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Soft Sensors for Quality Prediction in Batch Chemical Pulping Processes

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Abstract

For many chemical processes (for example, pulping process), some control variables cannot be measured directly or easily even though the special measurement techniques are used. In such a case, soft sensors can be used to deal with the problem. A soft sensor is an intelligent software or inferential measurements using numerical models, symbolic inference, computer graphics, as well as the data from other measurements or off-line laboratory test, which can provide the near-optimal values of non-measured variables for operators and on-line control systems. This paper discusses the characteristics, functions and configuration of a soft sensor. Then, an intelligent soft sensor (ISS) for batch digester quality control is presented. The sensor can support a batch sulphite pulping process operation at Fraser Inc. pulp mill at Edmundston of New Brunswick and assist operators to perform better operation though providing the estimated kappa number and the cooking time, as well as interpretation of the process operation variables. It can also be used to facilitate on-line supervisory control, to detect unexpected events and faults during pulping process operation.

I. Introduction

Chemical processes are highly-computerized human-machine systems. Most chemical process operations are usually run under such critical situations as high temperature, high pressure, low temperature, low pressure, easy to flame, to explode and to poison. In such an environment, some important control variables associated with product quality cannot be measured directly or easily even though the special measurement techniques are applied [1]. On the other hand, it is becoming increasingly difficult for operators to understand various signals and information from display board, video, and computer screen. Owing to the importance of the operator's role in process operation, the quality of interaction between human operators and computers is crucial. Thus, the development of soft sensors will better facilitate human interaction with the complex real-time monitoring and control systems.

In some cases that some important control variables associated with product quality cannot be measured, a number of non-specific measurements are available and it may be possible to combine these measurements to implement symbolic inferences for important, non-measurable quality variables. However, currently there does not seem to be a systematic way of developing soft sensors and integrating them as an overall control scheme. With increasing emphasis on product quality, control engineers need more often to control product quality. To deal with the problem, advances in on-line analysis are substantial and should be employed in practical measurements. Here inferential measurements, coupled with models could be used with model updating from off-line laboratory testing. Implementing such a soft sensor system need to well understand the data collected, model building and control system design.

There are two objectives for developing soft sensors: (1) providing near optimal values for important non-measurable control variables associated with product quality to improve real-time control systems; (2) providing the interpretation of the important process variables for operators to enhance the interaction between chemical processes and human operators, thus, to better control the product quality.

II. Chemical Batch Pulping Process Pperation

Kraft pulping process is a complicated chemical process, in which process control techniques and operation experience are highly concentrated. The objective of pulping process is to produce high quality pulp product with low cost. In many pulp and paper mills, high quality pulp is often produced by a chemical process under batch operation. This chemical process utilizes cooking liquor (cooking acid) to dissolve and remove the lignin from wood chips. And then, wood chips are cooked to a desirable degree of delignification (i.e., the desired kappa number). When a batch digester is used, the quality of pulp is often sampled and tested at the end of the batch cycle.

As a batch digester operates at high temperature and high pressure, it is not practical to remove a pulp sample and analyze its quality (kappa number) on-line. Especially, there exists no on-line measurement facility at this pulp mill where the process operation and quality control depend heavily on the operators' experience and skills to estimate the pulp quality and to decide the cooking time.

Currently, an intelligent soft sensor (ISS) for digester quality control has been developed to solve the problem encountered above. The soft sensor aids the process operation in two ways: it generates an optimal operation scheme, and makes the feasible operation recommendations to operators who take operation actions to control the pulping process.

ISS is implemented to support a batch sulphite pulping process operation at FRASER Inc. pulp mill at Edmundston of New Brunswick. By investigating the effect of all the available process quality inputs on the cooking time, the system can quickly process the knowledge and provide operation support. A mathematical model for determining the S-factor has also been implemented in the software system. ISS estimates the kappa number and determines the cooking time, as well as provides more information interpretation for process operation. It can also be used to facilitate

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on-line supervisory control, to detect unexpected events and faults during process operation as well as to train new operators and engineers.

A digester flow diagram is shown in Figure 1. Digesters cook wood chips to a specified degree of delignification, so-called as kappa number. At Fraser, the kappa number is determined by an off-line laboratory test involving titration performed on the pulp sample since it cannot be measured on-line during operation. The kappa number can be determined only after the process has been completed through a laboratory test. The lignin content in the wood (pulp) cannot be measured during the batch cooking cycle. The pulp sample is taken from the dump line after the cooking cycle is completed. The kappa number test is then performed on the sample, and the results are recorded on the digester log sheet. These values are used as a guide by the operators at the bleachery plant for the bleaching operation.

The target kappa number at the Fraser's sulphite mill is 28. A value between 26 and 30 is considered satisfactory. In the case that the laboratory test shows a kappa number higher than 30, indicating a high lignin content still remaining in the pulp, the bleachery operator needs to increase the rate of chlorine/chlorine dioxide for pulp bleaching. A low kappa number of the collected sample (i.e., below 26) indicates the loss of pulp strength, pulp brightness, and pulp yield in that particular batch cook. Occasionally, the quality is so bad that the pulp cannot be used for making good quality paper. Thus, the pulp made by a high grade pulping process can only be used to produce a low grade paper.

At the Fraser's sulphite mill, under normal conditions, a cooking time of 3:45-3:55 hours is required to produce the pulp with the satisfactory quality (i.e., a kappa number between 26 and 30). The problem may appears that the raw material qualities (cooking acid and wood chips) that are charged into the digester are not always as anticipated. The cooking acid is produced in an upstream recovery process, and its quality changes significantly, then affects the cooking time. The chip quality, which varies in terms of moisture content, species, and chip age, has the similar effect on cooking time. For example, a certain quality of raw material will require a cooking time of 3:35 hours, whereas under different circumstance, the batch cooking cycle would require 4 hours to obtain the satisfactory pulp quality.

The operators' objective is to control the digester to produce the best pulp based on the given raw materials by choosing the appropriate operating conditions. The operators must decide when to terminate the process by pressing the drain down button so that good quality pulp can be obtained in the digester at the end of the process. Since no general mathematical model is available for this process, a successful operation relies mainly on the operator's private knowledge (such as personal experience, expertise and heuristics). However, such experienced operators are few. The frequent shift operation among the eight digesters in this mill very often confuses operators, even experts.

There are several factors to cause that 38.2% of the cooks are poor quality. A main reason is the wrong interpretation of the process data by a human operator who is responsible for operating all eight digesters during a shift of 12 hours. Even for some experienced operators who have many years of operation experience and know the process very well, they are still inefficient to quickly recall the effect of data for a digester and other data for another digester. Thus, they are confused in operation. Again, the main criteria to produce the pulp with the desired quality is to choose the right cooking time and to maintain the optimal operating condition. Cooking time is a function of the raw materials quality (wood chips and cooking liquor) and the operating conditions (temperature and pressure).

III. Intelligent Soft Sensor

A soft sensor is an intelligent software with inferential measurements based on operators' skills, numerical models and laboratory test data, to obtain the approximate values of non-measurable variables. These variables have the following features:

- They are ill-formulated quantitative variables or qualitative ones,
- They are not measurable by the existing measurements and techniques,
- They are not sampled in real-time operation processes, and
- They are linked with other variables directly or indirectly.

System construction

The intelligent soft sensor (ISS) for batch digester quality control consists of:

- symbolic reasoning systems to codify operators' skills,
- numerical computation packages to deal with numerical models and laboratory data,
- graphic representation programs to display non-measurable variables, and
- a meta-system to integrate symbolic reasoning and numerical computation, as well as computer graphics,
- a database to store historical data,
- a multimedia interface to provide information interpretation for operators.

In ISS, both the qualitative and quantitative knowledge are integrated together and coordinated by a meta-system [3]. Symbolic reasoning, numerical computation as well as graphical representation are integrated together (Figure 2). Both qualitative and quantitative systems can be used by operators for decision-making. However, as the mathematical model is only a function of the pressure, temperature, total SO_2, and time, the quantitative computation system cannot be used when other input variables are out of their normal quality conditions. Also, the quantitative computation system does not provide qualitative information about the effect of input variables on the final pulp product.

Generally speaking, a computer system will take any input a user provides, even the wrong input data. In a real industrial application, it is very dangerous. The data to be entered into ISS which describes the process status must be physically significant. ISS works in domains where conditions are rarely certain. The wrong input information may result in an error-prone solution.

In order to prevent a user from entering wrong data to ISS, a simple common sense reasoning mechanism is built in ISS. For example, if the user enters the operating temperature at a value of 200 C°, ISS will not accept this value because it is physically impossible. When this happens, ISS automatically requests another value. If a new value is not entered, the corresponding input variable will get the default value which is the desired value. The rules which perform the screening of the non-physical numerical values are executed at the interface level so that these non-physical wrong data will not be used in the knowledge base, thus it makes the system to be more efficient and reliable.

If some process variables are not within their desired values, the system needs to couple the effect on the cooking behaviors and to derive a coupled required cooking time. Figure 3 shows how the process variables can be coupled together. Thus, different cooking time can be obtained at three different levels. Level I derives cooking time for each individual input variable. Level II provides the coupled cooking time for the wood chips (the system couples the effects of chip size, chip load, and chip quality together), the cooking acid (the system couples the effects of "Total SO_2" and "pH" together), and the operating condition (the system couples the effects of operating temperature and operating pressure together). Level III provides a coupled cooking time for all input process variables together. The coupled cooking time is provided to users thought the bar graph display under the **Options** selection in **Main-menu #1**.

The compilation of the effect of these process variables on the cooking time is done by adding the weight values in the weight array of each input variable. If a cumulative weight value is higher or lower than those presented, the system will be unable to provide the coupled cooking time. A total of 37,500 different possible combinations exist at level III of the coupled system.

As the numerical computation generates the rigid solutions, the quantitative computation system should be used first to predict the required cooking time for the production of good quality pulp, if the mathematical model is applicable. The qualitative reasoning system can be used for any situation by the users to obtain quality information about the process behavior. The qualitative system does not guarantee perfect solutions, but it can give the direction about the process behavior changes. Such a system increases the interactions between the operators and the actual process (digester). As mentioned before, the majority of the knowledge base of ISS are coded in C™ programming language, and developed using the Borland C™ compiler. The numerical computation program is written using FORTRAN™ language.

Knowledge base

The qualitative knowledge for each quality input variables is held in different arrays and matrices. Each array or matrix contains different type of quality information, and is kept separately. The knowledge contained in these arrays and matrices are described below.

float ranges: The data contained in this matrix are the different possible values of each process input variable ISS can process. Most process input variables are separated in a maximum of 5 different quality ranges. The current ISS can manage up to 10 different values for each process input variable.

status: The status array contains quality information about the input variables. Each input variable has its own status array. The quality information contained in the status array is such word as high, low, or desired.

time_required: The time_required array contains the estimated required cooking time. Each value in the ranges matrix has a corresponding cooking time.

situation: All other quality information about different values of each variable are held in a situation array. The information contained in this array are, for example, the results of the final pulp quality (e.g., high, low, or good pulp brightness) as well as the possible causes why the value of the input variable is out of the desired quality range. In some cases, the suggestions (e.g., what to do) are stored in this situation array. It should be mentioned that currently, the information contained in the above arrays and matrices are displayed to the user through a window system.

time_limits: As ISS provides the user graphical displays (e.g., bar graph) to show the effect of each input variable on the cooking time, an array time_limit is used to held the supper limit and lower limit of an estimated range for cooking time. For example, if "time_limits [][0] = +20", and "time_limits [][1] = +10", then the bar on the bar graph for that particular input variable will show a yellow colored section indicating that the estimated cooking time is about 10 to 20 minutes more than the normal required cooking time.

weight: The weight array contains weight values for input variables. These weight values are used for the bar graph to couple the effect from several input variables on the cooking time. When a less cooking time is required for the cooking cycle to achieve the desired pulp quality, the corresponding weight value in the weight array would contain a negative (-ve) value. When a longer cooking time is required, the weight will be a positive (+ve) value. Under the desired condition, the weight value is equal to zero.

The reasoning process of the qualitative system is exhibited by Figure 4. The process variable data are entered into the database. These data are processed in the knowledge base by the inference engine. The knowledge base which consists of arrays and matrices, receives the data in the module containing the ranges matrix. The ranges matrix and the values of that particular input are processed through a variable rule system to find the location (loc.) in the ranges matrix that satisfies the condition. The location (loc.) is returned to the inference engine. The inference engine feeds the location (loc.) back to the knowledge base for further processing by the remaining arrays (i.e., status, time_required, and situation). The information in these arrays at the location (loc.), which contains the qualitative knowledge corresponding to the value of the input variable being processed, can be displayed on the computer screen. The information provided by the qualitative reasoning system can be used by the human operators for on-line supervisory control.

A new technique (called variable rules) is used in developing the intelligent soft sensor, which allows ISS to substitute many different facts into the same general format. However, it must have a look up table. Such a technique is used to better organize knowledge base as well as to improve knowledge processing and to reduce the running time. Using a simple example below, we describe the function of variable rule. If all of other process variables are under normal conditions, with three different values, we can represent the operating temperature variable with three production rules as follows:

```
(Rule 1
   IF       operating temperature is < 162 C°,
   THEN     process requires longer cooking time,
            and pulp product has good brightness.)
(Rule 2
   IF       operating temperature is > 165 C°,
   THEN     process requires shorter cooking time,
            and pulp product has poor brightness.)
(Rule 3
   IF       operating temperature is between 162 C° and 165 C°,
   THEN     process requires normal cooking time,
            And pulp product has good brightness.)
```

However, we can use a variable rule to represent the rules above.

```
(Variable rule
   IF       operating temperature is X C°,
   THEN     process requires Y cooking time,
            and pulp product has Z brightness.)
```

Looking up table

	X	Y	Z
1	<162°C	longer	good
2	>165°C	shorter	poor
3	162-165°C	normal	good

The variable rule and looking up table represent the following knowledge:

Process requires (longer) cooking time and pulp product has (good) brightness under operating temperature (<162 C^{O}),

Process requires (shorter) cooking time and pulp product has (poor) brightness under operating temperature (>165 C^{O}), and

Process requires (normal) cooking time and pulp product has (good) brightness under operating temperature (>162 C^{O} and <165 C^{O})).

Database

The database of ISS is defined as an array containing the data of each of process quality variables. These values represent the status of a batch cooking process. As the configuration of ISS is separated into several different modules, the database is defined as a global array so that more systems can use it. The following example shows that the process quality variables are contained in the database.

```
database[0] = 38;      /* chip load */
database[1] = 1.0;     /* chip quality */
database[2] = 1.0;     /* chip size */
database[3] = 5.75;    /* Total SO2(0) */
database[4] = 3.50;    /* pH */
database[5] = 163;     /* Temperature */
database[6] = 680;     /* Pressure */
database[7] = 2.80;    /* Combined SO2 */
database[8] = 2.95;    /* Free SO2 */
database[9] = 0.00;    /* Total SO2(10) */
```

All the values in above example are default values. These values are automatically entered into the database when ISS starts running. However, each individual input can be modified by a user, and selected from the sub-menu. All values in the database are used to process the qualitative knowledge. Four values (temperature, pressure, total $SO_2(0)$, and total $SO_2(10)$) are used to process the quantitative knowledge. There is another array which contains the information about process behavior. This array is also a part of the database, and contains other required data for the quantitative computation system.

Quantitative computation

In the operation and control of cooking process, both qualitative and quantitative analyses are needed. Usually, qualitative decisions are efficiently based on symbolic and graphic information, while quantitative analysis is more conveniently performed using numerical information. Each method often complements the other [4].

ISS has a quantitative computation system to calculate cooking time and kappa number. The mathematical model implemented in ISS is based on the $S_{m\text{-factor}}$. This system is programmed with FORTRAN™ language and its module is called "cookmodel.for". The results from "cookmodel.for" are much precise and superior to those from the qualitative reasoning system. However, this numerical computing system can be used only when the chip size and chip quality are under normal conditions. The qualitative reasoning system using heuristics and private knowledge cannot guarantee the perfect solutions. However, it solves the ill-formulated problems and generates the suggestions about the possible direction of changing operation environment.

The computation process of the quantitative system is shown in Figure 5. The required data from the database array and the s_fact array (both are in a database) are passed to the numerical computation module by the inference engine to calculate the target $S_{m\text{-factor}}$. Here, the target $S_{m\text{-factor}}$ is calculated based on the target kappa number (i.e., 28). Total $SO_2(10)$ is required for the computation of $S_{m\text{-factor}}$, which is obtained 10 minutes after the operating temperature has reached the maximum value. Usually, it takes approximately 2 hours for the temperature to reach a maximum. In other words, the target $S_{m\text{-factor}}$ can only be calculated approximately 2:10 hours after the cooking cycle has been started. Once a target $S_{m\text{-factor}}$ is calculated, the inference engine passes the calculated $S_{m\text{-factor}}$ into different modules to calculate cooking kappa number. The result is then displayed on the computer screen through the user interface.

IV Illustration

ISS is a menu-driven system [5], which can be easily installed on any PC/MS-DOS platform. The main function modules contain the following modules. There are two main menus:

Main-menu #1

[Intro] [Pulping] [speC] [Inputs] [Situation] [Option] [Next menu]

Main-menu #2

[Prev. menu] [Operation] [Flow dia] [Shutdown] [Startup] [Editor]

When ISS is running, main-menu #1 appears on the top of the display screen. Each selection from the two main menus provides a sub-menu and/or a window system to display information to the user, or to receive information from the user. Some selections are linked together to better process the information. The main functions of each selection are described as follows:

[Intro]: This selection provides a brief introduction about ISS. It gives a user the quick understanding about each selection from Main-menu #1 and Main-menu #2.

[Pulping]: The **Pulping** selection gives an introduction about chemical pulping. It describes the purpose of digesting and concept of delignification.

[Spec]: This sub-menu provides the specifications about equipment related to the kraft pulping process. It provides, for example, the type of pump with its capacity, or the size/material of a tank for a selected system. ISS provides information for the following equipment and materials: digesters, acid, condensation, water, drain down, dump and flushing liquor system.

[Inputs]: The **Inputs** module takes the data entered by the user into ISS. The data are held in a database. These data are the process quality inputs that describe a batch cooking cycle. The data required by the $S_{m\text{-factor}}$ model are also entered from this sub-menu.

[Situation]: Situation module provides the qualitative knowledge as well as the quantitative knowledge based on the status of the database (i.e., information entered through the **Inputs** selection). The qualitative knowledge includes the estimated cooking time and the remaining cooking time, the effect of the process variables on the quality outputs, and the possible causes under which a certain process variable is out of its desired operating condition. The quantitative knowledge is the results from the $S_{m\text{-factor}}$ model that provides the on-line computed cooking time, the remaining cooking time, and the estimated kappa numbers during a cooking cycle.

If no information is entered into the database by the user prior to the selection of **Situation**, ISS will utilize the default values stored in the database.

[Option]: This selection has a similar function as the previous one (i.e., **Situation**). The **Option** selection can provide the cooking time by using a bar graph. It also recommends the cooking time of coupled process variables. This module can also display the desired conditions or the current conditions of all process quality inputs in one single window.

[Next menu]: By choosing the **Next menu** selection, the top bar menu will be changed from **Main-menu #1** to **Main-menu #2**.

[Prev. menu]: By choosing the **Prev. menu** selection, the top bar menu will be changed from **Main-menu #2** to **Main-menu #1**.

[Operation]: This module provides all the operations to be performed for a single batch cooking cycle.

[Flow dia]: This selection provides a graphical display of the batch digester system which includes the main pipes, circulating pump, dump valve, and liquor heater. It also provides the initial cooking liquor quality, the initial chip quality, and the direction of the circulating liquor.

[Shutdown]: This selection provides the required steps on how to shutdown the operation of digesters.

[Start-up]: This selection provides the required steps on how to start-up the operation of digesters.

[Editor]: It can access to the user. **Editor** used in ISS was PE2™, which is an IBM personal computer DOS™ editor. With PE2™, we can directly edit the files that are required for the proper operation of ISS. These files contain information about pulping, process specifications, process operations, and shutdown/startup procedures.

Let us select a particular batch cycle where the input process variables are assigned with the following data:

Chip load	32% gauge	**Total % SO_2**	5.39%
Chip quality	good quality	**pH**	3.4
Chip size	normal size	**Free % SO_2**	2.79%
Operating temperature	160 C°	**Combined % SO_2**	2.60%
Operating pressure	680 kPa		

These data are entered into ISS by selecting **Inputs** sub-menu from **Main menu #1**. Once all the required data are entered, the user may first select **Situation** to obtain the qualitative information about the process operation behavior. For instance, Figure 6 displays the qualitative reasoning results for operating temperature.

Since most users often prefer the graphic presentation of results, a bar-graph display system is built in ISS to provide the estimated cooking time. Figure 7 shows the estimated cooking time for each of the process variables (the coupled system at Level I), where the normal range (i.e., 3:45-3:55 hours) is given by a light gray colored horizontal bar. The input variable whose bar is within the normal cooking time range tells us that the pulp quality is within the desired value range. Similarly, ISS can display the estimated cooking time based on the selected coupled input variables (Level II) and the estimated cooking time based on all input process variables coupled together at Level III.

Now, we give another example to illustrate how to run the quantitative computation system. By selecting S_{factor} model, the following data are entered:

Chip load	38% gauge	**Operating temperature**	165 °C
Chip quality	good quality	**Operating pressure**	680 kPa
Chip size	normal size	**Total % SO_2(10)**	1.89%
Free % SO_2	3.05%	**Time of sampling (t_1)**	2:10 hs
Combined % SO_2	2.90%	$S_{m1\text{-}factor}$	125 a-hr
Total % SO_2	5.95%	**pH**	3.5

Figure 8 gives the estimated remaining cooking time and kappa number. The total required cooking time can also be displayed in the bar graph system (Figure 9).

V. Conclusions

- This intelligent soft sensor for batch digester quality control is the first prototype for investigating the structure and applications of soft sensors in the batch chemical pulping process.
- All the data and knowledge were collected from Fraser's sulphite pulp mill. It was so designed that it could be directly employed in the plant. Evaluation at Fraser's mill was very satisfactory, and the project was greatly appreciated by industrial operators and engineers.
- Qualitative reasoning function helps operators to select the near-optimal operation conditions based on the initial process variables and operating conditions. It provides "cooking time" for the production of good quality pulp, supervises the process operation, as well as diagnoses faults.
- Based on the quantitative computation, ISS can provide on-line supervisory control under the special process operation situations. It can advise the operator about the remaining cooking time before the drain down operation for a cooking cycle. It also estimates kappa numbers during the cooking cycle. Therefore, it works under the very limited environment where chip size and chip quality are under the normal situation.

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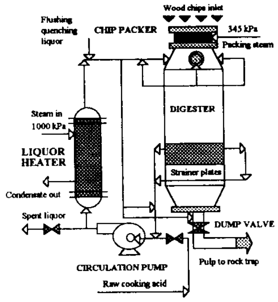

Figure 1 Process flow diagram

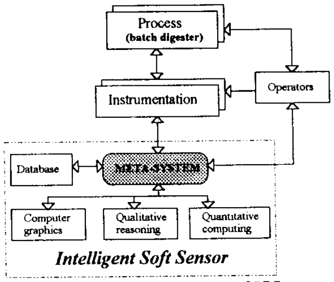

Figure 2 Architecture of ISS

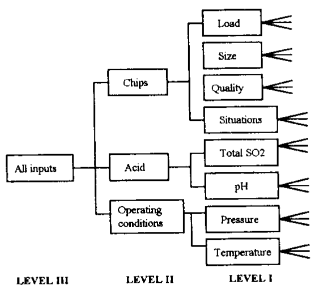

Figure 3 Coupling process variables

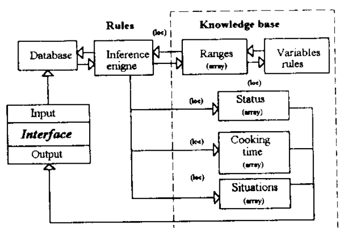

Figure 4 Reasoning process of qualitative system

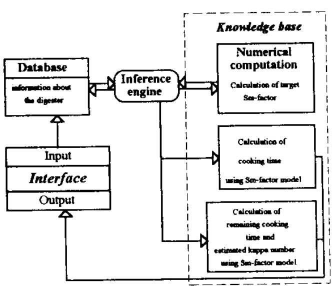

Figure 5 Computation of quantitative system

Table 1 Performance analysis of batch cooking operation (July 1990)

Quality	Number of cooks	Kappa of Number	Percentage
Best	114	28	12.7 %
Satisfactory	334	26-27	46.1 %
		29-30	
Poor	< 124	> 30	21.1 %
	> 153	< 26	17.1%

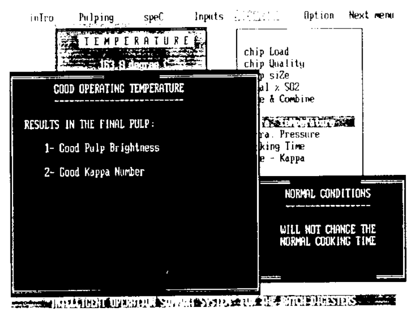

Figure 6 Qualitative reasoning results for operating temperature

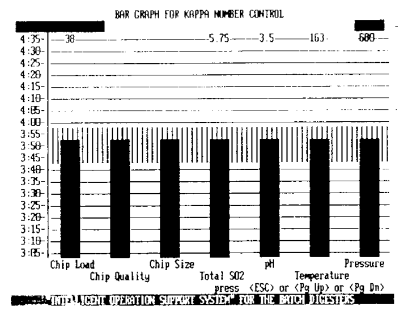

Figure 7 Estimated cooking time for individual input variables

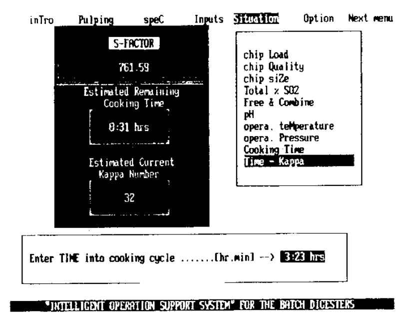

Figure 8 Estimated remaining cooking time and kappa number

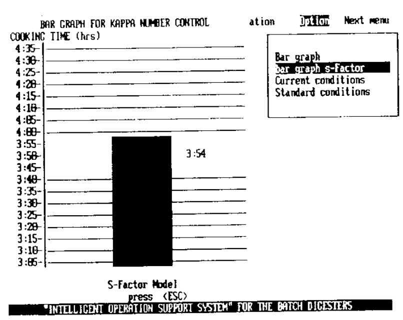

Figure 9 Graphical presentation of calculated total cooking time