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INTELLIGENT CONTROL OF THE LIME KILN PROCESS WITH RESPECT TO ENVIRONMENTAL REQUIREMENTS

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Dedicated to my wife Anne

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Abstract

Further reducing environmental impacts, such as reduced-sulfur emissions, will be among the major challenges facing the pulp and paper industry in the near future. It will not be easy to further decrease emissions at modern pulp mills because all the major emission sources have already been eliminated. New strategies, such as the prevention of emissions at their source, e.g. by means of improved control of the subsequent processes, will therefore undoubtedly be required in order to conform with the present and also future environmental requirements. An increase in the authorities and public's attention and awareness on environmental issues, together with intensifying interest in artificial intelligence (AI) and intelligent systems, were also prime motivator for this thesis work.

The primary objective of the research, which has been carried out as a co-operative effort between academic and industrial parties, has been to lower of the total reduced-sulfur (TRS) emissions from a pulp mill by means of intelligent control techniques. The research was focused on the lime reburning process, which is one of the main sources of the TRS emissions at modern pulp mills. In addition, the environmental requirements for lime kilns have become tighter and even at well-managed mills, the emissions tend periodically to exceed the limits set by the authorities. It has also been widely recognized that control of the rotary kiln used for lime calcination is, in many respects, a demanding task. So far, most of the kilns have therefore been operated without supervisory-level control system. However, there are outstanding economical and the environmental improvement potentials associated with improved control. Hence, supervisory-level control of the lime reburning process is undoubtedly a prospective application for intelligent control techniques.

In the first phase of the research, a comprehensive study of the operation of the lime

reburning process was carried out at one of the major Finnish pulp mills, with special attention paid to the factors affecting the TRS emissions. The results showed that, in addition to the considerable enhancement potential in the performance of the kiln process operation, improved kiln control is also a feasible means to reduce emissions. An overall supervisory-level control schema that takes into account both the environmental and operational requirements, was then designed on the basis of the results of the study.

The supervisory-level control system, embedded with a certain degree of intelligence, was then incrementally developed and implemented at the pulp mill. The control structure combines both feedforward (FF) control models and supervisory-level feedback (FB) controllers that are based on the linguistic equation (LE) approach, strengthened with certain capabilities for adaptation and constraint handling. Advanced capabilities and highly developed functionality of the control system were achieved by combining information from different knowledge sources, and by using appropriate techniques to solve each of the recognized problems. On the other hand, the complexity of the lime reburning process was handled by implementing a modular system structure, and by utilizing an incremental system development approach.

The results obtained during extended testing periods of the system demonstrate that the proposed control schema can be successfully realized in an industrial environment, and that it provides quantifiable benefits in both the economical and ecological respect. The major benefit from the ecological point of the view was an almost 30 % decrease in the mean of the TRS emissions and a considerable reduction, about 90 %, in the proportion of peak emission periods. The main verified economical benefits were an increase of about 5 % in the long-term production capacity. Improvements in reburned lime quality and enhancements in energy efficiency were also obtained compared to the situation during manual operation.

Preface

The major part of the work for this thesis was carried out at the Laboratory of Process Control and Automation, Department of Chemical Technology, Helsinki University of Technology. The experimental work was performed during the period 1996 and 2000 at UPM-Kymmene's Wisaforest pulp mill in western Finland.

I am grateful to my supervisor Professor Sirkka-Liisa Jämsä-Jounela for her support and interest during my post-graduate studies and course of the thesis work. Indeed, I should hardly ever have finished my thesis work without her inspiration. I also wish to thank Professor Antonio Dourado Correia of the University of Coimbra and Professor Panu Tikka of Helsinki University of Technology for their thorough review of the thesis and for their useful recommendations. Furthermore, I would also like to thank Professor Kauko Leiviskä and Esko Juuso from University of Oulu, and Professor Anna Soffia Hauksdóttir from University of Iceland for their useful advices and constructive comments during the work.

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Espoo, March 10th, 2003
Mika Järvensivu

List of publications

This thesis work is based on the following five (5) original publications, which are referred in the text by Roman numerals.

I. Järvensivu M., Mäenpää T., Jämsä-Jounela S.-L. and Saari K. Field survey of reduced-sulfur emissions from a modern Finnish pulp mill, *Environmental Progress* 19 (2000) No 3, 147-156.

II. Järvensivu M., Kivivasara J. and Saari K., A field survey of TRS emissions from a lime kiln, *Pulp and Paper Canada* 100 (1999) No 11, 28-31.

III. Järvensivu M., Saari K. and Jämsä-Jounela S.-L., Intelligent control system of an industrial lime kiln process, *Control Engineering Practice* 9 (2001) No 6, 589-606.

IV. Järvensivu M., Jämsä-Jounela S.-L. and Ahava O., Intelligent control system for low emissions and heat losses with maximum lime kiln production, *Solutions! for People, Process and Paper* 84 (2001) No 12, 41 (abstract), *Solutions! Supplement December* 2001, 64-96 and *TAPPI's website* at www.tappi.org (the full paper).

V. Järvensivu M., Juuso E. and Ahava O., Intelligent control of a rotary kiln fired with producer gas generated from biomass, *Engineering Applications of Artificial Intelligence* 14 (2001) No 5, 629-653.

The author's contribution in the publications

I. M. Järvensivu implemented the field study of the continuous reduced-sulfur emissions presented in the paper. He participated, together with J. Kivivasara and the co-author K. Saari, in preparing the research plan for investigating sporadic emissions. M. Järvensivu supervised, together with J. Kivivasara, the experimental work carried out by T. Mäenpää on sporadic emissions. M. Järvensivu carried out the calculations concerning the dispersion of emissions and the ground level concentrations. He wrote the manuscript.

II. M. Järvensivu carried out the literature survey of the total reduced-sulfur emissions from the lime kiln process. He drew up the research plan and also carried out the field survey of the emissions presented in the paper. The co-authors J. Kivivasara and K. Saari provided the author with site-specific information and process knowledge. M. Järvensivu carried out the statistical analysis of the data and analyzed the results. He wrote the manuscript.

III. M. Järvensivu carried out the field survey of the lime kiln process operation. The co-author K. Saari provided the author with site-specific information. M. Järvensivu designed the overall control schema and the structure of the system. He also carried out the major part of the development of the system. Part of the work was made by H. Sievola in his M.Sc. thesis, performed under the guidance of the author and E. Juuso. M. Järvensivu also carried out the assessment of the benefits obtained. He wrote the manuscript according to the guidelines provided by the co-author S.-L. Jämsä-Jounela.

IV. M. Järvensivu had the main responsibility for designing the overall control schema for the lime reburning process presented in the paper. He also carried out the major part of the development and testing of the system described in the paper. The co-author O. Ahava provided the author with practical advice. M. Järvensivu also analyzed the results. He wrote the manuscript in accordance with the guidelines provided by the co-author S.-L. Jämsä-Jounela.

V. M. Järvensivu had the main responsibility for implementing and fine-tuning the linguistic equation (LE) based controller for the hot-end temperature and the quality of the reburned lime. The fundamentals of the LE approach were provided by E. Juuso. The co-author O. Ahava provided the author with practical advice. M. Järvensivu adapted the LE control methodology to the overall control schema together with E. Juuso. M. Järvensivu analyzed the results and wrote the manuscript with the support provided by the co-author E. Juuso.

Table of contents

List of abbreviations and mathematical notations

AI	Artificial intelligence
AOX	Absorbed organic halogens
AS	Adaptive scaling
BOD	Biochemical oxygen demand
CH	Constraints handling
CP	Control power
CR	Cumulative rate
DCS	Distributed control system
FB	Feedback
FF	Feedforward
FFM	Feedforward control model
FL	Fuzzy logic
GA	Genetic algorithms
GUI	Graphical user interface
LE	Linguistic equation
LMD	Lime mud drier
LV	Linguistic value
MISO	Multiple inputs and single output
MPC	Model predictive control
NCG	Non-condensible gas
NLMD	Non-linear membership definition
NN	Neural network
PBA	Predictive braking action
RBES	Rule-based expert system
SC	Stabilizing controller
SISO	Single input and single output
SP	Setpoint
TRS	Total reduced-sulfur
VOC	Volatile organic compounds
WP	Working point

alv_i, alv_{ij}	Constants used in NLMDs for converting real values to linguistic values
arv_i, arv_{ij}	Constants used in NLMDs for converting linguistic values to real values
blv_i, blv_{ij}	Constants used in NLMDs for converting real values to linguistic values
brv_i, brv_{ij}	Constants used in NLMDs for converting linguistic values to real values
B	Bias term used in a linguistic equation to shift the model from the origin
bc_{ij}	Adjustable braking constant related to the controlled variable, j, in the equation for the manipulated variable, i
$BCu_i(k)$	Manually set bias correction for the manipulated variable, i
$brc_{ij}(k)$	Braking rate coefficient related to the controlled variable, i, in the equation for the manipulated variable, i
clv_i, clv_{ij}	The value corresponding to the lv of zero in NLMDs for converting real values to linguistic values
$cp_i(k)$	The control power used for manipulated variable, i
$cr_i(k)$	The cumulative rate of the corrections used for manipulated variable, i
crv_i, crv_{ij}	The value corresponding to the lv of zero in NLMDs for converting linguistic values to real values
d_{ij}	Constant used for determining the direction of the control action
$e_{ij}(k)$	The error of the controlled variable, j, in the equation for the manipulated variable, i
$FFMu_i(k)$	Most recent output of the FFMs module for the manipulated variable, i
hl_{ij}	The value of the variable, j, corresponding to the LV of 2 in NLMDs for converting real values to linguistic values
$HLCu_i(k)$	High-level corrections to the FF model for the manipulated variable, i
$Ie_{ij}(k)$	Initial error of the controlled variable, j, in the equation for the manipulated variable, i
$Ielb_{ij}$, $Iehb_{ij}$	Preset low and high boundary for the initial error of the controlled variable, j, in the equation for the manipulated variable, i
ll_{ij}	The value of the variable, j, corresponding to the lv of -2 in NLMDs for converting real values to linguistic values
$sc_i(k)$	Coefficient used for scaling the corrections of the manipulated variable, i
$u_i(k)$	New setpoint (SP) for the manipulated variable, i
u_i^{lr}, u_i^{hr}	Low and high range for the acceptable SPs for the manipulated variable, i

w_{ij}	Weight factor describing the direction and strength of the interaction between the input variable, j, and the output variable, i
$\boldsymbol{W}$	Interaction matrix that defines the directions and strengths of the interactions
we_{ij}	Weight factor of the error of the controlled variable, j, in the equation for the manipulated variable, i
wcp_i	Weight coefficient of the CP used in calculating the scaling rate coefficient for the manipulated variable, i
wcr_i	Weight coefficients of the CR used in calculating the scaling rate coefficient for the manipulated variable, i
$wp_i(k)$	The value of the working point used for manipulated variable, i
wwp_i	Weight coefficients of the WP used in calculating the scaling rate coefficient for the manipulated variable, i
wDe_{ij}	Weight factor of the derivative of the error of the controlled variable, j, in the equation for the manipulated variable, i
$x_{ij}(k)$	The value of the variable, j, used in the equation for the variable, i
X	Variable vector used in linguistic equations
$y_i(k)$	The value of the model output variable, i
$De_{ij}(k)$	The derivative of the error of the controlled variable, j, in the equation for the manipulated variable, i
$DCHu_i(k)$	Latest stepwise correction of the CH module for the manipulated variable, i
$DSCu_i(k)$	Latest feedback corrections of the SCs module for the manipulated variable, i
$Du_{ij}(k)$	The value of the correction to the manipulated variable, i, calculated on the basis of controlled variable, j
$Du_i(k)$	Weighted average of the correction to the manipulated variable, i
a_i, b_i	Constants used to calculate the high and low boundary for acceptable SPs

1. Introduction

1.1. Recent trends in the pulp and paper industry

In the face of strong competition and fluctuations in the prices of the end products, the pulp and paper industry is aiming at higher profitability through increased productivity and more efficient use of both energy and raw materials. Additional requirements for higher profitability are also set by the increasing demands of shareholder. On the global scale, the industry is also facing increasing market demands for higher product quality, more specialty products and improved production flexibility (Diesen, 1998; Karvinen and Karlsson, 2002). Furthermore, increasing public attention and awareness of ecological issues in general, and the authorities concern about environmental protection, have led to new, tighter regulations concerning the environmental impact of industrial operations. A comprehensive review of the new regulatory focus on air quality issues is presented in Blackwell (1996) and in Garner (2001). An overview of the public's perceptions of the pulp and paper industry is given in Martin et al. (1996). The report indicates, for instance, that a high proportion of the respondents associated the word "smelly" with the pulp and paper industry. It is thus inevitable that the pulp and paper industry, as well as all the other industries, need to continue their capital investments and efforts aimed at reducing the environmental impacts of industrial operations.

In fact, environmental demands and regulations will continue to be the single most important factor influencing technological change in the pulp and paper industry (Meadows, 1995). According to Sieppi et al. (2000), investments of about 56 million euros in environmental protection accounted for nearly 10 % of the total domestic investments made by the pulp and paper industry in Finland in 1999. Most of the investments made in 1999, i.e. over 27 million euros, were directed at reducing emissions into the air, and the main emphasis was on investments in the collection and treatment systems for malodorous sulfur-containing gases. The reduced-sulfur compounds (i.e. methyl mercaptan, dimethyl sulfide, dimethyl disulfide and hydrogen sulfide), cause subjective odor problems at very low concentrations and for this reason pulp mills, even with modern odor abatement systems, may produce a foul odor in the surrounding communities (McCubbin, 2001). During the past decade revised equipment design, changes within the production processes, and advances in the non-condensible gas (NCG) collection and treatment systems especially have, however, considerably decreased emissions, see e.g. Bell, 1996 and Tembreull et al., 1999. In Finland, the reduced-sulfur emissions of the pulp industry have, for instance, decreased by more than 75 % during the 90's, despite an increase in pulp production of over 10 %, according to the Environmental Reports (1990-1999) of Finnish Forest Industries Federation. The regulations set for the emissions are, however, expected to be tightened.

Consequently, as enhanced environmental protection successfully reduces both water effluents and gaseous emissions and, at the same time, the pulp and paper industry progresses towards the concept of the closed mill, the accumulation of waste products and increasing complication of the processes will make efficient operation of the processes increasingly difficult. On the other hand, environmental control systems provides substantial economic return due to recovery of valuable chemicals while reducing pollutant output. These points were also highlighted by Grant (1994) and McCubbin (1996) in their reports on solutions for mill effluent closure.

As a result of the above, extensive research is and will be conducted by the forest-product companies, the leading equipment and system suppliers, and research institutes to investigate how to modify and continuously improve the existing mills and production processes in order to attain the present and future goals concerning profitability, product quality and especially environmental protection. One alternative that is gaining increasing attention and appreciation by the mill management within the pulp and paper industry is the improved control of existing production processes by means of the latest measurement technology, intelligent systems and modern information technology.

Process improvements and enhancements related to advanced control applications can often be carried out at relatively low investment levels and subsequent maintenance costs, and without a long process downtime. This is not necessarily the case when new equipment technology and/or retrofits are implemented. These potential benefits of advanced control applications were also strongly argued by Anderson (1997) in his paper concerning the future directions of R&D in the process industry.

1.2. Research problem and asserted hypothesis

In addition to increasing market demands for more efficient use of both energy and raw materials, achieving further reductions in environmental impacts will be among the major challenges facing the pulp and paper industry in the near future. As described above, one alternative that has been receiving increasing attention is the improved control of existing production processes by means of intelligent systems.

During the past decade, the research in the field of artificial intelligence (AI) and intelligent control techniques has been very active. In most cases, however, the emphasis has been placed on theoretical frameworks and mathematical foundations rather than on what each specific technique could offer and/or on how the different intelligent techniques could be applied to solve real industrial-scale problems. For instance, a number of neural network architectures and learning algorithms have been developed even though, in addition to gaining a fundamental understanding of the underlying process, the quality of the data used in the training is typically the most critical point in the development of a successful application. Consequently, the reputation of the intelligent systems has suffered from an inability to transfer sophisticated techniques into applications with identifiable benefits.

As a result, even though a wide variety of software tools have been available to the industry for many years already, and provide a comprehensive set of intelligent techniques embedded in the existing general- and/or special-purpose software packages, most of the control applications adopted in the pulp and paper industry are based on more conventional methods. It is apparent that most of the applications could perform considerable more effectively if a certain degree of intelligence is embedded in the applications.

Recently, as general awareness of the intelligent techniques has grown, real industrial problems have fortunately gained intensifying emphasis. There are already several interesting applications in daily operation in the pulp and paper industry, but only a quit small number of them have long-term pedigree of sustained success in an industrial environment. Therefore, the next challenge in the field of intelligent systems is expansion of the available techniques into uninterrupted industrial use. Consequently, the focus of this thesis work has not been to go into the details of the different intelligent techniques, but rather to focus on a real industrial control application deployed with a certain degree of intelligence.

Accordingly, the hypothesis addressed in the thesis can be formulated as follows:

Intelligent control techniques have a high potential for considerable ecological and economical benefits in large-scale industrial applications such as the supervisory-level control of the lime reburning process. Advanced capabilities and highly developed functionality can be achieved in the system by combining information from different knowledge sources and by using appropriate techniques to resolve each of the recognized problems. The inherent complexity of the processes can be handled implementing a modular system structure and by taking advantage of an incremental system development approach in a systematic manner.

In essence, the above hypothesis is confirmed, in the first place, by designing, developing and implementing an intelligent control system for the lime reburning process in an industrial environment. The applicability of the proposed approaches is also demonstrated by verifying the system performance and by validating the obtained benefits from both the ecological and economical points of view.

1.3. Scope and significance of the thesis work

This thesis work on intelligent control of the lime kiln process with respect to environmental requirements can be divided chronologically into three partially overlapping phases as follows:

- knowledge acquisition, domain analysis and design of an overall control schema,
- incremental development of an intelligent supervisory-level control system, and
- evaluation of the operational results and assessment of the obtained benefits.

The research work focused at an early stage on the lime reburning process, which, according to the comprehensive field survey carried out at one of the major Finnish pulp mills (I), was found to account up to 20 % of the overall reduced-sulfur concentration at the ground level in the area surrounding the mill. During the first phase, in addition to comprehensive literature surveys and several interviews with domain experts, an extended field study was carried out on the operation of the lime reburning process at the mill in order to acquire domain knowledge and to obtain valuable process expertise. In the study that consisted of both process experiments and an extensive statistical analysis of the large amount of the process data collected, special attention was paid to the factors affecting the reduced-sulfur emissions from an industrial kiln equipped with an external lime mud drier (II). Based on the results and the practical experience gained during the field study, an overall control schema, which takes into consideration both the environmental and operational requirements, was then designed for the lime reburning process.

During the second and third phases, which were actually reiterated, an intelligent control system for the lime reburning process was then incrementally developed and implemented at the mill (see Chapter 5.1 and Fig. 9). A scaled-down prototype of the system (*Beta*) was first developed and implemented. It was used primarily to verify the selected development environment, and to demonstrate the core functionality of the system to the end users and the mill management. The prototype was also utilized in qualitatively evaluating the feasibility of the proposed control schema. Encouraged by the promising results, the research work was continued and new features were incrementally developed and implemented in the system (III). After multiple iterations, an extended testing period of the *Pilot* version of the system was then arranged. The functional performance of the system was verified and evaluation of the operational results was performed by means of statistical analysis of the data collected during the manual operation and the corresponding data obtained during the testing period. In addition, an assessment of both the economical and ecological benefits obtained during the testing period was carried out (III).

The analytical observations were then utilized, together with the accumulated practical experience, in designing the final version of the system (*Production*) intended for uninterrupted production use at the mill. After implementation, testing and fine-tuning of the system, an extended audition of the system was carried out and the obtained results were subsequently analyzed (IV, V). Overall, the system provides more comprehensive functionality than has conventionally been achieved in the systems implemented for controlling an industrial lime reburning process. The system also represents the first industrial application of an adaptive, supervisory-level controller based on the linguistic equation (LE) approach. The LE controller, which adapts to the changing operational conditions, was further developed specifically in order to resolve problems in the temperature control with producer gas generated from biomass (V).

1.4. Outline of the thesis

Chapter 1 consists of an overview of the latest trends in the pulp and paper industry. The research problem is then described and the asserted hypothesis presented. The scope and significance of the research work are also explained, and the chronological outline of the research is presented. In Chapter 2, an overview of the chemical pulping is first briefly presented. Then the fundamentals of the lime reburning process are explained and the literature concerning related work in the field of rotary kilns control is reviewed. In Chapter 3, a short review of the field of intelligent systems is presented. The LE approach is also presented to the extent that is relevant for this work.

The major results of the field studies on reduced-sulfur emissions and operation of the lime reburning process carried out at the Wisaforest pulp mill are briefly summarized in Chapter 4. The functional requirements established for the supervisory-level control system of the lime reburning process are also stated, and the proposed overall control schema is presented. Chapter 5 describes the overall structure and main functions of the control system. In Chapter 6, the results obtained during extended testing periods of the system are summarized. Chapter 7 includes the conclusions and Chapter 8 recommendations for future developments.

Five already published paper are attached. Publication I presents the results of the field survey of the reduced-sulfur emissions. Publication II describes a field study of the various alternatives for reducing reduced-sulfur emissions from a lime kiln. Publication III presents the overall structure and main functions of the *Pilot* version of the system. It also includes a comprehensive analysis of the results obtained during the extended testing period of the system. Publication IV describes the *Production* version of the system with the main focus on the functionality related to the reduction of emissions. Publication V focuses on the characteristics of the reburned lime quality and the challenges associated with temperature control with producer gas generated from biomass. Figure 1 below illustrates the structure of the thesis and links it to the phases of the work introduced in Chapter 1.3.

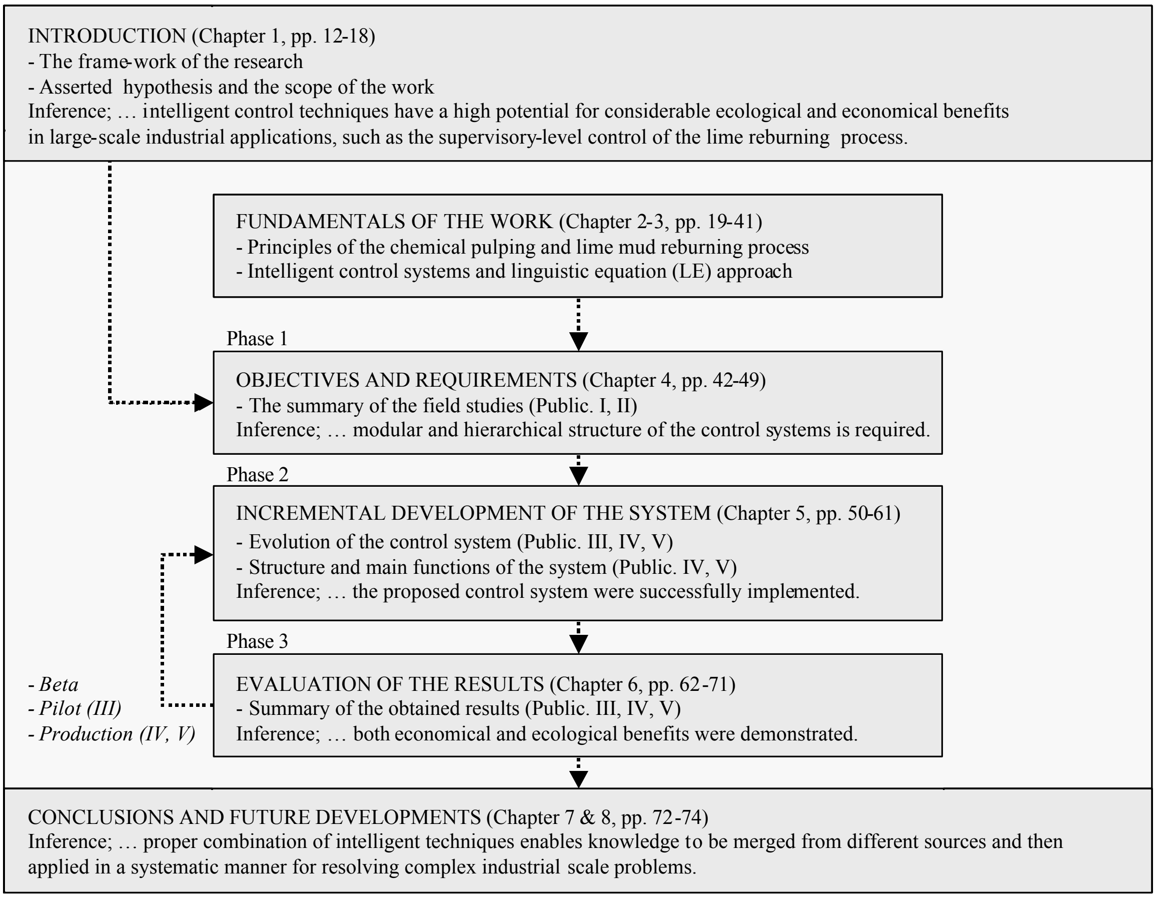


Fig. 1. The structure of the thesis work

2. Lime kiln as a part of the kraft pulp mill

In this chapter, the fundamentals of the chemical pulping are first briefly presented in order to provide an insight into the course of the application domain. The environmental control at the kraft pulp mill with the main emphasis on reduced-sulfur emissions are then shortly introduced to the extent that is relevant for understanding the inspiration behind this work. The principles of the lime reburning process are next presented. The control challenges and main objectives of the lime reburning process are also shortly described. In addition, a literature review of related work in the field of rotary kiln control is presented with the main emphasis on industrial-scale applications.

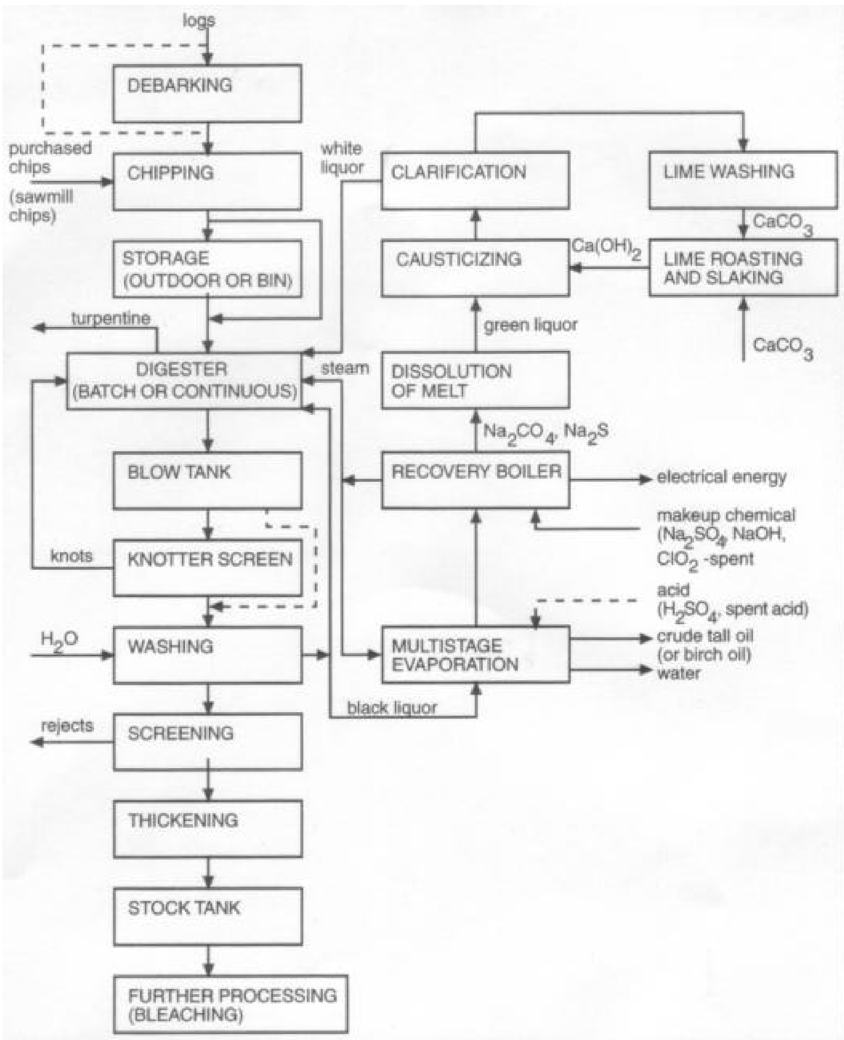


Fig. 2. Schema of the kraft pulp mill (Hynninen, 1998)

2.1. Overview of the chemical pulping

The aim of chemical pulping is to dissolve lignin and to free the wood fibers, and to give them the required characteristics. Chemical pulping is dominated by two processes – the sulphate process and the sulphite process. In sulphite pulping, the active chemical of the acid cooking liquor is hydrosulphite (HSO_3-). In alkaline sulphate pulping the active chemicals are sodium hydroxide (NaOH) and sodium sulphide (Na_2S). The alkaline (kraft) pulping process is the main method used for the production of chemical pulp (see e.g. Gullichsen and Fogelholm, 2000).

2.1.1. Fiber line and chemical recovery cycle

A kraft pulp mill consists of a wood yard, one or several fiber lines and a chemical recovery cycle (see Fig. 2). The wood is first debarked and chipped in the wood yard. The chips are then fed to the digester, which is the first operation in the fiber line. The digester is filled with cooking liquor, i.e. a mixture of regenerated white liquor and spent black liquor from a preceding cook, and subsequently heated with steam. The cooking temperature is maintained until the desired degree of delignification is reached. After cooking the pulp is washed, screened and then thickened and stored at elevated consistence for further processing. The brown pulp can be bleached (see e.g. Reeve, 1989) before it is dried and baled or fed to the paper mill in the integrated mills. The spent cooking liquor, which contains chemicals and dissolved wood substances separated from the pulp in the counter-current washing, is pumped to the chemical recovery.

The principal unit operations of the chemical recovery cycle are as follows (see e.g. Smook, 1992 and Vakkilainen, 2000):

- concentration of the residual liquor from the brown stock washers, i.e. weak black liquor, in multiple-effect, steam heated evaporators to form concentrated black liquor
- incineration of concentrated black liquor at 65 % - 80 % dry solids in a reductive recovery furnace to generate high pressure steam and to recover chemicals in the form of sodium sulfide (Na_2S) and sodium carbonate (Na_2CO_3)
- dissolving inorganic smelt flowing off the bottom of the recovery furnace in water or weak white liquor to form green liquor

- causticizing clarified green liquor with lime to form white liquor (see Eq. 1a and 1b) containing a minimum amount of unreacted chemicals for the cooking process
- lime mud ($CaC0_3$) washing and filtering, and reburning in a lime kiln to recover lime

The causticizing reaction occurs in two consecutive steps (Eq. 1a and 1b). The lime (CaO) first reacts with water (slakes) to form calcium hydroxide ($Ca(OH)_2$), which in turn reacts with sodium carbonate to form sodium hydroxide (NaOH), which is an active chemical used in pulping. The reaction (Eq. 1b) also produces lime mud, which mainly consists of precipitated calcium carbonate ($CaCO_3$) particles, as a by-product. The purpose of the lime reburning process is to convert the lime mud back into reburned lime for reuse in the causticizing process (Eq. 1a). The lime mud reburning process is described in more detail in Chapter 2.3.

$$CaO\ (s) + H_2O \text{ -> } Ca(OH)_2\ (s) \tag{1a}$$

$$Ca(OH)_2\ (s) + Na_3CO_3\ (aq) \text{ -> } 2\ NaOH\ (aq) + CaC0_3\ (s) \tag{1b}$$

2.1.2. Environmental control

The pulp mill uses amounts volumes of water. In fact the pulp and paper industry is one of the largest industrial process water consumer. The sources of the large amounts of wastewater containing suspended solids, and compounds that increase the BOD (biochemical oxygen demand), are wood handling and debarking, and the screening and cleaning operations that take place during the pulping process (Smook, 1992). The condensates from digesters and evaporators are a low-volume, but high BOD, effluent. Some of these condensates also contain reduced-sulfur compounds. Water effluents from the bleaching process also contain AOX, which is a measure of the halogens (chlorine) present in organic matter. Virtually all kraft pulp mills have wastewater treatment systems to reduce effluents (see e.g. Springer, 1993). In the past ten years, there has also been a desire to reduce the use of chlorine chemicals to bleach the pulp. According to Hynninen (1998), processes that make use of chlorine dioxide and oxygen compounds and ozone have gradually replaced the bleaching processes employing elemental chlorine.

The principal gaseous air pollutants formed during pulping and the chemical recovery processes are oxides of sulfur (mainly SO_2), oxides of nitrogen (NO_x), carbon monoxide

(CO), and total reduced-sulfur (TRS) compounds (Springer, 1993). In addition to these gaseous emissions, particulates are emitted from the combustion processes such as the recovery furnace and lime kiln, and power boilers. The emissions of oxides of nitrogen are formed whenever oxygen and nitrogen are exposed to high temperature. The main source of NO_x emissions is the lime kiln, because the temperature in the recovery furnace is not high enough to form noteworthy quantities of NO_x. Small quantities of nonsulfur organic compounds (hydrocarbons) and inorganic compounds are also released. Digesters and evaporators are the most concentrated sources of volatile organic compounds (VOC).

The main airborne emissions from the kraft pulp mill are, however, the sulfur compounds. The dominant source for sulfur dioxide emissions is the recovery furnace due to the presence of sulfur in the heavy black liquor. The lime kiln and smelt-dissolving tank also emit some sulfur dioxide. The major sources of TRS emissions include digester blow and relief gases, vacuum washer hood and seal tank vents, multiple-effect evaporation hot well vents, recovery furnace flue gases, smelt dissolving tanks, slaker vents, black liquor oxidation tank vents, lime kiln flue gases, and wastewater treatment operations (Springer, 1993; I). At modern pulp mills, venturi scrubbers and electrostatic precipitators are employed for particulate and gaseous emission control. In addition, virtually all the concentrated and most of the diluted NCGs (non-condensible gases) are treated by collecting the gases in sealed systems and eliminating odorous compounds by converting them into non-odorous forms, see e.g. Pinkerton (1999) and Das and Jain (2001)

The operations within the pulp mill also result in the formation of a range of solid and sludge-like wastes. In terms of volume, the major waste streams are wastewater treatment and scrubber sludges, boiler and furnace ash and wood processing residuals. There are also some smaller amounts of solid waste such as slaker grits and green liquor dregs derived from chemicals recovery (Springer, 1993). Potential environmental hazards from residual wastes are associated with trace constituents (e.g. chlorinated organic compounds) that partition from the effluent into the sludge. Two major disposal methods used at the pulp mills are incineration and land filling of the sludges (see e.g. Hynninen, 1998).

2.2. Lime reburning process

2.2.1. Lime calcination in a rotary lime kiln

The recausticizing plant is an essential part of chemical recovery at the pulp mill (see Fig. 2). It uses dissolved smelt from the recovery boiler as a raw material and consumes lime to produce white liquor, which is an active chemical used in pulping. It also produces lime mud, which mainly consists of precipitated calcium carbonate ($CaCO_3$) particles, as a by-product. The purpose of the lime reburning process is to convert the lime mud back into reburned lime for reuse in the causticizing process. The primary method used for the required high temperature treatment of the lime mud has been, and is still today even, a rotary lime kiln, as described e.g. in Mehra (1979) and in Schroderus et al. (2000).

The lime mud recovered from the white liquor clarification, which is the last stage in the causticizing process, contains substantial amounts of residual white liquor and therefore also large quantities of sodium hydroxide (NaOH) and sodium sulfide (Na_2S). These compounds must be removed from the mud because excessive amounts of sodium and/or sulfide in the mud will impair the operation of the kiln process. According to Prakash and Murray (1973), Steen and Stijnen (1984) and II, the amount of Na_2S fed into the kiln is also directly related to the TRS emissions. Furthermore, according to Tran and Barham (1991) and Tran et al. (1993), ring formation in the kiln is associated with a high residual sodium content of the mud. Furthermore, these sodium compounds are valuable chemicals, and need to be recycled back to the process. In order to avoid these problems, the lime mud must be washed and de-watered before it is fed into the kiln. At pulp mills a precoat type of rotary drum filter is normally used for mud washing and de-watering (see e.g. Arpalahti et al., 2000).

A lime kiln is a large, direct-contact and counter-flow heat exchanger with a length of between 50 and 120 m, and a diameter of between 2 and 4 m. The mud is fed into the cold-end of the kiln and it then moves down the gradient of the kiln as a result of the inclination and rotation. The reburned lime is discharged from the kiln through the product coolers located at the hot-end of the kiln. The typical retention time of solids in the kiln is in the range of 3 to 4 hours. The heat energy is supplied to the kiln by means of a burner installed at the hot-end of the kiln. According to Arpalahti et al. (2000), the energy consumption of a modern kiln operating near to nominal capacity is typically in the range of 5.5 to 6.5 GJs per ton of reburned lime produced.

The energy required for the calcination reaction represent roughly 50 % of the total energy consumption, assuming a mud moisture content of about 75 - 80 %. 15 - 20 % of the energy is typically wasted through shell heat losses and sensible heat losses of the reburned lime. The remaining 30 % - 35 % of the energy input is used for evaporating off the moisture, and lost as flue gas heat. According to Puhr (1988), Lewko (1995) and Jellison and Leichliter (1995), the energy efficiency of the kiln is, however, strongly dependent on design factors and how the process is operated. The most common fuels are natural gas and heavy fuel oil. Methanol and tall oil, which are readily available at pulp mills, are also sometimes used as an additional energy source (see e.g. Green and Hough, 1985). Some mills also use alternative fuels such as biomass (V). Primary combustion air is forced into the kiln, together with the fuel. In contrast, secondary combustion air is induced into the kiln by the low negative pressure maintained by a draught fan located in the exhaust system. The resulting flow of hot combustion gases distributes the heat along the length of the entire kiln.

Conceptually, the kiln can be divided into four process zones: drying the wet mud, heating the dry solids up to the reaction temperature, calcining the $CaCO_3$ into CaO, and subsequent agglomeration of the formed CaO powder. During drying the residual moisture present in the mud is removed thermally. After the drying stage, the temperature of the solids slowly starts to rise. The temperature rise settles down when the calcination reaction, depicted in Eq. 2, starts to consume heat energy (Green and Hough, 1985). The reaction heat required is 1786 kJ/kg of $CaCO_3$ decomposed at 900 °C.

$$CaCO_3\,(s) \rightarrow CaO\,(s) + CO_2\,(g) \qquad (2)$$

After calcination, the reburned lime is in the form of a very fine powder. Therefore, in order to produce a usable product, it needs to be heated further to achieve agglomeration of the fine CaO powder into granules. According to Hanson (1993), undesired sintering starts immediately when the $CaCO_3$ dissociates into CaO. Sintering has a detrimental effect on the reactivity of the reburned lime due to the considerable decrease in the specific surface area.

2.2.2. Lime kiln emissions

The flue gases from the lime kiln may contain dust, nitrogen oxides, sulfur dioxide and reduced-sulfur compounds (see e.g. Arpalahti et al. 2000). Dust formation in the kiln takes place through two mechanisms: the formation of lime mud dust during mud drying, and the vaporization of alkaline compounds at high temperatures. The lime mud dust mainly consists of relatively large $CaCO_3$ and $CaSO_4$ particles, and it can therefore be easily separated from the flue gas by a wet-scrubber and/or an electrostatic precipitator, as described e.g. in Hynninen (1998). In contrast, the vaporization of sodium compounds and their subsequent condensation when the flue gas cools down results in the formation of extremely fine Na_2SO_4 and/or Na_2CO_3 particles.

Nitrogen oxides are formed during combustion through the formation of thermal NO_x and the decomposition of organic nitrogenous compounds in the fuel (see e.g. Haspel, 1989). Thermal NO_x is formed when the N_2 and O_2 in the combustion air react with each other at temperatures above about 1100 ?C. The rate of NO_x formation increases along with an increasing excess of burning air or temperature. Therefore, according to Arpalahti et al. (2000), in addition to an appropriate burner design, the amount of excess burning air plays a critical role in reducing NO_x emissions. Decomposition of organic nitrogen compounds takes place already at about 650 ?C and the rate of decomposition is therefore primarily dependent on the content of nitrogen compounds in the fuel. Sulfur dioxide (SO_2) is also always formed during combustion if sulfur compounds are present. In the case of the lime kiln, the major sources of sulfur are the sulfur in the fuel and in NCGs (non-condensible gases), if they are burnt in the kiln. As long as the amount of sulfur is less than the stoichiometric amount of sodium in the mud, practically all of the SO_2 formed is, however, captured as sodium sulfate (Na_2SO_4), and returned back to the process.

TRS emissions from the lime kiln consist mainly of hydrogen sulfide (H_2S). According to Prakash and Murray (1973) and Steen and Stijnen (1984), the main source of H_2S, during normal operation, is the residual sodium sulfide (Na_2S) in the mud. The Na_2S content of the mud is dependent on the design and operation of the filters, as well as on the filtration properties of the mud (see e.g. Davey et al., 1989 and II). In the kiln, the mud is exposed to an atmosphere containing about 20 % carbon dioxide (CO_2). CO_2 is absorbed in the solution and lowers the pH of the remaining solution. At lower pH values and a temperature of about 200 °C - 250 °C, the soluble sulfide present in the mud decomposes to form H_2S, as shown in Eq. 3a. At higher temperatures, however, most of the H_2S formed will be directly oxidized to SO_2 (see e.g. Jäntti, 1999). According to Blosser et al. (1975), Steen and Stijnen (1984) and II, the oxidation reaction (Eq. 3b) speeds up as the temperature or excess oxygen content of the flue gas increase. Hence, the shorter the drying time of the mud and the higher the excess oxygen favoring H_2S oxidation to SO_2, the lower is the H_2S concentration of the flue gases.

$$Na_2S + CO_2 + H_2O \rightarrow H_2S + Na_2CO_3 \quad (3a)$$

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \quad (3b)$$

H_2S may also be formed in the hot-end of the kiln if sulfur-containing fuel is used or NCGs are burned in the kiln (Caron, 1989). According to Cardfelt and Steen (1976), this H_2S is, however, instantaneously oxidized to SO_2 in the normal burning-zone conditions due to the high temperature and the presence of excess oxygen.

TRS emissions can be decreased by chemical dewatering aids used to improve mud washing prior to the kiln (Ford, 1994) and/or by flue gas treatment with a specially designed wet scrubber (see e.g. Trauffer, 1995).

2.3. Rotary lime kiln control

2.3.1. Control challenges and objectives

The complex dynamics and multi-variable nature of the lime kiln process, with its non-linear reaction kinetics, long time delays and variable feed characteristics, make the process inherently difficult to operate efficiently. During its operation, many interconnected variables must be considered and control actions must be designed to meet multiple and sometimes conflicting objects. Furthermore, some of the measurements are unreliable and/or inaccurate. The operation may also be upset by severe disturbances. In addition, certain process variables must be maintained within predefined constraints in order to ensure safe operation of the process and to protect the environment. Control of the kiln process is thus, in many respects, a demanding task and therefore most of the kilns have been and are still operated without supervisory-level control system (Arpalahti et al. 2000). The absence of closed loop controls, however, results in inefficiencies in fuel consumption and variation in reburned lime quality (see e.g. Leiviskä, 1999). Furthermore, manual control increases the risk of environmental impacts, especially in the form of reduced-sulfur emissions (II, IV), and the probability of equipment failures such as damage to the refractory linings of the kiln.

In contrast, there are outstanding economical and the environmental improvement potentials associated with improved control. Firstly, according to Crowther et al. (1987), Pearson and Dion (1999) and III, the energy consumption can be decreased by 2.5 % to 10 %

when the kiln control is improved. The potential for reducing the overall costs of the operation is considerable due to the fact that the fuel costs are a major expense in lime production. The benefits associated with a more stable reburned lime quality can also be significant, although these improvements are not as easily quantified as energy savings. The quality of the reburned lime significantly influences the slaking and the rate of the causticizing reaction (Theliander, 1988). Furthermore, the reburned lime quality affects the separation properties of the mud produced, and hence also the white liquor quality. As a result, the improved reburned lime quality has an indirect effect on the entire pulp mill operation.

According to Uronen and Leiviskä (1989), Scheuer and Principato (1995) and IV, flue gas emissions can also be decreased by eliminating, or at least reducing, the occurrence of process upsets by means of improved control. The costs associated with repairing the refractory bricks can also be reduced. According to Moore et al. (1991) and McIlwain (1992), the service life of the bricks can be increased from 15 % to 30 % if the number of high temperature excursions is reduced. Furthermore, lime kilns are normally required to operate near or above design capacity, especially in older mills, see e.g. Brewster and Kocurek (1992), Osmond et al. (1994) and IV, and therefore the kiln process also often limits the production capacity of the pulp mill. As a result, if production capacity can be increased, it frequently has an impact on the overall production capacity.

The main objectives of the supervisory-level control system for the lime kiln process are to produce a sufficient amount of high quality lime meeting the requirements of the down stream process with the highest throughput possible, while minimizing its energy consumption, maintenance costs and environmental impacts.

2.3.2. Applied control approaches

The control of rotary kilns has been studied since the early 70's. The first applications were models based on the dynamics of the solids phase, the fundamental principles of heat transfer mechanisms, and the kinetics of the drying, heating and calcining reactions. The models were used to estimate the temperature of the solids, flue gas and refractory along the length of the kiln and also to predict the decomposition of the $CaCO_3$ to CaO. These models, and many of the models since developed, have provided a useful insight into the kiln process and also increased our understanding of the interactions and time delays inherent in the process (see e.g. Castro et al. 2001). Although phenomenological models have been relatively successful in simulating the operation of a rotary kiln, very few, if any, of these models have been extended from the simulation stage to the control of an industrial kiln. According to Barreto (1997), the main reason for this has been the difficulties in achieving an adequately accurate model of the rotary kiln process.

The main emphasis subsequently turned to developing kiln control systems based on empirical models, as described e.g. in Uronen et al. (1976) and in Uronen and Aurasmaa (1979). The first commercial supervisory-level system for the lime kiln was developed on the basis of these studies and its first industrial applications appeared already at the end of the 1970's in a Finnish pulp mill (Elsilä et al., 1979). Other kiln control systems based on empirical models were also reported during the 1980's in the Unites States (see e.g. Bailey and Willison, 1985). The structure and parameters of empirical models do not necessarily have any physical significance, and therefore, these models cannot be directly adapted to different operating conditions.

The first rule-based expert system (RBES) for kiln control was developed in 1982 and, since then, the system has been further developed, as described in Dekkiche (1991). Other rule-based systems for controlling rotary kilns have also been developed and reported, e.g. by Hall (1993) and Hagemoen (1993). The RBES approach, although it is widely used in various types of expert system, may lead to serious testing and maintenance problems in large-scale applications where the rule-base becomes extremely large.

The first experiments in applying fuzzy logic (FL) to rotary kiln control were carried out at a Danish cement plant in 1978. These experiments were inspired by instructions found in a textbook for kiln operators, which contained control rules for manual operation. The first two industrial installations took place the next year (King, 1986). According to Ostergaard (1996), the first lime kiln control system based on FL was installed in a Swedish pulp mill in the following year. Other industrial, FL-based kiln control applications have since been reported e.g. by Scheuer and Principato (1995) and by Nilsson (1997). Fuzzy logic provides a unified framework for modeling operator's actions and for taking incomplete information into account. However, acquiring the required knowledge, e.g. on the basis of operator interviews, may be a tedious and time-consuming task.

In addition to FL and RBESs, rotary kiln applications based on the model predictive control (MPC) approach have recently been reported in the literature. Simulation results are described in Charos et al. (1991) and in Zanovello and Budman (1999). The results of industrial applications can be found in Smith and Aggarwal (1998), in Pearson and Dion (1999), in Valiquette et al. (1999) and in Carter and Rozek (2000). In MPC, prediction of the future plant behavior is used to compute the appropriate control actions and, therefore, the controller requires a dynamic model of the process. Obtaining models that are applicable over the whole operational range of the process may, however, necessitate a considerable amount of identification work (see e.g. Morari and Lee, 1999). Nevertheless, the MPC approach is also widely used, in other fields of the industry, and it is inevitable that interest in MPC will continue and even intensify.

During the 90's, neural network (NN) based systems have been tested for the identification and control of the lime kiln process (see e.g. Ribeiro and Correia, 1995). NNs have also been tested for the quality prediction of the reburned lime, as described in Järvensivu and Seaworth (1998) and in Ribeiro (1998) and for the feedforward control of the kiln process in conjunction with supervisory-level feedback controllers (III). A rule-based kiln control system, in which NNs are used to represent the rule set, has been reported in Bo et al. (1997). A hybrid kiln control system incorporating a predictive-adaptive controller to maintain the process close to the setpoints generated by an expert system was described in Barreto (1997). Recently, the linguistic equation (LE) approach, which provides a novel technique for combining heuristic and data-driven knowledge, has also been applied for the control of an industrial lime kiln (III, IV, V).

To sum up, the state of the art in the rotary kiln control is that the systems based on the FL- and RBES approach have already proven their applicability for controlling industrial kilns. Control systems combining various intelligent control and prediction techniques that are capable of adapting to changes in the operating conditions will be the future trend.

3. Intelligent systems

In this chapter, the field of intelligent systems is first briefly reviewed and references to additional information are provided. The linguistic equation (LE) approach is then shortly introduced. The focus is on the principles applied in steady state LE models used for feedforward control and in adaptive feedback LE controllers. The basics of the LE approach and various LE-based applications in the field of process modeling, simulation and control are described in more detail by Juuso (1999).

3.1. Brief review of intelligent control techniques

The widely used term artificial intelligence (AI) refers, in the field of process engineering, to computer programs and systems that utilize intelligent implementation techniques such as rule-based expert systems (RBESs), fuzzy logic (FL), neural networks (NNs) and genetic algorithms (GAs), to extend the power of computers beyond the strictly mathematical and statistical functions (see e.g. Stephanopoulos and Han, 1996). According to Boullart et al. (1992), industrial process control and automation is undoubtedly an important application area for AI. In this field, intelligent techniques facilitate the creation of applications that have the ability to collect knowledge and, after reasoning with this knowledge, to resolve complex problems that require a certain degree of intelligence if they have to be solved by a human expert. These techniques also make it possible to extract useful information about the process and its behavior from the large amount of process data that is normally routinely collected and archived in databases by means of automation and information systems. This supplementary information can then be used in an intelligent manner to develop control systems that could never have been attained on the basis of the heuristic knowledge of domain experts alone.

According to Driankov et al. (1993), applications based on the rule-based expert system or fuzzy logic approach typically attempt to emulate the reasoning and decision-making process of an expert (or a set of experts) in a particular field, and/or to replicate, as closely as possible, the actions of operators controlling the process. They therefore rely for the most part on rules of thumb, as well as on practical experience of the process behavior. The knowledge that is often available in only a heuristic form is characteristically represented and formalized in the computer programs as a set of crisp and/or fuzzy if-then rules, i.e. rules having a condition and an action component, that are then executed in parallel. Consequently, both rule-based expert systems and fuzzy logic are especially applicable when a relatively comprehensive understanding of the process is available and an exact mathematical model of the process is either impossible or prohibitively expensive to develop. The potentials of fuzzy logic approaches in general grow as the degree of vagueness and nonlinearities in the controlled process increases (see e.g. Yager, 1997). Accordingly, Zumberge and Passino (1998) have demonstrated superior performance of fuzzy logic compared to conventional control techniques in strictly controlled laboratory experiments. A comprehensive review of fuzzy logic applications in process control and supervision is given, for instance, in Isermann (1998).

Neural networks, which try to replicate certain characteristics of the neural activity in the human brain, work in a very different manner. Mathematically, they are merely a collection of efficient algorithms used to approximate a nonlinear function. According to Zurada (1992) and Bartos (1997), the most important features from the practical point of view are their ability to learn and generalize underlying relationships from the historical process data, and to use this learned knowledge for predicting the future behavior of the process. Therefore, the natural domain for neural networks is in applications where first principle models and heuristic knowledge of the process are considered to be lacking, but a large set of process data containing relevant and representative information is available (Hunt et al., 1992; King, 1998). The practicality of such an inferential control schema has, for instance, been emphasized by Willis et al. (1992) where neural networks model were used to provide estimates of the controlled output for feedback control. Whereas, an extensive review of various applications utilizing neural networks for chemical process control is presented in Hussain (1999). The review shows the multilayered neural network as the most widely applied network architecture for process control applications.

Genetic algorithms, which mimic evolution in biological systems, are a systematic approach for finding a near-optimal solution in a reasonable time for a large problem that possesses numerous alternative solutions (Goldenberg, 1989). As a general rule, the genetic algorithms works with a population of individuals, each of which is a candidate solution to the problem. Each cycle, the fitness of each individual string is first assessed, subsequently a new population is formed by selecting strings from the current population with a probability determined by their fitness. A few members of the population are chosen at random and then reproduced, combined and/or adapted. In this way, the process evolve through hundreds or thousands successive generations toward a near-optimal solution, see e.g. Cartwright (1993) and Miettinen et al. (1999).

All intelligent techniques offer enhanced opportunities and more advanced task-oriented capabilities for solving highly complex, nonlinear problems that are beyond the scope of conventional control techniques, or which are too costly or time consuming. On the other hand, although each technique has its strengths and advantages, they also all possess weaknesses and practical limitations. For this reason, a technique superior for one specific type of problem may prove to be inadequate for another type of problem (Zadeh, 1996). In addition to finding a critical need that can be met by the intelligent techniques essential for the success in applying them to complex industrial-scale problems, is the knowledge of the process and the practical problems concerned. Furthermore, it is very important that appropriate techniques with specific capabilities and constrains are selected in order to resolve the recognized problems. The importance of process knowledge and the selection of appropriate techniques have also been highlighted by Fadum (1993) and Chiu (1997).

In fact, these intelligent techniques are, for the most part, complementary and synergistic rather than competitive, and better results can therefore be obtained when they are used in combination rather than in stand-alone mode. Since the launch of the concept of soft computing by Zadeh in the early 1990s (Zadeh, 2001), growing interest has been shown in systems that take advantage of the different intelligent techniques, in combination with more conventional techniques, for solving complex, large-scale control problems. Funabashi et al. (1995) and Zhou et al. (1998) have also concluded in their papers that this type of hybrid systems are the future direction of intelligent systems. Extensive reviews of industrial applications of soft computing are, for instance, presented by Ovaska et al. (1999) and by Dote and Ovaska (2001). The main limitation associated with the hybrid approach is the broad knowledge required about different soft computing techniques during system development, and an increased need for the training of the staff responsible for the maintenance of the system. There is also a lack of suitable design methods and theoretical considerations about the system analysis.

An example of this new era of AI and computational intelligence is the linguistic equation (LE) approach introduced in 1991 by Juuso and Leiviskä (1992). According to Juuso (2000), linguistic equations provide a very compact implementation method to combine both the quantitative and qualitative knowledge in the development of nonlinear multivariable systems (see also Fig. 3). Originally, the LE approach was applied merely for simulation and modeling, but since then its use has been expanded to process diagnostic, intelligent analyzers and also to supervisory-level process control purposes.

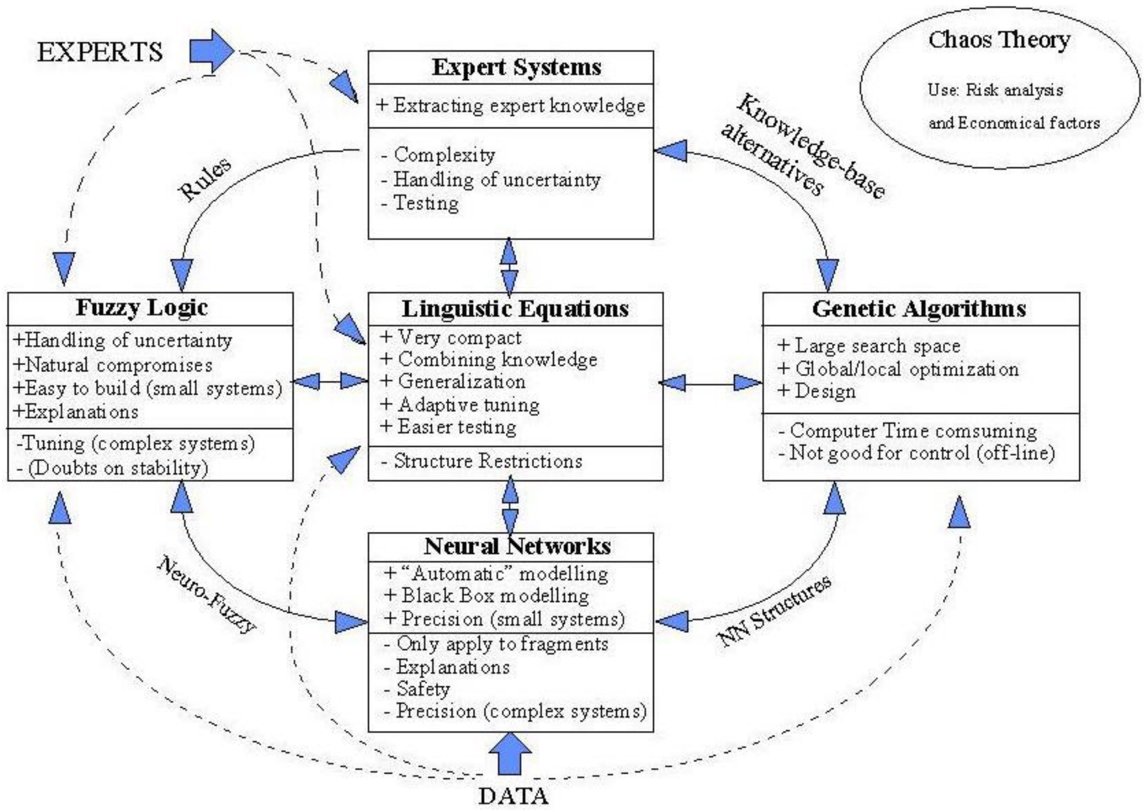


Fig. 3. Computational intelligence and the linguistic equation (LE) approach (Juuso, 1996).

3.2. The linguistic equation approach

The linguistic equation (LE) approach, in which traditional fuzzy systems described by means of rules and membership functions are represented by equations and non-linear membership definitions, provides a comprehensible and flexible environment for supervisory-level process control purposes. According to Juuso et al. (1997), the first direct LE-based controller was tested in 1996 at a solar power plant in Spain. Since then, however, the controller and also the entire concept of LE-based control has undergone continuous development, see e.g. Juuso et al. (1998) and Järvensivu et al. (2000). The framework of the LE-based control is especially applicable when adaptation to the changing properties and wide operating ranges of the process is required, and when efficient disturbances rejection capability of the controller is an essential requirement. The fundamental principles applied in steady state LE models and in multilevel adaptive LE controllers, which have been implemented as a part of the supervisory-level control system for the lime reburning process (see Chapter 5.3) are described in the following.

3.2.1. Steady state models based on the LE approach

The general LE model can be represented as follows:

$$W \cdot X^T + B^T = 0 \tag{4}$$

where a matrix ***W*** defines the directions and strengths of the interactions between variables given by a vector *X*. The bias term *B* can be used to shift the model from the origin. According to Juuso (1999), this linear equation can also be used for approximating non-linear systems by applying non-linear membership definitions (NLMDs) for the variables that are used in the LE model.

The MISO type of steady state LE models (see Fig. 4) can be represented for a specific output variable, y_i, as follows (V):

$$lv(\mathrm{Y}) = \sum_{j=1}^{n} w_{ij} \times lv(\mathrm{X}) \quad \mathrm{X} \in \{x_{ij}(k)\}, \mathrm{Y} \in \{y_i(k)\} \tag{5}$$

which is a special case of the equation $\boldsymbol{W} \cdot X^T = 0$, with the interaction weights $W = [w_{i1}\ w_{i2}\ \ldots\ w_{in}\ {-1}]$ and variables $X = [lv(x_{i1}(k))\ lv(x_{i2}(k))\ \ldots\ lv(x_{in}(k))\ lv(y_i(k))]$. $lv(y_i(k))$ is the linguistic value (LV) of the output (y_i) of the model. $lv(x_{ij}(k))$ is the LV of the input variable, x_{ij}, applied as an input in the model. w_{ij} is the real valued weight factor describing the direction and strength of the interaction between the input variable, x_{ij}, and the output variable, y_i (note: the sum of the weights should be 1.0). In practice, each predictable output variable (y_i, $i=1 \ldots m$) is represented by means of a specific equation with the pre-determined set of the input variables (x_{ij}, $j=1 \ldots n$).

The LVs of the input variables, $lv(x_{ij}(k))$, is determined by means of an NLMD, which transforms the value of the variable, x_{ij}, into LV with the range lv ∈ [–2, 2]. The LVs of -2, -1, 0, 1, 2 correspond to the linguistic terms very low, low, normal, high and very high, respectively. The NLMD consists of two second-order polynomials that are monotonously increasing and connected at the LV of zero. The first polynomial function is used for the LVs between -2 and 0, and the second for the LVs in the range between 0 and 2. Coefficients of the NLMDs can be obtained from the process data by fitting a second-order polynomial through the data points and/or by using the process expertise, i.e. based on the experts' knowledge of the process behavior (see Juuso, 1999).

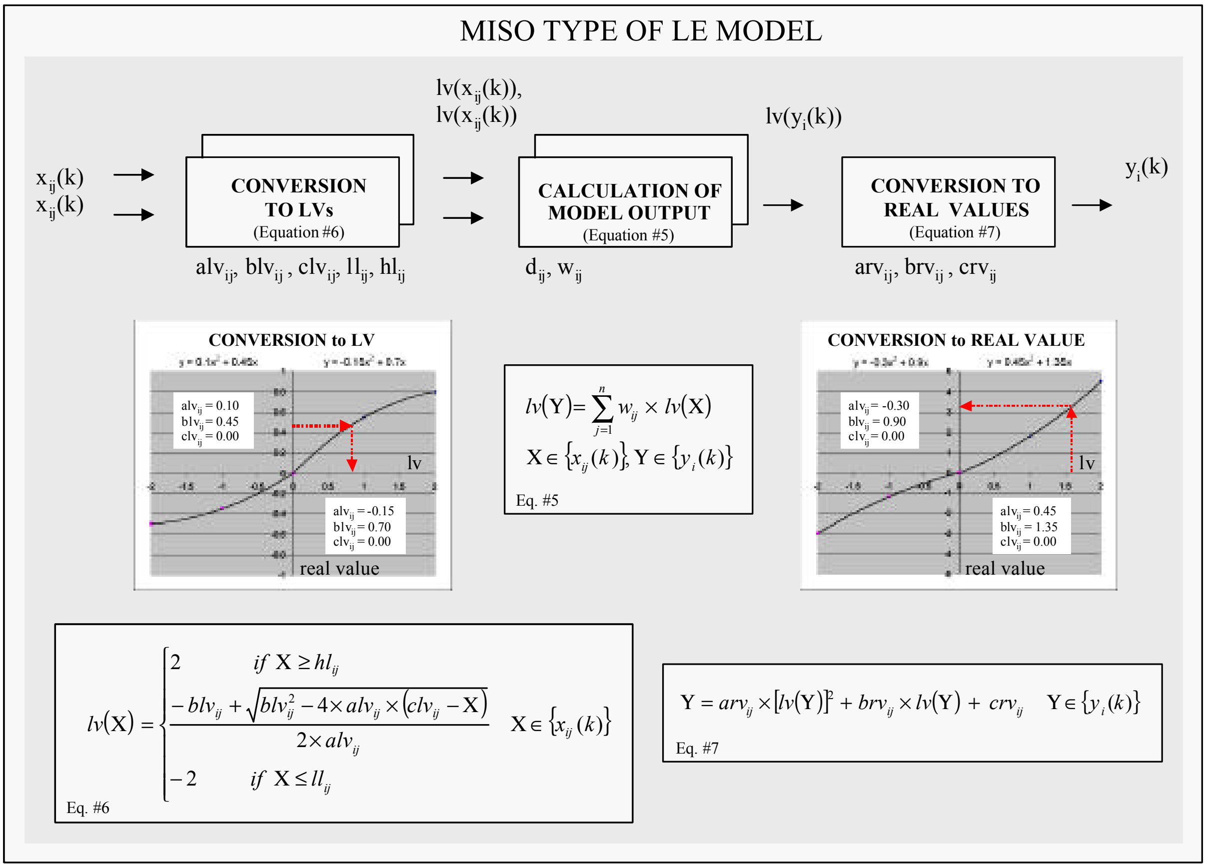


Fig. 4. Schematic presentation of the MISO type of LE model.

When the polynomial functions have been defined, conversion of the real values to the LVs can then be made using the following equation (III, V):

$$lv(X) = \begin{cases} 2 & if\ X \geq hl_{ij} \\ \dfrac{-blv_{ij} + \sqrt{blv_{ij}^2 - 4 \times alv_{ij} \times (clv_{ij} - X)}}{2 \times alv_{ij}} & \\ -2 & if\ X \leq ll_{ij} \end{cases} \quad X \in \{x_{ij}(k), e_{ij}(k), \Delta e_{ij}(k)\} \tag{6}$$

where alv_{ij}, and blv_{ij} are constants obtained directly from the polynomials (note: the constant alv_{ij} and blv_{ij} are different for the first and the second polynomial function). clv_{ij} is the value of the variable corresponding to the LV of zero. ll_{ij} and hl_{ij} are the variable corresponding to the LVs of –2 and 2, respectively. The above-described NLMDs and the conversion of the real values to the LVs correspond closely with membership functions and fuzzification applied in the traditional fuzzy systems. While, the implementation of Eq. 5 is compatible with the rule base, i.e. relations between rule premises and conclusions, and the inference engine used for interpretation and accumulation in fuzzy-rule based systems.

After calculating the LV of the model output, $lv(y_i(k))$, it is converted back to the value, $y_i(k)$, using the following equation (V):

$$\mathrm{Y} = arv_{ij} \times [lv(\mathrm{Y})]^2 + brv_{ij} \times lv(\mathrm{Y}) + crv_{ij} \quad \mathrm{Y} \in \{y_i(k), \Delta u_{ij}(k), sc_i(k)\} \tag{7}$$

where arv_{ij}, and brv_{ij} are the constants of the polynomials and crv_{ij} is the value corresponding to the LV of zero. This conversion of the LV to the crisp value is analogous with defuzzification in the conventional fuzzy-rule based systems. According to Juuso (1999), the output of the steady state LE model, $y_i(k)$, can be applied for feedforward (FF) control purposes (see Chapter 5.3).

3.2.1. Multilevel adaptive MISO type of LE controller

The first single equation LE controller tested at the solar power plant in 1996 has since been improved in many respect. According to Juuso et al. (1998), an operation condition controller and a predictive LE controller with braking action were introduced in 1997. This improved multilevel LE controller was adapted to the lime kiln control in 1998 (Juuso, 1999). Later the basic LE controller was extended to several controlled variables in order to accomplish the requirements of the lime kiln control application, as described by Järvensivu et al. (2000). In the kiln control application, adaptive scaling was based on adjustable parameters instead of separate working point model and also the predictive braking action was modified (V). The asymmetrical action was not used in this application (Juuso, 1999).

A schematic presentation of the structure of the multilevel adaptive MISO (multi input and single output) type of LE controller is presented in Fig. 5. This MISO type of supervisory-level feedback controller provides special features for handling non-linearities, large disturbances and changing operating conditions, which cannot readily be met by the standard PI algorithms. A comprehensible review of the features and limitations of PI algorithms is presented, e.g. in Åström and Hägglund (2001).

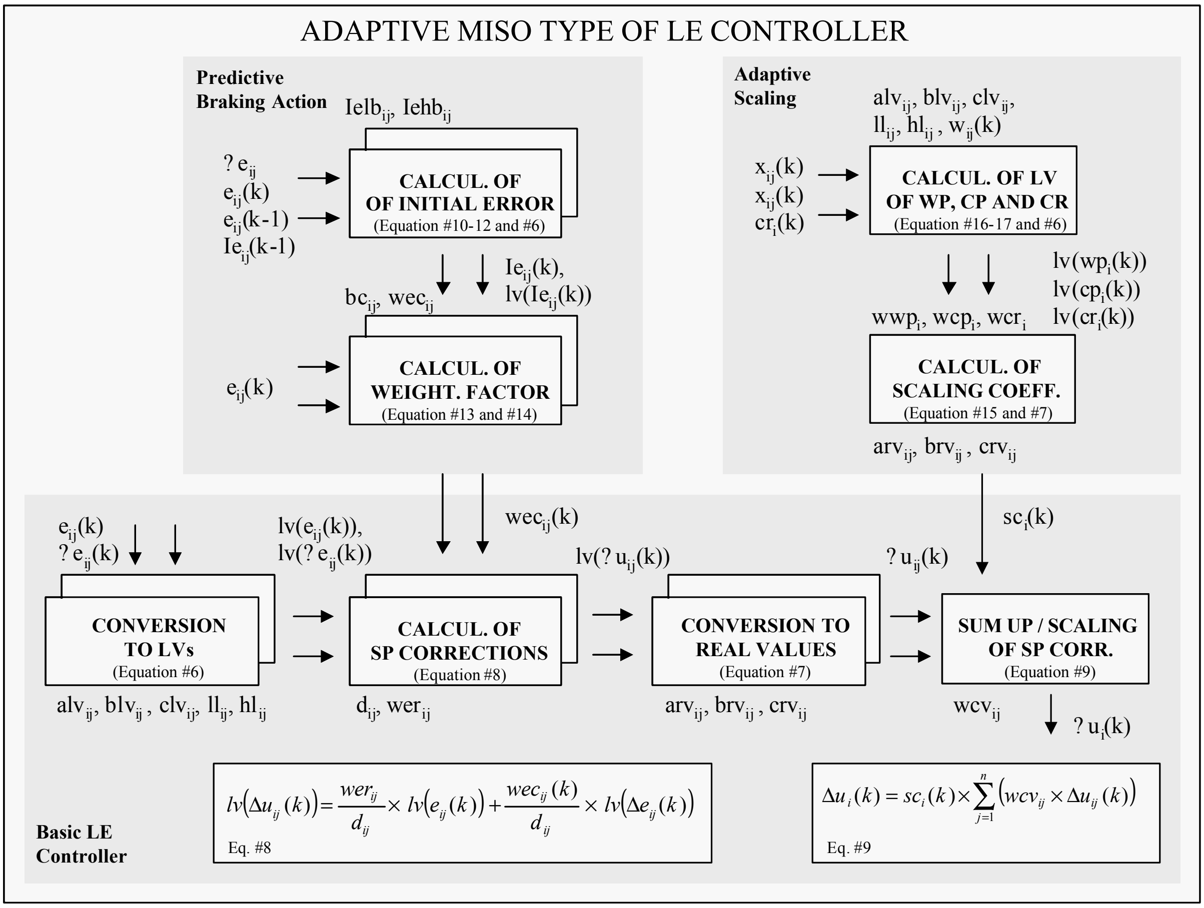


Fig. 5. Schematic presentation of the adaptive MISO type of LE controller.

3.2.1.1. Basic LE controller

A conventional PI type of controller (see e.g. Driankov et al. 1993) can be represented in a general discrete-time form by a single LE as follows (V):

$$lv(\Delta u_{ij}(k)) = \frac{wer_{ij}}{d_{ij}} \times lv(e_{ij}(k)) + \frac{wec_{ij}(k)}{d_{ij}} \times lv(\Delta e_{ij}(k)) \quad (8)$$

which is a special case of Eq. 4, with the interaction weights $W = [wer_{ij}\ wec_{ij}(k)\ -d_{ij}]$ and variables defined as $X = [lv(e_{ij}(k))\ lv(\Delta e_{ij}(k))\ lv(\Delta u_{ij}(k))]$. lv($\Delta u_{ij}$(k)) is the LV of the correction to the manipulated variable, u_{ij}, calculated on the basis of the controlled variables (j =$1...n$). $lv(e_{ij}(k))$ and $lv(De_{ij}(k))$ are the LVs of the error and the derivative of the error, respectively, calculated by means of Eq. 6 (note: $x_{ij}(k)$ is replaced in this case by $e_{ij}(k)$ or $De_{ij}(k)$). The default value for both weights, wer_{ij} and wec_{ij}, is 0.5 (see below for a description of the predictive braking action). $d_{ij} \in$ {-1 1} is a constant used for determining the direction of the control action. After calculating the LV of the correction, $lv(Du_{ij}(k))$, it is converted into the real value, $Du_{ij}(k)$, accordingly to the principle shown in Eq. 7 (note: $y_{ij}(k)$ is replaced in this case with $u_{ij}(k)$).

The output of the MISO type LE controller can then be calculated as the weighted average of the corrections, $Du_{ij}(k)$, determined independently on the basis of the controlled variables (j =$1...n$) as follows (V):

$$\Delta u_i(k) = sc_i(k) \times \sum_{j=1}^{n} \left(wcv_{ij} \times \Delta u_{ij}(k) \right) \tag{9}$$

where $Du_i(k)$ is the feedback (FB) correction to the setpoint of the manipulated variable, u_i (see also Chapter 5.3). $Du_{ij}(k)$ and wcv_{ij} are the correction and weighting related to each of the controlled variables (j=$1...n$). Note: the sum of the weights should be 1.0. $sc_i(k)$ is a dynamically updated coefficient used for scaling the corrections in accordance with the different operating conditions (see below for a description for the adaptive scaling).

3.2.1.2. Predictive braking action

In addition to the basic LE controller described in the above, the *predictive braking action* (PBA) is used to ensure smooth recovery after disturbances. The PBA reduces the risk of oscillation and large overshoot after a sizeable deviation in the controlled variable(s), both of which are common complications especially in processes with long dead times. This PBA concept is closely linked to the gain scheduling and predictive switching control approaches.

The initial error, which is used in calculating the braking rate coefficient (see also Eq. 13), is determined as the error, $e_{ij}(k\text{-}1)$, at the turning point where the derivative of the error changes from positive to negative, or vice versa (note: in practice moving average of the derivative of the error, De_{ij}, is used to avoid fluctuations in the braking). The initial error is defined by the following principle (V):

$$if\ Ie_{ij}(k-1)=0\ and\ e_{ij}(k)\leq Ielb_{ij}\ then$$
$$Ie_{ij}(k)=\begin{cases}0 & if\ \Delta e_{ij}<0\\ e_{ij}(k-1) & if\ \Delta e_{ij}\geq 0\end{cases} \tag{10}$$

$$if\ Ie_{ij}(k-1)=0\ and\ e_{ij}(k)\geq Iehb_{ij}\ then$$
$$Ie_{ij}(k)=\begin{cases}0 & if\ \Delta e_{ij}>0\\ e_{ij}(k-1) & if\ \Delta e_{ij}\leq 0\end{cases} \tag{11}$$

$$if\ Ie_{ij}(k-1)\neq 0\ then$$
$$Ie_{ij}(k)=\begin{cases}0 & if\ Ie_{ij}(k-1)\times\Delta e_{ij}>0\\ Ie_{ij}(k-1) & if\ Ie_{ij}(k-1)\times\Delta e_{ij}\leq 0\end{cases} \tag{12}$$

where $Ie_{ij}(k)$ and $Ie_{ij}(k-1)$ are the new initial error and the previous initial error, respectively. $Ielb_{ij}$ and $Iehb_{ij}$ are the preset low and high boundary for the initial error (note: the braking action is activated only when a relatively large deviation occurs, i.e. the error is above $Iehb_{ij}$ or below $Ielb_{ij}$).

The braking rate coefficient can be calculated after obtaining the LV of the initial error, $lv(Ie_{ij}(k))$, by the following principle (V):

$$if\ Ie_{ij}(k)\neq 0\ then$$
$$brc_{ij}(k)=\begin{cases}bc_{ij}\times lv\big(Ie_{ij}(k)\big)\times\dfrac{e_{ij}(k)}{Ie_{ij}(k)} & if\ Ie_{ij}(k)>0\\[2ex] bc_{ij}\times -lv\big(Ie_{ij}(k)\big)\times\dfrac{e_{ij}(k)}{Ie_{ij}(k)} & if\ Ie_{ij}(k)<0\end{cases} \tag{13}$$
$$else\ brc_{ij}(k)=0$$

where $brc_{ij}(k)\in[0, 2]$ is the braking rate coefficient related to the manipulated variable, u_{ij}, and controlled variable ($j=1\ldots n$). $bc_{ij}\in[0, 1]$ is a manually adjustable braking constant used for fine-tuning the force of braking. Braking reaches a maximum immediately after the tuning point, and then decreases as the error declines and the controlled variable approaches the target value (see the term $e_{ij}(k)/Ie_{ij}(k)$ in Eq. 13). The above-described principle for calculating the braking rate coefficient is recommended when there are long measurement delays. The original principle for calculating the braking rate coefficient, in which braking became stronger when the controlled variable approaches the target value, is described in more detail in Juuso (1999).

In practice, $brc_{ij}(k)$ is used to emphasize the influence of the derivative of the error by means of the following equation (V):

$$wec_{ij}(k) = \left(1 + brc_{ij}(k)\right) \times wec_{ij} \tag{14}$$

where *wec(k)* is the weighting factor used in Eq. 8.

3.2.1.3. Adaptive scaling of corrections

The operation of the basic LE controller is also enhanced by means of *adaptive scaling* (AS), which is used to adjust the control surface in accordance with the changing operating conditions. It therefore extends the accomplished working area of the basic LE controller. Determination of the scaling rate coefficient is made on the basis of the LV of the working point, the power of the control variable, and the cumulative rate of control actions (i.e. corrections made on the manipulated variable), using the following principle (V):

$$lv(sc_i(k)) = wwp_i \times lv(wp_i(k)) - wcp_i \times lv(cp_i(k)) - wcr_i \times lv(cr_i(k)) \tag{15}$$

where $lv(sc_i(k))$ is the LV of the scaling rate coefficient. $lv(wp_i(k))$, $lv(cp_i(k))$ and $lv(cr_i(k))$ are the LVs of the working point (WP), the control power (CP) and the cumulative rate (CR) of the corrections, respectively. wwp_i, wcp_i and wcr_i are weighting related to WP, CP and CR, respectively (note: the sum of the weights should be 1.0). Eq. 15 is a special case of the equation $\boldsymbol{W} \cdot X^T = 0$, with the interaction weights $W = [wwp_i \ {-wcp_i} \ {-wcr_i} \ {-1}]$ and variables $X = [lv(wp_i(k)) \ lv(cp_i(k)) \ lv(cr_i(k)) \ lv(sc_i(k))]$. The LV of the scaling coefficient is converted by using Eq. 7 to the real value, $sc_i(k)$, which is then applied by the basic LE controller (see Eq. 9).

The LV of the working point is determined by the following equation (V):

$$lv(\mathrm{Y}) = \sum_{j=1}^{n} w_{ij} \times lv(\mathrm{X}) \quad \mathrm{X} \in \{x_{ij}(k)\}, \mathrm{Y} \in \{wp_i(k),\ cp_i(k)\} \tag{16}$$

where $lv(x_{ij}(k))$ is the LVs of the variable, x_{ij} $(j=1...n)$, calculated by means of Eq. 6, and used for describing the loading state of the process (note: Eq. 16 and Eq. 5 are the same only input variables are different). $w_{ij} \in [0, 1]$ is the corresponding weight factor (note: the sum of the weights should be 1.0). The LV of the control power, $lv(cp_i(k)$, can be determined by the same principle as the loading state of the process. In this case, $x_{ij}(k)$, stands for the variable(s) related to the gain of the manipulated variable. For instance, variations in the heat energy content of the fuel can be handled with this technique (V).

Whereas, the LV of the cumulative rate of the corrections, $lv(cr_i(k))$, used by Eq. 15 is first calculated by means of Eq. 6 and then determined by the following principle (V):

$$lv(cr_i(k)) = \begin{cases} 0 & if\ \Delta u_i(k) \times cr_i(k) \leq 0 \\ |lv(cr_i(k))| & if\ \Delta u_i(k) \times cr_i(k) > 0 \end{cases} \qquad (17)$$

where $cr_i(k)$ represents the cumulative rate of the corrections, Du_i, made over the preset time period. Note*:* $lv(cr_i(k))$ receives only values between 0 and 2, and it is used to scale down the correction, $Du_i(k)$, when the absolute value of the cumulative rate of the corrections is increasing (see also Eq. 9).

4. Control objectives and requirements for the lime kiln

In this chapter, the field survey of the reduced-sulfur emission carried out at the Wisaforest pulp mill is first briefly summarized. The results of the survey are described in more detail in publication I. Next, the major results of a study that was carried out in order to design an intelligent control system for the lime reburning process are presented. The functional requirements established for the control system are then stated and an overall control schema is subsequently proposed. A more detailed description of various factors affecting the reduced-sulfur emissions and possibilities of reducing the emissions from a lime kiln is given in publication II. The functional requirements established for the control system are presented in more detail in publications IV and V.

4.1. Relative importance of lime kiln TRS emissions (I)

An extensive field survey were carried out at the Wisaforest mill in 1996 and 1997 in order to evaluate the relative importance of different emission sources. During the survey, all the main sources of the TRS emissions were analyzed, and the ambient air concentrations of reduced-sulfur compounds were also measured. According to the results of the field survey (see Järvensivu et al., 1997 and Mäenpää, et al., 1998), the mill complies well with the environmental regulations concerning odor abatement systems and sulfur emissions (Table 1). The main sources of continuous reduced-sulfur emissions were the vent gases from the smelt dissolving tanks, the flue gases from the lime kilns, and the highly diluted non-condensible relief gases from the fiber lines. The annual emissions during 1997 were 112 tones of sulfur per year. The flue gases from the lime kilns accounted for over 10 % of the total emissions.

The effects of continuous emission sources on ground level concentrations were estimated by means of a Gaussian plume model of emission dispersion (SCREEN3, developed by U.S. Environmental Protection Agency). The model is based on the concept of treating each emission source separately as a three dimensional Gaussian distribution (see e.g. Springer, 1993). The emission sources were then ranked on the basis of the estimated ground level concentrations and the momentary emission rates.

An example of the results, presented in Fig. 6, shows the proportion of each emission source out of the total concentration at a distance of 2.5 km from the pulp mill. The figure also shows that the emission sources with a major effect on the ground level concentration in the Pietarsaari city area, were the vent gases from the smelt dissolving tanks, diluted NCGs, and the flue gases from the lime kilns. These three sources accounted for almost 90 % of the total ground level concentration.

To sum up, the lime kiln was found to account for a marked proportion of the emissions and for a relatively high proportion (up to 20 %) of the ground level concentration of reduced-sulfur compounds. According to Järvensivu et al. (1998), the lime kiln emissions could, however, be further reduced by ensuring both a low residual sulfur content of the lime mud fed into the kiln, and proper conditions in the kiln process.

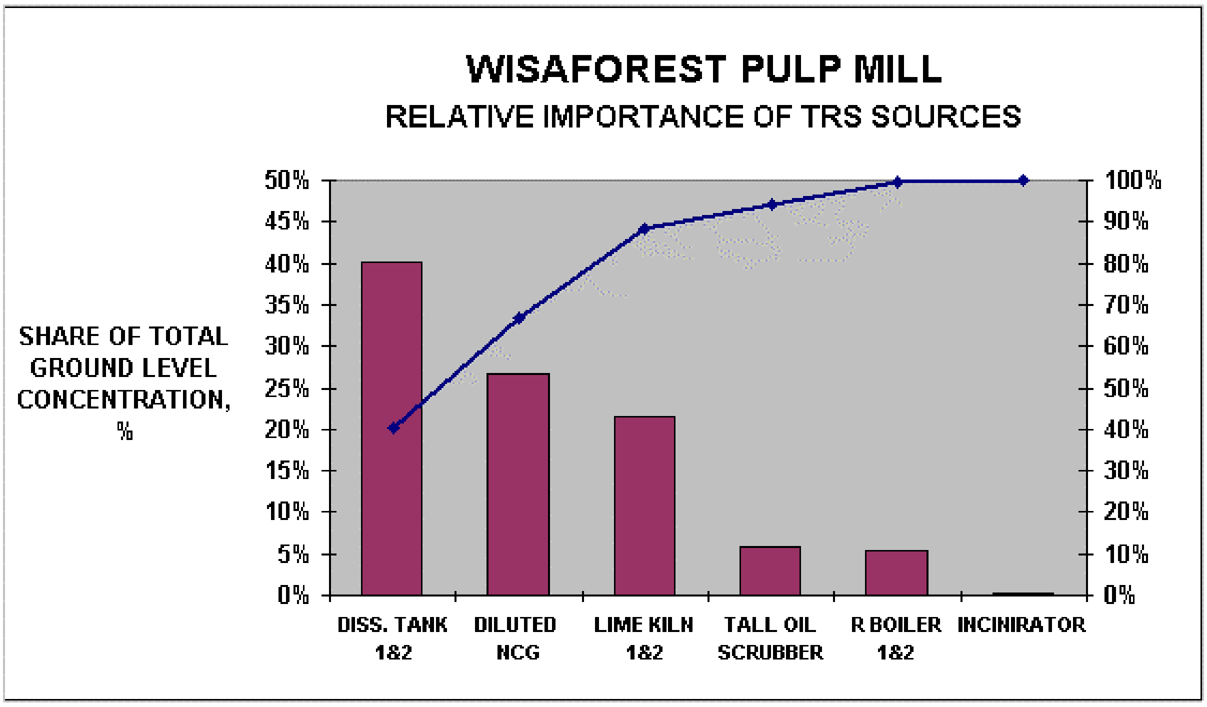


Fig. 6. Proportion of each emission source out of the total concentration in the Pietarsaari city area (I).

Table 1. The environmental regulations and operational results for 1995 and 1997 (I)

	Limit	1995	1997
Total Sulfur Emissions	< 3 kg (SO_2) / t_{pulp}	0.5 kg (SO_2) / t_{pulp}	0.4 kg (SO_2) / t_{pulp}
Dilute NCG Disposal	> 90 % disposal of all dilute NCG relief gases	80.3 %	90.0 %
Concentrate NCG System	In operation > 97 % of the time	99.9 %	99.1 %
Recovery Boilers #1	< 10 mg H_2S/Nm_3 over 95 % of the time on a monthly basis	96.5 %	100 %
Recovery Boilers #2	< 10 mg H_2S/Nm_3 over 95 % of the time on a monthly basis	99.1 %	100 %
Lime kiln #2	< 20 mg H_2S/Nm_3 over 90 % of the time on a monthly basis	92.4 %	97.1 %

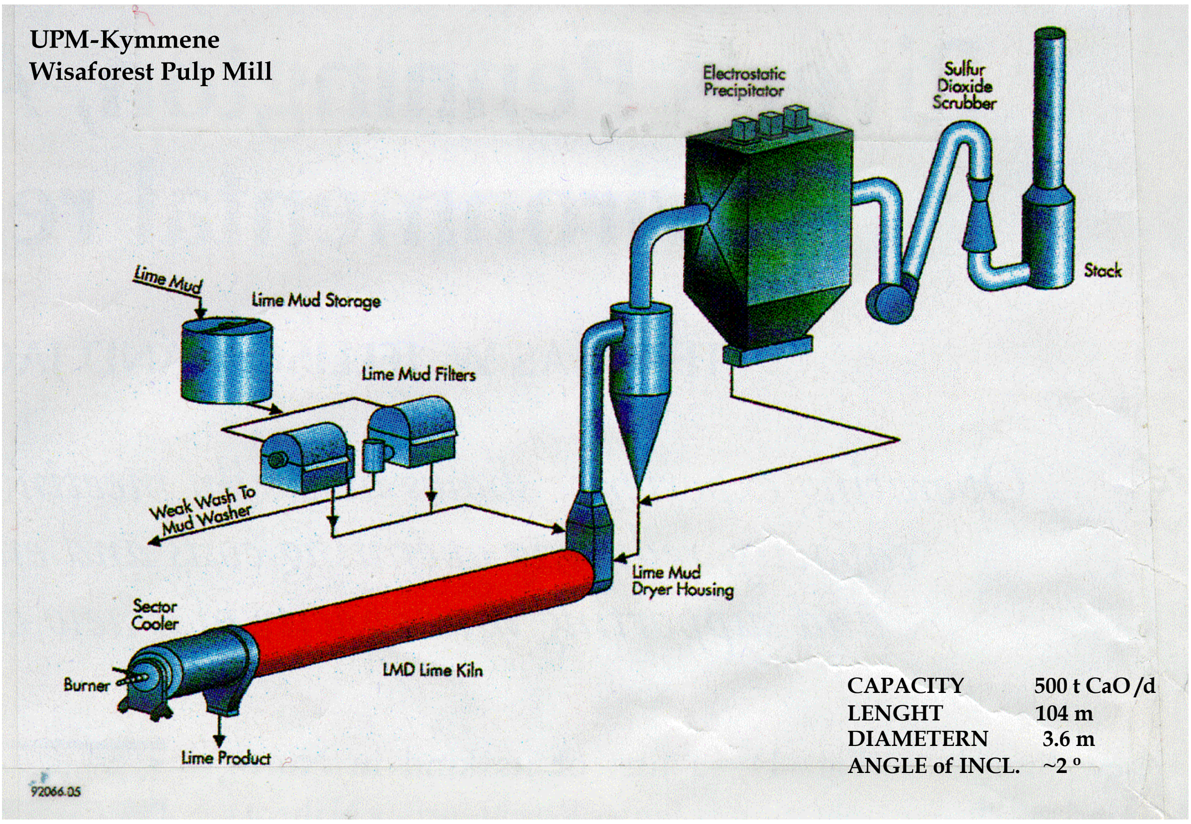


Fig. 7. Overview of the lime reburning process at the Wisaforest pulp mill (III)

4.2. Field study on the operation of the lime reburning process

4.2.1. The lime reburning process at the Wisaforest pulp mill

At the Wisaforest pulp mill, the smelt from two recovery boilers is dissolved and diluted with weak liquor and raw water. The green liquor is fed from the dissolving tanks into the mixing tank where the flow, temperature and density variations are smoothed out. It is then fed into the green liquor clarification in order to remove insoluble materials. After clarification, the green liquor is pumped into two parallel slakers, and the reburned lime is fed at a controlled rate into the slakers. The lime milk continually flows from the slakers into a series of causticizing tanks with a total retention time of about two to three hours. The white liquor produced is then clarified by means of pressurized disc filters, and the liquor is pumped in to the white liquor tanks, while the separated mud is pumped into storage tanks.

The mud discharged from the storage tanks is pumped into the two parallel precoat type of drum filters. After the filters, the lime mud (ca. 75 % dry solids content) is conveyed to a screw feeder, which distributes the mud into the flue gas duct. The fast-flowing flue gas carries the mud into an external lime mud drier (LMD). After separation of the preheated mud from the cooled flue gas, the mud is discharged from the bottom cone of the drier and fed into the cold-end of the kiln. After the LMD cyclone, the flue gas passes through an electrical precipitator and a two-stage venture type wet scrubber. The major part of the dust that escapes the cyclone is captured in an electrostatic precipitator and is fed back into the kiln. Drying and heating of the lime mud continues in the kiln as the mud powder moves down the gradient of the kiln. The heat from the hot reburned lime leaving the kiln is used to preheat the secondary combustion air. Primary combustion air, which is taken between the stationary hood and the product coolers, is forced into the kiln together with the fuel.

The primary fuel for the kiln is generator gas produced through biomass, i.e. sawmill dust, gasification. The wet sawdust, with a dry solids content of about 45 %, is first dried to around 85 % by the hot flue gas from the recovery boiler. The dried sawdust, which has a heat value of around 12 MJ/kg, is fed into the circulating fluidized bed gasifier, where the volatiles are converted into gas (see Karjaluoto, 1985). The generated gas is then led into the kiln and burnt in the air. The principal motivation for sawdust burning is the significant reduction in heat energy costs. One important advantage is that this also reduces the use of non-renewable fossil fuel. The secondary fuel is heavy fuel oil, which has a heat value of about 41 MJ/kg and sulfur content of 0.9 w-%.

The kiln has a total length of 104 m, an external diameter of 3.6 m and an angle of inclination of 2 ^{o}. The design capacity of the kiln is 500 tons of reburned lime per day. An overview of the lime reburning process is presented in Fig. 7.

4.2.2. Main results of the domain analysis (II, IV, V)

The major results of the domain analysis that are related specifically to the reduction of emissions (II, IV) and/or potential enhancements in hot-end temperature control (V) are summarized below.

- Lime kiln #2 has to be operated for most of the time close to the maximum sustainable production rate, and the mud storages have a tendency to accumulate slowly. Therefore, after every second or third week, old kiln #1, which is less energy efficient than newer kiln #2, has to be taken into operation. Furthermore, both the dust and TRS emissions from the old kiln are considerably greater than those from kiln #2.
- Unnecessary large changes to the production are repeatedly made by the operators in order to balance out increasing or decreasing levels of the mud storages. The pending production rate changes tend to cause considerable fluctuations in the kiln process, and these are difficult to stabilize. Large changes in the production rate also increase the risk of short-term emissions peaks.
- Irregular variations in the filtration properties of the mud and gradual deterioration in the shape of the filter induce oscillations in the dry solids content of the 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.
- Operating the kiln with a higher excess burning air level than is necessary for optimal combustion of the fuel is also a common practice. The resulting relatively high excess oxygen level is an obvious indication of avoidable heat losses. On the other hand, the large variation in the excess oxygen content occasionally brings about insufficient excess oxygen during mud drying, which instantaneously generates a marked peak in the TRS emissions.

- Operators often tend to over burn the lime, which reduces the reactivity of the reburned lime. “Over-burning” is a common practice during manual operation due to the fact that the kiln process is easier to operate at a somewhat higher temperature than the optimum temperature in respect to quality and energy efficiency.
- Random changes in sawdust quality and problems in regulating the feedrate result in variations in the heat energy input into the kiln. As a result, considerable fluctuations in the temperature are a common problem, which also causes variation in the quality of the reburned lime. Irregular variations in the energy input also creates fluctuations in the excess oxygen content of the flue gas which, in severe cases, cause a peak in the TRS emissions.
- Undesired dusting and ring formation occur from time to time, especially in the cold-end of the kiln. Large rings and also extensive dust circulation have a tendency to increase the influence of disturbances, thus making kiln control even more demanding. These also limit the maximum sustainable production capacity of the kiln process.
- The operator have different and even conflicting opinions about the kiln operation and the proper way of running the process. Different practices between the operators, combined with the long time delays, have a tendency to promote inappropriate control actions causing unnecessary fluctuations in the process.

4.3. Design of the overall control schema

4.3.1. Functional requirements of the system (IV, V)

The following functional requirements were applied in designing the control system. First of all, the frequent disturbances in the mass flow of lime 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 rather small increments or decrements. Changes in the fuel mixture need to be managed such that the total supply of heat energy is maintained as constant as possible during the change. Moreover, all the major regulatory level control loops need to be adjusted in a feedforward (FF) manner during the pending production rate changes

Furthermore, the temperature especially in the hot-end of the kiln, needs to be controlled in a closed loop manner by means of small corrections to the sawdust feedrate and/or fuel oil flow rate in order to maintain the hot-end temperature within the most favorable range for the reburned lime quality. The temperature and excess oxygen content of the flue gas need to be controlled by means of corrections to the draught fan speed to ensure low emission levels and heat losses. In addition, to the FB controllers, routines for handling severe disturbances are also a necessity.

In addition, the performance of the kiln process has to be supervised over long-term operation and, subsequently, the target values for the temperatures 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 TRS emissions while the process operation is optimized with respect to energy efficiency, reburned lime quality and production capacity.

4.3.2. Proposed control schema (III)

The proposed control schema, which accomplishes the stated functional requirements and also takes into account the process constraints and physical limitations, combines hierarchically structured, inter-related modules of the FF control models, stabilizing controllers and constraints handling, as illustrated in Fig. 8 (III). The main purpose of the *feedforward control models* (FFMs) module is to ensure smooth operation of the process during the pending production rate change. The FFMs module relies on the predetermined relationships that have been obtained from the large amount of process data. In practice, the module manages the production rate changes by means of appropriate adjustments to the setpoint of all the basic-level control loops in the process.

The primary purpose of the supervisory-level *stabilizing controllers* (SCs) module is to maintain controlled variables close to their target values by means of small corrections in the setpoints, despite the disturbances and gradual changes that occur frequently either in the lime mud filtration or in the kiln process. It also provides adaptation in case of inaccuracy in the FFMs. 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 CH module is also used to tackle large deviations from the target values by means of reasonably large stepwise changes in the SPs. Both the SCs and CH modules rely for the most part on the real-time inference of the actual state of the process with respect to the desired conditions and existing constraints.

The purpose of the highest level in the hierarchy is to optimize process operation by determining the optimum target values for the stabilizing-level controllers. The adjustments that are required in order to maintain the process close to the most optimal state are determined on the basis of the predetermined relationships and the reasoning of the process conditions.

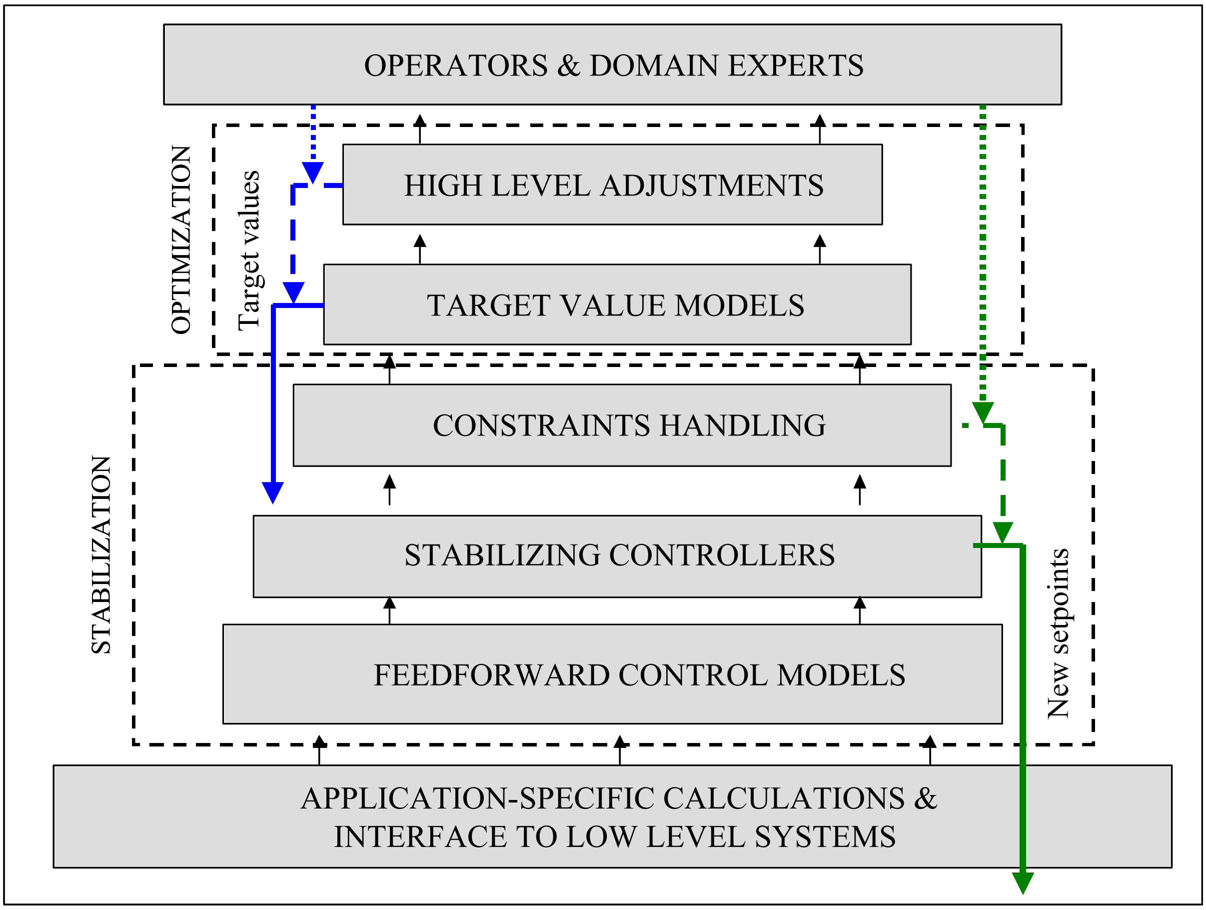


Fig. 8. Schematic presentation of the hierarchical structure of the system (IV, modified).

5. Intelligent control system for the lime kiln

In this chapter, the development of the kiln control system proposed in the last part of the previous chapter is described. The outline of the progress in the development of the system is first reviewed, and the overall structure and main functions of the system are then presented. The results obtained during extended testing periods are also briefly summarized. A more detailed description of the *Pilot* version and the results obtained during the testing of the *Pilot* system is given in publication III. The functions of the latest version, i.e. the *Production* system, with respect to the flue gas emissions and heat losses, and the reburned lime quality control, are presented in more detail in publications IV and V, respectively.

5.1. Evolution of the control system

Since the beginning of the 90's extensive research has been carried at the Wisaforest pulp mill in the field of lime kiln control. A draught fan speed control system based on fuzzy logic was developed in 1993. Further details of the system, which was formulated on the basis of operator interviews, can be found in Penttinen (1994) and in Ruotsalainen (1994). Fuzzy modeling and simulation of the lime kiln process has also been carried out at the mill, as described in Juuso et al. (1996).

The time schedule of this research work, which was a continuation of the earlier work done at the mill, is shown in Fig. 9 (V). A field study of the process operation, and application-specific requirements, constraints and objectives was first carried out at the mill. Next, an overall control schema, which takes both the environmental and operational requirements into consideration, was designed. The proposed control scheme was then divided into inter-related, hierarchically structured modules, and further into consequential functional sub-modules, which in practice specify the overall control scheme in smaller and simpler functional entities. The primary version of the modular structure is presented in Järvensivu and Seaworth (1998). After determining the overall structure of the system, different ways of realizing the system were then evaluated. Gensym's G2, which is an object-oriented environment for developing intelligent systems, was then selected on the basis of this evaluation.

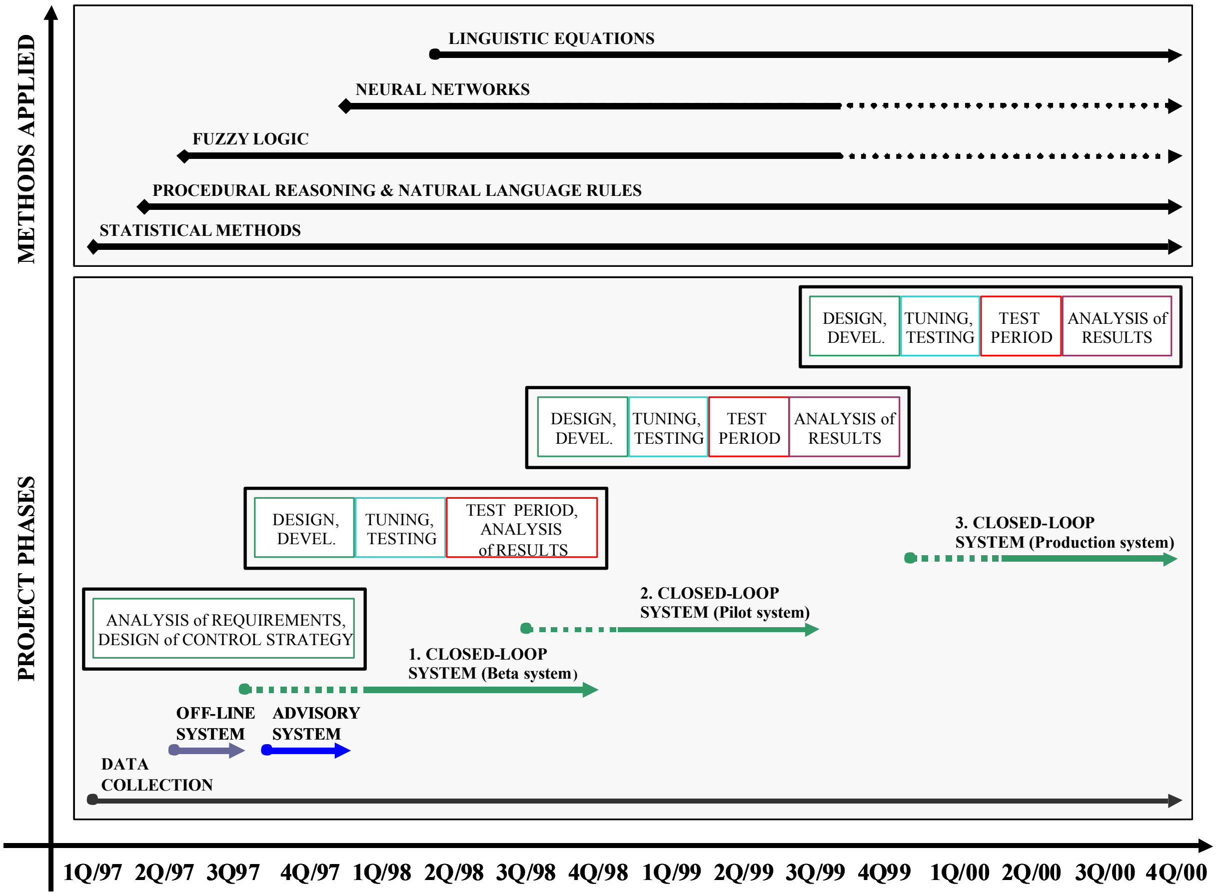


Fig. 9. Evolution of the control system (V, modified).

The control system was then incrementally developed (for information about the incremental development model see, e.g. Boullart et al., 1992). A scaled-down prototype of the system, marked with *Beta* in Fig. 9, was first developed and implemented at the mill, as has been described in Järvensivu (1998) and in Järvensivu et al. (1999). In the *Beta* version of the system neural network models were used for the FF part of the system and the FB controllers were based on fuzzy logic principles. The *Beta* system was mainly used to evaluate the overall feasibility of the proposed control schema.

The research work was then continued and new features were incrementally developed and integrated into the control system. In this phase, the LE controller was first installed for the hot-end temperature control (see Sievola, 1999). The original LE controller was pre-tuned with a dynamic LE model of the lime kiln, as described by Juuso (1999). An extended testing period of the developed *Pilot* version of the system was subsequently arranged. After the five-month testing period, comprehensive analyses of the results and system performance were carried out (for the results, see III). The outcomes of the analysis were then used, together with the accumulated practical experience, in the development of the final version of the system intended for uninterrupted production use at the mill (IV, V).

During the development of the *Production* version of the system, the use of the LE approach was extended. The multilevel adaptive MISO type of LE controller integrated with predictive braking action and adaptive scaling, was for instance implemented in the system (V). The neural network models applied in the *Beta* and *Pilot* versions of the system for the FF control were also replaced by the MISO type of LE models (IV, V). After the fine-tuning period, the ability of the system to control the process under varying operational conditions was verified and the results were analyzed on the basis of the data collected during the two-month auditing period of the system (IV, V). This *Production* version of the control system is presented in the next section with some references to the earlier versions of the system.

5.2. Overall structure of the control system

In addition to basic instrumentation, the control system of the lime reburning process at the Wisaforest mill consists of on-line flue gas analyzers, a process automation system, and a supervisory-level system. The supervisory-level system is divided into three hierarchically structured functional layers. The lowest layer of the system provides connections to the automation system. It also carries out validation of the input data and performs the application-specific calculations. The next level in the hierarchy, i.e. the stabilizing-level, executes supervisory-level control actions by means of the inter-related modules of the FF control models (FFMs), stabilizing controllers (SCs) and constraints handling (CH). Whereas, the highest level in the hierarchy determines the optimum target values for the stabilizing-level controllers.

The user interface of the system consists of a graphical user interface (GUI), implemented using the standard functionality of the automation system, and an enhanced supervision system. The GUI allows the users to monitor the operation of the process, and to carry out routine maneuvers. The supervision system provides complementary information about the performance of the system and the operational conditions in the kiln process. The operators can utilize the supervision system for proactively detecting detrimental process conditions, and for resolving critical problems before they disturb the productivity, and/or threaten the product quality or the environment.

An overview of the supervisory-level system is presented in Fig. 10, and the interactions between the software modules are illustrated in Fig. 11. Table 2 summarizes the functionality of the main modules of the *Production* system. In addition, the main modules are briefly presented in the next section. A more detailed description of the modules is given in publications III, IV and V.

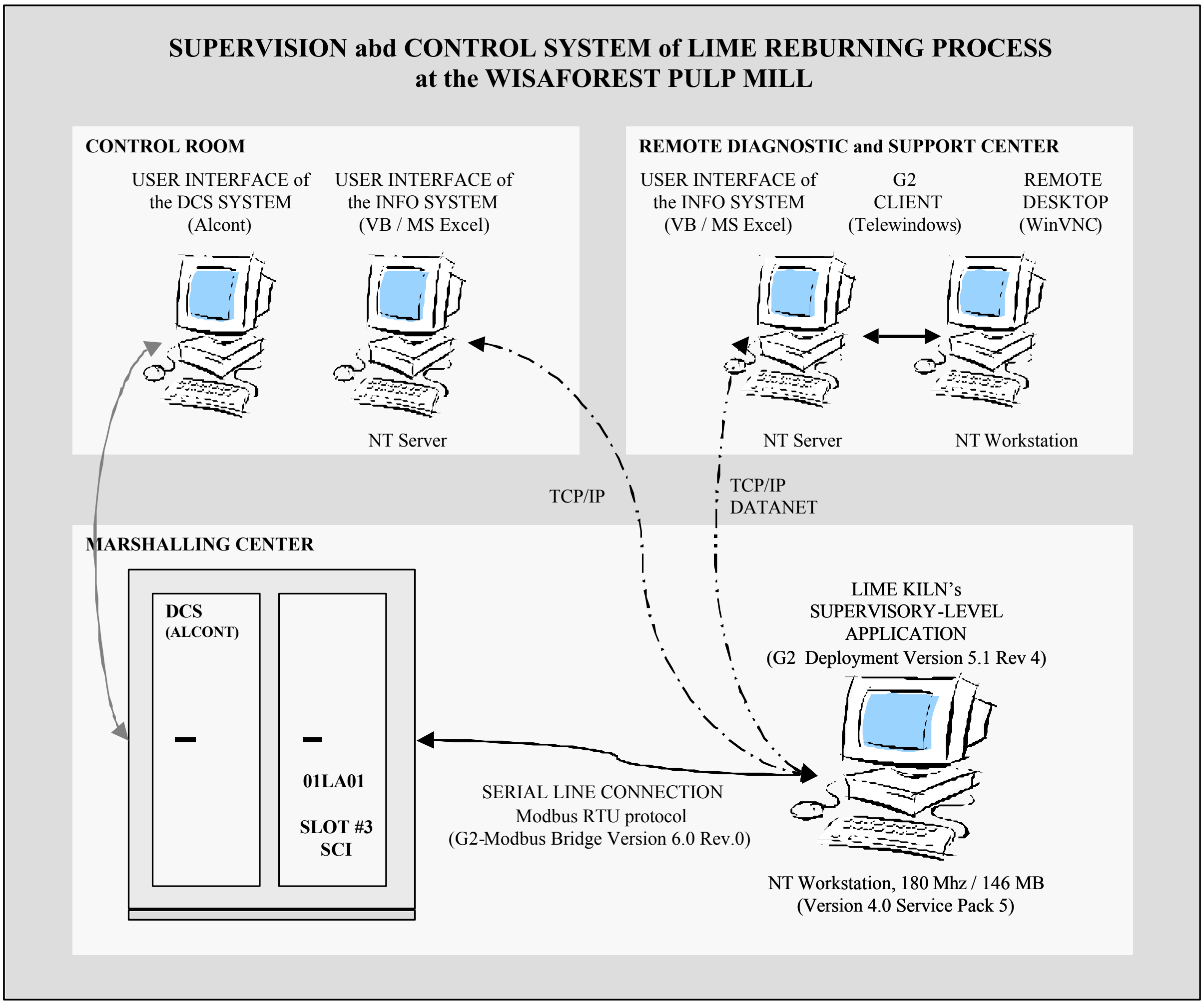


Fig. 10. Overview of the supervision and control system of the lime reburning process.

Table 2. The main modules and corresponding sub-modules of the control system.

OPTIMIZATION OF THE PROCESS OPERATION *(PCS-TVOPT-LK.KB)*
PRODUCTION RATE. This module determines the optimal production rate on the basis of the lime mud storage level together with the kiln process conditions. It also carries out adjustments to the kiln rotational speed in order to increase the maximum sustainable production rate.
ENVIRONMENT and ENERGY EFFICIENCY. This module adjusts the target value for the excess oxygen and cold-end temperature in order to ensure low emission levels while the heat losses are forced down. It also adjusts the wash water rate in the filters so that adequate washing of the mud is ensured.
PRODUCT QUALITY . This module maintains the quality of the reburned lime in the optimum range by means of small adjustments to the target value of the hot-end temperature. The adjustments are calculated on the basis of the results of the laboratory analyses.

STABILIZATION OF THE PROCESS OPERATION *(PCS-HLC-LK.KB)*
CONSTRAINTS HANDLING. This module is used to protect personnel, equipment and the environment in the case of severe disturbances and/or abnormal process conditions. It also handles large deviations from the target values by means of stepwise changes in the setpoints.
STABILIZING CONTROLLERS. This module maintains controlled variables close to the target values by means of small FB corrections to the setpoints of all the major manipulated variables in the process.
FEEDFORWARD CONTROL MODELS. This module maintains smooth operation of the process during pending production rate changes. It alters setpoints of the major manipulated variables according to the models obtained primarily from process data.

MISCELLANEOUS *(PCS-GUI-LK.KB, PCS-DV-LK.KB,G2-MODBUS.KB, PCS-DI.KB, PCS-DI-LK.KB)*
DATA PRE-PROCESSING. This module checks the input data and the setpoints before enforcing them into the automation system. It also carries out application-specific calculations.
PROCESS INTERFACE. This module provide an interface to the automation system.

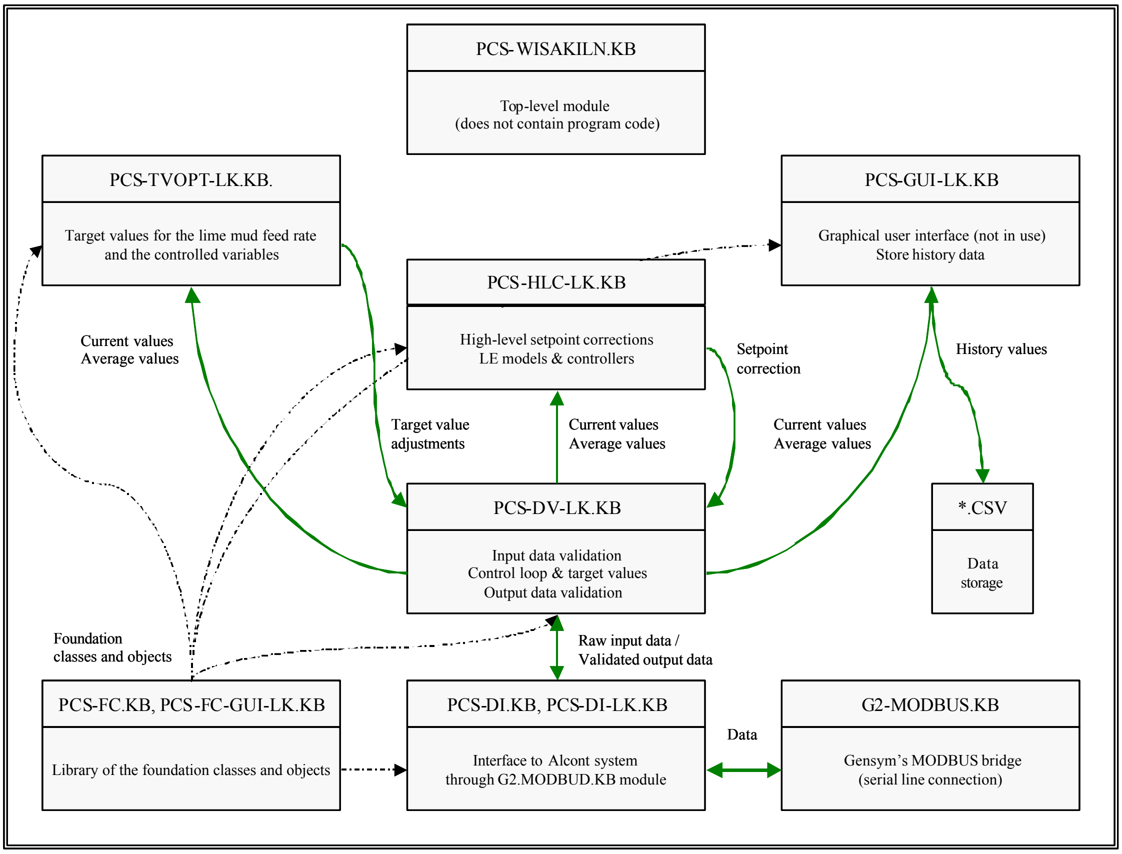


Fig. 11. Interactions between the software modules of the supervisory-level system.

5.3. Stabilization of process operation

5.3.1. Integration of the supervisory-level control modules (III, V)

The FFMs, SCs and CH modules are executed concurrently and, as a result, the new setpoints (SPs) for the basic-level control loops are determined as follows (V):

$$u_i(k) = FFMu_i(k) + HLCu_i(k) + BCu_i(k) \tag{18}$$

$$HLCu_i(k) = HLCu_i(k-1) + \Delta SCu_i(k) + \Delta CHu_i(k) \tag{19}$$

where $u_i(k)$, is the new SP for the manipulated variable, i. FFM$u_i(k)$ is the most recent output of the FFMs module. $HLCu_i(k)$ is the high-level corrections to the output of the FF model. This is calculated on the basis of the latest FB corrections of the SCs module, $DSCu_i(k)$, and the stepwise correction of the CH module, $DCHu_i(k)$. $BCu_i(k)$ is a bias correction, which can be adjusted manually. Before enforcing the new *SP*s in the *DCS*, they are checked with respect to the acceptable range for the *SP*s in order to ensure safe operation, and to protect the equipment against damage in the case of erroneous measurements and/or other unexpected fault situations (III, V). The acceptable range for the SPs is calculated by the system as a pipe around the most recent output of the FFM module.

The principle used in determining the SPs is also illustrated schematically in Fig. 12. The output of the FFMs module (FFMu_i) is shown in the figure as a curve in the middle of the range (u_i^{lr} and u_i^{hr}) for the acceptable *SP* (III, V). α_i and β_i are constants used to calculate the width of the range for acceptable *SP*s. The latest value of the high-level correction ($HLCu_i$), which is added to (or subtracted from) the FFMu_i determines the actual value of the SP. The tuning-parameter values used in the *Production* system are given in Table 1 in publication V.

5.3.2. Feedforward control models (III, IV, V)

FF controllers based on NN models, which were developed on the basis of the data collected during the field survey, were implemented already in the *Beta* version of the system (Järvensivu, 1998). These models, with some modifications, were also used in the *Pilot* system (III). In the *Production* version of the system, however, the NN models applied in the *Pilot* version have been replaced by non-linear models based on the LE approach. In the models, moving averages of the input variables are used to avoid fluctuations in the model output in the case of short-term disturbances in the input variables. In addition, by using appropriate moving averages, steady state LE models can be used to approximate the dynamic behavior of the process during gradual changes such as a pending production rate change. Furthermore, moving averages make it possible to handle the long residence time of the solids in the kiln. Note: fast and unexpected changes are handled by means of the SCs and CH modules.

Fig. 13 shows the output of the FF controller applied for the sawdust feed rate as an example of the models. The figure shows how the sawdust feed rate is raised when the first input of the model, i.e. the production rate that has a predominant influence on the output of the model, and/or the torque of the kiln drive (i.e. the second input of the model) increases, and vice-versa. The LE models applied for FF control in the *Production* version of the system are described in more detail in publications IV and V.

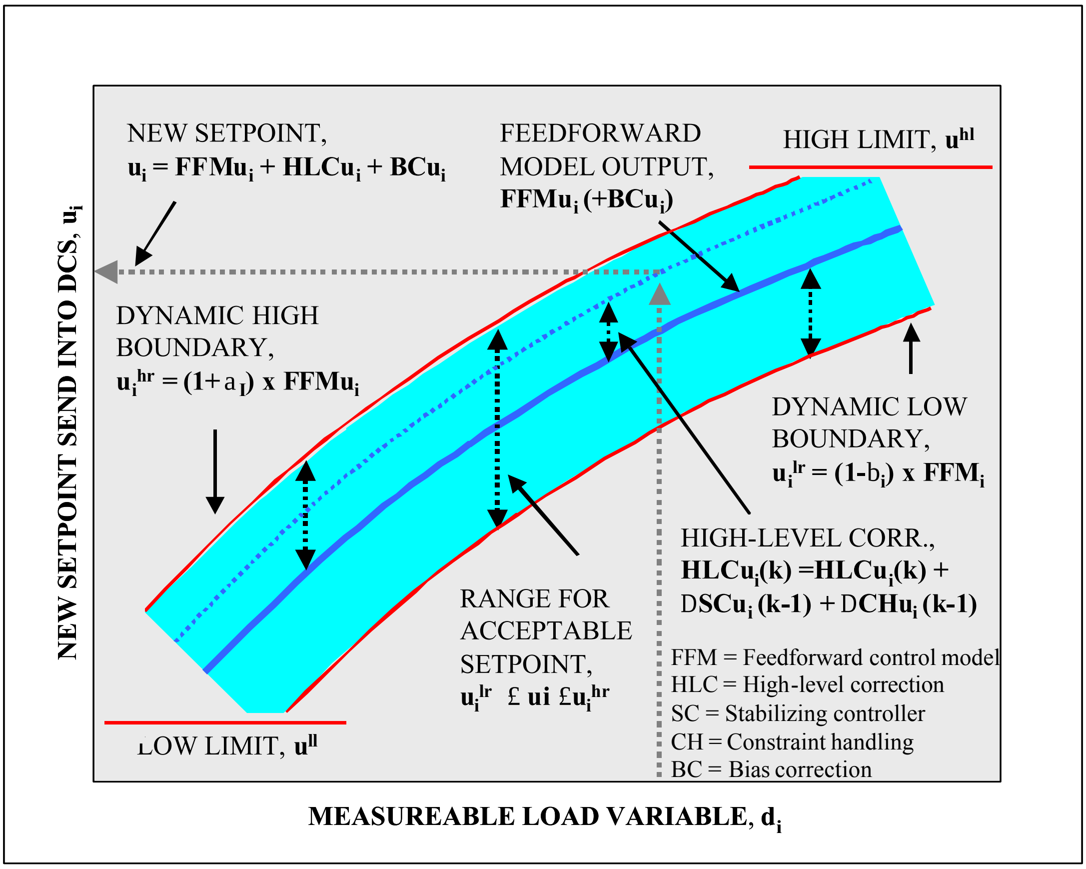


Fig. 12. Principles used in determining the SPs for basic level control loops (III, modified)

5.3.3. Stabilizing controllers and constraints handling (III, IV, V)

The major manipulated variables in the kiln process, i.e. the draught fan speed and the fuel supply into the kiln, are also controlled 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. An appropriate control action to the draught fan speed and/or the fuel supply 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.

A multilevel adaptive MISO type of LE controller is used for the control of both sawdust and fuel oil in the *Production* version of the system (V). In the earlier versions of the system, a comparable controller was available only for the sawdust, and the fuel oil was controlled manually (III). In the latest version of the system, a LE controller is also applied in order to determine corrections to the draught fan speed (IV). The LE controller replaces a corresponding controller based on the fuzzy logic approach, which was applied in the former versions of the system (III).

In the LE controllers, the corrections (*D*u) to the manipulated variable are determined on the basis of the linguistic values (LVs) of the error (e) and the derivative of the error (*D*e) of the controlled variables. Because two controlled variables are applied in the controllers, the actual control action is calculated as a weighted average of the independently determined corrections. In the LE controllers, the moving averages of the inputs are applied instead of the latest readings in order to avoid unnecessary and inappropriate control actions resulting from short-term fluctuations in the measurements.

The basic structure used in the LE controllers is similar, and the functional requirements are taken into account by means of the tuning parameters. The inputs used in the LE controllers and the tuning-parameter values are described in more detail in publications IV and V. An example of the control surface of the basic LE controller is, however, given in Fig. 14. In this figure the FB correction to the sawdust feed rate is presented as a function of the error and the derivative of the error of the hot-end temperature, which has the dominant effect on the output of the controller.

On top of the LE controllers, the CH module, which is based on structured natural language rules and procedural reasoning, is used to check that the constraint variables are in between both the dynamically calculated low and high boundaries and the preset limits. For instance, if the excess oxygen content drops below the low limit or rises above the high limit, the draught fan speed is immediately altered by means of a stepwise change (IV). In the case of large deviations or fast changes in the controlled variables the constraints handling (CH) module is also activated to make appropriate stepwise corrections to the corresponding manipulated variables.

In general, the stepwise changes carried out by the CH module are about 5 - 10 times larger than the corrections made by means of the corresponding LE controllers. Reasonably large changes are used to bring the process immediately back to within the safe operating range. A more detailed description of the CH modules applied for the draught fan speed and the fuel supply in the latest version of the system, are given in publications IV and V, respectively.

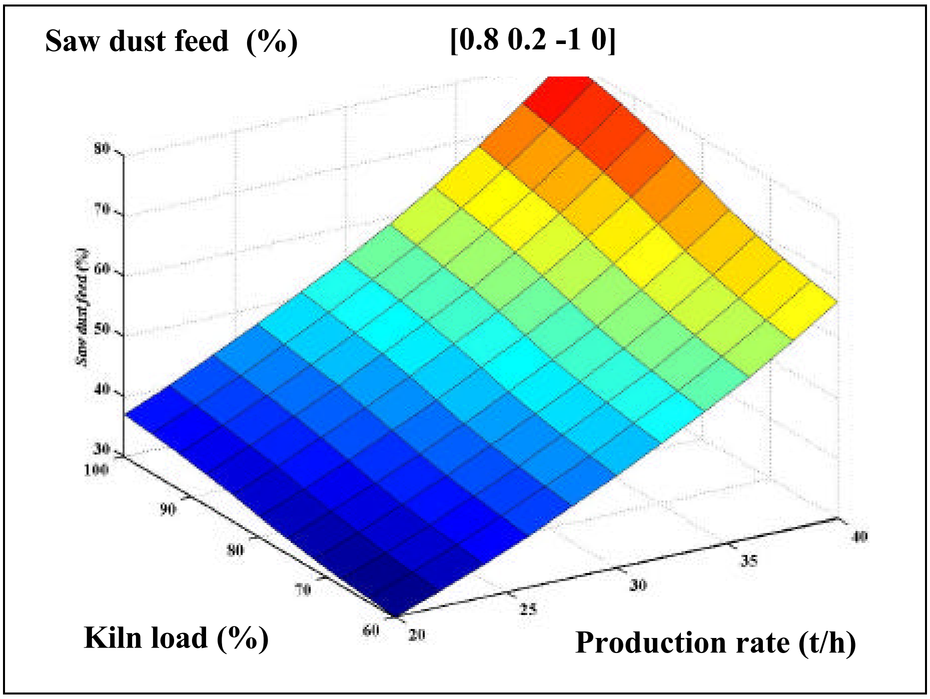


Fig. 13. Output of the FF control model for the sawdust feed rate as a function of the production rate and torque of the kiln drive (V).

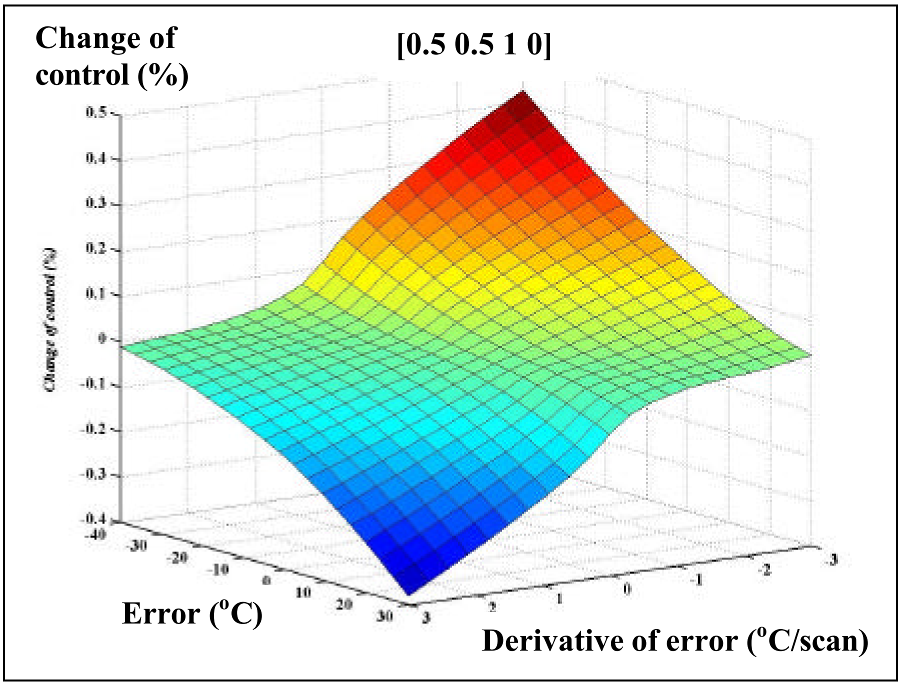


Fig. 14. Control surface of the basic LE controller of the sawdust feed as a function of the error and the derivative of the error of the hot-end temperature (V).

5.4. Optimization of process operation

The improved stability of the kiln process obtained with the supervisory-level control modules 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, however, certain adaptive features in the system. The operation of the process therefore needs to be supervised over an extended period, and the target values 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 briefly below. A more detailed description of the modules applied in the *Production* version of the system is given in publications IV and V.

5.4.1. Production rate maximization (IV)

The target value for production is determined by means of the production rate maximization module. The state of the mud storage is first evaluated, and a small correction is then calculated for the production rate on the basis of the state of the storage and the current loading of the process. The maximum rate of production that the process can sustain is determined by checking several indirect indications of the loading state of the kiln. For instance, the excess oxygen content of the flue gas and the level of TRS emissions are 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 (LVs) of the variables used to indicate the loading state of the process. The mean of the LVs is then used to scale the correction determined primarily on the basis of the state of the mud storage. The actual change in the production rate is implemented by means of small, stepwise increments or decrements.

5.4.2. Environmental protection and energy efficiency (III, IV)

The target value for both the temperature in the cold-end of the kiln and the excess oxygen content of the flue gas, i.e. the most advantageous conditions for mud drying in respect to the environmental protection and energy efficiency, are determined by means of the environmental protection module (IV). The module replaces the NN model, which was used in the *Pilot* version of the system (III). 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 TRS 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. The low and high boundaries for the TRS emissions are calculated on the basis of the current production rate. The module also adjusts the bias correction of the models used for FF control of the wash water rate. For instance, the magnitude of the wash water rate is raised in order to achieve better washing of the mud if the emissions rise above the high boundary.

5.4.3. Reburned lime quality (III, V)

Although the temperature in the hot-end of the kiln and the quality of the reburned lime are closely coupled, it is impossible to specify a constant temperature target that would guarantee optimal quality over long-term operation. For instance, the process conditions have an impact on the demand of the heat exposure, and hence also on the required temperature. Consequently, in order to ensure a uniform reburned lime quality, adjustments to the target value of the hot-end temperature are made by means of the quality optimization module (V). The module replaces the NN model, which was used in the *Pilot* version of the system for calculating the target value for the temperature (III). The module determines the adjustments to the target value on the basis of the most recent laboratory analysis of the residual CaCO3 content. It also takes into account the kiln production and the fuel oil flow rate, which has a considerable influence on the temperature measured by a thermometer.

6. Summary of the results

The results presented here 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 *Beta* system (03/98–01/99). The third five-month period represents the first extended testing period of the *Pilot* system (2/99–6/99). The fourth two-month period represents the auditing period of the *Production* version of the system (9/00–10/00). First in this chapter, the utilization rates of the *Beta*, *Pilot* and *Production* system are presented and the dynamic performance of the system is demonstrated with examples. Then, operational results are described by means of statistical values and as a final point assessment of the benefits is presented.

6.1. Utilization of the system (III, IV, V)

The average runtime[*)] of the supervisory-level controllers between March 1998 and October 2000 is shown in Fig. 15 on a monthly average basis. The average runtime in the closed loop mode was about 45 % between March 1998 and January 1999 during the incremental development of the *Beta* system (III). The average running time in the closed loop mode was over 85 %, between February 1999 and June 1999 during the five-month testing period of the *Pilot* version (III). During the auditing of the *Production* system the average utilization rate of the system was in the region of 95 % (IV, V). During the auditing period, the system was entirely supervised by the operators, and reached a high utilization level of the system, which justifies the system acceptance by the operators.

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 % (IV) during the audition of the *Production* system. Optimization of the target value for the cold-end temperature, which is more related to the heat balance in the kiln, reached a utilization rate of approx. 66 % (IV). The utilization rate of optimization of the target value for the hot-end temperature related to the control of reburned lime quality was in the region of 55 %. The production rate maximization module, which was implemented in the system during the testing and fine-tuning phase of the *Production* system, reached over 90 % utilization during the auditing of the system (IV).

[*)] *The average runtime is calculated as the mean time of the draught fan speed, the fuel supply (i.e. the sawdust feed rate and/or the fuel oil flow rate) and the rotational kiln speed control loops in the closed loop mode divided by the time that the process has been in operation and the sawdust has been burned alone or together with heavy fuel oil.*

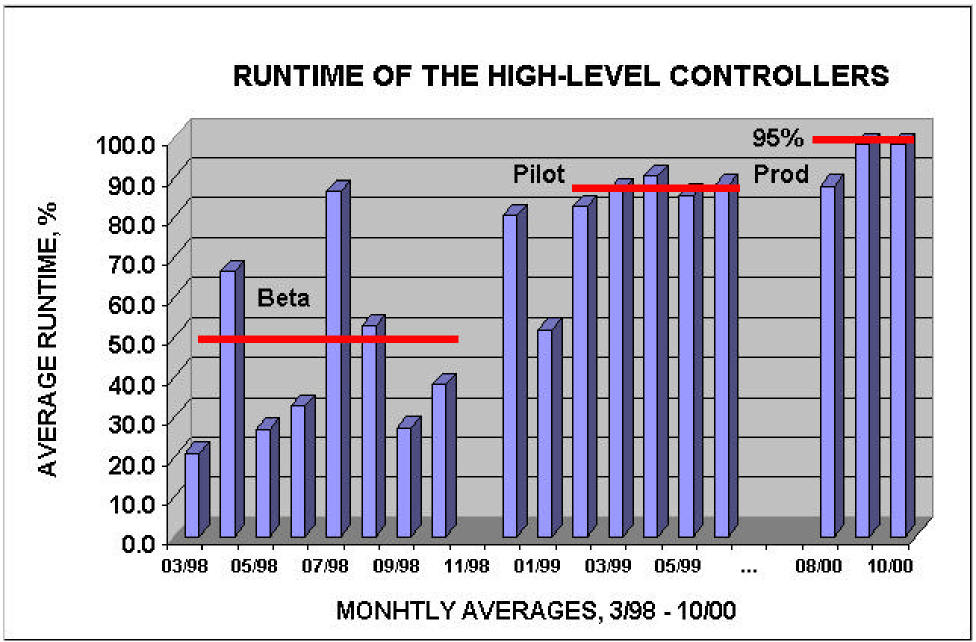
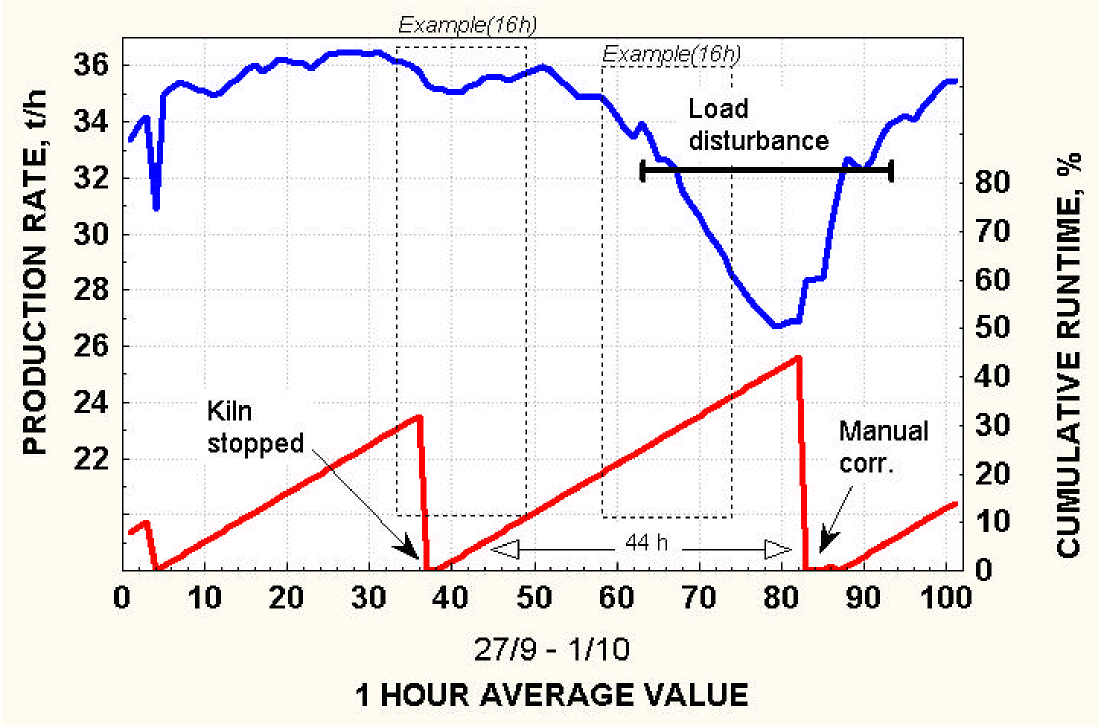


Fig. 15. Average run time of the supervisory-level controllers between March 1998 and October 2000 (III, updated).

6.2. Dynamic performance of the system (III, IV, V)

The dynamic performance of the system was verified on the basis of the data collected during the four-day runtime span of the *Pilot* version at the beginning of April 1999 (III), and of the *Production* system at the end of September 2000 (V) and in the middle of October 2000 (IV). In addition to extended periods of kiln operation at a constant production rate, these example periods intentionally include large changes made to on the production rate and considerable disturbances in the process, as well as changes in the fuel mixture. Overall, the verification of the dynamic performance demonstrated the ability of the system to track the target values of the controlled variables even in the face of considerable load disturbances. The periods examined also exemplified the capability of the system to handle severe disturbances. An example of the dynamic performance of the *Production* system is shown Figs. 16 and 17. A more detailed presentation of the example is given in publication V.



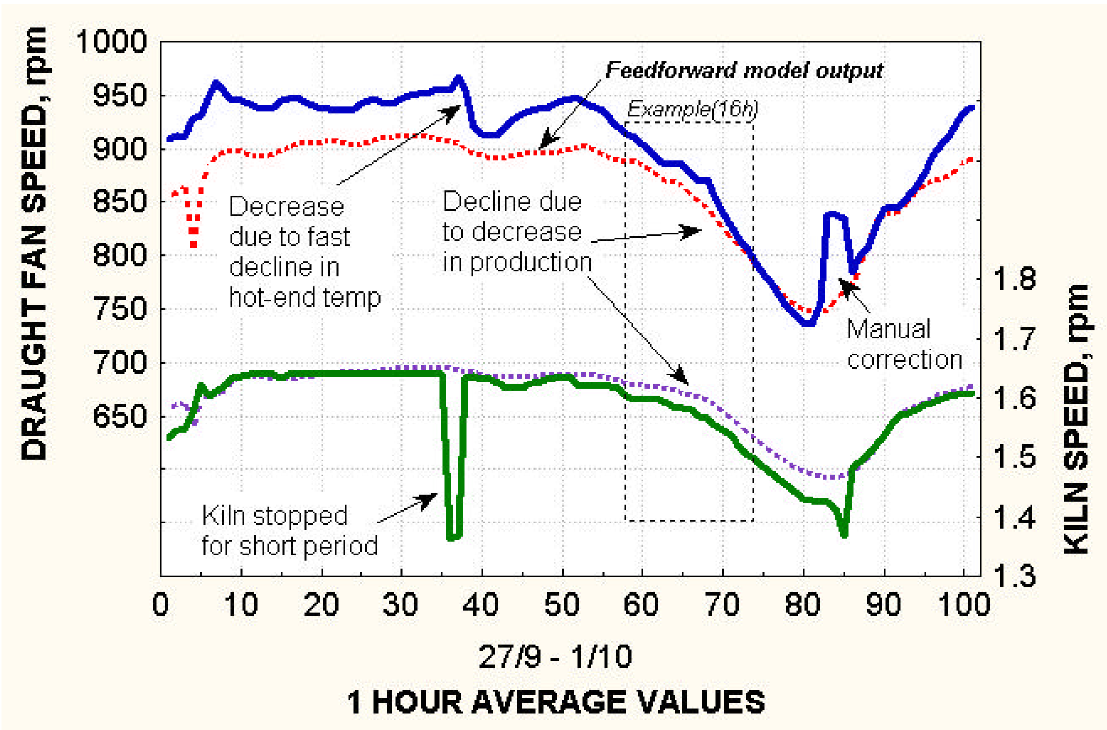


Fig. 16. Example of the performance of the system during a 4-day operating period (V).

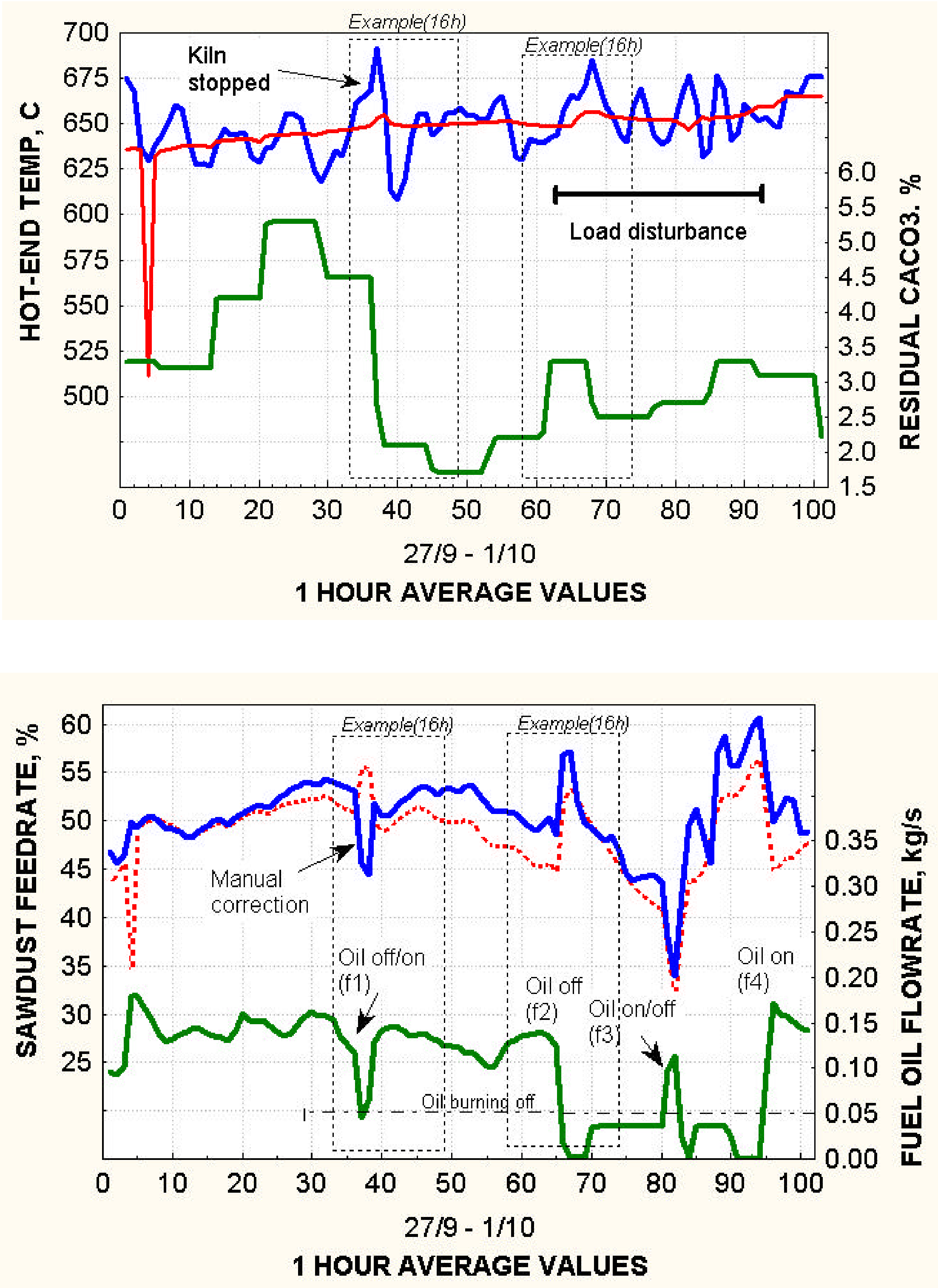


Fig. 17. Example of the performance of the system during a 4-day operating period (V).

6.3. Evaluation of the operational results (III, IV, V)

Evaluation of the operational results was carried out by means of statistical analysis of the data collected during the 15-month manual operation period, and the corresponding data obtained during the five-month testing period of the *Pilot* version (III) and the two-month auditing period of the *Production* version of the system (IV, V).

First, the large amount of process data was pre-processed. During pre-processing, the measurements collected e.g. during scheduled long-term shutdowns were systematically rejected (III). After rejecting inconsistent data, a comprehensive statistical analysis was then performed. Table 3 shows the most important variables in the process and a summary of the calculated statistics of the data collected during manual operation (Man), the testing of the *Pilot* version (Pilot) and the auditing period of the *Production* system (Prod). The statistics concerning the dry solids content of the lime mud (IV), the excess oxygen content of the flue gas (III, IV), the LMD temperature (IV), and the hot-end temperature (III) have been discussed in more detail in the individual publications. Therefore, only some examples of the analysis are presented here.

For instance, the mean value of the excess oxygen content obtained during the auditing of the *Production* system (3.2 %) has been reduced by more than 15 % compared to the corresponding value during manual operation (3.8 %). The frequency distribution of the excess oxygen measurements during manual operation and system auditing are presented in Fig. 18 (IV). 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 been increased by more than 25 %, from 57 % to 72 %. Similarly, when the data collected during the testing period of the *Pilot* version of the system (III) were compared with the corresponding data gathered during manual operation, the quartile range and the standard deviation of the hot-end temperature have declined by nearly 50 % and more than 30 %, respectively.

6.4. Assessment of the benefits (III, IV, V)

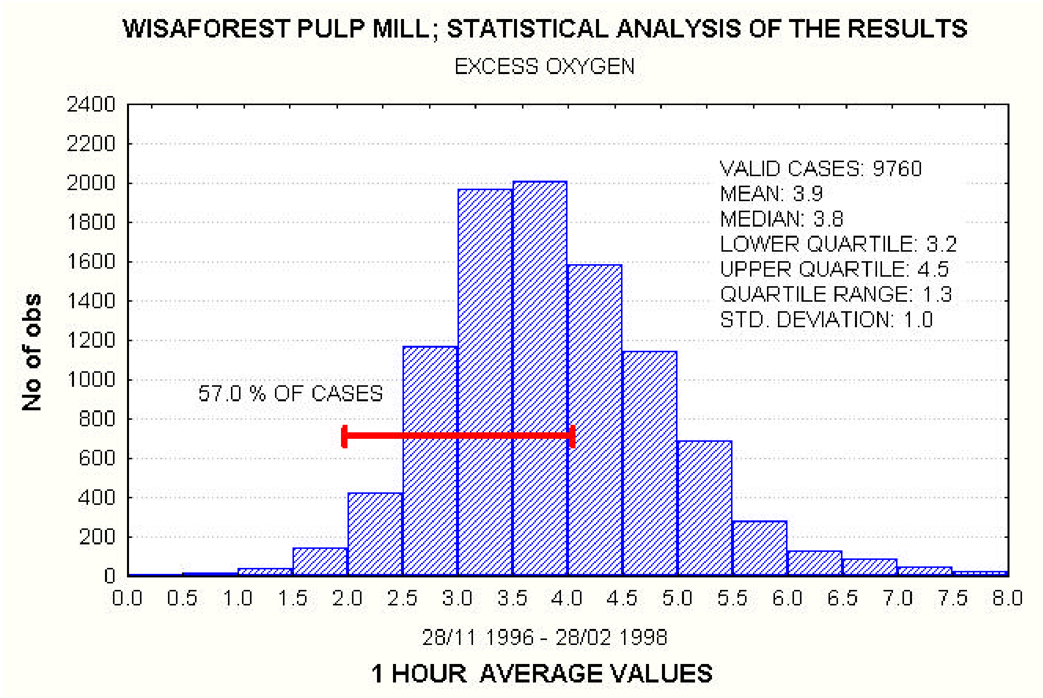
The major verified benefits in economic terms were a marked reduction (nearly 7 %) in the heat energy consumption (III), and an approx. 5 % increase in the long-term production capacity (IV). A decrease in the energy consumption is mainly related to a decrease in the excess of burning air (III, IV). An increase in the production capacity is associated with improved stability of the process in general and the operation of the production rate maximization module (IV).

Improvements in reburned lime quality have also been obtained compared to the situation during manual operation (III, V). For instance, the proportion of residual $CaCO_3$ contents between 1.5 % and 4.0 %, which is an adequate range from the point of view of both energy consumption and reburned lime quality, has increased by more than 25 % after the completion of the latest version of the fuel control (V). Correspondingly, the proportion of values above 5.5 % and below 1.0 % has been reduced by approximately 20 % and by more than 85 %, respectively. Improvements in reburned lime quality can be expected already on the basis of the reduction in the variability of the temperature measurements (III). In addition, temperature excursions in the hot-end of the kiln were rare during the testing periods (III, V). This has reduced the thermal stress on the refractory lining, and an increase in the service life of the refractory bricks can therefore be expected.

The major quantifiable benefits from the ecological point of view was the decrease in TRS emissions (III, IV). According to the statistics, the mean of the TRS emissions decreased by over 10 % during the testing period of the *Pilot* system compared to the situation during manual operation (III). The emissions were, however, further reduced during the *Production* system auditing period. The mean and the upper quartile were reduced by about 30 % compared to manual operation (IV). Furthermore, the proportion of values above 12 ppm, caused predominantly by short-term emission peaks, has been reduced by almost 90 % (IV). The frequency distribution of the TRS emissions collected during manual operation and during the auditing period are presented in Fig. 19. During the testing of the *Pilot* system (III), the reduction in the emissions was primarily achieved through improved control during high production rate periods. The decline in emissions over the entire production rate range during system auditing (see Fig. 20), which was achieved even though the mean of the excess oxygen content was reduced, is due to the improved dewatering of the lime mud prior to the kiln, and a subsequent increase in the temperature during mud drying (IV).

Table 3. Summary of the descriptive statistics of the most important variables in the process.

VARIABLES		Valid	Mean	Min	Max	Low Quart	Upper Quart	Range	Quart Range	StdDev
1) All data										
Lime kiln feed	Man	10360	31.8	1.9	38.6	30.7	34.9	36.8	4.2	4.67
t/h	Pilot	3197	31.5	2.2	39.9	30.0	34.0	37.7	4.0	4.58
	Prod	1338	33.5	0	38.9	32.7	35.9	38.92	3.2	5.45
2) Normal operation										
Lime kiln feed	Man	9421	32.7	15.0	38.6	31.5	34.9	23.6	3.4	3.06
t/h	Pilot	2866	32.6	16.2	40.0	31.8	34.0	23.8	2.2	3.02
	Prod	1285	34.2	19.6	38.9	33.0	36.0	19.3	3.0	2.79
Draught fan	Man	9421	842	703	968	803	881	266	78	54.13
rpm	Pilot	2866	801	702	921	770	830	219	61	45.39
	Prod	1285	909	706	981	871	952	275	81	53.99
Kiln rotation	Man	9421	1.57	1.40	1.74	1.52	1.60	0.34	0.07	0.06
rpm	Pilot	2866	1.62	1.41	1.72	1.60	1.66	0.31	0.06	0.07
	Prod	1285	1.58	1.41	1.69	1.55	1.62	0.28	0.07	0.06
Specific heat energy	Man	9421	5.9	4.0	9.0	5.4	6.2	5.0	0.8	0.66
GJ/tCaO	Pilot	2866	5.5	4.0	8.8	5.1	5.8	4.8	0.7	0.55
	Prod	-	-	-	-	-	-	-	-	-
LMD temperature	Man	9376	247	181	320	227	264	139	37.3	25.59
°C	Pilot	2849	239	180	319	219	256	138	36.5	25.91
	Prod	1284	263	194	319	253	275	125	22.0	17.95
Cold-end temperature	Man	9406	635	554	693	622	648	139	26.6	19.00
°C	Pilot	2853	616	551	690	603	630	139	27.5	19.28
	Prod	1283	638	569	672	629	648	103	19.2	15.05
Excess oxygen	Man	9393	3.84	0.51	7.98	3.16	4.46	7.5	1.31	1.01
%	Pilot	2861	3.34	0.55	7.23	2.80	3.74	6.7	0.94	0.88
	Prod	1284	3.19	0.69	7.99	2.48	3.72	7.3	1.25	1.07
TRS emissions	Man	8481	8.5	1.0	30.0	4.8	10.4	28.9	5.6	5.00
ppm	Pilot	2865	7.2	1.1	29.7	4.5	9.1	28.5	4.7	4.12
	Prod	1285	6.0	1.2	25.8	4.3	7.2	24.6	3.0	2.76
Lime mud dry solids	Man	8908	76.0	70.0	82.0	74.0	78.0	12.0	4.0	2.59
%	Pilot	2825	77.4	70.1	86.5	75.1	79.6	16.4	4.5	3.10
	Prod	1283	78.7	72.7	84.3	77.2	80.2	11.5	3.0	2.32
Hot-end temperature	Man	9420	628	460	716	610	660	256	50.4	45.73
°C (thermometer)	Pilot	2865	599	463	669	591	619	206	28.4	31.29
	Prod	1282	647	544	714	633	665	170	31.7	23.73
Residual $CaCO_3$	Man	8996	2.6	0.2	7.9	1.8	3.3	7.7	1.5	1.24
%	Pilot	2826	3.2	0.3	7.9	2.2	4.1	7.6	1.9	1.53
	Prod	1239	3.0	0.0	6.0	2.1	3.6	6.0	1.5	1.18



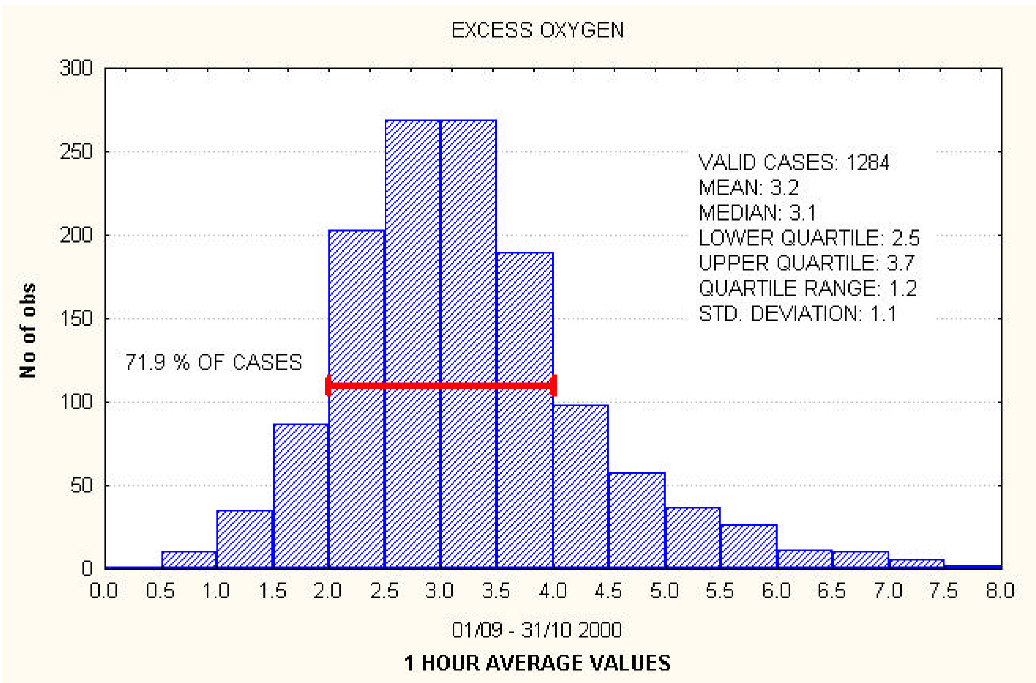
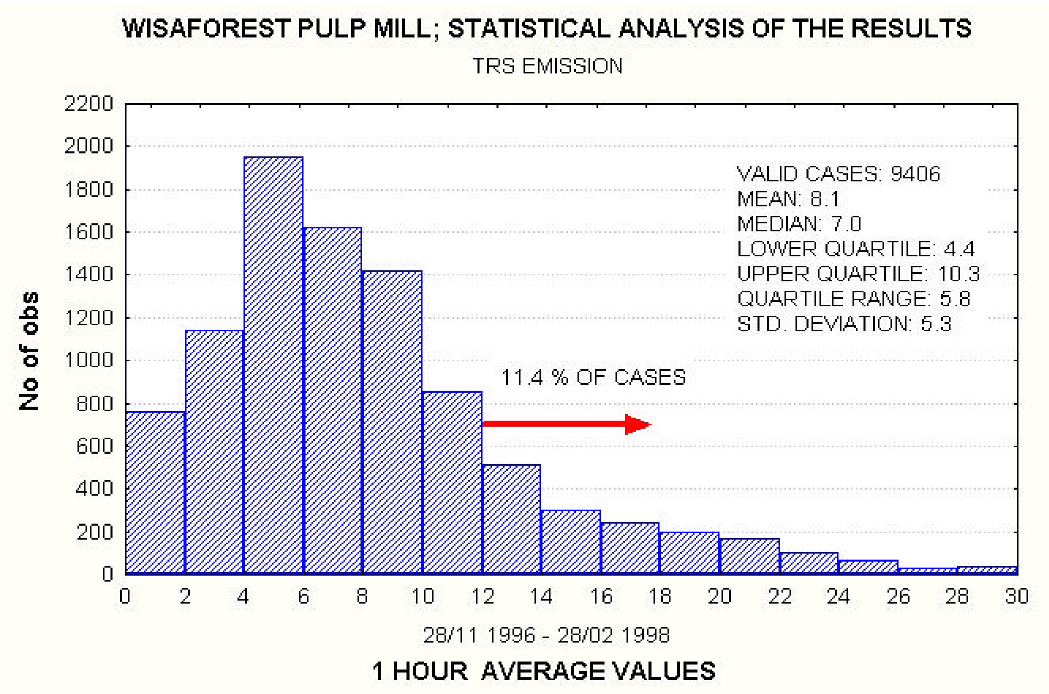


Fig. 18. Frequency distribution of the excess oxygen content (%) during manual operation (above) and auditing of the *Production* system (below) (IV).



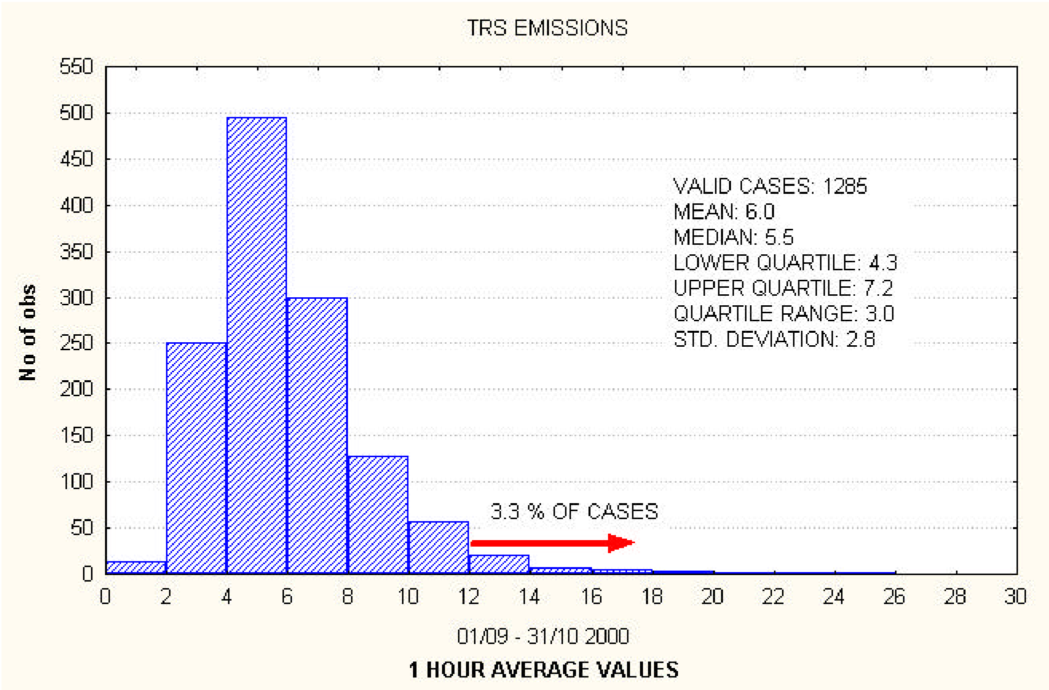
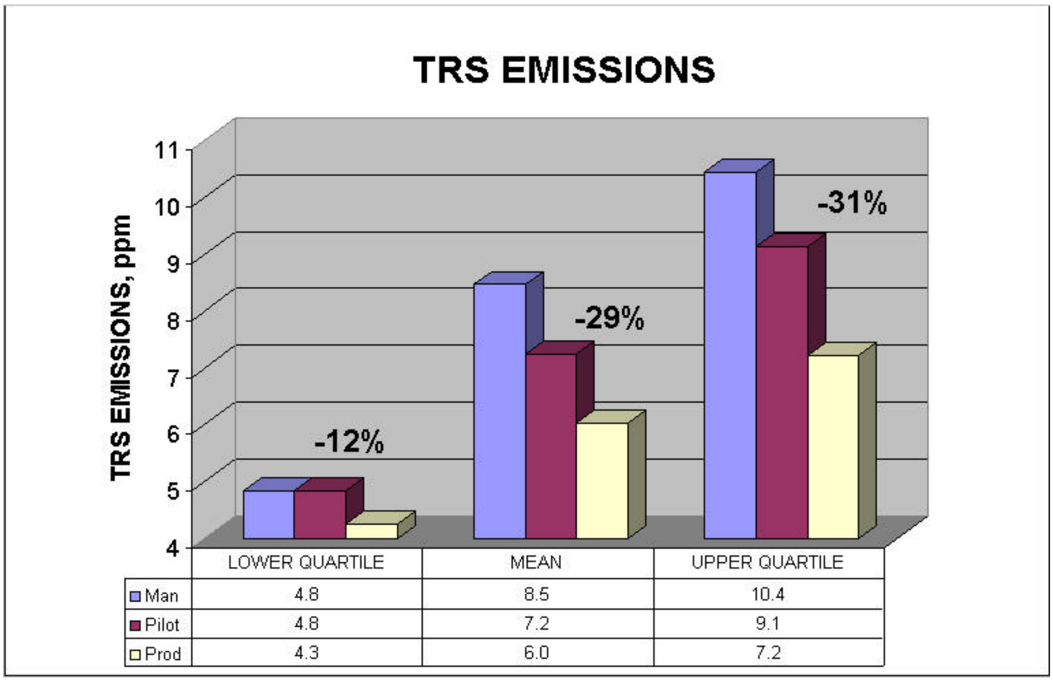


Fig. 19. Frequency distribution of the TRS emissions (ppm) during manual operation (above), and auditing of the *Production* system (below) (IV).



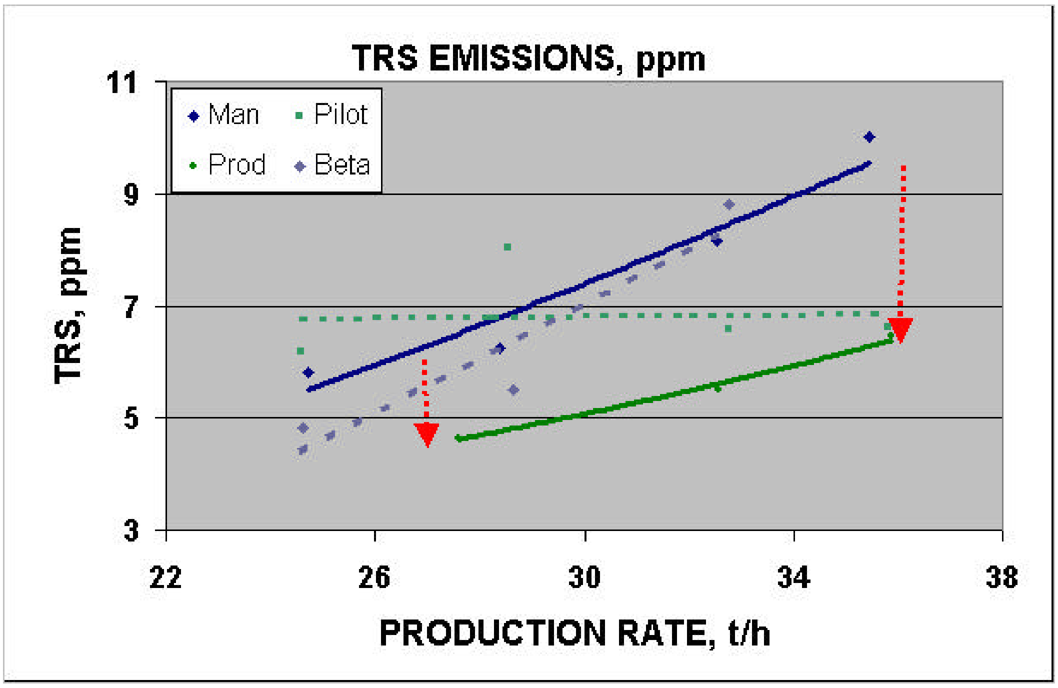


Fig. 20. Lower quartile, mean and upper quartile of the TRS emissions (above) and the mean of the TRS emissions as a function of the production rate (below) (IV).

7. Conclusions

Non-linearities, combined with the long delay times inherent in many industrial processes, set special requirements on the operation of supervisory-level controllers. Ability to handle severe disturbances is also an essential requirement for industrial control systems. In addition, understanding the wide range of operating conditions and their consequences on the behavior of the process in the perspective of both the economical and environmental aspects is, in many cases, critical for the successful implementation of the control system. The lime reburning process is, for instance, inherently difficult to operate efficiently and at the same time environmentally friendly, and the control of the lime kiln process is in many respect a demanding task that is difficult to solve by applying conventional control techniques alone. As a result, supervisory-level control of the lime kiln with respect to environmental requirements could therefore be considered as a prospective application for intelligent control techniques.

A comprehensive study of the operation of the lime reburning process was first carried out at one of the major pulp mills in Finland with the intention of designing an overall control schema for the lime kiln process. The overall control schema was divided into inter-related, hierarchically structured modules in order to manage the complexity of the system. The proposed control system was then incrementally developed and successfully implemented at the Wisaforest pulp mill. The control structure combines both feedforward (FF) control models and supervisory-level feedback (FB) controllers, strengthened with certain capabilities for adaptation and constraint handling.

The FF control part of the system is founded on the MISO type of steady-state models that are based on the linguistic equation (LE) approach. These non-linear models rely on predetermined relationships that were primarily obtained from the large amount of data. The directions and strengths of the inputs in the self-explanatory LE models can be understood on the basis of process expertise, which was also the reason why the neural network (NN) models applied in the earlier versions of the system were replaced by the LE models.

The FB part of the system is based on a multilevel adaptive MISO type of LE controller structure. In the controller, a basic LE controller is integrated with the predictive braking action (PBA) and adaptive scaling (AS) of the correction. The braking action is closely linked to the predictive switching control, whereas the scaling of the control actions based on the operating conditions extends the applicability of the controller over wide range of operating conditions. Improved dynamic performance of the kiln process also provides a basis for reducing the safety margins and, consequently, also for determining the most advantageous target values for the controlled variables.

The functional performance of the control system has been verified and the quantitative evaluation of the results has been carried out by means of statistical analysis of the data collected during the extended testing periods. First of all, the obtained results confirm that the proposed overall control schema can be realized in practice in an industrial environment. The results demonstrate the ability of the system to track the target values of the controlled variables even in the face of considerable load disturbances. The results also explicates the importance of the constraint handling capabilities of the system. An assessment of both the economical and ecological benefits has also been made. The major quantifiable benefits from the ecological point of view were an almost 30 % decrease in the mean of the total reduced-sulfur (TRS) emissions, and a reduction of about 90 % in the proportion of high TRS emissions periods caused predominantly by short-term emission peaks. In economic terms, the main verified benefits were an increase in the production capacity, improvements in the reburned lime quality and enhancements in the energy efficiency of the process.

Furthermore, both the engineers and operators at the pulp plant now have a much more comprehensive understanding of their process and its restrictions than in the past. In addition, the operator's workload has fallen, variations between the shifts have decreased, and the operational flexibility has improved compared to manual operation. As a result, the operators also have a chance to review and enhance their own procedures, which will generate additional improvements in the future. Periodic maintenance of the system and the major measurements connected to it will, however, be essential in order to guarantee proper functioning of the implemented system.

What is of more general relevance is that, the experiences gained during the research have shown that a proper combination of techniques enables knowledge to be merged from different sources, e.g. heuristic knowledge from domain experts and experimental knowledge in the form of empirical models, and then applied in a systematic manner for resolving complex industrial scale problems.

8. Future developments

Some topics for further development of the control system also arose during the course of the research. First of all, improvements related to the instrumentation are suggested. An on-line flue gas analyzer that measure the traces of carbon monoxide (CO) formed could be an extremely useful source of information about the actual state of the process. A nitrogen oxides (NOx) analyzer could also provide supplementary information about the burning conditions. In addition, accurate temperature measurement of the burning zone and reburned lime at discharge, obtained e.g. by combining a video image and a pyrometer, could provide valuable information for the system. The need for an reliable indicator of the reburned lime quality is also apparent, and therefore the development of a soft-sensor for predicting the $CaCO_3$ content of the reburned lime is also a potential candidate for future developments of 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. The development of a similar type of intelligent control system, which takes into consideration the environmental requirements, for other industrial processes also is a potential candidate for future developments.

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