Fuzzy vs. "manual" control in a FeNi plant

Article *in* Journal of Intelligent and Fuzzy Systems · August 2000

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Fuzzy vs. "manual" control in a FeNi plant

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In this paper the effect on energy consumption and pollution of fuzzy automatic control of a rotary kiln is investigated. The computer-based fuzzy control system is installed at the Larko ferronickel plant in Larymna, Greece, by the Danish firm F.L. Smidth & Co. A/S. Operation characteristics for the manual operation against automatic control are defined and compared. Preliminary results show substantial energy savings and reduced pollution levels. Payback period for the investment was calculated at approximately 1.2 years.

1. Introduction

Energy saving is a major concern in today's industries [2, 7, 9]. The metal industry, in particular, is one area where energy saving results in big overall production cost savings, because of their large electricity consumption. However, cost saving is not the only benefit of energy saving: environmental pollution is also reduced as a result of more efficient energy practices.

The use of automation, whenever possible, is one of the possible ways for reducing energy consumption. The type and extent of automation depend on the particular application and technological capabilities. However, because of the complexity of industrial processing plants, automation was largely confined to simple PID loops. Even though PID control has a succesful history of applications to process control, it has a major limitation. Its performance depends heavily on the operating parameters of the system. Once these parameters change, a significant amount of effort is required to retune the PID controllers manu-

ally. As a result, the average industrial process plant operator ends up running over 50% of the PID loops in manual mode [17]. Recently, the development of control theories based on heuristic knowledge, such as expert systems and fuzzy sets, made it possible to fully automate processes, by mimicking the behavior of human expert operators. A sample of industrial applications of fuzzy logic and intelligent systems appears in [3, 15, 16]. Typical applications in this area include hydrogeneration control [24], polymerization control [26], gas-fired water heater control [22], petrochemical process control [20], grinding process control [13], nuclear reactor control [1, 4, 21] and cement kiln control [10, 12]. In the metal processing industry, attempts at using fuzzy logic control ideas are described in [27].

Rotary kilns exhibit time-varying and non-linear behaviour and relatively few measurements are available. The usual approach of establishing a mathematical model fails, since the resulting model is either too simple to be of any practical value or too complicated to possess any general applicability. There is a striking contrast between the difficulty of establishing adequate automatic control strategies based on mathematical models, and the ease with which human operators train to control the same process. Thus, it seems that control of kilns is especially amenable to fuzzy control ideas, since fuzzy logic is conceived to handle mathematically linguistic expressions like "high", "low", "slightly increase" etc. As a first step, the control statements, appearing in kiln operating manuals, can be encoded into appropriate fuzzy control rules. Further refinement is possible, by extensive interviews of skilled operators and feedabk evaluation from operation data [23]. F.L. Smidth are the pioneers in this field, starting with a test on a small heat exchanger in 1975, while in 1978 the first system was installed on an industrial kiln system, a rotary lime-reburning kiln in a paper mill in Sweden [11]. Oestergaard and Holmblad describe a number of such installations, which numbered more than 50 cement plants worldwide by 1987 [10, 18].

The industrial complex of Larko S.A., in Larymna, Greece, is one of the largest metal processing plants

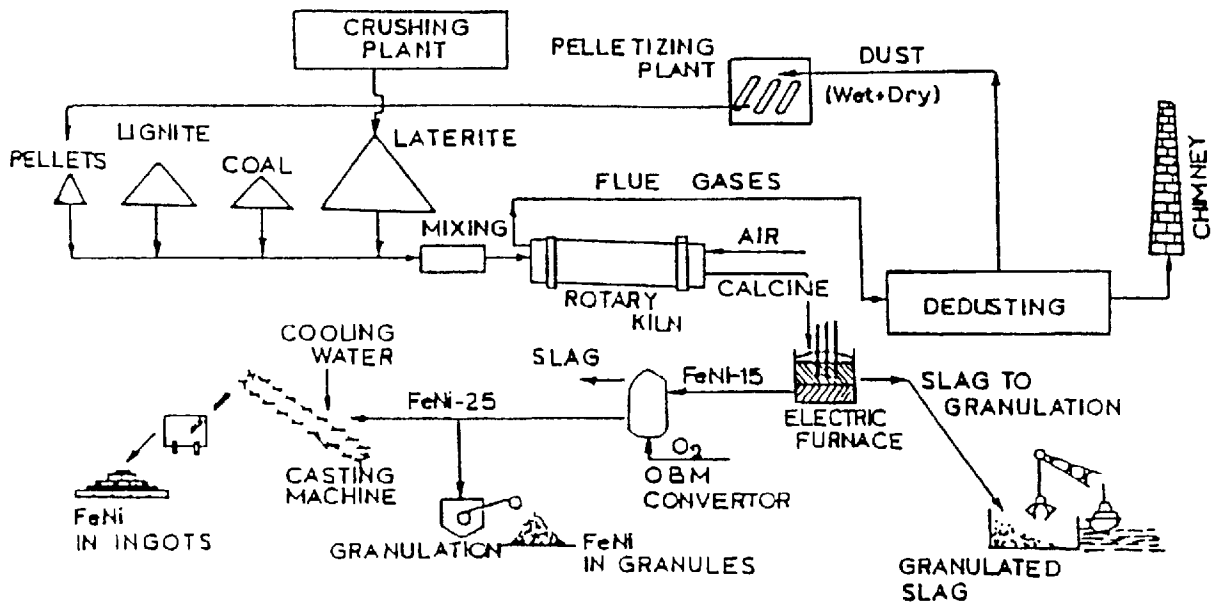---

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Fig. 1. FeNi production proces.

in Europe. It produces ferronickel (FeNi with 18–24% Ni), which forms the basic raw material for the production of stainless steel. Most of the product is exported to European countries. The company has faced heavy financial problems, and has been put in a state program for reorganization. In an effort to become more productive, the company's management has decided to modernize certain areas of the production process. In this context, the "manual control" of one of the rotary kilns was decided to be converted to a fully automatic control system based on fuzzy logic. It is the scope of this paper to investigate the effects of the new system on energy saving, environment (CO emission), operator comfort as well as to estimate the economic benefits and payback period of the investment.

The structure of the paper is as follows: in Section 2 an outline of the overall metallurgical process is given. In Section 3, a more detailed view of the rotary kiln process is given, especially for rotary kiln IV (R/K IV), which is the one that was converted to automatic fuzzy operation. Operating problems and causes are also discussed. Section 4 discusses the design objectives set and the way implementation was carried out to meet them. Finally, in Section 5 a comparison between the "manual" and fuzzy system operation is carried out, based on actual plant operation data of the relevant parameters.

2. Plant description

Ferronickel is produced from Greek laterite in four stages: mixing of feed, proreduction, fusion and enrichment (Fig. 1). A brief description of each stage follows.

Stage 1: Formation of metallurgical mix

Laterite pellets smaller than 15 mm mix with lignite and coal, to form the metallurgical mix, before entering the next stage. The resulting mixture is stored in silos and forwarded with weight measuring conveyor belts to the next stage. The typical consistency of the mixture depends on the available mineral resources as there are two laterite deposits available:

- laterite A with Fe 32%, SiO_2 17%, Ni 1.1%,
- laterite B with Fe 32%, SiO_2 32%, Ni 1%.

Usually, a mixture of 30% laterite A and 70% of laterite B is used for inventory control purposes, determining also the consistency of the fuel. Approximately there is a need of 200–250 kg of solid fuel composed of a 1:3 ratio of lignite to coal per 1 tn of laterite.
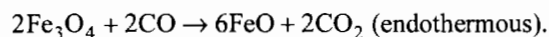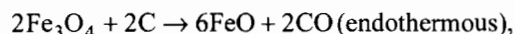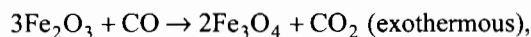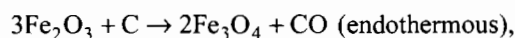
Table 1
Rotary kiln characteristics

Kiln	Length of kiln (m)	Inclination (%)	Kiln diameter (m)	Working capacity (tn/h)	Motor power (KW)
R/K I	90	2	5.2	120–130	216–480
R/K II	90	2	4.2	80	230
R/K III	90	2	4.2	90	220
R/K IV	125	2	6.1	180–220	2×950

The use of a mix of fuel elements aims at a more efficient use of their ingredients in the proreduction and preheating of laterite, as well as at reducing production cost.

Stage 2: Proreduction of laterite in rotary kilns

Proreduction aims at partially reducing ferrous and nickel oxides to ferronickel and lower ferrous oxides. This is achieved in four rotary kilns. Their characteristics are tabulated in Table 1.

The kilns are protected from high temperatures by an interior shell of fire bricks. The mix is forwarded to the kilns due by the rotary motion (1 rev/min) and the falling gradient inclination (2%). As a result of this motion, the protective shell wears out and has to be replaced regularly. There is approximately a 15 lt crude oil consumption per ton of laterite during the necessary time (4 h) for the procedure. The interactions taking place during this operation are:

$$C + O_2 \rightarrow CO_2,$$

$$C + CO_2 \rightarrow 2CO,$$

$$NiO + C \rightarrow Ni + CO \text{ (endothermous)},$$

$$NiO + CO \rightarrow Ni + CO_2 \text{ (endothermous)},$$

$$3Fe_2O_3 + C \rightarrow 2Fe_3O_4 + CO \text{ (endothermous)},$$

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2 \text{ (exothermous)},$$

$$2Fe_3O_4 + 2C \rightarrow 6FeO + 2CO \text{ (endothermous)},$$

$$2Fe_3O_4 + 2CO \rightarrow 6FeO + 2CO_2 \text{ (endothermous)}.$$
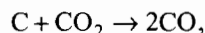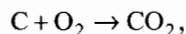
The resulting reduction degree is about 55%–65%. This is calculated as the ratio of disthenic ferrite to total ferrite. The necessary air flow for correct combustion is supplied by two induced draught fans at the kiln entrance and side fans on the kiln body. The produced dustair is filtered through the dust chamber, polycyclon and a Venturi scruber or electrostatic dedusting. They are then emitted through a 155 m chimney to the environment. Dust collected by the filters is rich in nickel and carbon and is therefore "pelletised" with the use of concrete, and recycled back to the first stage, contributing up to 7% of the overall feed mix. The product output from the kilns is loaded while still hot into bennes and forwarded to the next stage via bridge cranes.

Stage 3: Smelting in electric kilns

Smelting is performed in five electric kilns of 148 MW total power. Three Sodeberg electrodes in each kiln melts the mixture. The necessary temperature is of the order of 1500 °C, thus a protective fire-resistant chromium-magnesium brick shell and water cooling where possible, are used. Concurrently with smelting, the reduction of Fe oxides is taking place. Thus, it is produced FeNi 15, containing all of the Ni and part of Fe, and rust consisting of Fe and Si oxides. The Ni percentage in FeNi 15 can be regulated by the amount of coal in the fuel mix. The performance index of the plant is calculated from the Ni losses in the rust (approximately 0.17%). The power necessary for smelting amounts to 450–460 kW per tn of mixture, corresponding to 55–60 MW per produced tn of Ni. The removal of FeNi15 and rust is accomplished through specially consrtucted holes in the body of the kilns. Rust represents 85% of the mixture, but it can be pelletized and sold to cement or sandblasting industries. FeNi 15 is forwarded to the next stage.

Table 2
Desired temperature profile

Pyrometer	Pyrometer position (m)	Desirable temperature (°C)
T_1	17.8	830
T_2	34.1	720
T_4	55.9	560
T_5	67.1	520
T_6	79.5	460
T_7	95.1	400
T_8	115.6	300

T_3 was intentionally out of order

Stage 4: Enrichment and purification of FeNi

Enrichment and purification of FeNi is done in the exchangers of the plant. The desired enrichment of Ni in the FeNi is achieved by burning Fe with propane and oxygene in an OBM exchanger. Oxygen is produced at the plant, while propane is bought. The purification is achieved with the addition of CaO+MgO (dolomite lime) or $CaCO_3$+$MgCO_3$ (dolomite limestone) so that sulfur and phosphorus are limited to commercially accepted levels. Temperatures required at this stage reach 1600–1700°C. The final product is forwarded to a cooling tank where it is formed in pellets (3–40 mm) with: Ni 18–24%, S 0.07–0.12%, P < 0.1%. The produced rust is also pelletized and sold for underwater pipe coating.

3. The rotary kiln

The fuzzy logic control system under study is installed in one, out of the four in total, rotary kilns, the R/K IV. It is the newest kiln, installed in 1979, with superior technical specifications compared to the other traditionally controlled kilns (see Table 1).

There are two rotation speeds: the first (0.8–1.1 rev/min) is for normal operation and the second (1/14 rev/min) for maintenance purposes since a halt in the rotation of the kiln endangers warping of the kiln body. The interior protecting sleeve is made of Al_2O_3+SiO_2 (Al_2O_3 33–37%) fireproof bricks which are placed ver-

tically or horizontally. There are also two rings for lessening the slope of the product.

Temperature is measured by pyrometers. At the output of the kiln, the product's temperature is measured by T_0. Its desired temperature is 860°C. Along the kiln are 8 pyrometers establishing the profile of the temperature. Table 2 shows the desired temperature profile along the kiln. Acceptable limits are at ±20%.

Five nozzles provide the necessary oxygen. Ignition of the mix is performed in a crude oil burner located at the front end of the kiln, and housed in a special fireproof chamber, called the flame-chamber. A bottleneck at the exit of the kiln decelerates the mixture in the high temperature zone in order to achieve a better reduction degree. Also at the exit, a sieve with 60 mm holes classifies the outcoming product.

The burner is a standard crude oil burner of external combustion, which can move on rails, if needed, in order to be protected from possible big pieces of outcoming product. It consumes 2500 lt/h and comprises of the fuel tank, the preheater, filters and circulation pumps, nozzles, regulator valves and the gas ignition system.

The fuel is pumped from the fuel tank, preheated at 110–130 °C and supplied through filters and pumps to the nozzles under pressure. From then onwards it can follow an axial or circular course. The fuel is then sprayed into compressed air, which is supplied axially or circularly by a input fan. In this way better controllability of the flame is achieved (i.e., its length and width), which is important as the mixture load varies.

The produced dustair is abducted using induced draught fans. In case of failure, dedusting ususally stops and natural draught is used. However, R/K IV does not have a natural draught chimney, therefore the kiln operation must be halted, and dustair extracted untreated. Dustair follows the path shown in Fig. 2.

In the dust chamber, approximately 5% of the dust is removed, mainly the thick grain portion. For safety reasons, temperature, measured by T_9, 128 m from the kiln end, should not exceed 420°C. The amount of CO, CO_2 and O_2 in the gases is checked on-line by two sensors. The proportion of CO in the dustair should be less than 1.5% in volume, as there is a risk of explosion due to the high temperature in the dust chamber. If the amount of CO exceeds 2.5%, the operation stops until proportion returns to normal.

Next, dustair goes through electrostatic precipitators which charge it, via a pair of electrodes, at 70000 V keeping 99% of total dust volume. Dust is collected
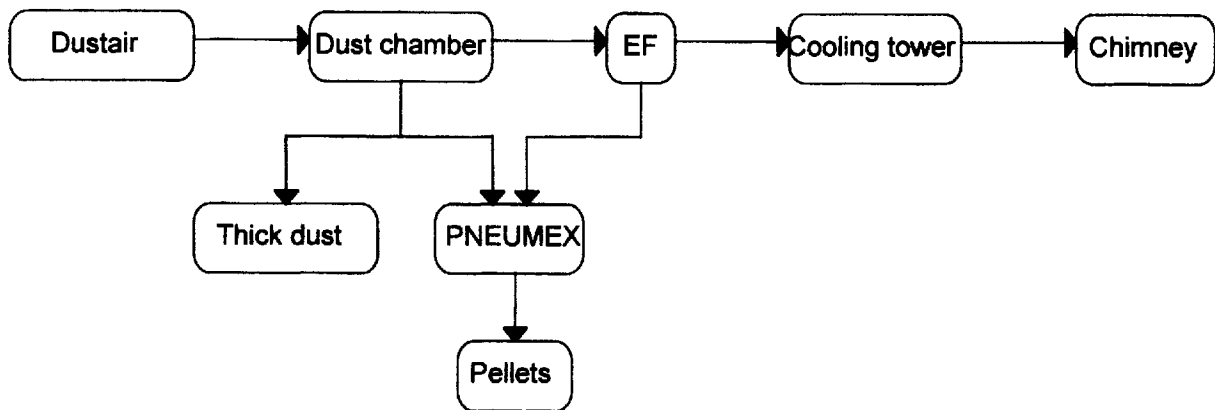
Fig. 2. Path of dustair.

by the earthed electrodes (positively charged). Temperature, which is measured by pyrometers T_{10} and T_{11}, at the filters' input should be less than 380°C. At 420°C a fan reduces the temperature and if failed the kiln is set out of operation. Also the ceiling temperature of the filters should be less than 320°C. Similarly, if temperature exceeds 320°C the kiln is set out of operation. Dust solidified in the filters is removed by appropriate hammers and forwarded to PNEUMEX storing and forwarding silos. When the storing silo is filled, compressed air forwards the dust from the forwarding silo to the pellets silos. Flue gases are diverted to the 155 m chimney.

During the first few meters of the kiln, the mixture is dried due to its contact with the dustair, followed by pyrosis where Fe_2O_3 becomes Fe_3O_4. The temperature reaches 250°C at this stage. Then follows the reduction (proreduction) stage which reaches approximately 860°C at the kiln's exit. An optimum temperature profile is needed in order to produce the desired product and to avoid interior sleeves formed by material solidification. In case of continuously increasing temperature the following measures are taken by the operator:

1. Induced draught is decreased by regulating the dampers of the fans or by decreasing the crude fuel supply.
2. Air supply is reduced by regulating the appropriate dampers.
3. For a long term temperature decrease, the proportion of solid fuel in the metallurgical mixture is reduced.

In general, a temperature increase at the kiln exit should be avoided as it results in sleeve formation. If this happens, sleeves must be removed by breaking them and recycled, after proper treatment, back to the metallurgical mix. The use of a proper 1:3 ratio of lignite to coal fuel mixture is important. Lignite contents volatile fuels, thus helps the ignition and is burned during the first part of the kiln. Then, coal provides the necessary energy for the correct temperature profile and reduction process. Also important are the length of the kiln, the rotation speed and the time that the mixture remains in the kiln (approximately 4 h), as they are all factors of the reduction degree. The rotation speed affects the blending procedure, by allowing greater amount of the mixture to interact with the hot gases, thus increasing the interaction speed. The problem of defining the desirable mix grain size is difficult to resolve. Though smaller grains allow for a better reduction degree, there are also more easily abducted with dustair. Bigger grains are not kilned down to the core. Also, there is no proven relation between grain size and sleeve formation.

Sulphur, which is present in the metallurgical mix and crude oil, presents a corrosion problem. When extracted with the dustair, it produces sulfuric and sulfurous acid and corrodes parts of piping. The presence of chloride in the dustair also causes some corrosion problems.

The master control is located in the front part of the kiln, behind the burner. This supervising position provides the operator with full control over the kiln exit and access to the whole installation. However, working conditions are very harsh due to noise, heat and

dust from the process. Control of the kiln is achieved through a control panel equipped with the necessary operating levers for the supply valves, the fan switches, the dampers etc. and the gauges for the pyrometers and gas analysers.

3.1. Operating problems

The main operating problems in rotating kilns are high temperatures of the dustair, formation of interior sleeves due to material solidification and high CO content of dustair.

The formation of interior sleeves from material solidification, affects the quality of the product and deteriorates the capacity of the kiln, because of the decrease in usable volume of the interior of the kiln. Though nowadays the acquired experience has improved the situation, there is still a need for further progress. The main reasons for material solidification are the formation of FeO, very thin or very thick metallurgical mix grain, temperature increase and intense burning conditions. To deal with the problem, thermal shocks, i.e., fast cooling followed by heating, of the load are applied. If the procedure fails, the kiln is halted at a suitable position, so that the sleeves can be blown up by a special canon fired from the kiln's exit.

Temperature increase results in insufficient heat exchange which boosts the level of CO. A slight overstep of the limit can be confronted by reducing the temperature or by pumping atmospheric air into the gases. If failed, the kiln has to stop and opeation postponed until CO reaches normal level. To completely remedy the problem, the proportions in the metallurgical mix have to be changed.

4. Control objective and implementation

The overall operation objectives can be divided into control objectives for safe operation and control objectives for optimum operation.

For the safe operation the following control objectives must be met:

1. CO content in dustair must be less than 1.5% because of danger of explosion inside the electrostatic precipitators.
2. Ceiling temperature of electrostatic precipitators (measured by pyrometers T_{21} and T_{23}) must be

less than 320 °C, in order to protect the electrostatic precipitators installation.
3. Temperature of dustair, before their entry through the induced draught fans, must be less than 200 °C because of their operation characteristics limitations.

For optimum operation the following objectives are set:

1. Reduction degree for the rotary kiln product in the range [55%, 65%].
2. Temperature of material output of rotary kiln (pyrometer T_0) at around 860 °C. Furthermore the temperature profile along the kiln, should resemble that of Table 2.
3. Feed rate of kiln as near to maximum as possible. A value between 180–200 tn/hr is acceptable.
4. Levels of CO much less than 1.5% for reasons of better utilization of fuel.
5. Reduction in crude oil consumption.
6. Reduction of electric power consumption in electric kilns I and V which are fed with the output of the rotary kiln IV. Current consumption ranges between 450–460 Kwh/tn of product.
7. Reduction in kiln shut-down time because of failures.

Using "manual control", optimal operation was attained with the following manipulations:

1. Regulation of crude oil supply.
2. Regulation of central damper for control of draught.
3. Regulation of feed rate of metallurgical mix to the kiln.
4. Regulation of kiln rotation speed, independently of the kiln's rotation speed/feed diagram.
5. Manual regulation of air supply to the kiln body through the body's fans.
6. Correct proportion of solid fuel in the metallurgical mix. Incorrect proportion may be due to bad quality of solid fuel or wrong weighing.
7. Sampling and chemical analysis of feed materials and final product.

Although points 6 and 7 affect optimum operation quite significantly, the system under study cannot take them into account automatically due to lack of appropriate sensors.

To implement the fuzzy control system, a new master control room for R/K IV was built. From there, the

kiln is controlled remotely, thus providing better working conditions for the operators and safety for the control equipment. A remote controlled camera monitors the procedure in the burning chamber for the inspection of the kiln exit, providing controllability over the burners flame and ability to prevent the formation of interior sleeves due to material solidification.

The fuzzy control system can regulate four inputs to the overall kiln control system: crude oil feed rate, metallurgical mix feed rate, central damper opening and kiln rotation speed. Their values depend on specific fuzzy rules which are encoded in propriatory software modules of FLS Automation. Their overall structure is described in the Appendix, while details of the system are described in [8, 19, 28]. Their range of values is fixed as follows:

- Crude oil feed rate: [800 lt/h–2500 lt/h];
- Metallurgical mix feed rate: [140 tn/h–220 tn/h];
- Central damper opening: [35%–55%];
- Kiln rotation speed: [0.65 rpm–1.1 rpm].

Control actions depend on nine parameters whose values are checked by the system. Each parameter is assigned a priority number, so that if more than one parameter is out of prescribed limits, the parameter with the highest priority is first controlled. Checks and priorities are as shown in Table 3.

Furthemore, the system checks for variations in the metallurgical mix feed rate, and adjusts for a smooth transition of current ctude oil feed rate to new one. This results in better burning of the mix in the kiln.

4.1. Hardware implementation of the fuzzy control system

The rotary kiln fuzzy control system is designed and installed by F.L. Smidth & Co. A/S of Denmark. It is implemented around a Micro Vax minicomputer. In Fig. 3 the overall flow diagram of the computerised control system is depicted. The control elements of the installation (sensors, actuators etc.) are controlled via Siemens Simatic S5 PLCs, which are programmed by a dedicated PC microcomputer. Sensor signals are analogue, while motor and burner signals are analogue and digital. System information is fed to the main Micro Vax workstation which runs the main SDR (Supervision Dialogue and Report System) software. This program stores and analyzes incoming information and displays it on the three operator micros DOP1-3. On those micros the software SDR Opstation

is installed. This performs the functions of installation overlooking, control and fault diagnosis. These tasks are performed via mimic diagrams, fault catalogues, kiln motor groups and graphics utilities. For example, Fig. 4 shows the mimic diagram for the kiln control.

On the DOP3 micro the software SDR Fuzzy Logic Control is installed. When the option "automatic operation" is selected, this program performs all the necessary calculations for the automatic operation of the rotary kiln system. Every relevant information, such as operation targets, their current values, control actions and variation of basic operation parameters, is displayed on the terminal. When "manual operation" is selected, the human operator controls the system via the SDR Opstation software.

5. Comparison of system performance

In order to evaluate the effectiveness and economic feasibility of the fuzzy control system, the values of the parameters that affect the safe and optimum operation of the rotary kiln will be examined. Examination is done over two periods: the first period covers the "manual control" operation, while the second covers the automatic operation. Table 4 summarizes the relevant information.

For the first period, values for the first fourteen parameters have been calculated over a period of three months, while values for the last four parameters over a period of fifteen months. The second period extends over three months. For each parameter its mean value, standard deviation, fluctuation range and target are shown. Deciphering of the table shows that the main differences between manual and fuzzy system are:

1. Both CO analyzers show CO content is reduced and kept at very low levels.
2. Ceiling temperatures of electrostatic precipitators, as measured by pyrometers T_{21} and T_{23}, are kept at temperatures much lower than the safety limit (320 °C). However both systems perform equally well.
3. Temperature of dustair before entering the induced draught fans, as measured by pyrometer T_{14}, is kept at a distance from the safety level (200 °C).
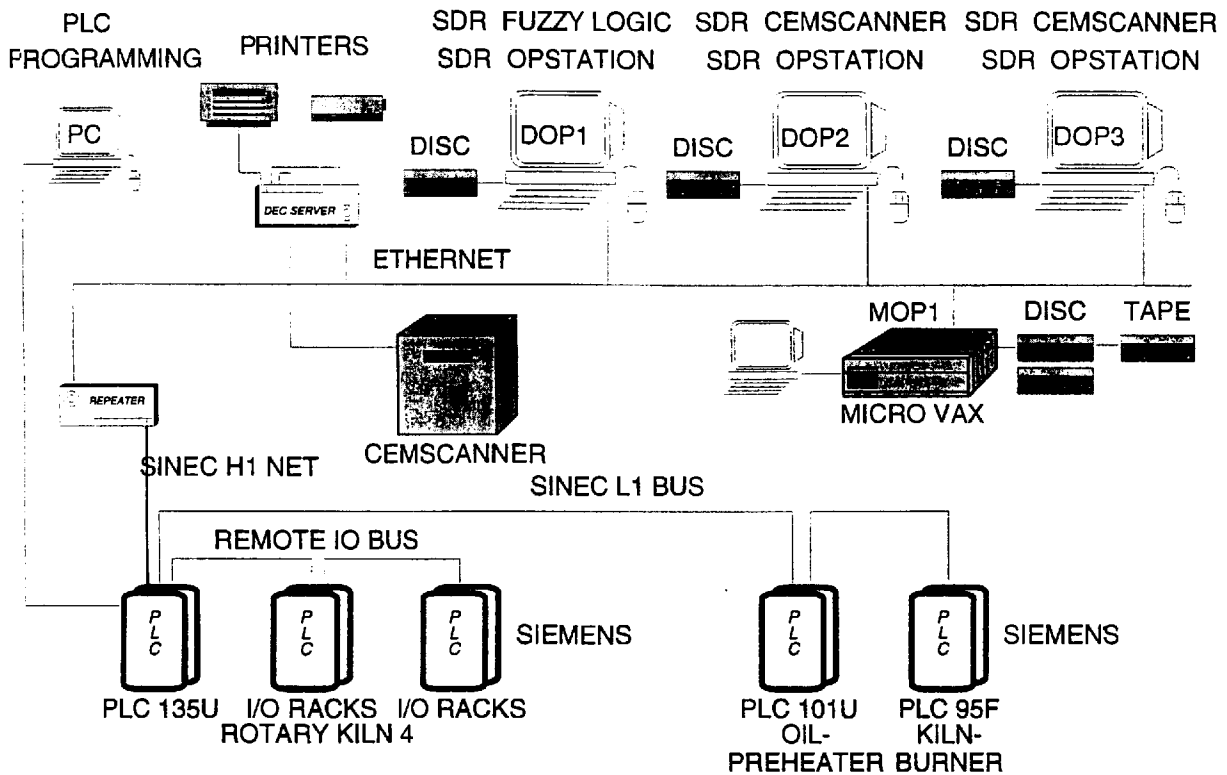4. The degree of reduction of final product is maintained at desirable levels (55%–65%).

Fig. 3. Computer system overview.

Table 3
Control parameters

| Parameter	Priority	Start control	Stop control
High CO content	1	> 1%	< 0.8%
Electrostatic precipitator ceiling temperature	2	> 310 °C	< 300 °C
Dustair temperature before entering induced draught fans	2	> 195 °C	< 190 °C
Sleeve formation in kiln's shell	3	Human operator dependent	Human operator dependent
CO content	3	> 0.8%	< 0.5%
Fast temperature drop at T_1 and T_2	4	$T_1 < 800\,°C$, $T_2 < 690\,°C$ or tangent slope $< -1\,C/min$	Tangent slope $= 0\,°C/min$
Very low temperature at T_1 and T_2	4	$T_1 < 780\,°C$ $T_2 < 670\,°C$	$T_1 > 790\,°C$ $T_2 > 680\,°C$
Temperature profile along kiln different from specified	5	$T_i > T_i^t + \varepsilon_i$, where T_i^t, the top threshold for T_i is defined by the profile and ε_i, the tolerance level by the process conditions	$T_i < T_i^b - \varepsilon_i$, where T_i^b, the bottom threshold for T_i is defined by the profile, and ε_i, the tolerance level by the process conditions
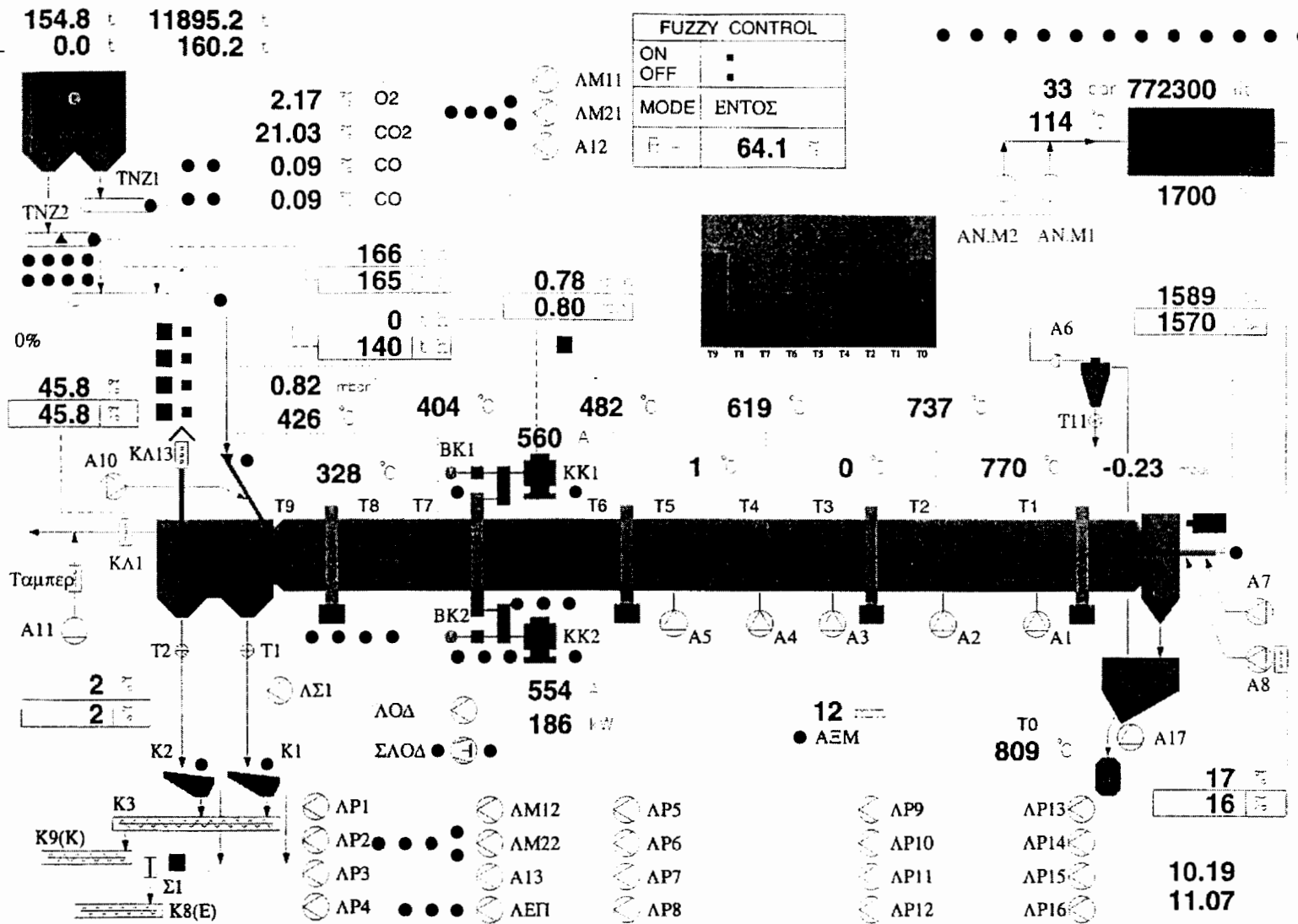
Fig. 4. Mimic diagram of kiln process.

Table 4
Statistics for operation parameters

Operation parameter	Mean value		Standard deviation		Variation interval		Target
	Manual system	Fuzzy system	Manual system	Fuzzy system	Manual system	Fuzzy system	
1. Pyrometer T_0	855.02 °C	855.60 °C	18.49 °C	17.96 °C	[836.53, 873.51]	[837.64, 873.56]	860 °C
2. Pyrometer T_1	817.04 °C	826.63 °C	30.42 °C	38.77 °C	[786.62, 847.46]	[786.86, 864.40]	830 °C
3. Pyromrter T_2	686.63 °C	723.92 °C	33.29 °C	37.51 °C	[653.34, 719.92]	[686.41, 761.43]	720 °C
4. Pyrometer T_4	529.21 °C	569.93 °C	40.84 °C	38.08 °C	[488.37, 570.05]	[531.85, 608.01]	560 °C
5. Pyrometer T_6	378.69 °C	441.42 °C	37.36 °C	38.86 °C	[341.33, 416.05]	[402.56, 480.28]	460 °C
6. Pyrometer T_7	352.33 °C	401.23 °C	40.33 °C	35.98 °C	[312.00, 392.66]	[365.25, 437.21]	400 °C
7. Pyrometer T_9	401.94 °C	405.67 °C	22.19 °C	22.19 °C	[379.75, 424.13]	[383.48, 427.86]	420 °C
8. Pyrometer T_{14}	185.12 °C	171.26 °C	8.44 °C	11.08 °C	[176.68, 193.56]	[160.18, 182.34]	< 200 °C
9. Pyrometer T_{21}	273.53 °C	276.95 °C	8.91 °C	14.90 °C	[264.62, 282.44]	[262.05, 291.85]	< 320 °C
10. Pyrometer T_{23}	273.53 °C	272.91 °C	8.91 °C	15.33 °C	[264.62, 282.44]	[257.58, 288.24]	< 320 °C
11. CO (1st analyser)	0.31%	0.13%	0.23%	0.13%	[0.08%, 054%]	[0.00%, 0.26%]	< 0.5%
12. CO (2nd analyser)	0.34%	0.23%	0.18%	0.18%	[0.16%, 0.52%]	[0.05%, 0.41%]	< 0.5%
13. Feeding M.M.	164.03 tn	173.28 tn	28.34 tn	21.66 tn	[135.69, 192.37]	[151.62, 194.94]	[180.220]
14. Reduction level	61.09%	61.18%	7.52%	7.35%	[53.57%, 68.61%]	[53.83%, 68.53%]	[55%, 65%]
15. Operation hours/day	21.278 h	22.95 h	–	–	–	–	24 h
16. Product	264.3 tn	3018.95 tn	–	–	–	–	increase
16. Grude oil consumption	15.7 lt	14.65 lt	–	–	–	–	decrease
17. Electricity consumption	465.76 KWH	–	–	–	–	–	decrease

5. The kiln's temperature profile, as measured by pyrometers T_1–T_9, has improved as a result of the automation. The final product temperature, as measured by pyrometer T_0, is kept at acceptable limits (840 °C–880 °C).

6. The metallurgical mix feed rate has increased by 9.25 tn/hr.

7. Operation time of the kiln has increased by 1.672 hr/day. This is attributed to reduced downtime as a result of the automated process.

8. Production has increased by 377.65 tn/day.

9. Crude oil consumption has been reduced by 1.051 t/tn of product.

10. Electricity consumption has been reduced by 20.24 kWh/tn of product.

As a result of the raw product volume increase, the company increased its production of FeNi by 3.195 tn/day or 99.045 tn/month. The company's profit from selling FeNi at the time of the study is $0.5/lb (1 lb = 453 gr), which results in net profits from increased FeNi production of $109321/month.

The crude oil consumption was reduced by 1.05 lt/tn of product. Cost of crude oil is $0.172/kg. To con-

vert litres to kilograms, the temperature of prehating of crude oil, as measured by T_1, must be taken into account as follows:

specific weight at $T_1 = (0.9869) - (T_1 - 15 \,°C)$

$$\times \, 0.00064$$

Thus, for the two systems, s.w. at 90 °C = 0.9389 (manual) and s.w. at 110 °C = 0.9261 (fuzzy). The crude oil consumption for the manual system is 15.7 lt/tn of product or 14.74 kg/tn of product. Crude oil consumption for the fuzzy system is 14.65 lt/tn of product or 13.57 kg/tn of product. Therefore, crude oil consumption was reduced by 1.08 kg/tn of product, resulting in reduction of production cost by $0.186/tn of product or $17407/month.

Electricity consumption in the electric kilns E/K1 and E/K5 was reduced by 20.24 kWh/tn of product. Electricity cost at time of study was $0.0315/kWh, giving a cost reduction, because of electricity savings, of $0.64/tn of product or $59896/month.

Therefore, overall profit adds up to $186624/month. Initial cost of the investment was roughly $2,330,000. This gives a payback period of just over 1 year. Even though our calculations are not very detailed and data not of a sufficient time period, it is believed that the actual payback period will not deviate significantly from this estimated value, which represents an excellent figure.

However, economic considerations is not the only field of comparison. One must take into account environmental impact and operator comfort. Both of these aras are improved since CO content and electricity consumption are lower with the fuzzy system. Also operator comfort is improved as a result of the computer supervision and control, which facilitates control from a distance, thus avoiding intense heat and pollution areas near the kiln's entrance and immediate surroundings.

6. Conclusion

The figures of this study show that the installed fuzzy control system has improved the performance of the rotary kiln under examination as shown by most performance indices. Where significant improvement was not noticed, indices were at least as good as the ones observed for the "manual" control period. Sleeve formation, one of the major concerns, was less frequently observed, resulting in reduced kiln downtime. Production cost has fallen as a result of reduced crude oil consumption, increase of final product volume and decrease of electricity consumption in E/K 1 and E/K 5. Because of the same reasons reduced pollution levels are expected. The new remote control room, has resulted in improved working conditions for the operators.

As a whole this study shows that beyond doubt a well designed fuzzy control system can replace skilled operators in complicated processes, like the one of the metallurgical rotary kiln, provided their expertise is carefully taken into account. The whole system could easily be transferred to a similar plant, possibly with minor modifications, due to changes of parameter values, but the point remains that such systems provide viable alternatives to classical manual control. The fact that in such complicated processes model-based methods can hardly be applied, fuzzy control may be the only answer to converting these systems to automatic. Furthermore, this study shows that apart from improved reliability and fuel savings resulting as a consequence of automation, environmental benefits are a factor that cannot be overlooked.

Appendix

Description of the Fuzzy Control System

The fuzzy control system is implemented using a propriatory programming language and program interpreter, developed by FLS Automation, for the specification and execution of control strategies. FCL is similar to other interpretation-based languages such as BASIC, but is oriented towards handling fuzzy control rules. FCL users are operation personnel and are not necessarily acquainted with computer programming. FCL's characteristics are:

- The computer utilizes the same measurement information about the process, as used by the human operators.
- The control strategy is composed of Control Groups which implement a sequence of Control Objectives describing the relationship between process conditions and control actions.
- The control rules are formulated as linguistic expressions, involving terms like "high", "low", "increasing", etc.
- Control rules are evaluated using fuzzy logic.

```
0                 NAME: W1X2CTL\60\
1       *
2       *
3       *      Control of oxygen through regulation of coal
4       *      feed rate.
5       *
6       INPUT O2\W1W01X1, 0.7, 1.6, 3\
7       OUTPUT DCOAL\W1V19SP, 0.5\
8       *
9       IF LOW(O2) THEN MNEG(DCOAL)
10      IF OK(O2) THEN ZERO(DCOAL)
11      IF HIGH(O2) THEN MPOS(DCOAL)
12      *
13      END
```

Fig. 5. Typical FCL program.

A control strategy consists of one or more FCL programs. A typical FCL program is shown in Fig. 5.

The first line of the program (line 0) specifies its name (W1X2CTL) and a time interval (60 secs.) that specifies the time between subsequent executions. The other program lines contain variable statements, fuzzy logic control rules, arithmetical calculations, program control lines and comments. In this example, which facilitates control of oxygen level by adjusting coal feed rate, O2 is the oxygen percentage and DCOAL the coal feed rate. The basic FCL statements are:

```
INPUT v1\pCODE, n1, n2, n3\
```

e.g. `INPUT O2\W1W01X1, 0.7, 1.6, 3\`

```
OUTPUT v1\pCODE, n1\
```

e.g. `OUTPUT DCOAL\W1V19SP, 0.5\`

```
IF <condition> THEN <control
   actions>
```

e.g. `IF LOW(O2) THEN MNEG(DCOAL)`

The INPUT statement states the pointer (pCODE = W1W01X1) in the measurement data base where the value that v1 (= O2) is assigned, resides. Constants n1 (= 0.7), n2 (= 1.6) and n3 (= 3) specify the values for scaling the low, normal and high v1 value respectively. The OUTPUT statement defines correspondingly where the calculated value v1 (=DCOAL) will be stored (pCODE=W1V19SP), and its upper limit (n1=0.5).

The IF-THEN statement is composed of fuzzy primary terms, fuzzy terms and basic terms describing control actions. Table 5 lists the primary fuzzy terms of FCL, as well as values for a, b, c used to calculate membership functions by the formula:

$$\mu(x) = 1 - \exp\left(-\left(\frac{a}{|c-x|}\right)^b\right).$$

thus, the membership functions are continuous exponential expressions in the interval $(-1, 1)$, see Fig. 6. Hence the need for transforming input variables by scaling factors. FCL uses the following fuzzy operators:

NOT $\mu(x) = 1 - \mu(x)$,

$\mu_A(x)$ AND $\mu_B(x) = \min(\mu_A(x), \mu_B(x))$,

$\mu_A(x)$ OR $\mu_B(x) = \max(\mu_A(x), \mu_B(x))$.

Evaluation of the <condition> term results in a number C, which is called the degree of fulfillment of the rule. The <control action> term is defined as a variation R of the control variable. For example the control action MNEG(DCOAL) of line 9 defines a medium negative change of the setpoint. When a control strategy for a control variable U (= DCOAL in example), consisting of N (=3 in example) control rules is executed, <condition>$_i$ of rule i results in a number C_i between 0 and 1 according to fuzzy arithmetic [4]. If one considers the <condition>: LPOS(0.8) AND NOT LOW(0.3) the answer is $C = 0.73$. In essence,
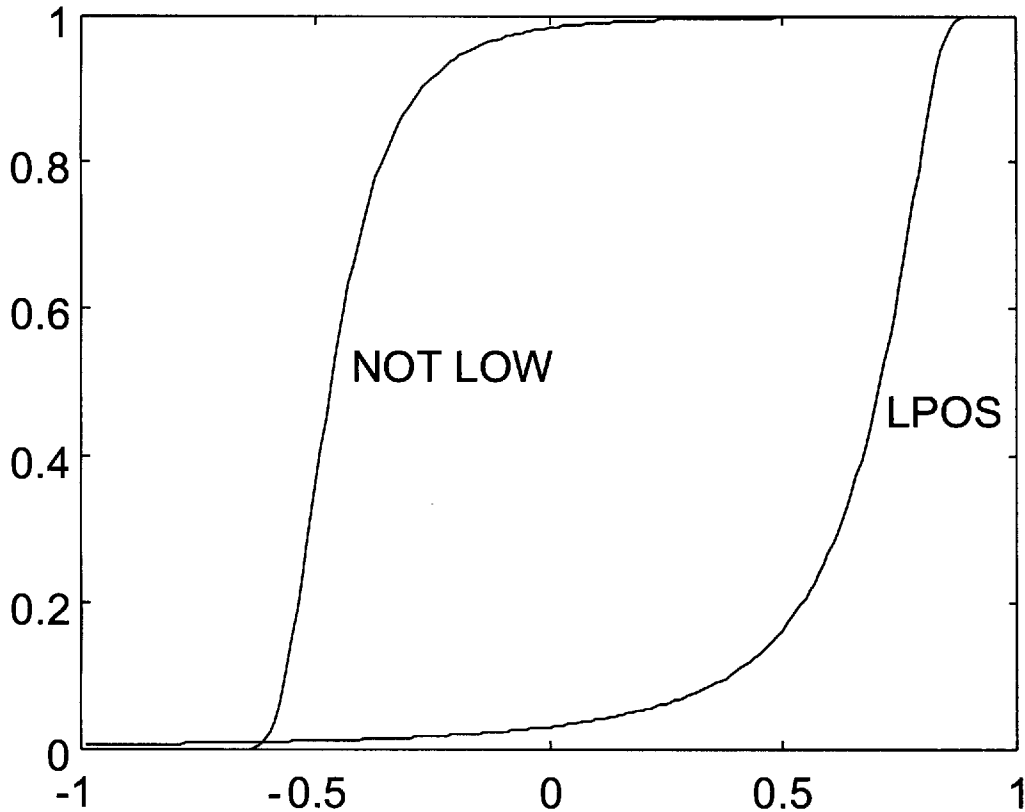
Fig. 6. Graphs of typical membership functions.

Table 5
Primary fuzzy terms of FCL

Fuzzy terms	Short name	a	b	c
Large positive	LPOS	0.25	2.5	1.0
Medium positive	MPOS	0.25	2.5	0.7
Small positive	SPOS	0.25	2.5	0.4
Zero positive	ZPOS	0.10	6.0	0.1
Zero	ZERO	0.25	6.0	0.0
Zero negative	ZNEG	0.10	6.0	−0.1
Small negative	SNEG	0.25	2.5	−0.4
Medium negative	MNEG	0.25	2.5	−0.7
Large negative	LNEG	0.25	2.5	−1.0
High	HIGH	0.50	6.0	1.0
Ok	OK	0.60	8.0	0.0
Low	LOW	0.50	6.0	−1.0

C_i represents the weight by which control rule i influences the final adjustments resulting from evaluation of all the control rules. Next the terms <control action>$_i = R_i$ are evaluated, by,

$$R_i = C_i \mu(U).$$

Note that these are areas (functions) and not numbers. The control action resulting from consideration of all control rules, is then composed as,

$$R(U) \quad \max\{R_1, R_2, \ldots, R_N\}.$$

Finally, the actual control adjustment U (single value), is determined by selecting that value in the interval $(-1, 1)$ which divides the area under $R(U)$ in two areas of equal size. In this way, it is ensured that the more a rule is fulfilled, the more it contributes to the final control.

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