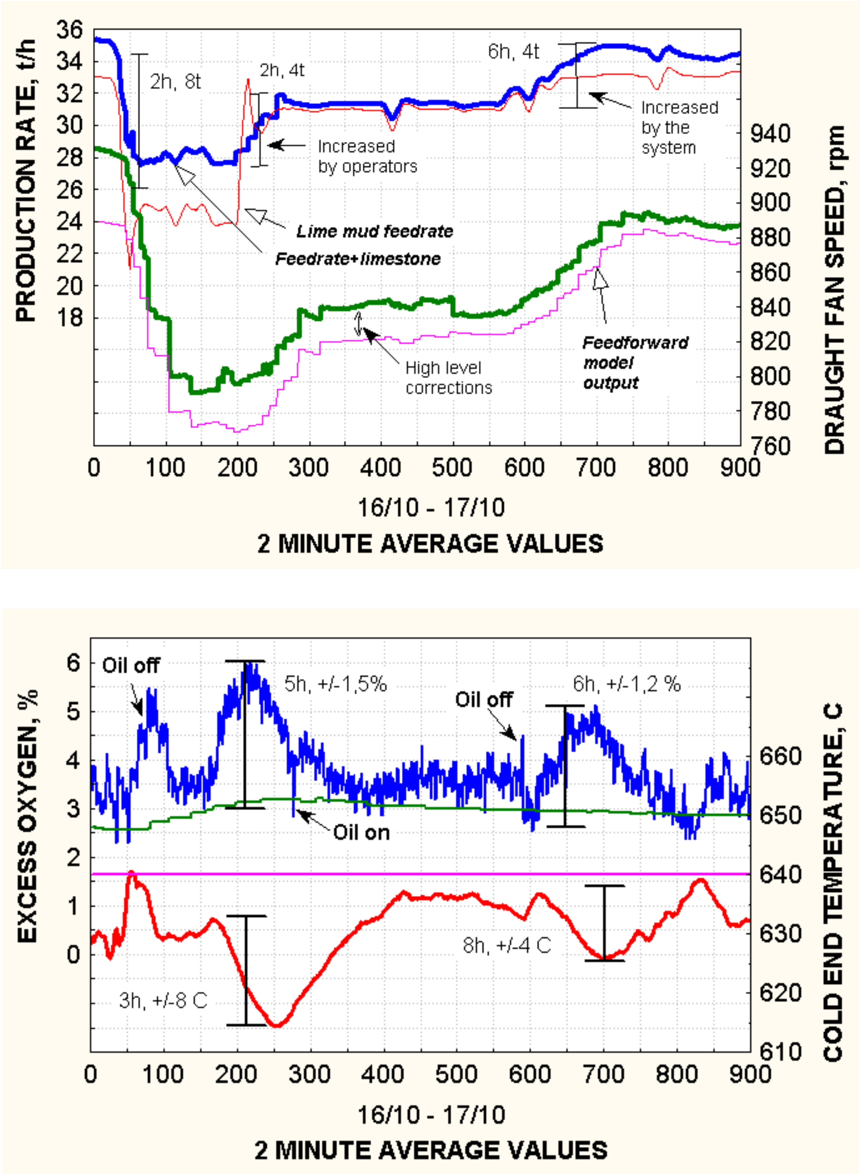


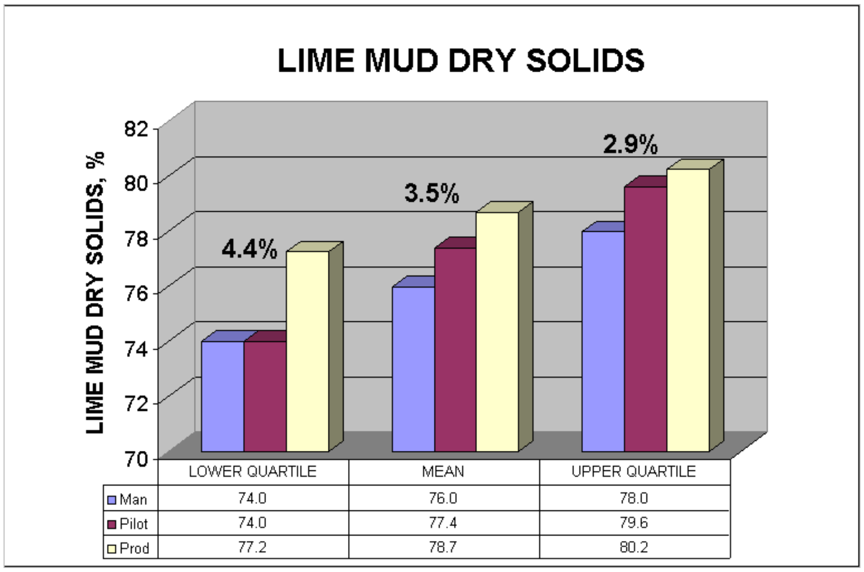
Figure 12. Example of the dynamic performance during a 32-hour period (above; production rate and draught fan speed, below; excess oxygen and cold-end temperature).

Statistical analysis of the operational results

Dry solids content of the lime mud fed into the kiln

The lime mud fed into the kiln is routinely sampled at the Wisaforest mill at an 8-hour time interval. The dry solids content of the sample (%) is then analyzed in the laboratory, with a delay time of about 1 to 2 hours. Although delayed laboratory analyses are a problem from the point of the view of control, they are useful in analyzing the operation of the process. The lower quartile (i.e. 25th percentile) and the mean of the dry solids content during the manual operation were about 74% and 76%, respectively. During the auditing of the system the corresponding values were 77% and 79%, respectively. According to the statistics, the means have increased by about 3.5 abs-%, and the lower quartile even slightly more (also shown in **Figure 13**). **Figure 14** presents the mean value as a function of the production rate after the preprocessed data had first been classified into groups* according to the production rate and the mean in each group calculated. The figure shows that the raise in the dry solids content has been considerable over the entire production rate range. This increase in the dry solids can be explained to a certain extent by the fact that the use of the re-circulation filtrate for controlling the filter vat level has intentionally been reduced. The dirty filtrate has been replaced by hot water, which has a positive effect on the washing and especially on the dewatering of the mud cake. The rotational speed of the filter drum has also slightly increased, which reduces the thickness of the cake, and hence also the filtration resistance of the cake.

**The groups used for the data collected during the beta and pilot periods were 22-26 tons/hour, 26-30 tons/hour, 30-34 tons/hour, 34-40 tons/hour. However, three groups, i.e. 22-30 tons/hour, 30-34 tons/hour, 34-40 tons/hour, were applied for the data gathered during the auditing of the system. This was done because there was only a small number of samples in the 22-26 tons/hour range.*



	LOWER QUARTILE	MEAN	UPPER QUARTILE
□ Man	74.0	76.0	78.0
■ Pilot	74.0	77.4	79.6
□ Prod	77.2	78.7	80.2

Figure 13. Statistics of the dry solids content (%).

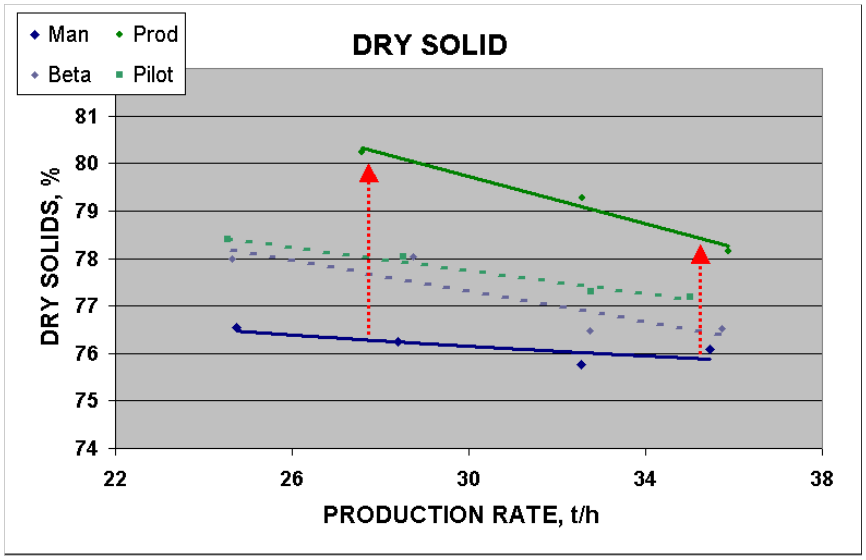


Figure 14. Mean of the dry solids (%) as a function of the production rate (tons/hour).

Figure 15 shows the amount of water fed into the kiln, which is calculated on the basis of the dry solids content and the lime mud feed rate. The figure clearly illustrates the decisive effect of the dry solids content on the amount of the moisture that needs to be evaporated off during mud drying. For instance, the amount of water fed into the kiln at a production rate of 36 tons/hour and dry solids content of 80% is approximately the same as that at a production rate of 26 tons/hour and dry solids content of 75%.

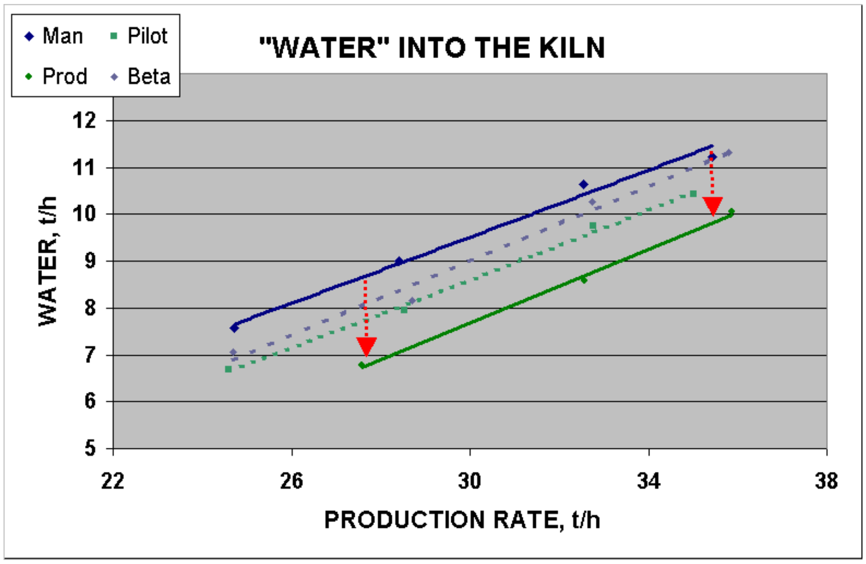
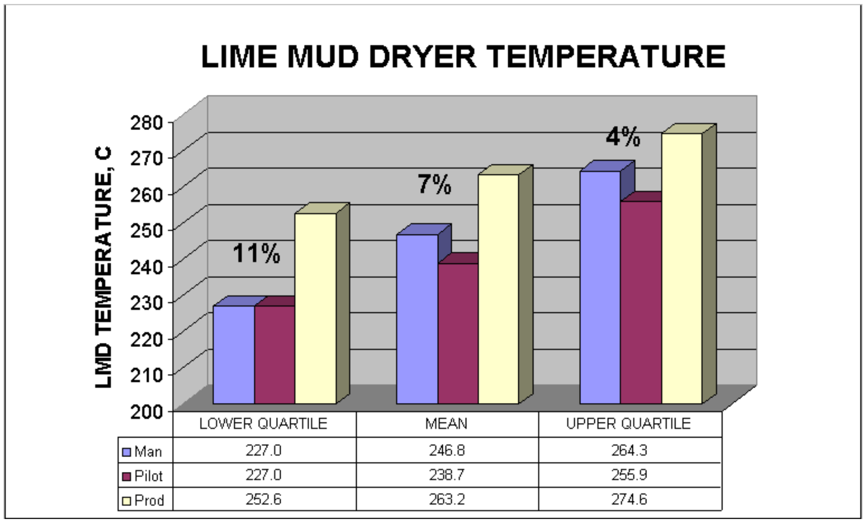


Figure 15. Mean of the moisture content of the lime mud (tons/hour) as a function of the production rate (tons/hour).

Conditions during the lime mud drying

The temperature of the flue gas after the LMD provides a consistent indication of the temperature also during the course of mud drying. The temperature is directly related to the amount of water fed into the kiln, and inversely correlated with the drying time of the lime mud. The mean value of the LMD temperature was 247 °C during manual operation, and the lower and upper quartiles were 227° C and 264° C, respectively. During the system auditing the mean value was 263° C, and the lower and upper quartiles were 252° C and 275° C, respectively. According to the statistics, the mean value has been increased by about 7% and the quartile range, which is computed as the upper quartile value minus the lower quartile value, has been decreased by over 40 % (see **Figure 16**). The mean value of the LMD temperature is presented in **Figure 17** as a function of the production rate. The figure shows that there has been a considerable increase in the temperature over the entire production rate range, and that the incline has been the greatest at high production rates. An increase in the temperature can already be assumed on the basis of the marked reduction in the moisture content of the mud.



	LOWER QUARTILE	MEAN	UPPER QUARTILE
▨ Man	227.0	246.8	264.3
▨ Pilot	227.0	238.7	255.9
☐ Prod	252.6	263.2	274.6

Figure 16. Statistics of the LMD temperature (˚C).

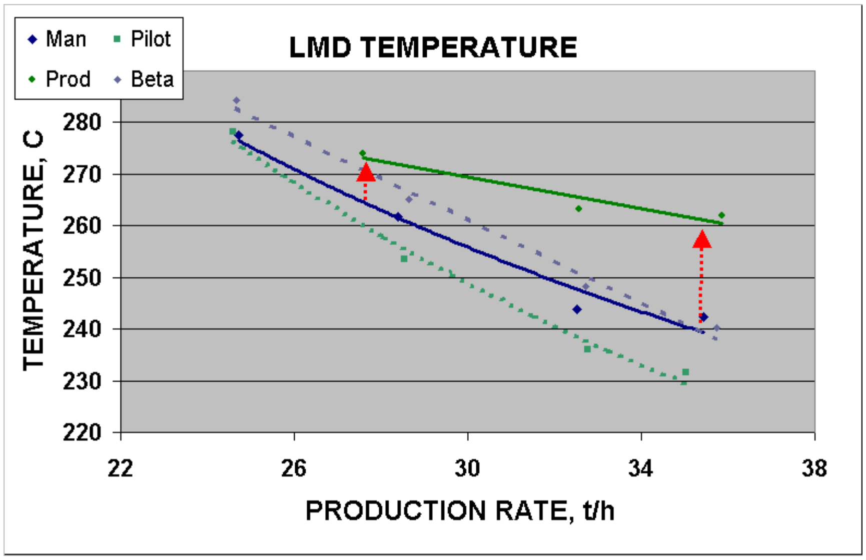
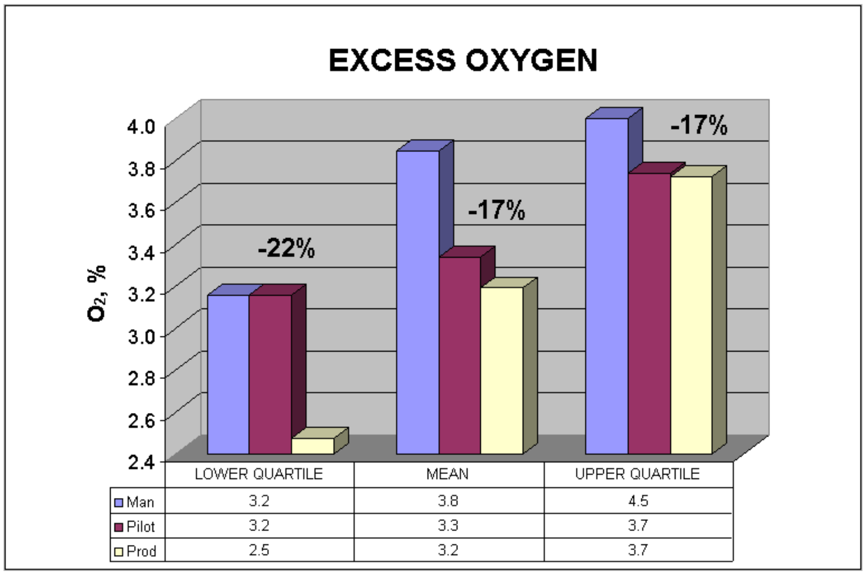


Figure 17. Mean of the LMD temperature (˚C) as a function of the production rate (tons/hour).

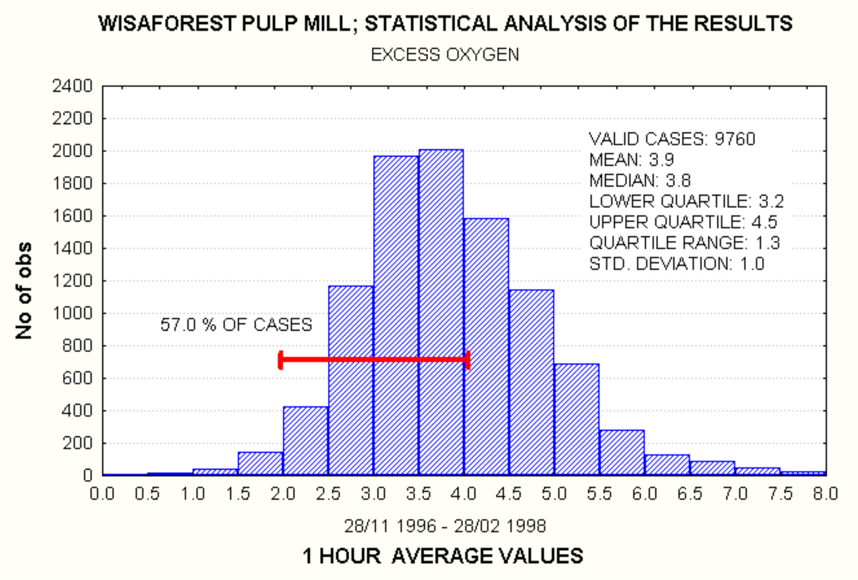
The excess oxygen content of the flue gas (%) is measured by means of a flue gas analyzer located after the lime mud dryer. The measured value also includes the amount of oxygen passing into to the kiln as a result of air infiltration through casing leaks. The oxygen analyzer is unable to distinguish between the sources of oxygen and, in practice, the measured excess oxygen level in the flue gas therefore needs to be higher than the theoretical amount of oxygen needed for complete combustion. Process experiments have shown that the low limit for the excess oxygen content in the Wisaforest kiln is between 1.5% and 2%. At a lower level the rate of oxidation of the reduced sulfur compounds, that are always formed during mud drying, to SO_2 is significantly decreased due to a deficiency of oxygen, which correspondingly increases the TRS emissions.

The mean value of the excess oxygen content was 3.9% during manual operation, and the lower and upper quartiles were 3.2% and 4.5%, respectively. During system auditing, the mean value of the excess oxygen was 3.0%, and the lower and upper quartiles were 2.5% and 3.7%, respectively. According to the statistics, the mean value has been reduced by more than 15% (see **Figure 18**). The frequency distribution of the excess oxygen measurements during manual operation and system auditing are presented in **Figure 19**. The frequency distribution shows that the proportion of values between 2% and 4%, which is the most favorable excess oxygen range from the point of view of both environment protection and energy efficiency, has increased from below 60% to over 70%.



	LOWER QUARTILE	MEAN	UPPER QUARTILE
■ Man	3.2	3.8	4.5
■ Pilot	3.2	3.3	3.7
□ Prod	2.5	3.2	3.7

Figure 18. Statistics of the excess oxygen (%).



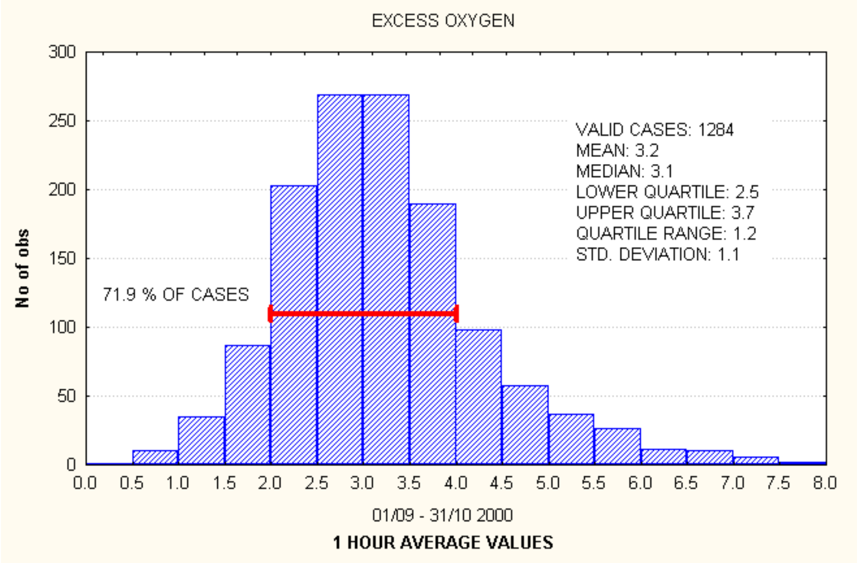
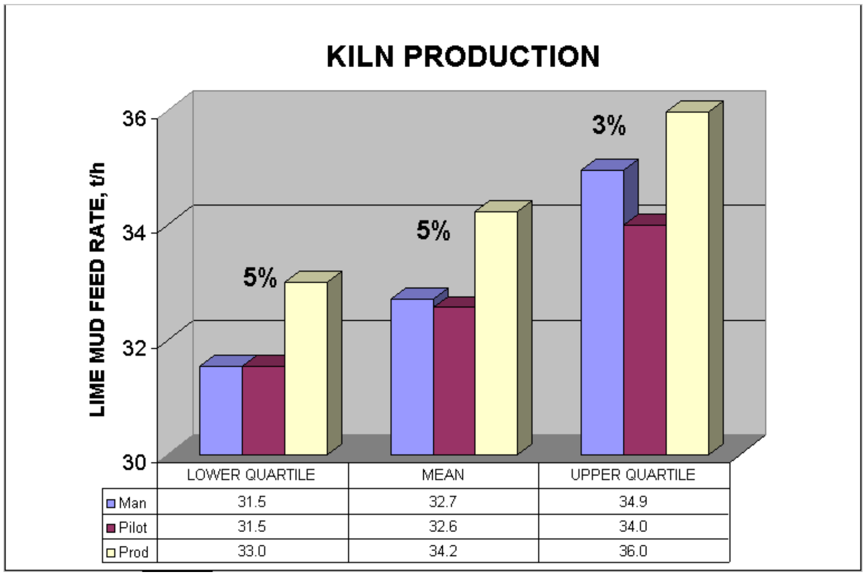


Figure 19. Frequency distribution of the excess oxygen content (%) during manual operation (above) and auditing of the production system (below).

Assessment of the benefits

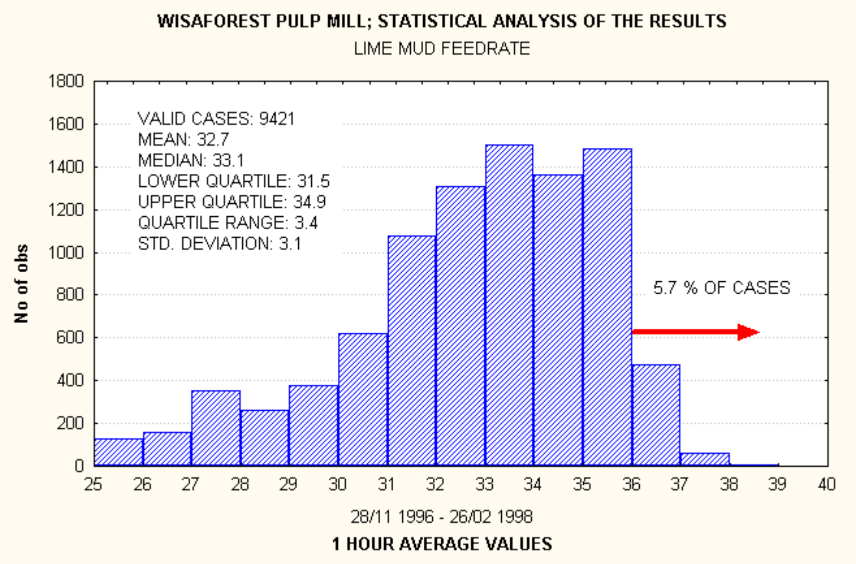
Production rate

One of the major features to be analyzed during the auditing of the production system was the performance of the production maximization module. The mean of the production rate was 32.7 tons/hour in manual operation, and the lower and upper quartiles were 31.5 tons/hour and 34.9 tons/hour, respectively, when only the data collected during the normal operation of the process were used in the statistical analysis. During the system auditing the mean was 34.2 tons/hour and the lower and upper quartiles 33.0 tons/hour and 36.0 tons/hour, respectively. The mean has increased by ca. 5%, and the upper quartile has increased by almost 3% (see **Figure 20**). The normal operating conditions of the kiln process were assumed to be fulfilled by a production rate of over 25 tons/hour, draught fan speed of over 700 rpm, kiln rotation of over 1.2 rpm, heat energy supply of over 70 GJ/h, and temperature in the cold-end of the kiln and flue gas temperature after the LMD of over 550° C and 180° C, espectively. The histograms in **Figure 21** show the variation in the production rate in manual operation and during the auditing of the production system. It clearly demonstrates the increase in the proportion of operating levels above 36 tons/hour, which has been approximately the high limit for the production rate during manual operation. In addition to the statistics shown above, further proof of the considerable increase in production is that the old kiln (#1) has not had to be run at all, even though production at the pulp mill has been at a level close to the production record during the auditing period.



	LOWER QUARTILE	MEAN	UPPER QUARTILE
Man	31.5	32.7	34.9
Pilot	31.5	32.6	34.0
Prod	33.0	34.2	36.0

Figure 20. Statistics of the production rate (tons/hour).



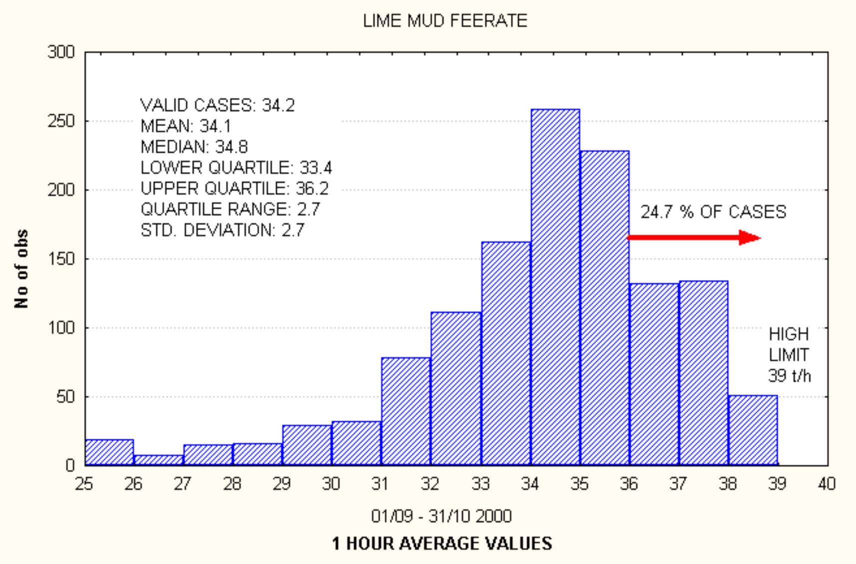


Figure 21. Frequency distribution of the production rate (tons/hour) during manual operation (Man) and auditing of the production system (Prod).

TRS emissions

TRS emissions from the kiln have been analyzed online by means of a continuous emission monitoring system (CEM). The CEM system used for measuring the emissions is based on the continuous flow of extracted sample, which is first filtered to remove particulate material and then diluted. The diluted sample stream is then led to an external measuring device. Measurement of the TRS emissions is carried out using two calibrated UV fluorescent SO_2 -analyzers. The sample stream is first split into two equal streams. One stream is directed through the thermal converter prior to the SO_2 -analyzer in order to convert the reduced sulfur compounds into SO_2 before the actual measurements. The other stream is fed directly into the other SO_2 -analyzer. The concentration of the TRS emissions, as H_2S in ppm, is then calculated on the basis of the difference between the SO_2 concentrations. Both measurements are made on the same wet basis as the initial flue gas, thus eliminating the need for an additional moisture sensor.

The mean of the TRS emissions was 8.5 ppm in manual operation, and the lower and upper quartiles 4.8 and 10.4 ppm, respectively. During the testing period of the pilot system, the mean of the TRS emissions was 7.2 ppm, and the lower and upper quartiles 4.5 and 9.1 ppm, respectively. The corresponding values during system auditing were 6.0 ppm, 4.3 ppm and 7.2 ppm, respectively. When manual operation and the testing period of the pilot system are compared, the mean has been reduced by over 10%, and the upper quartile by about 12%. The emissions have, however, been further reduced during the system auditing period. The mean and the upper quartile have been reduced by about 30 % compared to manual operation (see **Figure 22**).

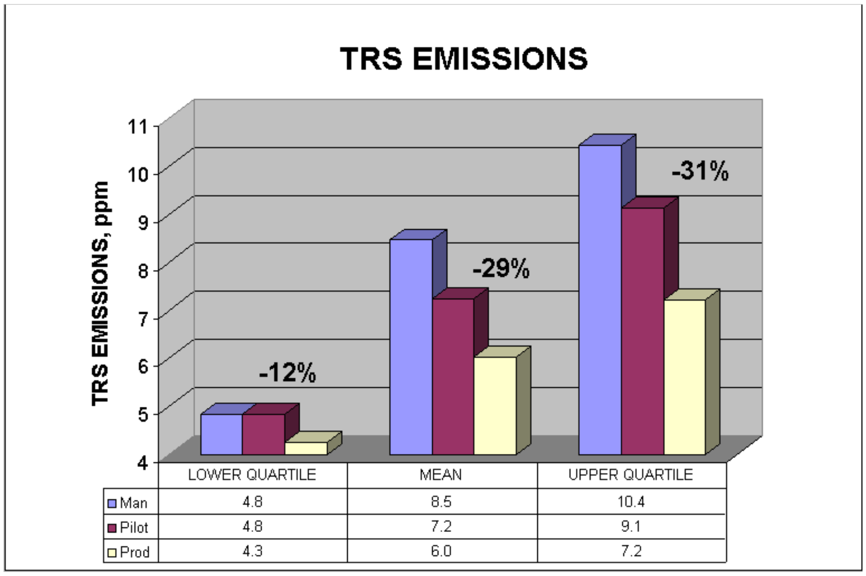
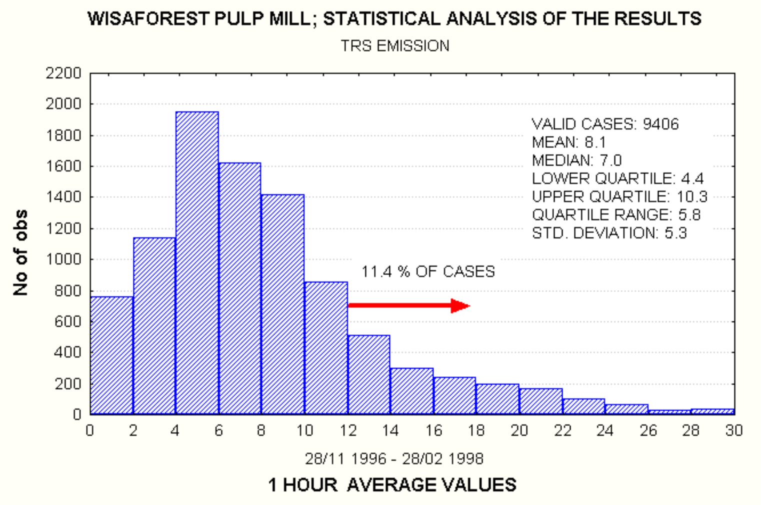


Figure 22. Statistics of the TRS emissions (ppm).

A frequency distribution of the emissions during manual operation, the testing period of the pilot system and the auditing of the production system are presented in **Figure 23**. The figure shows that the proportion of values above 12 ppm, caused predominantly by short-term emission peaks, has been reduced by almost 90%. During the testing of the pilot system, the reduction in emissions was primarily achieved through improved control during high production rates periods (see **Figure 24**). The decline in emissions over the entire production rate range during the system auditing, which was achieved even though the mean of the excess oxygen content was reduced, is most probably due to the improved dewatering of the lime mud prior to the kiln, and a subsequent increase in the temperature during mud drying (see also Figures 15 and 17).



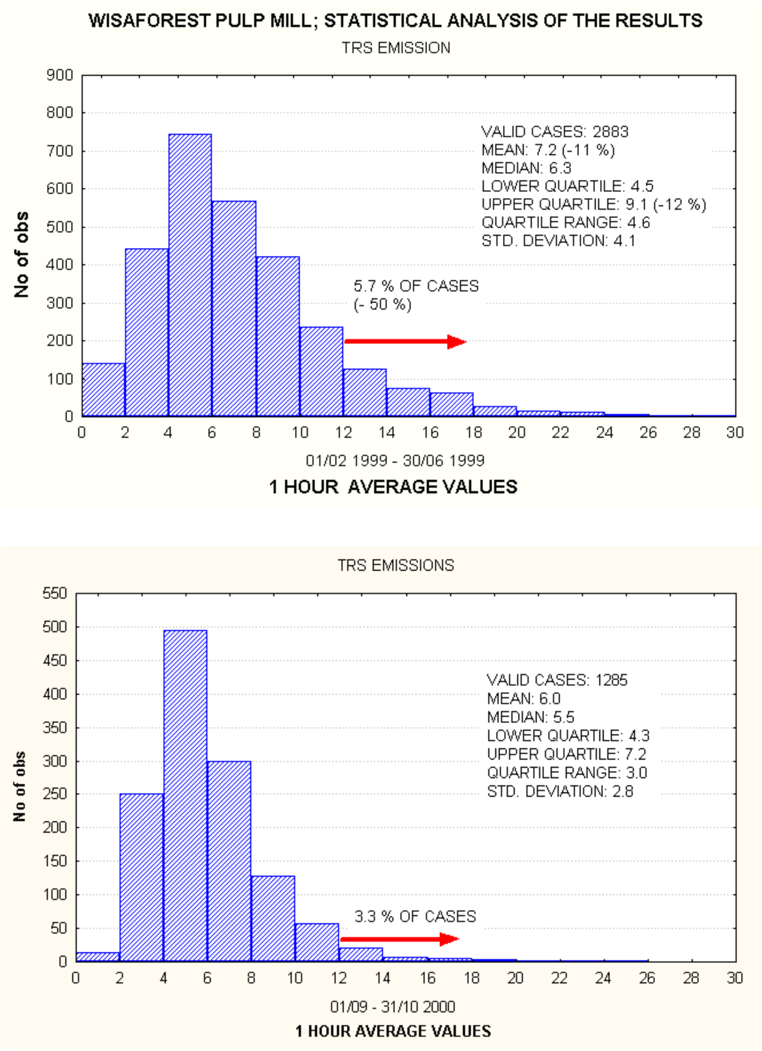


Figure 23. Frequency distribution of the emissions (ppm) during manual operation (above), testing of the pilot system (center) and auditing of the system (below).

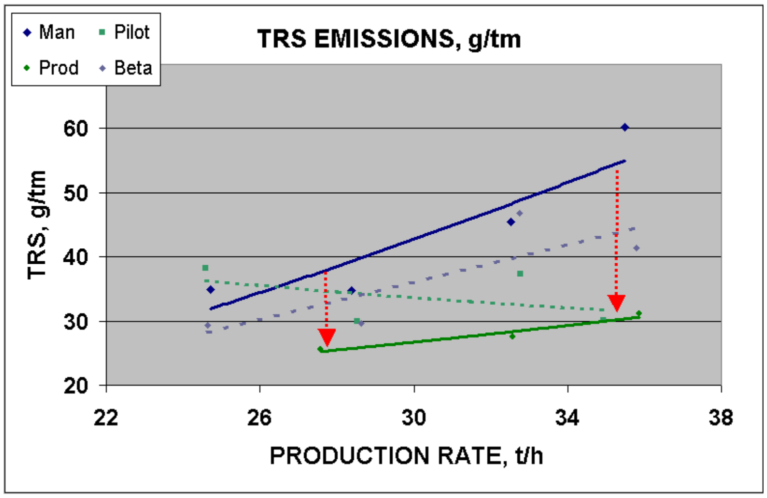


Figure 24. Mean of the TRS emissions (ppm) as a function of the production rate (tons/hour).

CONCLUSIONS

The intelligent control system of the lime reburning process, which has been developed for ensuring low flue gas emissions and heat losses while simultaneously improving production efficiency, has been successfully operated the Wisaforest mill. The dynamic performance of the system has been verified, and evaluation of the results has been carried out by means of statistical analysis of the process data collected during manual operation and the corresponding data obtained during extended testing periods. The results confirm that the proposed overall control scheme, which takes into consideration both environmental and operational requirements, can be realized in practice in an industrial environment. From the ecological point of the view, the major quantifiable benefit was an almost 30% decrease in the average TRS emissions, and a reduction of about 90% in the frequency of peak emission periods. The main verified economic benefit was an approx. 3% increase in the production capacity.

Furthermore, the plant personnel now have a much more comprehensive understanding of the process and its restrictions. In addition, the operator's workload has been reduced, variation between shifts decreased, and the operational flexibility of the process improved, compared to manual operation. As a result, the operators have the possibility to review and enhance their own procedures, and this will most probably bring additional improvements in the future. There is also an ongoing opportunity to continue developing the system.

One potential candidate for future development is to extend the functionality of the system by developing an intelligent diagnostic module that keeps an eye on the process and carries out the appropriate actions needed to prevent high-impact problems from developing, and/or advises the operators by means of informative messages in the case of abnormal process conditions. What is of more general relevance is that, the experiences gained during the project has demonstrated that, through a proper combination of different methods, makes it possible to merge knowledge from different sources and at different level of accuracy, and then apply it in a systematic manner for resolving complex and highly demanding industrial-scale control problems. The development of a similar type of control system, embedded with a certain degree of intelligence, is therefore also a potential candidate for the future development of other industrial processes.

ACKNOWLEDGEMENTS

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APPENDIX A

Linguistic equations approach

The linguistic equations (LEs) approach, in which traditional fuzzy systems described by means of rules and membership functions are represented by matrix equations and non-linear membership definitions, provides a comprehensible and flexible environment for the modeling and control of both data- and knowledge-intensive applications (see e.g. Juuso & Leiviskä, 1992 and Juuso, 1999).

LE models applied in the system

For FF control purposes, the MISO (multiple inputs and single output) type of steady state LE model can be represented for a specific output variable as follows

$$lv\left|y_i\right| = \sum_{j=1}^{n} w_{ij} \times lv\left|x_{ij}\right| \qquad \text{(A1)}$$

which is a special case of the matrix equation AX = 0, with the interaction matrix $A = [w_{i1}\ w_{i2} \ldots w_{in}\ {-1}]$ and variables $X = [x_{i1}\ x_{i2} \ldots x_{in}\ y_i]^T$. $lv|y_i|$ is the linguistic value (LV) of the output of the model that is subsequently used for the FF control of the manipulated variable i. $lv|x_{ij}|$ is the LV of the variable j (j = 1…n) applied as an input in the model. w_{ij} is the real valued weight factor, between -1 and 1, describing the direction and strength of the interaction between the input variable and the output. These weights (w_{ij}) can be determined on the basis of the collected process data and/or expert knowledge of the process behavior. Correspondingly, the SISO (single input and single out) type of LE models are obtained using interaction matrix $A = [w_{i1}\ {-1}]$ and variables $X = [x_1\ y_i]^T$.

The LVs of the input variable, $lv|x_{ij}|$, are determined by means of the non-linear membership definition (NLMD), which transforms the real value (RV) of the variable into LV with the range [-2 +2]. This can be considered as a non-linear pre-scaling technique, which linearises the actual LE model. The NLMDs consist of two second-order polynomials that are monotonously increasing and connected at the LV 0. The polynomials can also be obtained from the process data by fitting a second-order polynomial through the data points and/or on the basis of process expertise. When the polynomial functions have been defined, conversion of the real values (RVs) to the LVs can then be performed using the following equation:

$$lv\left|x_{ij}\right| = \begin{cases} 2 & \text{if } x_{ij} \geq x_{ij}^{hl} \\ \dfrac{-b_{ij} + \sqrt{b_{ij}^2 - 4 \times a_{ij} \times \left(c_{ij} - x_{ij}\right)}}{2 \times a_{ij}} & \\ -2 & \text{if } x_{ij} \leq x_{ij}^{ll} \end{cases} \qquad \text{(A2)}$$

where a_{ij}, and b_{ij} are constants obtained directly from the polynomials. c_{ij} is the RV of the variable corresponding to the LV 0. x^{ll} and x^{hl} are the RV of the variable corresponding to the LV –2 and 2, respectively.

Correspondingly, after calculating the LV of the model output, lv|yi|, is converted to the RV, y_i, using the following equation:

$$y_i = a_i \times lv|y_i|^2 + b_i \times lv|y_i| + c_i \qquad \text{(A3)}$$

where a_i, and b_i are the constants of the polynomials. c_i is the RV corresponding to the LV 0.

However, before the model outputs, y_i (i=1…m), are applied in the system for FF control purposes they are checked with respect to the acceptable range as follows

$$FFMu_i = \begin{cases} y_i^{hl} & \text{if } y_i + b_i \geq y_i^{hl} \\ y_i + b_i & \text{if } y_i^{ll} < y_i + b_i < y_i^{hl} \\ y_i^{ll} & \text{if } y_i + b_i \leq y_i^{ll} \end{cases} \qquad \text{(A4)}$$

where $FFMu_i$ is the output of the FFMs related to the manipulated variable i. b_i is a bias term which can be used for fine-tuning purposes. y^{ll} and y^{hl} are the preset low and high limits for the output. **Table A1** summarizes the tuning-parameter values used in the LE models applied for FF control of the lime mud filters and the draught fan speed.

LE controller applied in the system

The LE approach, which has primarily been used for simulation and modeling, can be also expanded for high-level, FB control purposes. Consequently, a PI type of controller based on the LE approach can be represented in a general form by a single LE equation as follows

$$lv|\Delta u_{ij}| = \frac{1}{d_{ij}} \times \left(we_{ij} \times lv|e_{ij}| + w\Delta e_{ij} \times lv|\Delta e_{ij}| \right) \qquad \text{(A5)}$$

which is a special case of the matrix equation AX = 0, with the interaction matrix A = $[we_{ij}\ w\Delta e_{ij}\ -d_{ij}]$ and variables defined as X = $[lv\ |e_{ij}|\ lv\ |\Delta e_{ij}|\ lv\ |\Delta u_{ij}|]^T$. lv| Δu_{ij} | is the LV of the correction to the manipulated variable, i, calculated on the basis of the controlled variables j. lv |e_{ij}| and lv |Δe_{ij}| are the LVs of the error and the derivative of the error, respectively, calculated by means of Eq. A2 (note: x is replaced by e or Δe). we_{ij} and $w\Delta e_{ij}$ are the corresponding weight factors (the default value for both weights is -0.5). d_{ij} is a constant (-1 or 1) used for determining the direction of the control action (i.e. if d_{ij} is -1 and the error is positive, the output will be negative, and vice versa). After calculating the LV of the correction, lv|Δu_{ij}|, it is converted into the RV, Δu_{ij}, using the principle shown in Eq. A3 (note: y is replaced with u).

The output of the MISO type LE controller is then calculated as a weighted average of the corrections determined independently on the basis of the controlled variables as follows

$$\Delta u_i = \sum_{j=1}^{n} w_{ij} \times \Delta u_{ij} \qquad \text{(A6)}$$

where Δu_i is the FB corrections to the setpoint of the manipulated variable i. Δu_{ij} and w_{ij} are the correction and weight related to each controlled variable j (j = 1…n).

However, before the output of the controller, Δu_i, is applied in the system for high-level feedback control purposes, it is checked with respect to the acceptable range as follows

$$\Delta SCu_i = \begin{cases} \Delta u_i^{hl} & \text{if } s_i \times \Delta u_i \geq \Delta u_i^{hl} \\ s_i \times \Delta u_i & \text{if } \Delta u_i^{ll} < s_i \times \Delta u_i < \Delta u_i^{hl} \\ \Delta u_i^{ll} & \text{if } s_i \times \Delta u_i \leq \Delta u_i^{ll} \end{cases} \qquad \text{(A7)}$$

where $SCu_i(k)$ is the output of the stabilizing controller module (SCs) related to the manipulated variable i. s_i is a constant, which can be used for fine-tuning purposes. Δu^{ll} and Δu^{hl} are the preset low and high limits for the correction per one scan interval. **Table A2** summarizes the tuning-parameter values used in the LE controller applied for high-level, FB control of the draught fan speed.

FEEDFORWARD CONTROL MODELS; LIME MUD FILTER #21 / #22										**LIME KILN #2**			
LEC-F21/2*-MODEL Description Eng.-units		**DENS**(i) Density kg/dm^3		**WATER**(i) Wash water l/s		**RPM**(i) Rotation rpm		**LEVEL**(i) Level %		**FAN**(i) Draught fan rpm			
		Input1		Input1		Input1		Input1		Input1		Input2	
Input name (x_j)		30min-ave FPROD (j)		30min-ave FPROD (j)		30min-ave FPROD (j)		30min-ave FPROD (j)		1hour-ave KPROD (j)		8hour-ave CEPRESS (j)	
Input conversion	lv	Nlmd	Coeff	Nlmd	Nlmd	Coeff	Nlmd	Coeff	Coeff	Coeff	Nlmd	Coeff	Coeff
a_i (rv > c_i)	+2	20	0	20	0	20	0	20	0	40	0	0	0.2
b_i (rv > c_i)	+1	17.5	2.5	17.5	2.5	17.5	2.5	17.5	2.5	35	5	-0.8	1.4
c_i	0	15	15	15	15	15	15	15	15	30	30	-2.0	-2.0
a_i (rv < c_i)	-1	12.5	0	12.5	0	12.5	0	12.5	0	25	0	-3.2	-0.2
b_i (rv < c_i)	-2	10	2.5	10	2.5	10	2.5	10	2.5	20	5	-4.0	1.4
Input1 high limit (x^{hl})		20		20		20		20		40		0	
Input1 low limit (x^{ll})		10		10		10		10		20		-4.0	
Weight (w)		1.0		1.0		1.0		1.0		0.8		0.2	
Output conversion	lv	Nlmd	Coeff	Nlmd	Coeff	Nlmd	Coeff	Nlmd	Coeff		Nlmd	Coeff	
a_i (rv > c_i)	+2	1.24	0	4.8	0.05	4.1	0.05	26	0.5		950	15	
b_i (rv > c_i)	+1	1.235	0.005	4.0	0.35	3.9	0.35	22	2.5		890	105	
c_i	0	1.23	1.23	3.5	3.5	3.6	3.6	19	19		800	800	
a_i (rv < c_i)	-1	1.225	0	3.2	0.15	3.3	-0.05	17	0.5		710	-5.0	
b_i (rv < c_i)	-2	1.22	0.005	3.0	0.35	3.1	0.35	16	2.5		650	105	
Output bias (b)		0		0		0		0			0		
Output high limit (y^{hl})		1.24		4.8		4.1		26			950		
Output low limit (y^{ll})		1.22		3.0		3.1		16			650		

Table A1. Tuning-parameter values used in the FF models.

HIGH-LEVEL LE COTROLLER; DRAUGHT FAN SPEED													
LEC-FAN-* Description Eng.-units		**O2** (j) Excess oxygen %				**CET** (j) Cold-end temp. C				**HET** (j) Hot-end temp. C			
		Error		Error change		Error		Error change		Error		Error change	
		MV-TV		e(k)-e(k-1)		MV-TV		E(k)-e(k-1)		MV-TV		e(k)-e(k-1)	
		MV 10-min-ave TV 30-min-ave				MV 30-min-ave TV 30-min-ave				MV 30-min-ave TV 30-min-ave			
Input conversion	lv	Nlmd	Coeff	Nlmd	Nlmd	Coeff	Nlmd	Coeff	Coeff	Coeff	Nlmd	Coeff	Coeff
$a_i (rv > c_i)$	+2	0.8	0.1	0.4	0.05	35	-2.5	2.0	-0.2	20	-2.5	4.0	-0.5
$b_i (rv > c_i)$	+1	0.55	-0.45	0.25	0.3	15	12.0	0.8	0.6	8	7.5	1.5	1.5
c_i	0	0.0	0	0	0	0	0	0	0	0	0	0	0
$a_i (rv < c_i)$	-1	-0.35	-0.15	-0.25	-0.05	-15	2.5	-0.8	0.2	-10	2.0	-2.0	0.5
$b_i (rv < c_i)$	-2	-0.5	0.7	-0.4	0.3	-35	12.5	-20.0	0.6	-25	6.0	-5.0	1.0
Input high limit(x^{hl})		0.8		0.4		35		20		20		4.0	
Input low limit (x^{ll})		-0.5		-0.4		-35		10		-25		-5.0	
Weight (w_I)		0.5				0.3				0.2			
Output conversion	lv						Nlmd	Coeff					
$a_i (rv > c_i)$	+2						4.5	-0.3					
$b_i (rv > c_i)$	+1						1.8	0.9					
c_i	0						0	0					
$a_i (rv < c_i)$	-1						-1.2	0.45					
$b_i (rv < c_i)$	-2						-3.0	1.35					
Output high limit(u^{hl})							15						
Output low limit (u^{ll})							-10						

Table A2. Tuning parameter values used in the high-level controller applied for draught fan speed control.

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