PITCH EXPERT: A PROBLEM-SOLVING SYSTEM FOR KRAFT MILLS

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Abstract

Pitch Expert was developed to make expertise available to mill-site engineers to solve pitch problems in kraft pulp mills. These problems have been estimated to cause losses to the Canadian pulp and paper industry in excess of $100 million per year. The design of the system took into account not only the complexity of the process interactions and the need for accuracy and completeness of recommendations, but the ongoing need for training mill personnel and the requirement that the system be maintainable and expandable without constant involvement of the developers. Pitch Expert is now accessible by modem and the savings achieved through use of the system have covered the development costs within six months of release.

1.Introduction

Pitch Expert is a large knowledge-based system which analyses and diagnoses problems in kraft pulp mills related to pitch deposition and pitch dirt. By making scientific expertise directly available to mill engineers, it augments their problem-solving capability while relieving the human expert of much of the burden of routine problem-solving and training. The development and delivery of this system also served as a case study to determine the usefulness and relevance of knowledge-based technology in solving real problems in the pulp and paper industry.

Pitch Expert is now serving as a significant productivity aid to industry. At the time of writing, there were already 36 mills, representing over 20 companies, registered as active users. Current estimates are (see Section 6) that these mills will save approximately $28 million Canadian a year by using Pitch Expert. Its performance has been documented in an initial 12-month study as well as by records of more recent use. To our knowledge, Pitch Expert is the largest deployed knowledge-based system anywhere in the pulp and paper industry. The system can now be used directly via modem by mill process engineers.

Although previous publications, (Kowalski & Gauvin 1992), (Kowalski & Gauvin 1992a), (Kowalski & Lebensold 1989), have reported on the promise and potential of Pitch Expert, the past eighteen months have seen that promise fulfilled, and the proof of its positive impact, obtained from this initial two-year period of industrial use, constitutes a main area of focus of this article. In addition, a retrospective analysis of the underlying reasons for success is provided in more depth than was previously possible. Many factors contributing to the success of the project could be assessed only after the system had been used for a significant length of time (more than a year). This paper highlights these factors by:

- A quantification of actual savings rather than mere projections of expected results.
- A determination of which parts of the system design proved to be most useful or even crucial to its success, and why.
- An analysis of how useful and beneficial the aspects of the design related to system maintenance and update were, over an extended period of time.
- An examination of the magnitude of the benefits which were derived from the addition of extra capabilities to the system, beyond those which normally form part of a knowledge base (i.e. conflicting information identification, compact explanation capabilities, extensive meta-knowledge).

The successful development and delivery of Pitch Expert were largely the result of certain important design decisions. In particular, the structures and mechanisms used to build the system were specialized and customized to fit the specific needs of a system operating in the real-life pulp mill environment. Moreover, the system was designed from the beginning to be maintained on an ongoing basis without the involvement of senior knowledge engineers.

2. Background

2.1 Kraft Pulp Mills

In the manufacture of paper, wood is first pulped to separate its fibers from each other. One of the predominant processes for this is done in a kraft pulp mill and consists of: cooking wood chips at elevated temperature and pressure in the presence of certain chemicals (alkali and sulfide), washing the resultant brown pulp, bleaching to make the pulp white, and drying the pulp for shipment to a paper mill.

2.2 Pitch

Pitch, or wood resin as it sometimes called, is the material in wood which is insoluble in water but soluble in organic solvents. It usually comprises 1 — 4% of the weight of wood after the bark is removed and is often a very sticky material. With this much glue-like material passing continually through a kraft mill, it is not surprising that under some circumstances a certain amount deposits on the surfaces of the process equipment. Compounding this is the fact that there are other depositable materials present, such as, under certain conditions, hard water soaps and defoamer components. In addition, there are other materials which have a tendency to become entrained in deposits and increase their rate of growth. These include: calcium carbonate from poor white liquor clarification, carbon particles from fly ash or green liquor dregs, bark particles, sand introduced with wood chips, etc. Although they contain many materials besides wood resin, the deposits are still usually referred to as pitch deposits.

2.3 Kraft Mill Pitch Problems

Kraft mill pitch problems can take a number of forms, but the one most frequently encountered occurs as follows. The pitch or wood resin is partially liberated from the wood during pulping and tends to co-deposit with the other materials mentioned above on the surfaces of the process equipment. These deposits grow in thickness until they reach a size at which they break away from their surfaces of attachment. When this happens, the chunks of deposit are carried with the pulp and are broken up by the pulp agitators and pump impellers. The result is small dirt particles in the final product which can result in sale of the pulp at a discounted price or even the loss of a customer.

This is the most common kind of pitch problem. Others may include: plugging of screens and cleaners, deposits on the pulp machine, sticking problems on press rolls, customer complaints of excessive resin, etc.

2.4 Economic Significance

It is difficult to place an exact figure on the cost of pitch problems, even for a given mill. However, kraft mill pitch problems are estimated to cost, on average, several million dollars per year per mill in North America, which in Canada alone translates to $100 million per year.

Components of the cost include: sale of off-grade pulp contaminated with pitch-dirt, premature replacement of machine clothing, time lost for clean-ups, and the cost of additives to control the problem. The additives may include detergents and solvents for cleaning surfaces, pitch dispersants for stabilizing the resin in suspension, and talc for detackifying the deposits. Even if a mill is successfully controlling pitch with these additives, substantial savings can often be achieved if the addition rate can be reduced.

2.5 Technology of Pitch Control

Many factors are important in determining whether or not a kraft pulp mill has pitch problems. Examples of these include: the species and storage time of the wood being processed, the degree of bark removal, the purity and concentration of the cooking liquor, the thoroughness of pulp washing, how foam control agents are used, process pH, water hardness, temperature of the process, and how additives are used for pitch control.

In solving pitch problems, chemical analysis of pitch deposits is often an important key. There are numerous analytical chemical methods for determining the composition of the deposits. In a troubleshooting situation, this leads to a better knowledge of what is depositing and usually points to a course of action to solve the problem.

There are also a number of diagnostic tests that mill personnel can perform on the pulp suspension, which can provide information useful for determining how to solve a pitch problem at a mill.

2.6 Why Knowledge-Based Technology was Required

All of this information must be taken into account when attempting to diagnose a pitch problem in a kraft pulp mill. Furthermore, the information, and the conclusions drawn from it, carry various degrees of certainty, reliability and subjectivity. Missing, incomplete and even inaccurate data are also a fact of life in pulp mills, as is the use of ambiguous and synonymous terminology. All of this is taken into account by the expert when determining further questioning and making recommendations. A conventional programming language would clearly be incapable of describing this situation adequately.

Furthermore, the questioning strategy which one must follow in diagnosing pitch problems is dynamic in nature. One must consider all of the information to date before determining which is the most appropriate question to be asked next. This is especially true since a given piece of information (such as species of wood, seasoning time, pH values, etc...,) may be relevant to several possible causes of pitch deposition (Kowalski & Gauvin 1992) and (Kowalski & Gauvin 1992a).

The mechanism for handling the questioning logic of the system also had to be flexible enough to allow for the easy addition of more sophisticated features at a future date, without the need to redesign that part of the system. Such features could include an answer retraction capability (Reiter and de Kleer 1987) as well as a mixed-initiative mode of use which would allow the user to enter information immediately, rather than being required to wait for the appropriate question (Kowalski & Gauvin 1992) and (Kowalski & Lebensold 1989).

Pitch Expert was designed to meet all of these functional requirements and satisfy the above-mentioned constraints. However, it was equally important for the system to be easily maintainable and updatable so that, as new methods of pitch control are discovered, the expertise could be quickly and efficiently incorporated into the system. In this way, state of the art expertise could always be accessible to mills across the country. Similarly, Pitch Expert could be kept up to date with regard to changes in kraft bleaching technology. This requirement was therefore carefully considered from the initial designs through to the final implemented version and in retrospect, the high priority accorded this issue largely contributed to the system's success (Kowalski & Muise 1990).

Finally, there was one additional requirement which necessitated the building of the system as a knowledge base. Pitch Expert had to be able to explain itself clearly and concisely, in relation to every aspect of its interaction with the user, including questions it might pose, as well as conclusions and recommendations. This was important for two reasons.

First, before a mill manager will authorize the implementation of a recommendation which may result in a significant expenditure (such as adding or increasing the feed rate of a chemical additive), he must have confidence that such a measure will have a positive effect on production in the mill. This confidence can be gained only if that same mill manager is able to obtain a logical justification for the action from the system. Furthermore, our experience has shown that such a justification must be short and concise so that the user can grasp the essential reasoning without getting lost in a multitude of rules and facts.

Second, Pitch Expert was to be used as a training tool. In this respect, allowing the users to ask the system questions such as "why is this question important", "what do you mean", "how do I find the answers to this question" and "why do you make this recommendation or conclusion" is extremely valuable. Also, offering this same user the ability to specify the level of detail with which the answer is displayed further enhanced this use of the system.

2.7 The Need for Training of Mill Personnel

The experience of the domain expert (L.H. Allen) in solving kraft mill pitch problems now spans over twenty years. Although there are still some grey areas in our understanding of the various interacting phenomena of pitch deposition and dirt formation, experience suggests that we have sufficient practical knowledge to provide expertise for solving most pitch problems in kraft mills. As a result of this and the complexity of pitch problems, a considerable amount of time has been spent helping mill personnel with pitch problems on a consulting basis.

At the mills, with time, certain personnel learn through reading, consulting sessions, and experience, how to avoid pitch problems. Nevertheless, one reality of life in a kraft mill is that, over the years, there is a constant influx of new engineers and technical staff. Thus, there is a constant need for training. At present there are no text books dealing with this subject.

3. Implementation

Pitch Expert was implemented using the A.R.T. (Automated Reasoning Tool) expert system development tool on top of the LISP programming language. The hardware platform was a Sparcstation 1 with 32 megabytes of RAM and 500 megabytes of hard disc storage. The system contains approximately 1,200 rules and 3,000 schemata. In addition, there is a collection of about 200 functions and daemons (procedures attached to knowledge structures) present in the system.

Pitch Expert was built over slightly more than four years, from March 1988 to July 1992 when the completed system was transferred to Paprican. A time line showing important dates in the evolution of the Pitch Expert project appears in Figure 1. During this time, some 21 person-years of effort were expended on the project (15 for scientific and managerial personnel plus 6 for support staff). This represents the lion's share (85%) of the approximately $2.8 million Canadian project cost ($1.1 million direct cost). The remaining expenditures were mainly for project-related equipment and software.

A smaller ongoing effort is also foreseen for system maintenance. This is expected to represent about one and one-half person-years for each of the next few years, for an anticipated cost of about $175,000 Canadian per year.

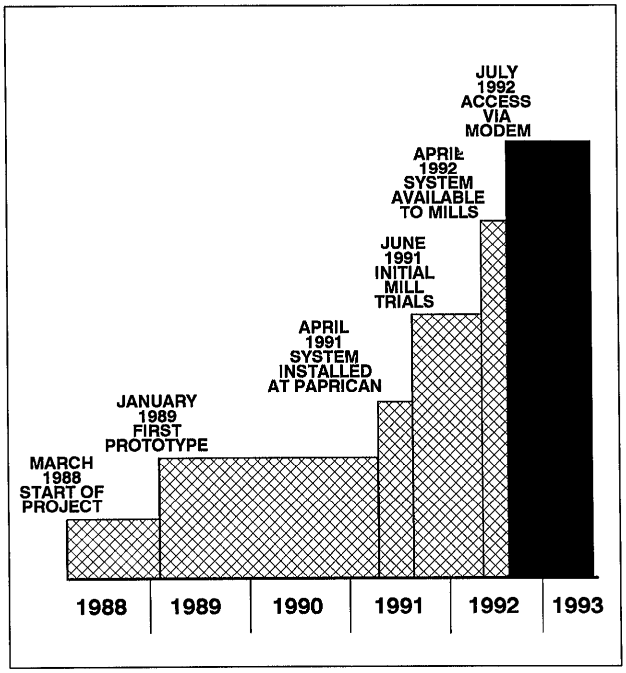

Figure 1. Important dates in Pitch Expert project.

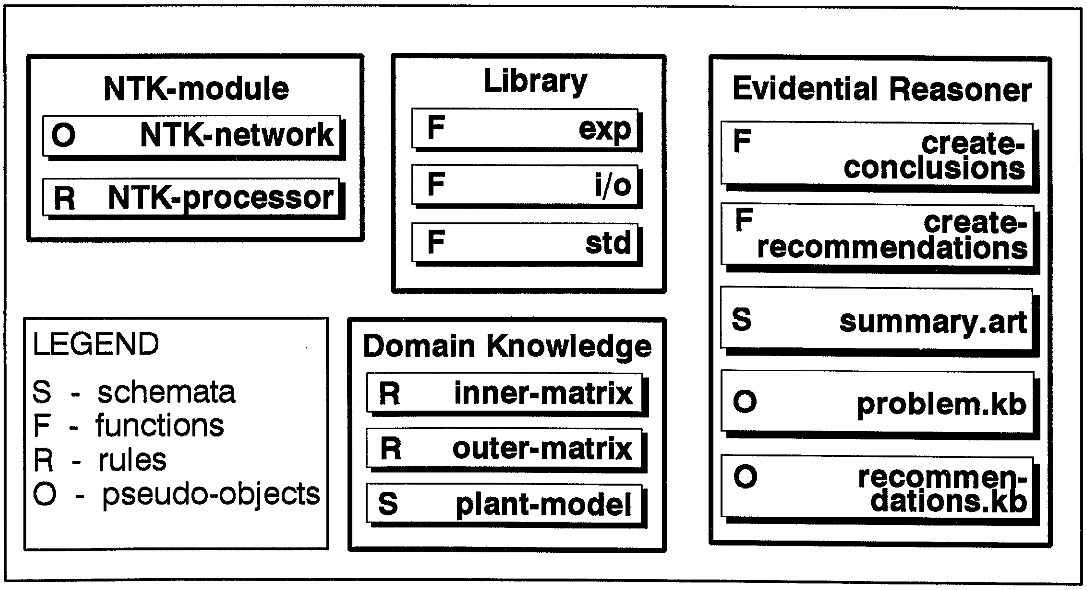

Figure 2. Major components of Pitch Expert.

Figure 2 shows the division of Pitch Expert into its four main reasoning modules: the Domain Module, the NTK-Module, the Evidential Reasoner, and the Library Module. Each module incorporates one or more specific reasoning strategies and uses a set of specialized knowledge representation structures.

3.1 NTK-Module

3.1.1 Description of the NTK-Module

An expert's knowledge includes not only facts and reasoning, but also what questions to ask in what order and under what circumstances. The goal is to get to the best and most complete possible understanding of the problem (to make good recommendations) while asking the fewest possible questions (to avoid wasting time and effort). To complicate matters further, the answers to earlier questions may change the relevance or importance of later ones.

The term "NTK" stands for "need to know" and refers to the function of this module: to determine and implement dynamically the best questioning strategies to obtain information from the user as needed for the reasoning.

The NTK-module is composed of an NTK-network and an NTK-processor. The module consists of several hundred nodes connected by a set of specialized relations to form a complex network (the "NTK-network"). Each node represents either a question ("NTK"), a fact which is inferred directly from the answer to a question ("NTKF"), or a normalized fact (i.e., a relative value) which is inferred via a daemon from an NTKF ("NTKIF"). A typical question description is shown in Figure 3.1.

These nodes are connected by multiple links to form a bi-directional network. These links in turn combine to form two separate threads of reasoning running through the network. The first thread involves "comes-from" links which trace back the questioning path or paths which can produce a given piece of information (i.e., fact). The second thread, which operates in the opposing direction, may be composed of several types of links, depending upon the nature of the two nodes linked together. More specifically, a particular link may specify which answer is required to produce a given fact, which fact is required to make a given question relevant, or which fact and value set is required to produce a normalized value.

The NTK-processor accepts a request from the diagnostic module to search out a given piece of information and then navigates through the NTK-network trying to find that information. Figures 3.2 and 3.3 illustrate the operation of the NTK-network.

```
(defschema ntk-216
IS-A: ntk-question
TEXT:
HAS-BEEN-ASKED:
CAN-BE-ASKED:
ANSWER-CONSTRAINT-TYPE:
ANSWER:
SAVED-ANSWER:
COMES-FROM:
LEADS-TO:
WHAT-DO-YOU-MEAN:
HOW-DO-I-FIND-OUT:
WHY-ARE-YOU-ASKING:
```

Figure 3.1. Typical NTK-question description.

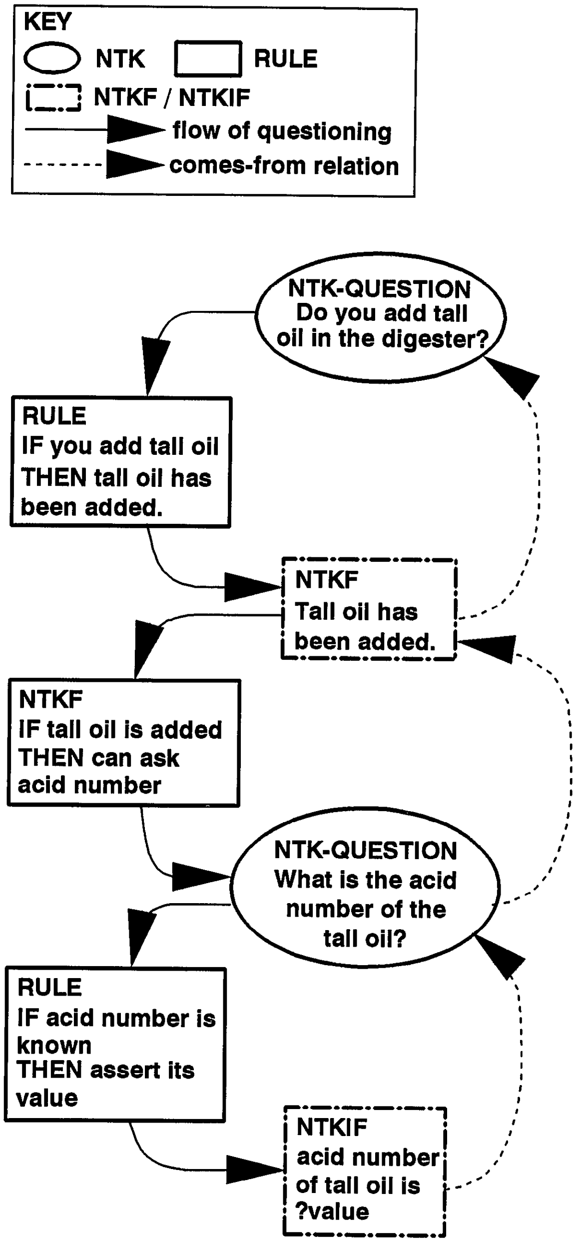

Figure 3.2. Operation of reasoning in NTK-network.

3.1.2 Benefits of the NTK-Module

This separation of questioning logic and control into a distinct module (Hughes 1987), and the use of a network of object-type structures (as opposed to implementing the logic completely in the form of rules) has greatly simplified the task of maintenance and development (Kowalski & Lebensold 1989). As new questions were acquired from the expert, they were added to the system with relatively little work, since all that was required was to find:

•The appropriate position of the question in the

NTK-network.

•The relevant facts which could be derived from answers to that question.

•The relevant connections between these facts and other facts already existing in the network.

Questioning paths or strategies can also be easily changed since these changes need to be reflected in only one part of the system (the NTK-network). This was especially important for Pitch Expert since many questions, and the relevant information derived from their answers, play an important role in more than one cause of pitch deposition. As a result, the answers to questions related to one cause of pitch problems can dynamically affect the questioning path for a second cause.

In the two years which have passed since Pitch Expert was delivered, the NTK network has undergone almost continuous modification aimed at improving the questioning strategies of the system. These modifications have been performed exclusively by the Paprican maintenance team (as opposed to the senior knowledge engineers), always utilizing the NTK diagrams and method, and this has proven itself to be a straightforward and simple method of maintenance. It is clearly one of the aspects of the system design responsible for the continuous and smooth improvement in the system's performance since its delivery.

The nodes of the NTK-network also offer an ideal centralized repository for information on the status of each question (i.e. has it been asked, can it be asked, if asked what was the answer, etc...). Without these structures, it would be necessary to have a set of complex and difficult-to-manage rules to determine when and if it was necessary and meaningful to ask a given question.

Furthermore, these NTK-nodes provide an easy attachment point for various kinds of deep knowledge and even meta-knowledge, for example on-line help facilities ("what do you mean", "why are you asking", "how do I find the answer", "what are acceptable answers", etc.). These help facilities have been found to add greatly to the ease of use of the system, thus gaining the confidence of the pulp mill personnel. They have also made it possible to use Pitch Expert as a training tool, which is important because of high turnover in the mills. This training capability is seen by the users (i.e., mill personnel) as a feature of great importance and is one of the reasons for its enthusiastic acceptance. Our analysis of the use of the system in its first two years shows a common trend among initial users to make very heavy use of this feature. In fact, many first-time users have run a complete session of well over 100 questions asking "why" for each one. Such an exercise has allowed them to gain a deeper understanding of the true complexities of pitch deposition problems.

The NTK-network also allows Pitch Expert great flexibility in handling incomplete information. When a question is answered with "unknown", alternative questioning paths are already explicitly laid out in the NTK-network and can quickly and efficiently be activated.

Other potential features which can be implemented easily and efficiently using this approach include:

•Multilingual operation and more advanced help and explanation capabilities.

•Answer retraction capability. The truth maintenance issue is not affected, but the ability of the system to readjust the questioning strategy automatically and dynamically would be of great help.

•Mixed initiative mode capability. The installation of such a capability would be greatly simplified by the already existing model of the relationship of each question/answer set to all of its immediately related facts and questions.

3.2 Domain Module

The Domain Module contains the actual domain knowledge relating to pitch problems. It consists of two major components: the mill model and the diagnostic module.

3.2.1 Mill Model

As shown in Figure 4.1, the mill model consists of five semantic networks, each of which describes a typical kraft pulp mill from a particular perspective (locations, substances, equipment, processes and observables). These five networks are connected as appropriate at various points. Together they provide a model of the pulp mill with both a lateral and hierarchical frame of reference which is critical to the proper and efficient functioning of the rules in the diagnostic module. In addition, three semantic networks relating to problems, tests and recommendations are used in reasoning about the mill model.

The eight networks combined form a model consisting of over 2,000 nodes (implemented as schemata) and over a dozen relations, most of them both customized and complex. Figure 4.2 shows a small portion of one of these networks, describing the locations in a pulp mill. Although not a model-based system as formally defined (Winston & Shell 1990) and (de Kleer & Williams 1989), the mill model provides some of the same advantages (de Kleer 1991) by supporting and supplementing the diagnostic heuristics of the system.

Although the use of such a structure allows the option of customizing the models to match any particular mill exactly, our experience to date has shown the need for such a fit to be less than urgent. The generic model of the mill has served very well in approximating the configuration of the actual mills which have used the system. It remains to be seen if the customization option becomes more important as use of the system grows and kraft process operations change.

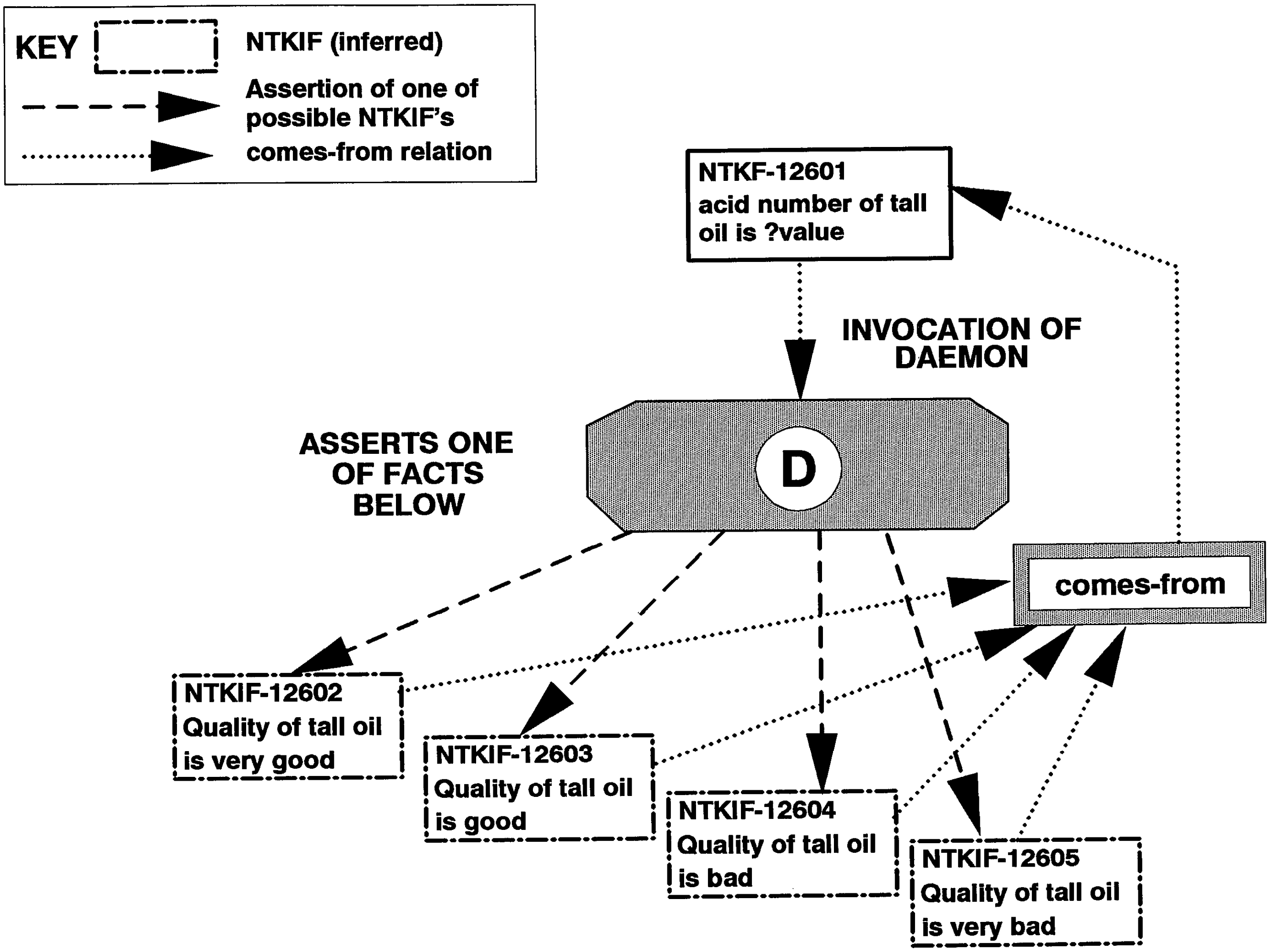

Figure 3.3. Operation of typical daemon.

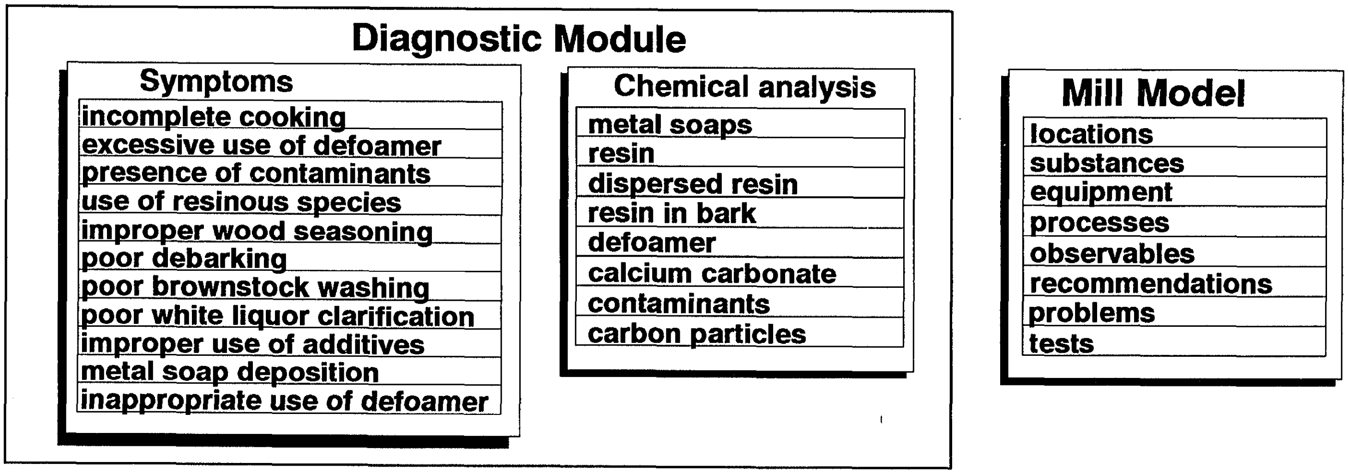

Figure 4.1. The modules containing Pitch Expert's domain knowledge.

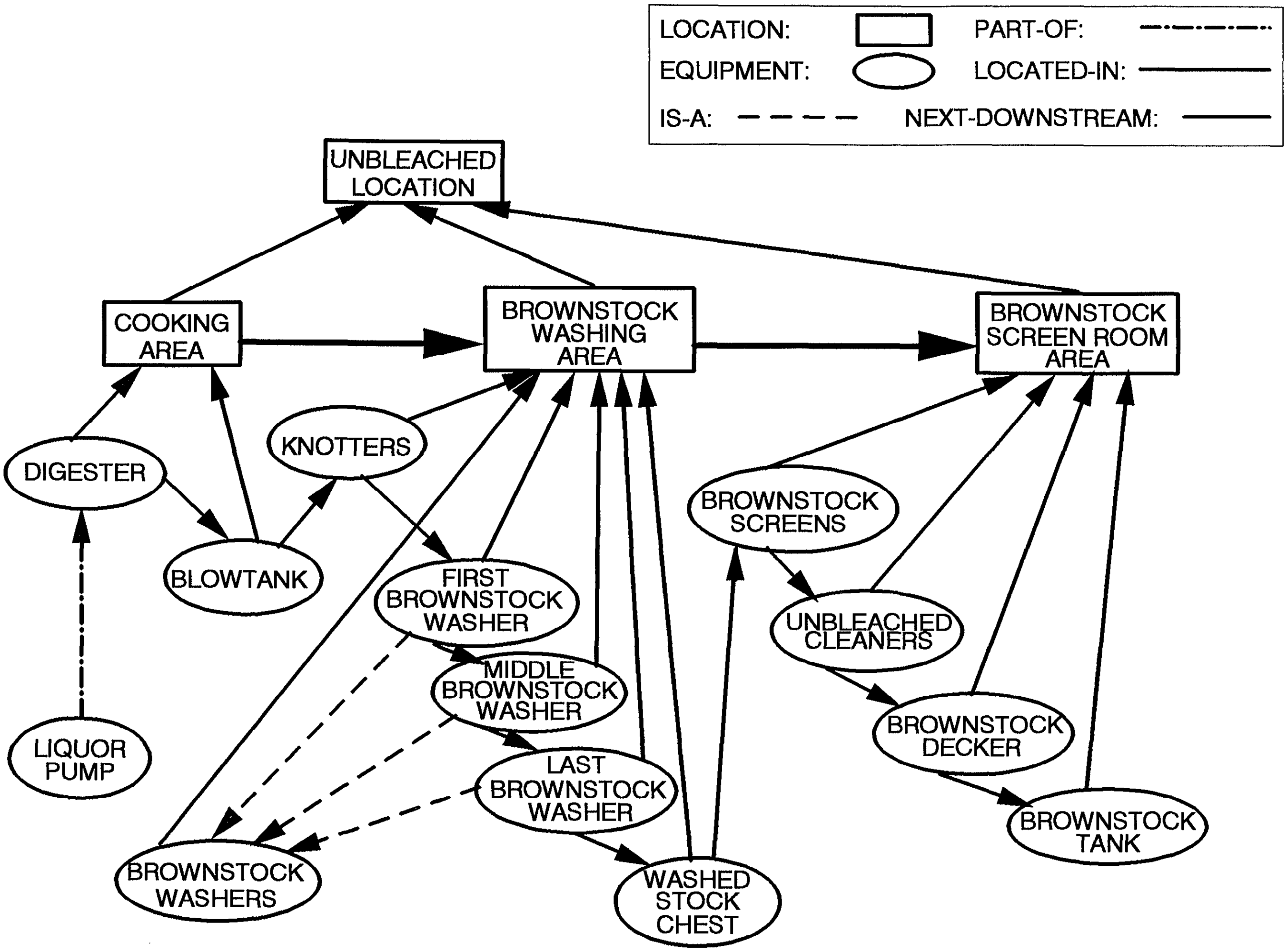

Figure 4.2. Portion of pulp mill locations network.

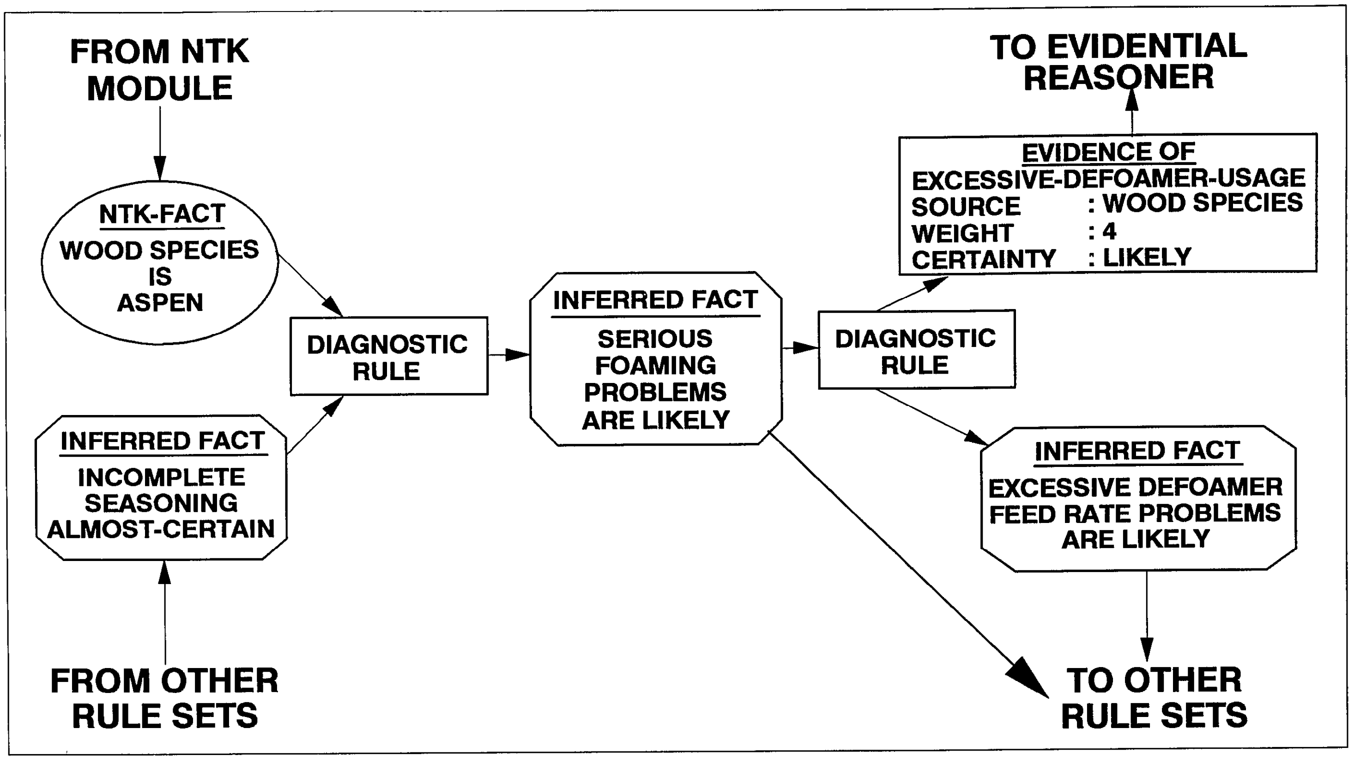

Figure 5.1. A chain of inference related to excessive defoamer usage.

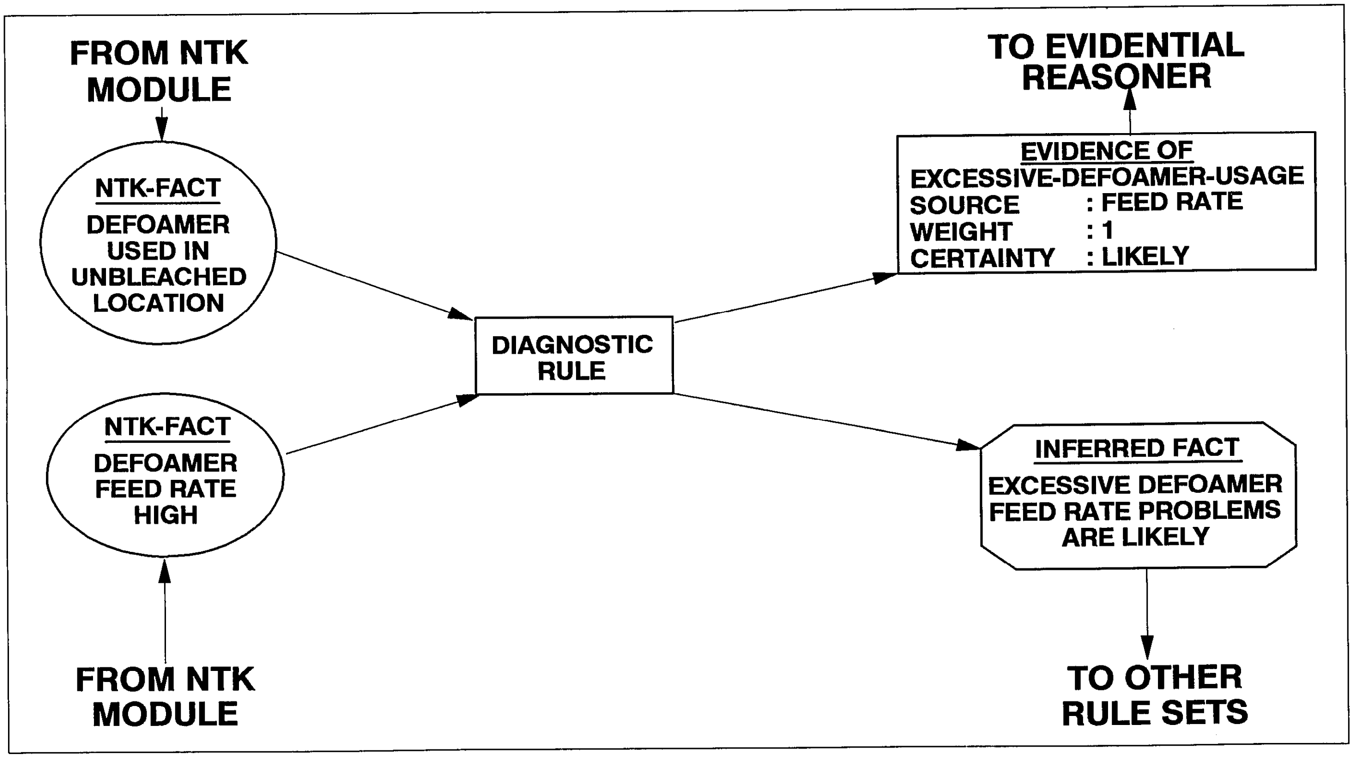

Figure 5.2. A different chain of inference leading to similar conclusions.

3.2.2 Diagnostic Module

The diagnostic module implements the diagnostic reasoning strategies related to pitch problems. As shown in Figure 4.1, it consists of 19 components, each of which addresses one particular aspect of pitch diagnosis, either symptoms of pitch problems or chemical analyses performed to diagnose pitch problems. Each component uses five types of structure to produce its diagnoses:

NTK—facts: described in the preceding section. They are mentioned here only because they serve to satisfy the conditions of diagnostic rules.

meta-asserts: commands which send a message, when appropriate, to the NTK-module,instructing it to track down a particular piece of information which is needed for the diagnosis. Note that the sending of this message is the only involvement of the diagnostic module with the questioning strategy (and is comparable to message passing for encapsulated objects).

inferred facts: created from the diagnostic rules when the conditions of the rules are satisfied by NTK-facts and previously inferred facts, they serve, in turn, to satisfy other diagnostic rules (creating the inference chains of the system).

evidence: these structures are created by the diagnostic rules. They represent conclusions about the likelihood of a particular cause of pitch deposition based upon the certainty and reliability of one source of information. Naturally, for any given cause of pitch problems, there may be several sources of information, each of which will produce a separate piece of evidence. When all of the information available has produced all of the relevant pieces of evidence, the evidential reasoner (see below) collates, sorts and prioritizes them to reach its final conclusions.

rule: standard, diagnostic If/Then rules which use facts (both NTK and inferred) to create other inferred facts as well as pieces of evidence.

Figure 5.1 shows a portion of the rule set pertaining to the problem of excessive defoamer usage. This example shows how the various knowledge representation structures and modules of Pitch Expert work together in a co-ordinated fashion.

A message is sent to the NTK-module indicating the need to know the species of wood being used. If the species is aspen, and it has been inferred in another rule set that the wood is incompletely seasoned, then it will be inferred that serious foaming problems are likely to occur. If that is the case, a second rule will infer that it is likely that excessive amounts of defoamer are being used. This same rule will also create an instance of evidence specifying the appropriate weight and certainty. Both of the inferred facts created in this rule set may be used to satisfy rules in other rule sets. The instance of evidence (along with all other instances of evidence) will be processed at the appropriate time by the evidential reasoner.

This example clearly shows how this line of reasoning, using the species of wood and information about its seasoning, is unaffected by any new lines of reasoning using other information. In this way, maintenance requirement related to the addition of new lines of reasoning are kept to a minimum.

Figure 5.2 diagrams a second line of reasoning from the same rule set, which uses information from the NTK-module related to the feed rate and site of addition specified by the user to produce an inferred fact and an instance of evidence with the appropriate parameters.

3.3 Evidential Reasoner Module

Due to the functional requirements of the system (see Section 2.6), it was clear early on in the design of Pitch Expert that a standard approach to dealing with uncertainties such as the certainty factors of MYCIN or implementation of the Dempster-Schafer Theorem would have been inadequate (Buchanan & Shortliffe 1985). Instead, a customized evidence-handling strategy was developed.

Figure 6 shows a typical "piece of evidence", which consists of:

- A specification of an associated cause of excessive pitch deposition.
- The source of the information (the specific piece or pieces of information obtained from the user which led to the conclusion of the evidence).
- A weight representing the reliability of the source of information from which the evidence was derived.
- A value specifying the certainty associated with the conclusion.

```
Schema 2311.5.3                        ( instance-of evidence )

( instance-of    excessive-defoamer-usage          )
( source         defoamer-feed-rate                )
( weight         1                                 )
( certainty      unlikely                          )
```

Figure 6. Instance of evidence.

Each instance of this evidence structure serves as a central storage place for information pertaining to one particular line of reasoning. This compact storage of information offers three advantages:

- First, it allows the system to treat the conclusions of each line of reasoning separately. This is important because it keeps the rules simple and easy to maintain. New lines of reasoning can be easily added, creating new pieces of evidence, without the need to modify existing lines of reasoning. Since delivery, many new lines of reasoning have been added in this manner, without any resulting errors in the existing lines of reasoning. This is due to the fact that the collation and analysis of the collection of evidence is handled separately by the evidential reasoner (as will be explained below).
- Second, it allows a flexible and concise system of explanations and justifications (Millet 1989) to be offered to the user (as explained below). This ability to present explanations has been recognized as a critical component in more recently built knowledge-based systems (Cawsey 1991) and (Suthers, Woolfe, & Cornell 1992) and was a key factor in gaining the confidence of mill personnel. A large majority of the sessions run by the mills make very heavy use of this facility. Interestingly enough, there has been very little interest shown by the users in the facility for back-tracking beyond these concise explanations, in order to view the specific facts and rules comprising the chain of logic for a given conclusion.
- Third, the creation of a collection of evidence for each possible cause of pitch deposition has made possible the development of a customized approach to the issues of uncertainty, reliability and even accuracy of the information. By explicitly separating out the process of combining conclusions from different sources of information, Pitch Expert can perform a sophisticated analysis and comparison of all of the individual pieces of evidence. This greatly enhances its ability to arrive at highly accurate final conclusions and also flag critical inconsistencies of input.

The evidential reasoner gathers up all of the instances of evidence, then sorts, collates and analyses them and finally presents them to the user in a variety of ways. The reasoner includes:

- A network of non-encapsulated objects which represent the set of problems which can lead to pitch deposition.
- A network of non-encapsulated objects which represent the set of possible recommendations for solving problems leading to excessive pitch deposition.
- A set of nodes representing the various tests which can be performed on either pitch deposits or pulp, and which problems these tests shed light on.

The evidential reasoner sorts evidence by problem. Evidence is then divided on the basis of whether it supports the existence of a problem (positive evidence) or refutes it (negative evidence). Then the evidence both for and against is summed up, taking into account the certainty and reliability of each source of information in a manner specific to each problem, to produce a final positive and negative weight. These two weights are then combined to produce a final conclusion for the particular problem. In addition, if both the positive and negative evidence are very strong then the system will flag this as a very important inconsistency, inform the user that inaccurate information has been provided, and advise the user to re-check the relevant information. This feature has proven to be essential for dealing with the real-life inaccuracies which are part of life in the mills.

The summary conclusions (indicating that one or more problems have been found to exist) activate the appropriate nodes in the problem network, which in turn activates the appropriate nodes in the recommendation network as well as the chemical test network (indicating what should be done about the problem(s)), at which point the relevant output is displayed. Such an approach makes it easy to offer the user the chance to peruse in more detail any conclusion or line of reasoning. Such a flexible presentation style has proven its worth very convincingly, since virtually all real sessions with the system result in several problems being identified, with several degrees of certainty. It has been observed that users often like to peruse many of the conclusions and recommendations in more detail, very often coming back to look at certain information repeatedly.

As shown in Figure 7, the user is first offered a concise list of all of the conclusions drawn by the system, prioritized by strength of supporting evidence so that the problems most likely to be causing the excessive pitch deposition are listed first and those least likely are listed last. In addition, any conclusion for which a serious conflict of information exists is tagged with a warning message.

The user may, at this point, request a more detailed explanation of any or all of these conclusions. This feature is especially useful in obtaining a better understanding of why important conflicts exist. An example is shown in Figure 8. In this example, two pieces of evidence relating to the problem of excessive defoamer usage have been created by the system. Each piece of evidence is derived from a particular source which is considered very reliable, specifically "test results" and the "defoamer feed rate".

The result of chemical tests performed on the deposit show it to contain 29.8% defoamer. Such a high content of defoamer in the deposit indicates that it is almost certain that an excessive amount of defoamer must have been added to the pulp during production.

On the other hand, the feed rate of the defoamer (0.2 kg/tonne) is considered extremely low and leads to the conclusion that it is almost impossible that an excessive amount of defoamer was used.

These two lines of reasoning conflict strongly with one another and lead Pitch Expert to identify this as a physically impossible situation, indicating that at least one of the lines of reasoning stems from incorrect data input to the system. Having identified such a conflict, Pitch Expert can now relay a warning to the user to recheck the appropriate information.

Such inaccurate data could have been caused by many factors, but their presence in any given session is a realistic possibility given the number of complex processes that are running simultaneously in a pulp mill and the variable quality of available process information.

If the user so desires, an even more detailed step-by-step backtrace of the chain of reasoning is available as well, with the relevant rules and facts at each step in the reasoning process shown in full detail.

A similar display can be obtained for the recommendations, as shown in Figure 9.

3.4 Library Module

This module contains a collection of Lisp functions and ART daemons which perform tasks such as normalizing measurements, testing on value constraints, and collating and analyzing pieces of evidence. These functions and daemons ensured a custom fit between the system and the knowledge, and greatly enhanced the system's performance.

4. Maintenance

As mentioned in Section 1, the design of Pitch Expert explicitly addressed the issue of ease of maintenance. Although Pitch Expert is now in full operation, changes continue to be made to the knowledge and rule bases, both to make the knowledge representation more complete and accurate and to cover new contingencies. These changes affect mainly the NTK-module, rules, and functions, with occasional minor changes to the mill model.

Most of the changes now being made involve the addition of new knowledge not previously included, in order to improve or extend system performance (Allen & Kowalski 1992). In some cases the new knowledge is meant to fill a specific gap in the knowledge base, in other cases it is a matter of adding knowledge as it becomes available. In other words, as research identifies new information relevant to solving pitch problems in kraft pulp mills, it is incorporated into Pitch Expert. In this way, the system is kept up-to-date and obsolescence is avoided.

At this time, the maintenance is performed on an incremental scale and there are no immediate plans to add large amounts of new knowledge to the system.

********* Conclusions *********

Pitch Expert has deduced that the following has occurred with the certainty shown below

Very Strong

- **Inconsistent Suspended Solids Concentration**
- **Poor Barking**

Strong

- **Poor White Liquor Clarification**

Very Weak

- **Excessive Defoamer Usage** ◄—— **Very Important Conflict Here**

Pitch Expert has deduced that the following has NOT occurred with the certainty shown below

Very Strong

- **Metal Soap Deposition in the Pulp Machine Area**

Standard

- **Poor Brownstock Washing**

Figure 7. Typical list of conclusions by priority.

4.1 Specialized Knowledge Structures

Specialized structures have played a major role in ensuring the maintainability of the system. Foremost among these are the NTK-structures (Section 3.1), the "evidence" construct (Section 3.3), and customized relations such as that described in the example below.

4.2 Example: Customized Relations and Maintenance

The specialized "next-downstream" relation is used extensively in Pitch Expert to build the model of pulp mill locations (see Section 3.2.1). This relation, made possible by the sophisticated relation-building capabilities of the ART shell, describes the relative position of two locations in a mill in terms of pulp or water flow between them. The resulting directionally linked chains can be used to make locational comparisons, even between different levels of abstraction. This proved to be another critical factor in the success of the system, for three reasons:

- The relation allowed easy insertion of new or additional locations just by modifying a few links. No other rules or functions needed to be changed. In this way, the pulp mill model could be constantly and easily refined.
- Because the relation is transitive (via a more general "downstream" relation), diagnostic rules can use it to compare locations to determine which is downstream of the other. For example, consider the location of a pitch deposit and the location at which talc has been added. If the talc was added downstream of the deposit, it is unlikely that the talc has contributed to the problem (since the talc is unlikely to swim upstream). If on the other hand the talc was added upstream of the deposit, it is possible that the talc addition has influenced the deposition problem. If the talc was added directly upstream of the deposit, then it is probable that the addition of talc has influenced the deposition problem.
- The relation allows comparison of locations at different levels of specificity. For example, the first-brownstock-washer is downstream of the cooking area as a whole since it is downstream of each component of the cooking area. This sort of concept is simple for human beings but can be extremely difficult and complex to represent effectively in a computer program. The ability to incorporate this knowledge into a single customized relation speaks volumes about the utility of powerful knowledge-base shells, and the relevance of such a feature to ease of maintenance is self-evident.

4.3 Knowledge Representations

A second strategy which has facilitated both development and maintenance is the use of three coordinated pools of knowledge: a data base, a collection of graphical blueprints, and the ART source code. Each pool contains the exact same information, but in a form which offers particular benefits.

In the data base, each instance of knowledge is stored as a record. These records can be accessed by queries and sorts based on various indices to identify, for example, all the places where a fact, fact element, or class of facts appears. This makes it possible to change or augment the knowledge base quickly and without errors or omissions.

The graphical blueprints contain the same knowledge as the data base, but in a form which visually highlights links between knowledge structures such as rules, questions, and evidence. Both the expert and the system developers have found it useful to be able to look at the diagrams and grasp the essence of the logic without having to wade through masses of source code and system commands. Each blueprint can contain a large amount of information of various types, ranging from natural language versions of the rules to specialized meta-knowledge commands. Different people can focus on the information of current interest to them, yet all work with a single diagram, which helps to ensure consistency from concept to design to implementation and finally through testing, debugging, and maintenance.

USER INPUT ⟶
why ... Excessive-Defoamer-Usage
This was based on the following information:

Very Reliable

- Test-Results, specifically the 29.8% defoamer in the dry deposits, indicate that it is almost-certain that it has occurred.

Very Reliable

- Defoamer-Feed-Rate, specifically the 0.2 Kg/tonne, indicates that it is almost-impossible that it has occurred.

Based on this information Pitch Expert can conclude that it has occurred with a very-strong confidence but based on this information Pitch Expert can also conclude that it has not occurred with a very-strong confidence.

Figure 8. Typical explanation of conflicting evidence.

The code itself serves both as the ART implementation of the system and as a repository of knowledge. Code for each rule, schema, and function includes a history of when each was created and modified, by whom and for what reason. Furthermore, each function and daemon contains extensive documentation in a standard form explaining its purpose and approach and all parameters used.

Since the knowledge in Pitch Expert exists in three forms (diagrams, data bases, and code) which are not automatically integrated, procedures were established to make sure that consistency was maintained among these three repositories of knowledge. Each instance of each structure (except for the rules) must be entered into the data base. Each instance of each structure including the rules must of course be coded in ART. To create the blueprints, printouts of individual structures from the data base or the source code files are physically pasted onto the diagrams and manually linked together. Further checking includes, for example, obtaining a printout from the data base of which facts exist as input (LHS of a rule) and which as output (RHS of a rule) and checking this printout against the diagrams. All this almost assures that the blueprints represent the actual state of both the data base and the code.

```
PITCH EXPERT MAKES THE FOLLOWING
RECOMMENDATIONS WITH THE INDICATED
LEVELS OF IMPORTANCE

VERY STRONG RECOMMENDATIONS
=====================

IMPROVE THE EFFICIENCY OF THE
BROWNSTOCK WASHERS.  THIS WILL LOWER
THE CONCENTRATIONS OF DISPERSED
WOOD RESIN - DISSOLVED SOAPS -
DEFOAMER - CALCIUM CARBONATE
PARTICLES - AND OTHER DEPOSITABLE
MATERIALS.

  -  THIS WAS RECOMMENDED FOR
     CORRECTING THE FOLLOWING
     PROBLEM(S) :
       -  POOR-BROWNSTOCK-WASHING
       -  METAL-SOAP-DEPOSITION-IN-
            BROWNSTOCK-SCREEN-ROOM

*** hit return to continue or why for more
    details ***

why

CHOOSE ONE OF THE FOLLOWING
PROBLEMS:

1 POOR-BROWNSTOCK-WASHING
2 METAL-SOAP-DEPOSITION-IN-
  BROWNSTOCK-SCREEN-ROOM
3 NEXT-RECOMMENDATION
```

Figure 9. Typical recommendation display.

The success of this approach is attested to by the fact that significant improvements in accuracy and completeness (as outlined in Section 6) have been achieved by changes made by Paprican personnel with minimal supervision by the senior designers. Considering the day-to-day use that is still being made of this maintenance system to maintain and upgrade the knowledge base, its importance to the success of the project cannot be overstated.

This maintenance mechanism has withstood the test of real-life use and still serves today as the control and self-checking mechanism that has allowed an ongoing dynamic environment to be created in which constant modification of the knowledge, rather than being a hindrance, serves as one of the system's attractions. Response from the users has shown that the ability to have state of the art expertise always available is a strong source of their motivation to use it.

The perception and development of Pitch Expert as an ongoing evolving system, rather than a static entity, was a key factor in its success. The provision of such a maintenance capability, in whatever form proves workable, should be given serious consideration in the development of any major industrial knowledge base.

5. Use of Pitch Expert

Pitch Expert resides on a Sparc workstation at Paprican and is accessed via modem. The system operates in a question-and-answer mode, posing questions to the user one at a time and accepting typed answers until it has all the information it needs. At important decision points during a run, Pitch Expert also displays numbered menus of available options.

Each answer is checked for acceptability as soon as it is entered. The criterion can take the form of a list of specific acceptable answers, a class specification, or a requirement that the answer be a number. If an unacceptable answer is entered, Pitch Expert displays a message and then asks the question again.

Any question can also be answered with one of Pitch Expert's keywords. These activate special features such as on-line help, access to intermediate conclusions and recommendations, and saving an incomplete session for later retrieval.

Missing information is handled via two keywords, "later" and "unknown". "Later" is used when an answer is expected to be obtainable but is not available right now, "unknown" when no better answer can ever be expected. When answers become available for questions originally answered by "later", the session can be retrieved and re-run, and these questions will be asked again.

Each answer, as it is processed, may create NTKF's and, indirectly, NTKIF's. These in turn may activate more NTK's or they may lead domain rules to fire, creating inferred facts or pieces of evidence. In either case, the chain of rules eventually leads to the creation of a collection of evidence, to be evaluated by the evidential reasoner.

At any point in a Pitch Expert session, the conclusions and recommendations which are supported by the evidence asserted up to that point can be viewed on the user's screen by use of the "recc" keyword. These conclusions and recommendations are, of course, not final and will change during a session to reflect new information as it becomes available.

Three kinds of help are available for questions and can be accessed via keywords. "What" provides a re-worded version of the question in case the original was unclear. "How" gives further detail on how to obtain the information required to answer the question. "Why" expands on why it is important to ask this question in the context of pitch control.

Since a typical session can take an hour or more, a facility has been provided (via the "save" and "restart" keywords) to save the current session at any point in a form from which it can be picked up again at a later time. A common use of this feature would be to store a session in which "later" answers were given to one or more questions, with a view to retrieving and continuing the session when answers to these questions became available.

When Pitch Expert has an answer to all the questions it judges necessary to its reasoning, it completes its reasoning process and then offers to display on the screen the conclusions it has reached and the recommendations it has made. Conclusions and recommendations are shown one by one, in order of priority, each with its supporting evidence in order of reliability.

Recommendations are displayed in a similar manner. By typing "why" in response to a recommendation display, the user can obtain a summary of the reasoning leading up to that recommendation.

Pitch Expert can produce a summary report of the session just completed, or of any earlier completed session. This report includes all conclusions reached, recommendations made, and conflicts noted. The report will be displayed on the screen and incorporated into the transcript of the session.

6. Performance

There are two fundamental measures of expert system performance: the quality of the expert reasoning, and the benefits (economic and other) provided by use of the system.

The most basic requirement of expert system performance is that it reproduce acceptably well the reasoning of the human expert. In the case of Pitch Expert, this means that its conclusions and recommendations must be accurate (that is, the same ones the human expert would have come to in the same situation) as well as complete (nothing the human expert would have concluded or recommended has been left out).

6.1 Initial Mill Trials

To evaluate the benefits of the system, financial and otherwise, a set of initial mill trials were conducted from May 1991 to April 1992. The trial runs were conducted with the cooperation of thirteen kraft pulp mills from across Canada (Allen & Kowalski 1992) and (Turney 1992).

During this test period, the sessions were all conducted with the aid of an intermediary at Paprican. This person was responsible for manning the phone and acting as the contact between the mills and the system. When mill personnel called in, they would verbally convey the relevant information about their particular mill to the intermediary, who would in turn enter all the information into the system. The corresponding output would be checked for accuracy and completeness by Dr. Allen himself, and then would be sent out (with corrections if necessary) to the mill. Using the results of each session, modifications were made to the knowledge base to address any errors or inconsistencies which had been discovered.

The early sessions achieved an accuracy of 60% and completeness of 70-80%. As the system was fine-tuned with each new mill test run, the system's performance was continuously improved and at the time of this writing, it stands at 90% accurate and 93% complete. Further progress is expected. All thirteen mills were to perform a complete evaluation of the benefits of the system. As of October 1992, three had completed their evaluation, seven more were in progress and three had suspended the study for various reasons stemming for the most part from severe constraints on resources.

The three completed evaluations showed a combined annual savings of almost $2.4 million Canadian, due for the most part to an overall reduction in the amount of pitch-contaminated pulp produced, as well as a decrease in the quantities of additives used. This figure is especially impressive in light of the fact that it represents savings for just 3 kraft pulp mills. There are over 40 such mills in Canada alone. These savings alone almost equal the $2.8 million development cost of Pitch Expert to date. The 36 mills already using Pitch Expert can expect to save $28 million a year.

6.2 Detailed Discussion of the Three Completed Evaluations

Given the importance that these savings represent, it is worth examining them in greater detail. In the interest of brevity, we will focus on those mills whose evaluations of the effects of Pitch Expert were complete.

For reasons of confidentiality, the company names and locations of the particular mills cannot be specified. They will be referred to as mill #1, #2, and #3. They are, however, real and very typical kraft pulp mills and the sessions of Pitch Expert which they ran involved real data representing real pitch problems.

The cost savings reported by these mills are summarized in the table below.

TABLE I

Mill Number	1	2	3
Off target before	5%	2%	N/A
Off target after	1%	0%	N/A
Annual production (tonnes)	170,000	360,000	450,000
Annual estimated savings	$527,000	$1,080,000	$742,000

6.3 Modem Access to Pitch Expert

As a result of this evaluation exercise, there was an almost universal agreement among the mills involved that the system should be made directly accessible to the mills via modem, rather than through a Paprican technician. Mill personnel would then be free to use the system as a training tool by making extensive use of the "what", "how" and "why" facilities, as well as being able to evaluate numerous "what if" scenarios. Direct modem access to the system was implemented in July 1992.

It was, however, decided not to install Pitch Expert at individual mill sites. Given the size and complexity of the system and the fact that it continues to evolve, it was judged that updates would be easier with a single copy stored at Paprican. Having a single copy at a central site also greatly facilitated the restriction of access to authorized users.

What is particularly of interest here is that the initiative and enthusiasm for modem access came from the mill personnel themselves. This highlights the enthusiasm with which Pitch Expert was received by industry.

Once Pitch Expert was made accessible by modem, its usage grew quickly. Eight months after its release (March 1993), 80% of Canadian kraft pulp mills, representing 90% of Canadian production capacity and over 20 companies, had accessed the system. In fact, acceptance and use of Pitch Expert by the mills, up to this point, has been limited only by the necessity for mill personnel to be given introductory training on the proper use of the system. With limited manpower available for this task, it has been impossible to provide this training to more than one mill at a time.

Given the rapid growth in the number of users and the limited resources available, it has not been feasible to perform an exhaustive analysis of system use beyond the initial 12-month study. Rather, ongoing day-to-day observations are made of usage patterns. Having a centralized system, accessed by modem, has made this possible; studying usage of a number of copies of the system installed on-site at each mill would have been much more difficult.

Based upon these observations, after two years of use, the following patterns have been observed:

- Initial use of the system is usually for educational purposes rather than troubleshooting. This involves heavy use of the help facilities to learn why the system asks its questions, and why it makes its recommendations, as well as "what-if" exercises using hypothetical data. Such use illustrates to the user just how complex and difficult accurate pitch problem diagnosis really is. This period will last anywhere from several weeks to several months.
- Following the initial exploration of the system, a more methodical use beings, with real-life data pertaining to the particular mill. Gathering these data can often take several weeks, depending upon the availability of personnel at the mill. As more data are entered into the system, the updated recommendations are usually produced with stronger certainty, and are perused in more detail, making heavy use of the explanation facilities.
- Over the long term, roughly half of users access the system at least once a month and half less often.

To date, Pitch Expert users have all been members of Paprican. As members, they are considered to have paid for development of the system via their industrial membership fees. Making the Pitch Expert system available for use by non-member companies is now being considered. There has already been strong interest from several countries. Although the fee structure has not yet been determined, it is clear that if non-member companies are given access to the system, they will be charged for its use.

Mill No. 1:

This mill has an annual production rate of 170,000 tonnes of pulp. The production of off-target (i.e. pitch-contaminated) pulp represents a loss of $50.00 per tonne. The defoamer used in this mill is purchased at a cost of $1.10 per kg.

Before running a diagnosis with Pitch Expert, Mill #1 had 5% of the pulp it produced contaminated with pitch. In addition it was using 3.8 kg of defoamer per tonne of pulp.

After running a full diagnostic session with Pitch Expert, entering all of the required information, and implementing the resulting recommendations, Mill #1 had reduced its off-target pulp to just 1% of total production. In addition, the rate of defoamer usage had been reduced to 2.8 kg defoamer per tonne of pulp.

The resulting annual savings, in Canadian dollars, can be calculated as follows:

<u>savings from reduction in off-target pulp</u>

5% - 1% = 4% x 170,000 tonnes of pulp per year
= 6800 tonnes of pulp per year x $50.00 per tonne
= $340,000

<u>savings from reduced use of defoamer</u>

3.8 kg/t - 2.8 kg/t = 1.0 kg/t
1.0 kg/t x 170,000 t/year = 170,000 kg/year
170,000 kg/year x $1.10 = $187,000

<u>total yearly savings = $340,000 + $187,000= **$527,000**</u>

Mill No. 2:

This mill has an annual production rate of 360,000 tonnes of pulp. The production of off-target (i.e. pitch-contaminated) pulp represents a loss of $50.00 per tonne. The defoamer used in this mill is purchased at a cost of $1.35 per kg.

Before running a diagnosis with Pitch Expert, Mill #1 had 2% of the pulp it produced contaminated with pitch. In addition, it was using 4.5 kg of defoamer per tonne of pulp.

After running a full diagnostic session with Pitch Expert, entering all of the required information, and implementing the resulting recommendations, Mill #2 had **completely eliminated the presence of pitch contaminated pulp**. In addition, the rate of defoamer usage had been reduced to 3.0 kg defoamer per tonne of pulp.

The resulting annual savings can be calculated as follows:

<u>savings from reduction in off-target pulp</u>

2% - 0% = 2% x 360,000 tonnes of pulp per year
= 7,200 tonnes of pulp per year x $50.00 per tonne = $360,000

<u>savings from reduced use of defoamer</u>

4.5 kg/t - 3.0 kg/t = 1.5 kg/year
1.5 kg/t x 360,000 t/year - $540,000 kg/year
540,000 kg/year x $1.35/kg - $729,000

<u>total yearly savings = $360,000 + $729,000 **= $1,089,000**</u>

Mill No. 3:

Mill #3 offers an excellent example of how Pitch Expert can help a mill achieve significant cost savings even when pitch deposition is already being successfully controlled.

This mill has an annual production rate of 450,000 tonnes of pulp. The defoamer used in this mill is purchased at a cost of $1.25 per kg.

In this mill there was no significant pitch deposition at the time of system use. However, the rate of defoamer use was 2.7 kg/tonne of pulp, and other additives were being used to prevent possible pitch deposition.

After running Pitch Expert and implementing the resulting recommendations, Mill #3 had reduced the defoamer feed rate to 1.5 kg defoamer per tonne of pulp.

The resulting annual savings can be calculated as follows:

savings from reduced use of defoamer

2.7 kg/t - 1.5 kg/t = 1.2 kg/t
1.2 kg/t x 450,000 t/year = 540,000 kg/year
540,000 kg/year x $1.25/kg = $675,000/year

Pitch Expert was also able to reduce the use of other additives (talc, tall oil, etc..) resulting in a projected savings of $45,000/year.

In addition, it was estimated that use of Pitch Expert would reduce the need for changes of machine clothing, which would translate to a savings of $22,000/year.

Projected total yearly savings in this mill are therefore:

= $675,000 + $45,000 + $22,000 = **$742,000**

6.4 Other Benefits of Pitch Expert

A number of less quantifiable but equally real benefits have also been realized in participating mills. Pitch Expert provides training in pitch control techniques to mill engineers. Many pulp mills are in less desirable remote locations and tend to be staffed by engineers who are inexperienced or new to the industry, and who have a high turnover rate. The help and explanation facilities are particularly useful in this context. During development of the system, the expert commented that when he visits mills, he spends much of his time educating mill personnel as well as investigating pitch problems. It is important that Pitch Expert be able to perform both these functions.

Using Pitch Expert also encourages mill personnel to do more information gathering and testing on a regular basis, thus improving their overall problem-solving capability. The sequence of questions serves to highlight information that should be obtained when solving pitch problems, and the help facilities instruct users on what to look for in the mill and how to perform tests and procedures.

The session transcripts also serve as a record of the problem-solving process. This can be important because pitch problems in a given mill may be intermittent and a successful solution procedure may be forgotten by the time the problem recurs.

7. Conclusions

The Pitch Expert project is a success. The system is now used by an ever-growing number of kraft pulp mills from many companies all over Canada. Its possible use by mills in other countries is now being considered, as some companies outside Canada have already expressed interest.

The analysis of system performance shows that knowledge-based technology can indeed have a dramatic impact on productivity and costs. The savings realized by mills using Pitch Expert and following its recommendations clearly justify the expense of development. Although the continued introduction of this technology into the pulp and paper industry in the form of other knowledge-based systems will have to proceed in a methodical step-wise manner, it is clear that the success of Pitch Expert has realized the first step towards this goal.

From the technical standpoint, it is clear that the success of the project was due to the philosophy of custom fitting the system to the knowledge, as well as the careful attention which was paid to the issue of ongoing maintenance. This involved the selection of a large, sophisticated and powerful shell (in this case ART), followed by customizing in order to achieve a perfect fit with the needs prescribed by the domain knowledge.

Finally, Pitch Expert serves to highlight the fact that large and sophisticated expert systems can and do provide distributed and up-to-date expertise in a readily available and accessible fashion, which translates into improved productivity and a more competitive industry.

The major achievements of the Pitch Expert project can be summarized as follows:

- A large knowledge-based system is being regularly used by mill personnel to solve real industrial problems. Very few systems in the pulp and paper industry reach this stage of practical usefulness. Mills already using the system can be expected to save a total of $28 million per year.
- A sophisticated question-asking mechanism (the NTK-module) has been developed to enable Pitch Expert to obtain the information it needs without asking unnecessary or irrelevant questions;
- A flexible strategy has been developed for combining pieces of evidence of various strengths and weights to reach conclusions about the existence and importance of problems;
- A powerful set of customized relations and knowledge structures has been developed for modelling an industrial process;
- Thanks to its maintenance-oriented design and associated strategy, Pitch Expert is being successfully maintained with minimal involvement by AI specialists.

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