SYNTHESIS REPORT

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PROJECT COORDINATOR	British Maritime Technology Ltd
PARTNERS:	BMT Ltd. Siemens AG Companhia de Celulose do Caima Roermond Papier bv K.U. Leuven

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2. CLEAN - CASE-BASED LEARNING ENVIRONMENT FOR PLANT PROCESS MANAGEMENT

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3. ABSTRACT

The CLEAN project developed a system for automatic on-line process optimisation in pulp and paper plants. Optimisation is here defined as producing pulp or paper to a given specification consisting of permitted ranges for several measurable quality and environmental parameters, while minimising the cost per tonne of output subject to these constraints. This was achieved by implementing an adaptive controller using "Case-Based Learning" techniques, originally developed under research into artificial intelligence, supported by neural nets modelling some of the parameters. Quantified results are presented for one pulp mill and one paper mill. The technique is applicable to other industries where the variable quality of the raw materials causes control problems.

4. INTRODUCTION

Pulp manufacture is a stage in the manufacture of paper. The input material is wood. This is broken down into chips, which are then "digested" by mechanical or chemical means, removing the lignin content and leaving cellulose. Bleaching may follow this. The output is either a solid material similar to thick blotting paper, or a slurry of this suspended in water. Customers specify their requirements in terms of a few quality parameters, including permanganate number, breaking length, dirt count and brightness. Cost of production is dominated by wood consumption (i.e. the mass of wood required to produce one tonne of pulp), energy for the digestion process, but the cost of chemicals (e.g. for bleaching) is usually significant. The major control problem is that the wood used as a raw material is subject to strong variations in quality, e.g. dryness and wood type, which make it difficult to produce a workable traditional controller.

Paper mills (which may be integrated with pulp mills) may use this "virgin" pulp as the input material, or may combine it in any proportions with pulp formed mechanically by breaking down recycled paper. A mill using virgin pulp is more controllable than a pulp mill, since the input material is of more consistent quality. However recently market forces and environmental legislation have led to mills recycling paper as part or all of the raw material. This is much more variable in quality, particularlyif post-consumer *waste is* used, leading to a high standard deviation in the output quality measurements e.g. burst strength. Typically in order to ensure that the lower quality limits are met, the *average* quality produced has to be maintained well above the acceptable lower limits. This is expensive, particularly if starch is used to raise the quality. If *the* standard deviation in the quality parameters can be reduced, the average quality and hence the cost of production can still be used while still meeting customer's requirements.

The aim of this project was not to maximise quality, but to minimise production costs while guaranteeing that the minimum physical specifications given by the customers will be met. CLEAN had two demonstrators Caima Constancia manufactures pulp from wood, typically *Eucalyptus globulus*. The process is a chemical one, with both batch (digester) and continuous production aspects, with different time scales, necessitating the use of two intercommunicating controllers. The objectives in this plant were:

- to reduce the amount of rejects by 50°A (our original target was 25% for the late prototype, but this was increased to 50°A after good experiences with the first prototype)
- to reduce the standard deviation of the difference between the target and measured permanganate number by 50°/0 (20% in early prototype), allowing the system to be run closer to the limits of acceptable quality without transgressing those limits, permitting a saving in operating costs under some conditions
- to reduce energy (steam) consumption by 10%(5%)
- to increase pulp resistance (a quality parameter) by 50°A (20%.)
- during the project an additional goal of increasing the massic yield by l% was set

Roermond Papier, on the other hand, produces paper from a 100?4o waste paper input. This is a physical, high-speed continuous process, whereby the input material is physically broken up into a thin aqueous suspension, sprayed uniformly in two layers over a *"wire"* (a *fine* mesh), and dried by vacuum and heat. The objectives in this plant were:

- water savings of 10-200/0

- energy savings of 5-10%
- starch savings of 5-10% - starch is used to raise the quality of paper, but is expensive - more consistent paper quality will allow starch to be reduced, producing paper closer to the limits of acceptable quality without transgressing those limits
- reduction in degradation of product, 3-5%
- up-time increase of 1 -2°A - mainly by reducing paper breaks

5. TECHNICAL DESCRIPTION

5.1 OVERALL ARCHITECTURE

The system is built as a distributed set of separate programs running under MS Windows for Workgroups, communicating by transfer of ASCII files over an ethernet network. Experience has shown that a modular architecture of this type is an advantage in development in that modules can be developed and tested off at separate sites. It also helps with extension of the system during the exploitation phase, allowing components such as the HCI or database to be replaced in a modular fashion without disturbing other components. In order to develop the system at several sites, the consortium has used an evolving working document called the *Integration Architecture of the Find Prototype*, which holds the interface specification for the whole system. Caima and Roermond share similar architectures, although some differences were forced by the different plant designs.

The software is made of multiple Site Control Units, which may feed data into each other. This reflects the fact that across certain boundaries in the factory (e.g. the digesters at Caima), an aliquot of wood does not retain its identity due to mixing, hence a single controller is not possible, but time-averaged information is still of use to the next SCU. Figure 5.1- I shows how a single SCU interfaces to the others. By suitable configuration of the initialisation files, any of the chained input, chained output, or case output may be suppressed (Caima exhibits an example of all three). Roermond uses a single SCU, with no chained input or output. Note - a "DEPM" in this diagram is a Data Entry/Processing Module. It may supply a user interface for data not obtainable from the plant automation systems, e.g. quality data.

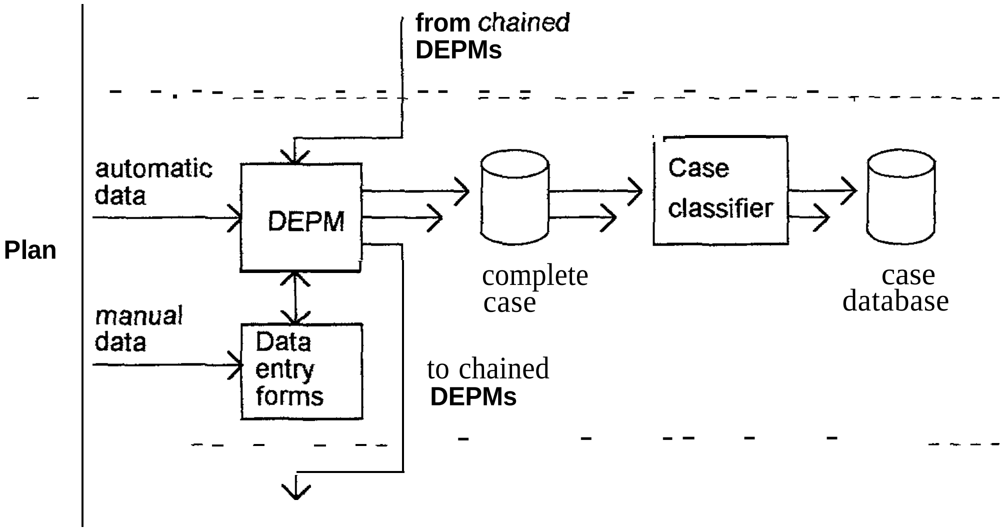

Figure 5.1-1- Data flow in system for one Site Control Unit

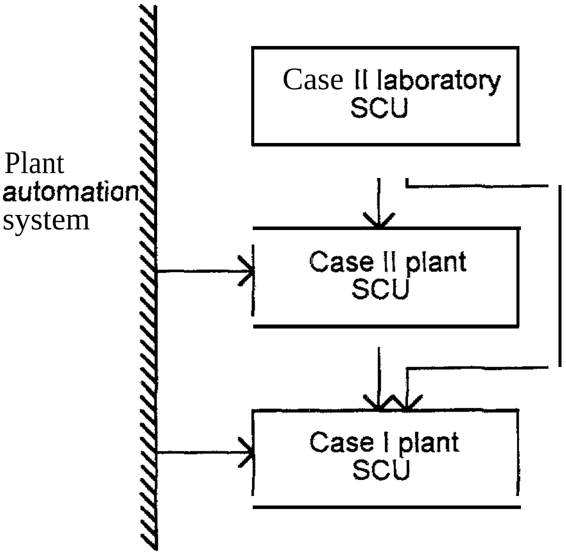

Figure 5.1-2- Interconnection of SCUs at Caima

The view presented in Figure 5.1-1 is very simplified: Figure 5.1-3 shows more of the detail of a single SCU. This a full final integration diagram of the Caima CLEAN system. R should be noted that this view is of the modular system, and, as such, it does not represent the physical hardware and software layout of the demonstrator. All inter-modular links are performed either with the use of ASCII text files on the same machine or over an ethernet Local Area Network, or with the use of internal application data transfer. As a deliberate result of this design decision, the physical distribution of these modules thus becomes unimportant. Further, the use of standard 386 and 486 PCs operating under MS-DOS and Window's for Workgroup and the use of soft-coded initialisation file techniques rather than hard-coded configurations wherever possible, has enabled operators to move or reconfigure modules within the CLEAN system with the minimum of effort.

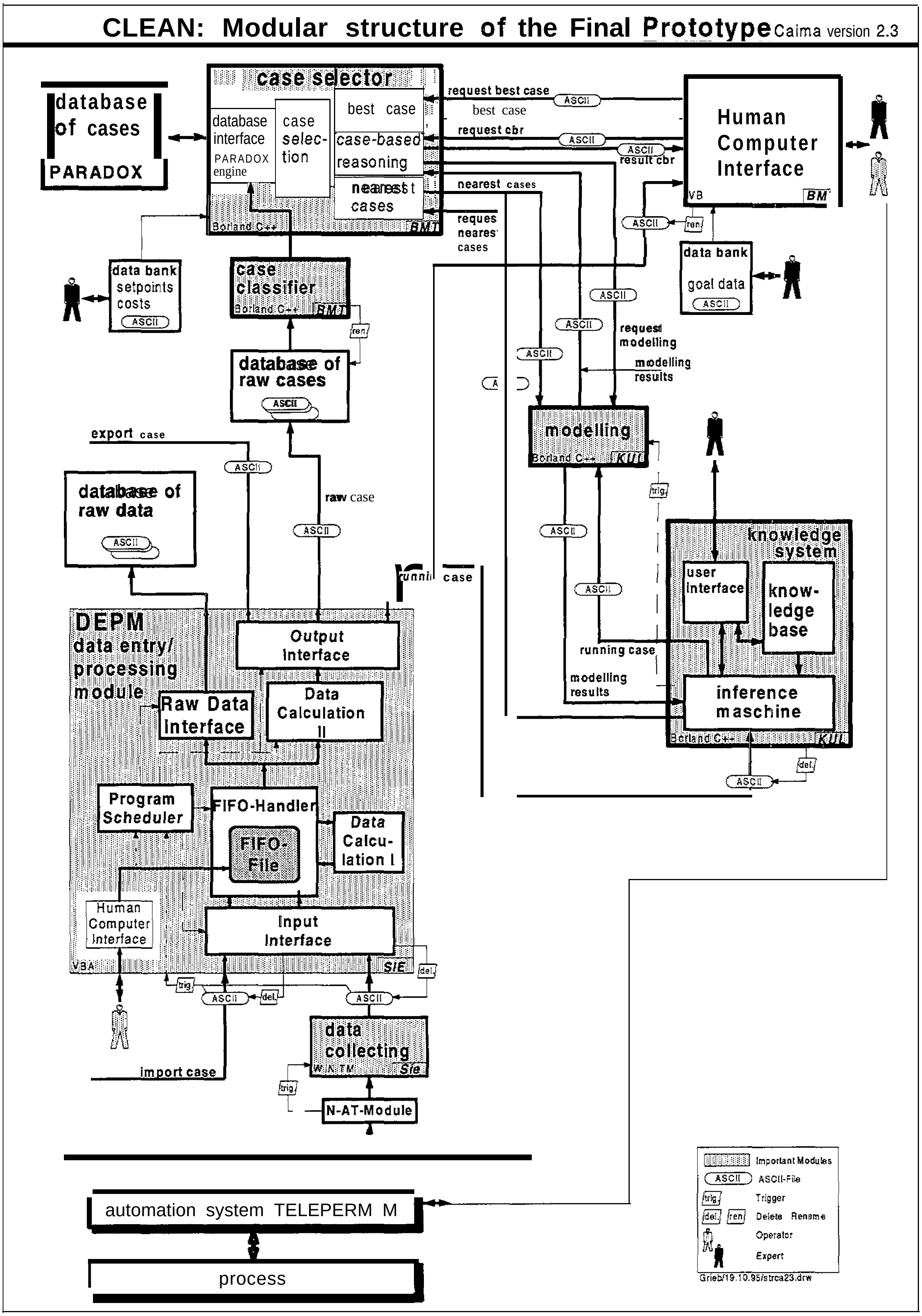

Figure 5.1-3 *Modular Structure of the Final Prototype for Caima*

Perhaps the clearest demonstration of this modular flexibility has come in the installation at Caima where as a direct consequence of the physical layout of the plant it has been convenient to think of the process not only as a single *continuous* system but also to consider the digester cooks as four *batch* processes. These are known as Case 1 and Case 2 respectively, and in effect two separate CLEAN systems have been installed. The knowledge base, database of cases, case selectors and HCIs are all kept distinct from each other and it is only in the Data Collection Module that there is necessarily some interchange of information.

5.2 PLANT INTERFACE

For CLEAN, the Automation System is regarded as an already existing facility of the plant, which needs only an adaptation to perform the data exchange with the CLEAN System. Since the hardware platform of the TELEPERM M System is a system specific one and hence being completely distinct from the standard PC platform of the CLEAN System, two different hardware systems have to be put together. The connection of these two systems as far as hardware is concerned is carried out by means of the TELEPERM M System bus CS 275 and the N-AT-Module that is a special PC board enabling the connection of a PC-to the bus CS 275.

The Data Collecting Module collects the data from the Automation System and hence it interacts directly with the Automation System. Because of its direct interaction with the Automation System the Data Collecting Module is a tailor-made solution for the respective make of the automation system. The data acquisition can take place in two different manners, that are either cyclic or non-cyclic. In the cyclic method of data acquisition the process data are captured time depending always after equal periods. In contrast to this, in the acyclic method the data capturing depends on an event taking place e.g. in the process. This event sets a trigger signal that causes the single capturing of the data whenever the signal occurs. In this way the capturing can be entirely controlled by the process. In CLEAN the Data Collecting Module is realised by means of the WIN TM program.

5.3 CASE CONSTRUCTION

The input data of the DEPM are combined to form “cases”. For continuous processes a case is a data record which contains a history of all the setpoints and measurements which applied to a single aliquot of raw material as it travelled through the plant. The transformation from raw sensor readings to cases is non-trivial, and depends on modelling the sample mixing and process delays in the plant. The assignment of the calculations to the respective process data as well as the pararneterisation of the used functions depends on the technical process or the local circumstances respectively. For that reason the assignment and the parameterisation is user-configurable on the basis of a provided set of basic functions. Examples for the provided function set are arithmetic calculations and mean value functions, moving averages etc. Every case is unambiguously identifiable by a unique identifier which is also used for the assignment of the input data to a case. Unique identifiers can be the date or any serial number depending on the process (e.g. batch number). At this stage the assignment of data corresponding to the state of the process is carried out.

5.4 CASE-BASED LEARNING

The Case-Based Reasoning System prototype is designed to answer queries of the form:

> *Given the plant's current conditions, which setpoints should be changed to reduce the cost while still producing the same quality of product.*

Or:

> *Given the plant's current conditions, which setpoints should be changed to change to a different quality of product while keeping the cost as low as possible.*

Thus the Case-Based Reasoning module requires two general sets of information

1. The current plant settings and measured process values - for a continuous process these are easily obtained simply as the complete set of current values and settings of the plant, but for a batch process such as for the individual pulp cooks at Caima, this information is an incomplete collection of settings observed so far within this batch, possibly supplemented by the other values from the previous batch

2. The desired qualities required by the plant operators. In general these will be in the form of upper and lower bounds directly on product qualities which are measured and recorded within the CLEAN system. However, in some situations there may be additional constraints placed on parameters which the operator wishes fixed or which directly relate to qualities which are perhaps not themselves recorded within CLEAN.

The Case-Based Reasoning Module receives these quality desires and the process data, and then, if the user has additionally requested an intelligent modelling approach, makes a request to the Neural Networks for iterated modelling data lying close to the current plant situation. This modelling data gives a local linear model of the influence of some of the parameters on the key qualities currently being investigated by the operators. Further as part of this model, there will be additional constraints placed upon the Case-Based Reasoning request because of the limits of the validity of the linearity of this local model.

The next stage in the request is for the Case-Based Reasoning Module to select from all the historical cases stored in the CLEAN database those cases most closely resembling the quality goals sought. The optimisation which lies at the heart of the CBR Module's work is then performed upon this set of historical cases.

In principle the algorithm visualizes the running case as a point in the m-dimensional space of the m setpoints and considers the n historical cases found in the database as the points defining a volume (a convex polygon in this m-space) around the running case. Then also in this m-dimensional space we have a cost function defined. This function is in general a linear function and can thus be considered as a simple vector in the space. However, at the Caima Case 2 demonstration - the batch model of the pulp cook, there has been a very reliable cost function produced which has a non-linear factor within it. It is thought that this factor would be reproduced if other similar batch processes were to be considered and so it was important to take this cost into account. Upon examination, though, this non-linear factor was found to be constant for any given batch - it was not a value which could be altered once a cook had been started. Thus, for any given batch, the cost function can be calculated and it can be considered as a linear function (and thus as a vector to be used for the calculation of a scalar product) in the setpoint space.

The optimisation then seeks to minimise the value of the cost function upon the m setpoints within the constraints of the historical evidence, i.e. within the volume bounded by the n historical cases. This is achieved using a well-established technique known as the Simplex Algorithm which has been extensively used and developed for linear programming problems such as this one.

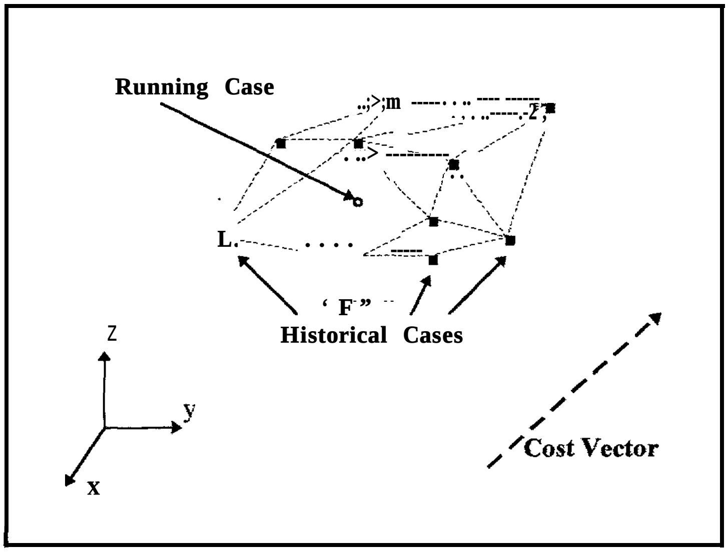

Figure 5.4-1 *The basic setpoint space in which optimisation can occur*

Mathemetically this problem can be formulated into standard linear programming format as:

Minimise $\underline{c}.\underline{x}$ subject to restrictions on the linear domain $\underline{x}$

and subject to linear constraints $\underline{A}.\underline{x} \leq \underline{b}$

where $\underline{c}$ is the cost vector and the matrix $\underline{A}$ and the dual cost vector $\underline{b}$ are calculated from the constraint region defined by the convex hull surrounding the historical raw cases found.

This is the basic principle of the process. However, it was apparent from the start of the project that it would be very difficult to physically implement a recommendation of form “change all setpoints” and that the operators would be unlikely to trust such a large change from the current process settings. It was suggested that the recommendations produced by the Case-Based Learning to be restricted by a conservative principle which demands that only a few (typically 1 or 2) of the setpoints are altered.

This restriction upon the setpoints has resulted in the algorithm described above being altered so that in fact several smaller problems are first solved and then the solutions to the smaller problems are compared to give some overall recommendations.

One identified potential flaw of our approach to the Case-Based Learning is the effect that one erroneous raw case could have on the whole optimisation process. A case where, for example, one or more of the sensor readings was affected by a large amount of noise or by some mechanical failure could fool the system into encouraging the operators along a false or unreliable route to a cheap, quality product. To prevent this it was decided to encourage the physical implementation of the case-based learning algorithm to follow a route which allowed for many links directly between the cases and the recommendations. This innovation, which further allowed a great deal of speed improvement in parallel with the Query Optimisation Module, means that the user gets a good indication of the strength of historical evidence behind any particular recommendation and can also potentially then examine “bad” or untypical cases, removing them from the CLEAN database if necessary, or perhaps even using them as the basis for future experimentation if they prove promising.

5.5 PLANT MODELS

The Knowledge Module hence consists of two parts: a static part containing proofed plant/process knowledge and capable of giving advice to the operators: *The Knowledge Base System*. The second part is the dynamic part which generates on-the-fly knowledge, reflecting the actual process conditions. For this a mathematical modelling approach was chosen hence the name *ModelZing Module*. *Neural* Network modelling proofed to be the most interesting.

The running case is fed regularly to the Knowledge System. The modelling takes this running case - the actual plant condition - and generates instantaneously dynamic knowledge i.e. relations between process parameters and quality parameters (quality meaning whatever you want to achieve at the end of your case. This dynamic knowledge is then confronted with the static knowledge in the Knowledge Base System and hence the mental model of the plant/process is continuously updated.

The Modelling can as well give a prediction of the expected quality value even before the ending of a case. If there is a decline in quality to be expected the Case Based Learning Module can give the operators advice on what corrective actions should be undertaken. To assist the Case Based Learning Module in this task, the Modelling can provide parameter sensitivity information to give an indication on what actions are best suited for the moment.

The process knowledge residing in the Knowledge Base System is considered fixed and accurate at all times. This Knowledge Base can be consulted to give advice to operators on what effect parameters have on the quality and on what parameters can be changed to affect a quality. The knowledge is represented in the form of rules. Although the rules currently present in the prototypes are all one-to-one relations (much in the way operators think about their process) the rule representation was conceived to be as general as possible and takes the following generic form:

```
if Parameter_P1 increases with AP1, between LowerBound_PI and UpperBound_P1
AND
if Parameter_P2 increases with AP2, between LowerBound_P2 and UpperBound_P2
...
THEN
Quality_Q1 will increase with AQI, between Lowerbound_Q1 and UpperBound_Q1
AND
Quality_Q2 will increase with AQ2, between Lowerbound_Q2 and UpperBound_Q2
...
Rule Priority RI
```

For the dynamic part of the knowledge module, initially, both a linear modelling approach (using the Partial Least Squares method) and a non-linear approach (a Back Propagation Neural Network) were tested out. Since real-world processes are typically non-linear, the neural network gave superior results.

6. RESULTS

6.1 ROERMOND

The goals in the total mill figures as stated in the CLEAN Technical Annex are:

water savings 10-20% =15-30 m3 /hour= NLG 30,000-60,000/year

The goals in the main product of PM3 (paper machine 3) are:

energy savings 5-10% = 15-35 kW /ton= NLG 450,000-900,000 /year

starch saving 5-10% = 500-1,000 tons /year= NLG 76,000-128,000 /year

less degradation of product 3-5%= 190-320 tons /year= NLG 76,000-128,000 /year

up-time increase 1-2% = 3,700-7,0010 tons /year = NLG 1,100.000-2,200.000 /year

The total production of PM3 is 170,000 tons /year. The main product "Coramedium" production is 156,000 tons /year. As base period Roermond took Coramedium (the main paper type) from the month January 1993, which was the start of the project. The evaluation period is the month October 1995.

	Base period 01-31 Jan. 1993	Evaluation period 01-31 Oct. 1995	Target	Result	saving per year NLG[1]
Average water consumption m^3/hour	79.09	60.02	-1 0-20%	-24.11%	40,000
Average energy consumption kW/ton	354 (all paper types)	323 (all paper types)	-5-10$'40	-8.76%	202,000
Average Starch consumption n [kg/ton)	37.85	36.45	-5-1O*A	-3.7%	185,000
Up-time increase (breaks and standstill)	13.5%	15.6%	1 -2%	-2. 1%	-1,219,000 (riot caused by CLEAN)
	Average 92	Average 95			
Degradation of product p	5 .9?40	2.4%	-3-5% (of the degradation g) ercenta e	-59?40 (CLEAN =20%	2,233>000 (CLEAN =756,000))

Table 6.1-1 *Economic results of CLEAN*

The total production of PM3 up to and including November is 176,000 tons. Over the whole year of 1995 including December this will be approximately 192,000 tons of which 159,500 tons is Coramedium the main product of PM3. This means a production increase of 13% in total production of PM3 compared to 1992 and an increase of 2% in the production of Coramedium.

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[1] based on current prices

The reduction of degradation of product is 59% in 1995 compared to 1992. This production is not entirely due to CLEAN but to lab research. However, CLEAN had an important part in this research which resulted in a decrease of degradation of product of about **20%.**

Other important results that have been achieved are:

- Learning from CLEAN made it able to select all the paper machine and process settings that result in better paper characteristics.
- Production presetting now allows the papermaker to switch product more often and more convenient to customer needs without the losses that occurred in the past.
- Because of an exact registration of starch consumption it is now possible to examine the several factors of influence on the starch consumption thoroughly.

Up-time increase

Due to increase in production and therefore increase in speed the up-time increase is negative. The speed increase causes more breaks and stand stills and as a consequence the average break and stand stills percentage of October 1995 is higher then January 1993. However, the loss in up-time would have been even greater if the knowledge of CLEAN hadn't been used. Moreover, the gain resulting from the production increase is much higher than the loss in up-time increase.

Starch consumption

Reduction of the starch consumption between 5 and 10 % is another target that was not met completely. This was caused by a change in the production procedures of Coramedium in July 1994. In that month Roermond Papier introduced a new procedure for Coramedium paper type due to sheet break reasons. This procedure needs a lower linear pressure and consequently needs more starch. Starch consumption had been strongly reduced from January 1993 up to July 1994 by increase of the linear pressure which is explained in section 4.4.8. However, the average starch consumption in October 1995 for Coramedium is still 3.75 lower than the average starch consumption for Coramedium in January 1993. If the change in the production procedure had not occurred then it would have been possible to save starch up to 30% (see section 4.4. 8). After the investment program of 1996 and 1997 it will be possible to increase the linear pressure and thus save more starch in future.

6.1.1 Best Case versus Running Case

In this subsection the results are presented that can be achieved by using the Best Case as running case for all weights of Coramedium. The cost of the cases is based on the following calculation:

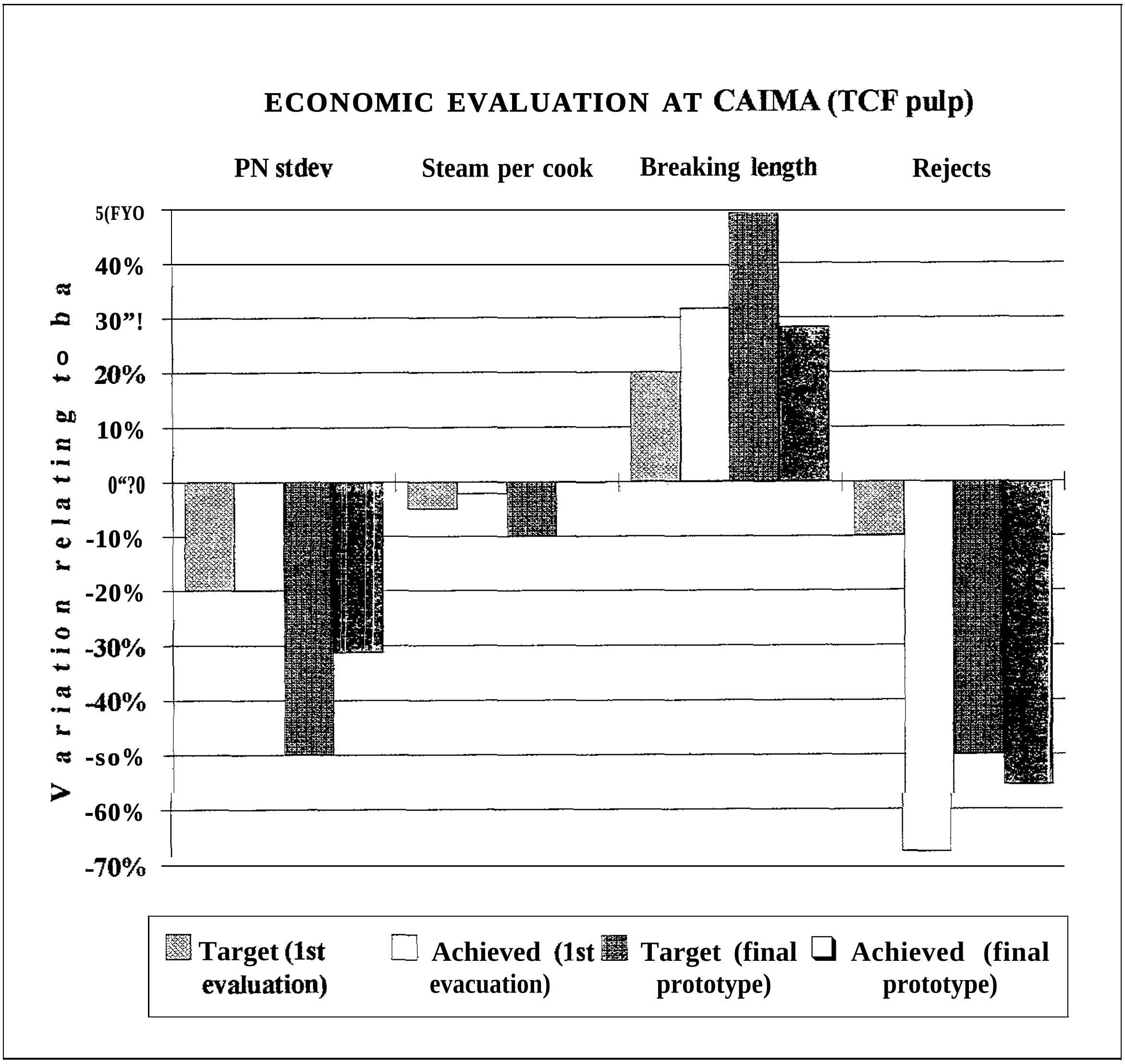
$$\frac{2.25 \text{ x starch} + 1.6\text{x steam} + 0.5\text{x } water + 0.6\text{x } additives + 0.25\text{x } electricity}{production\ /\ tons}$$

CORAMEDIUM	DATE OF RUNNING CASE	COST OF RUNNING CASE	COST OF BEST CASE	POSSIBLE COST SAVING
105	05.12.95	76.18	56.30	19.88
110	08.07.95	72.17	59.28	12.89
112	09.11.95	70.42	59.63	10.79
115	19.11.95	81.86	60.62	21.24
120	29.11.95	64.91	57.74	7.1’7
125	06.04.95	74.75	55.31	19.44
127	12.11.95	67.19	54.42	12.77
130	10.09.95	59.78	53.64	6.15
140	11.09.95	59.57	52.71	6.86
145	20.11.94	56.47	54.99	I .48
147	04.09.95	63.29	52.78	11.51
150	19.09.95	61.34	53.29	8.15
160	19.09.95	58.26	52.20	6.06
170	03.09.95	60.48	50.43	10.05
180	12.09.95	58.05	54.64	3.41

Table 6.1-2 *Cost of Best case versus cost of Running Case for Coramedium*

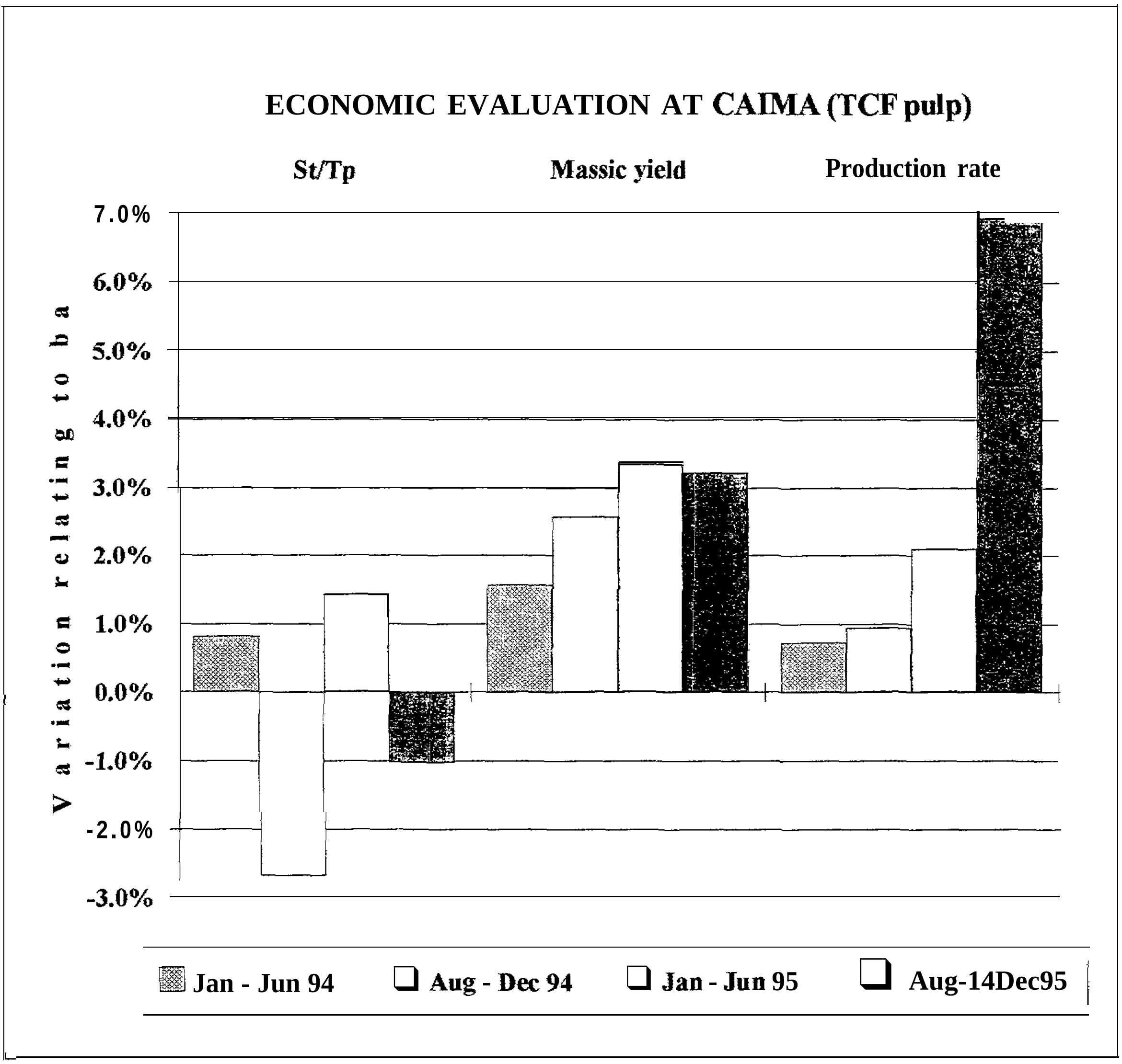
6.2 CAIMA

The following results were achieved at Caima.



	PN stdev (PNsp-PNlab)	Steam per cook (ton/cook)	Breaking length (m)	Rejects (Kg/Week}
Base period **(Mar-Apr 92)**	1.36	30.1	1417.9	11270
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Final prototype (20 Nov -15 Dec 95)	**0.93**	30.0	1819.2	5000
VARIATION RELATING TO BASE PERIOD				
Target (1st evaluation)	-20%	-5%	20%	-10%
Achieved (1st evaluation)	-20%	-2%	32%	-68%
Target (final prototype)	-50%	-10%	50%	-50%
Achieved (final prototype)	-31%	0%	28%	-56%

Figure **6.2-2-** *Economic evaluation at Caima*



	Savings (kPTE)	Savings (kECU)	Percentage
Increase Massic Yield	99126	496	95
Decrease total Steam	3456	17	3
Decrease Rejects	1568	8	2
Total	104150	521	100

7. CONCLUSIONS

The CLEAN system has now been installed at two greatly differing plants and has demonstrated its ability to optimise the processes, satisfying the goals set for the project. Due to its nature as an adaptive controller, its performance may be expected to show further marginal improvements over the following years, particularly at Caima where the slow cycle time restricts the learning speed.

As a side benefit, the greater process knowledge given by CLEAN has also indicated areas where alterations to the plant hardware maybe beneficial.

8. ACKNOWLEDGEMENTS

This project was funded under EU contract BREU-CT92-0189.

9. REFERENCES AND PUBLICATIONS

9.1 PATENTS

The project has given ride to two European patents: 93118903.9 and 95108187.6. ‘Method and device for controlling a technological process.”

9.2 PUBLICATIONS

15/4/1993	Press release in German and English send to 84 mainly German publishers (see ANNEX 1993/6)
5/10/1993	Furumoto, H. "Erfahrungen und Kenntnisse der Bediener genutzt". in Handelsblatt vom 5.10.1993 (see ANNEX 1993/8)
19/05/1994	Visit of the Austrian journalist Dr. Bauer from Papier aus Österreich.at mill side in Caima. Publication of his impressions in "Ein Investment, das sich rechnet" in Papier aus Österreich (1994)6, page. 13-15 (see ANNEX 1994/2)
22/6/1994	Furumoto, H., Grieb, H., Linzenkirchner, E. "Fallbasiertes Lernen optimiert Prozeßführung und Produktqualitat” Neue Techniken der Informationsverarbeitung, page. 29-35 (see ANNEX 1994/3) will be published in a book
June 1994	Furumoto, H. Schwarz "Forschungsförderung-wie funktioniert alas” blickpunkt ANL June 1994, page. 18 (Siemens Newspaper(see ANNEX 1994/4))
August 94	Effenberger, Furumoto, Abel

	"Optimaler Betrieb eines MgO-Rückgewinnungskessels durch wissensbasierte prozeßführung" VGB Kraftwerkstechnik 75(1994)9, S. 755-762 (see ANNEX 1994/5)
Spring 95	Effenberger, Furumoto, Abel "Optimization of MgO-recovery boiler with the help of knowledge based process management" VGB Kraftwerkstechnik International edition
24-26/7/95	Loossens K. and van Houtte G. (1995) No Knowledge to Waste. Learning more about Processes. This article was presented at the IEEE/ECLA/IFIP International Conference on Architectures and Design Methods for Balanced Automation Systems in Vitória, ES, Brazil. One of the sponsors of this conference was the European Community - Latin America Exploratory Collaborative Activity on Distributed Information Systems for CIM goals. The article is published in *L. M. Camarinha-Matos and H. Afsarmanesh (eds.) Balanced Automation Systems: Architectures and design methods*. Chapman & Hall, 451-458.
22-27/5/95	Loossens K. and Van Houtte G. (1995) Predicting Process Evolution with a Neural Network. A window on relevant data. presented at:*1995 International IEEE/IAS conference on industrial automation and control: emerging technologies., Taipei, Taiwan. 35-40.* The goal of this conference was to bring factual, practical, ready to use information in the areas of Industrial Automation and control to IEEE members and companies world wide. This conference , with about 140 papers organised in two volumes totalling nearly 1100 pages, has made an exceptional start toward meeting this *ambitious goal*.