A grain storage information system for Canadian farmers and grain storage managers

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Mann, D.D., Jayas, D.S., White, N.D.G., Muir, W.E. and Evans, M.S. 1997. **A grain storage information system for Canadian farmers and grain storage managers**. Can. Agric. Eng. 39:049-056. Stored grain is susceptible to invasion by pests or infection by fungi, either of which has the potential to cause economic losses. Researchers have developed improved management techniques, but these new strategies must be made available to farmers and grain storage managers. This paper discusses the development, capabilities, and testing of an expert system, the Grain Storage Information System (GSIS), developed to transfer information to western Canadian farmers and grain storage managers. Much of the information used in the GSIS was gathered from the published literature. The current prototype is capable of teaching users why certain actions are more likely to be successful than others. Teaching rather than simply dictating instructions should help the users gain confidence in the program, allowing it to be used to its full potential. The GSIS functions well as a teaching tool, although it requires field testing.

Le grain entreposé est susceptible d'être envahi par des animaux nuisibles ou des champignons, ce qui peut entraîner des pertes économiques. Les chercheurs ont amélioré les techniques de gestion du grain. Cependant, ces stratégies nouvelles doivent être mises à la disposition des agriculteurs et des gestionnaires d'entrepôt de grains. Cet article parle du développement, du potentiel et de l'essai d'un système expert, le Système d'Information sur l'Entreposage des Grains, qui fut conçu pour diffuser des informations auprès des agriculteurs de l'Ouest canadien et des gestionnaires d'entrepôt de grains. Une grande partie des informations contenues dans le système expert proviennent d'articles déjà publiés. Le prototype actuel peut montrer aux utilisateurs pourquoi certaines décisions sont plus profitables que d'autres. La démonstration plutôt que l'imposition d'instructions devrait aider les utilisateurs à avoir confiance dans le programme, ce qui permettra d'exploiter plus à fond son potentiel. Le système expert est un bon outil d'enseignement, bien qu'il doive encore être testé auprès des utilisateurs.

INTRODUCTION

Stored grain is susceptible to invasion by pests (e.g. stored-product insects, mites, birds, or rodents) or infection by fungi, either of which has the potential to cause economic losses. Researchers have spent much time and effort trying to understand the stored-grain ecosystem with the goal of identifying improved management techniques. Significant gains have been made to address some of the problems faced by farmers and grain storage managers (hereafter "farmer" will refer to anyone who manages stored grain). This new information, however, must be made available to farmers.

Computers can be used to transfer information from researchers to farmers. One type of computer program which has been used successfully for transferring grain storage information is the expert system (Wilkin and Mumford 1994; Longstaff 1994; Flinn and Hagstrum 1990; Ndiaye and Fleurat-Lessard 1994). These expert systems have emphasized the control of stored-product insects because the presence of stored-product insects is a serious problem for grain storage managers in countries such as Australia and the United States. In these countries, grain is often harvested hot and dry, so there is little chance for fungal deterioration. In Canada, however, grain is often harvested tough which means that fungal deterioration is much more prevalent. Stored-product insects are not a major problem, but must not be present in the grain at the time of sale. Consequently, the management of stored grain in Canada differs from other countries, making the development of an expert system for Canadian grain storage managers a necessity.

An expert system is defined as "... an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution" (Feigenbaum 1982). There are many problems that, despite an incomplete understanding, need to be solved. When a person works in the same area, or on the same problem for several years, that person becomes an expert. Due to valuable experience, the human expert is capable of repeatedly finding the "right" answer, even when there is no proven method for solving the problem.

Like a human expert, an expert system should find the "right" answer in the absence of a proven algorithmic solution. This can be accomplished by emulating the decision-making ability of the human expert (Holt 1989). In other words, the computer program should use the same "best guesses" and "rules-of-thumb" as the human expert.

The objective of this research was to develop an expert system program, the Grain Storage Information System (GSIS), for western Canadian farmers. The GSIS encapsulates expertise from researchers working in the area of grain storage management at the Cereal Research Centre of Agriculture and Agri-Food Canada in Winnipeg and the Department of Biosystems Engineering, University of Manitoba. This paper discusses the development, capabilities, and testing of the current prototype.

DEVELOPMENT OF THE GSIS

Sources of knowledge for the GSIS

There were several sources of knowledge employed in the development of the GSIS. Drs. D.S. Jayas and W.E. Muir, Professors, Biosystems Engineering, University of Manitoba and Dr. N.D.G. White, Research Scientist, Cereal Research Centre of Agriculture and Agri-Food Canada were the main sources of expert knowledge or expertise for this program. The large base of scientific literature on grain storage and grain storage management was also used as a resource. In addition, several computer simulation models have previously been developed which model processes within grain bulks. Because much expertise has gone into the development of these models, they were an excellent addition to the GSIS. A final source of knowledge was the farm background of the first author. Although difficult to quantify, a practical understanding of grain storage techniques did contribute to the development of the GSIS.

Knowledge acquisition for the GSIS

Knowledge acquisition is defined as "the transfer and transformation of problem-solving expertise from some knowledge source to a program" (Buchanan and Shortliffe 1984). For knowledge acquisition to work effectively, the person gathering the knowledge (e.g. the knowledge engineer) must be familiar with the terminology used in the problem domain. Often, the knowledge engineer (KE) must spend some time learning about the problem domain. This project was no exception. Despite having a practical understanding of grain storage management as the result of his farm background, the KE (D.D. Mann) did not have a scientific understanding equivalent to that of the domain experts (Drs. Jayas, Muir, and White). The first stage of knowledge acquisition, therefore, consisted of the KE reading and reviewing the scientific literature available on grain storage and grain storage management.

While reviewing the literature, the KE found preliminary answers to many of his unanswered questions about grain storage. These answers were distributed to the experts and were discussed in a group session. This procedure worked quite well and was used a number of times. This procedure put less demand on the domain experts' time than the "traditional" interview process that is described in most textbooks on the development of expert systems and, therefore, may be considered by future KEs as an alternative to the "traditional" interview process.

Due to the success of the group validation procedure, the KE gathered much of the knowledge for the GSIS by reading previously published scientific papers. When questions arose, however, it was not always possible to meet as a group so the KE usually met with one or more of the experts on an individual basis. This eliminated the problems involved with scheduling group meetings and can be used by future KEs when dealing with multiple domain experts.

The KE must be aware that experts are not alike. Each expert has different areas and levels of expertise which can result in questions being answered differently by each of the experts. The KE must decide how to combine the different perspectives or whether one should be chosen over the others.

When gathering information from the literature, the KE must also remember that biological variability can exist when research is conducted in various regions around the world. In some cases, more than one value was found for the same characteristic. In these cases, the choice of one number over another was an arbitrary decision.

In addition to gathering knowledge from the literature, the KE also attended a university course on stored-product entomology taught by one of the domain experts (Dr. White). This worked well because the information was presented in an organized and structured format.

THE GRAIN STORAGE INFORMATION SYSTEM

Program philosophy

At the conceptual design stage, our philosophy was that the program would collect all of the necessary information from the user and then tell the user what to do to protect the stored grain. During the development of the program, however, our philosophy for the program changed. Rather than simply telling the user what to do to protect the grain, the program should teach the user why certain actions are more effective than others. We believe this revised philosophy has improved the program for two reasons. First, farmers have gained valuable experience storing grain in previous years. They may have made observations which they are unable to measure or explain. If the program is able to provide them with an explanation, their understanding of the dynamics of a stored grain ecosystem will increase, thus helping them become better grain storage managers. The second reason for this revised philosophy is that some farmers do not have confidence in computers. For the program to earn their confidence, they need to use it extensively. This will not happen by dictating instructions without any explanation. The program must be designed in such a way that the user feels it is user friendly.

Purpose of the GSIS

The management of stored grain is a challenging task. To remain in business, farmers cannot afford to make grain management decisions that result in reduced grain quality. Farmers need assistance to deal with the rapid changes in the agricultural industry. Researchers have recognized this need. The main purpose of the GSIS, therefore, is to teach users the current knowledge of grain storage to enable them to become better grain storage managers.

How does the GSIS work?

The underlying chain of reasoning for the GSIS remains the same from consultation to consultation (Fig. 1) and is described below.

1. The initial grain conditions are input by the user.
2. The grain storage life is calculated by mathematical

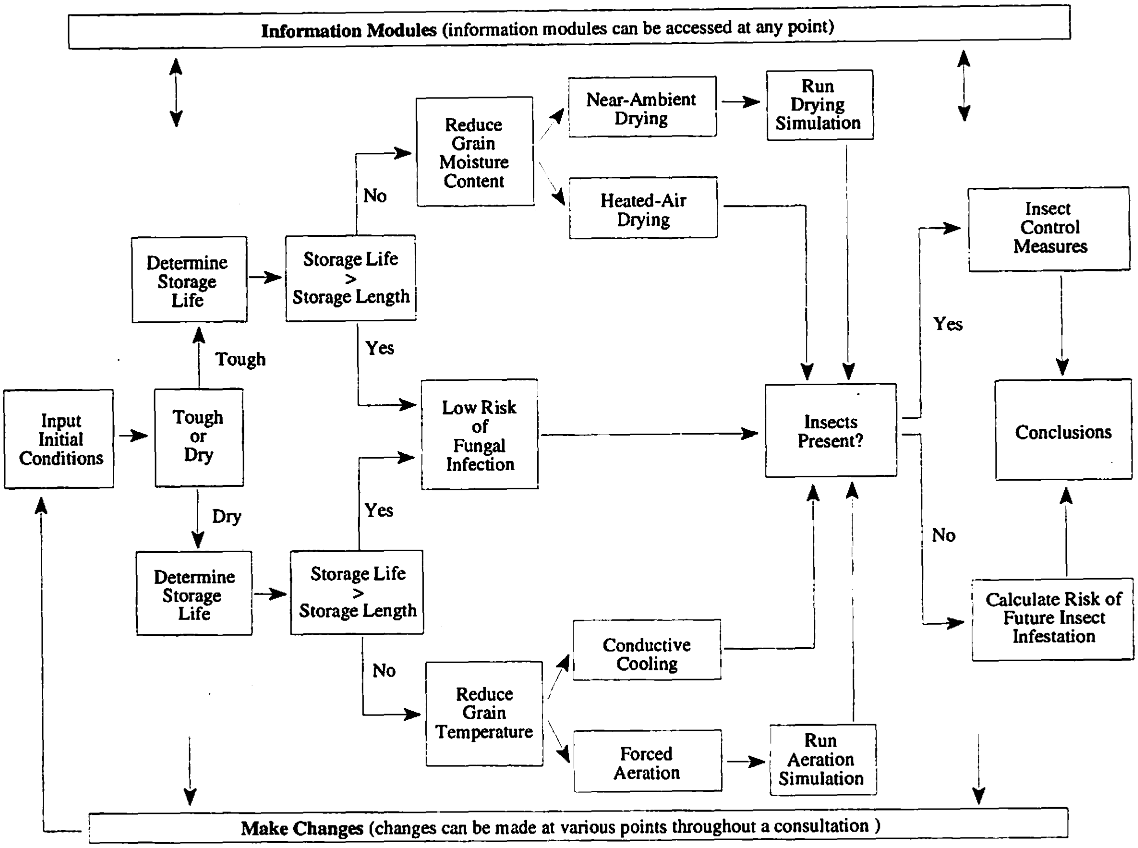

Fig. 1. The chain of reasoning used by the GSIS in a given consultation.

equations developed by several researchers (for wheat: Fraser 1979; for canola: Muir and Sinha 1986; for barley: Kreyger 1972). The safe storage life is described as the period of time before germination drops by 5% or visible mould appears. The storage life is based on the grain temperature and moisture content.

3. The storage life is compared with the intended storage period.
4. If the storage life is less than the intended storage period, either the grain moisture content or grain temperature should be reduced. If the grain condition is not dry, appropriate drying actions are explored using a near-ambient drying simulation program. High temperature drying is also discussed as an option if near-ambient drying equipment is not available. If the grain condition is dry, appropriate cooling actions are explored using an aeration simulation program. Both of these simulation models are accessed by the GSIS in the GRAIN89 program (Huminicki et al. 1986).
5. If the storage life is greater than the intended storage period, the grain should be safe from fungal deterioration, however, insects must still be considered. If insects are currently present, possible control measures will be indicated. An insect identification module is included. Even if insects are not currently present, the risk of a future insect infestation is presented.
6. Changes can be made to the initial grain conditions so that the user can consider possible effects of several storage options.
7. Information screens are available throughout the consultation.

Capabilities of the GSIS

Initial grain conditions The first step in a consultation is the collection of information about the grain to be stored and the storage structure in which it will be stored. The GSIS asks for information on the following items: preferred measurement units for temperature (e.g. °C or °F), distance, and volume; grain type; moisture content; grain temperature; grain damage (e.g. frost, mechanical, sprouting); foreign material (e.g. small particles, large particles); granary sanitation; presence of insects; previous infestations; harvest date; intended selling date; bin dimensions; aeration equipment; heated-air drying equipment; and availability of a pneumatic grain conveyor.

A beneficial characteristic of the GSIS is that the user is able to answer "unknown" to most of the initial-grain-condition questions. If the user answers "unknown", the GSIS will assume a value for the parameter and offer a short explanation of why the particular assumption was made. When all the questions have been answered, the GSIS displays a summary screen to remind the user of the selections which were made. At this point, the user can change one or more answers. The user can also read a brief explanation of how each parameter affects the storage of the grain.

Calculation of storage life The storage life of grain is the predicted length of time for which the grain will remain in good condition. Researchers have used different criteria for deciding when the end of the safe storage period occurs. Fraser (1979) assumed that the safe storage life would be the number of days before germination drops by 5% or visible mould appears on the grain. Kreyger (1972) determined the safe storage life as the time to the appearance of visible mould in barley.

The storage life equations used in the GSIS are:

wheat: (Fraser 1979)

$W = 12$ to 19%, $T = 5$ to $25°C$

$$\theta = \exp(6.234 - 0.212\,W - 0.053\,T) \tag{1}$$

$W = 19$ to 24%, $T = 5$ to $25°C$

$$\theta = \exp(4.129 - 0.0997\,W - 0.057\,T) \tag{2}$$

canola: (Muir and Sinha 1986)

$W < 11\%$, $T = 5$ to $25°C$

$$\theta = \exp(6.224 - 0.302\,W - 0.069\,T) \tag{3}$$

$W \geq 11\%$, $T = 5$ to $25°C$

$$\theta = \exp(5.278 - 0.206\,W - 0.063\,T) \tag{4}$$

barley: (Kreyger 1972)

$W = 12$ to 16%, $T = 5$ to $25^{o}C$

$$t_m = 2.79 + 0.0417 \exp\{5.124 + (39.6 - 0.8107\,T)[1/(W - 12) - 0.0315 \exp 0.0579\,T]\} \tag{5}$$

where:

W = moisture content (% wet mass basis),

T = grain temperature (^{o}C),

θ = storage life before germination drops by 5% or visible mould occurs (d), and

t_m = time for mould to appear (d).

These equations were developed for a limited range of temperatures. In the absence of other equations, however, the GSIS allows the user to input temperatures outside of this range. Extrapolation outside the given range will introduce some error to the approximation.

The storage life of grain depends mainly on the grain temperature and grain moisture content. This implies that the storage life of a bulk of grain will be altered if either the temperature or moisture content is changed. Theoretically, it should be possible to lengthen the storage life of grain by drying, cooling, or both.

The predicted storage life is a very important component of the GSIS. The need to dry (or cool) the grain occurs when the predicted storage life is shorter than the intended storage period. The storage life equations assume constant temperatures and moisture contents throughout the storage period. If either parameter changes, the prediction may no longer be accurate. The storage life equations provide a good starting point. The storage life equations, however, do not consider damage caused by insects.

Drying considerations Grain can be dried using heated-air or near-ambient air. The choice of one type of drying over the other depends on several factors. The first consideration must be given to the equipment which the farmer owns. If there is no limitation due to lack of equipment, consideration must be given to the time constraints on drying. A well-designed heated-air drying system provides a rate of drying that can accommodate the rate of harvesting grain, allowing the grain to be dried in a short period of time. Near-ambient drying, however, requires a longer period of time. It is important that the entire grain bulk be dried before any significant amount of grain spoils. If the grain will not be dried before spoilage starts, then it may be advisable to use heated-air drying.

When neither equipment nor time causes any constraints, the selection should be based on cost and convenience. Near-ambient drying is usually more convenient because it requires little labour. Near-ambient drying can be less expensive if only the energy cost is considered. When the overdrying penalty is also included, however, it is difficult to predict which type of drying will be less expensive.

If the GSIS determines that the grain should be dried and if the bin is equipped with a near-ambient drying system, the user will have an opportunity to run the near-ambient drying simulation model. The GSIS selects an appropriate airflow based on the recommended minimum airflow requirements for Manitoba using a fully-perforated floor and a level grain surface (Friesen and Huminicki 1987). The user can view these recommended airflow charts and change the value if desired. The drying simulation program which was previously validated by Sanderson et al. (1989) predicts drying based on 10 selected years of historic weather data for Winnipeg. For each simulation year, the GSIS determines whether the grain has dried before November 15. If the simulation model predicts the grain will be dried by November 15 in an average year, the GSIS will recommend near-ambient drying. Otherwise, the GSIS will recommend heated-air drying.

The drying simulation model as included in the GSIS is valid only for grain stored in circular steel granaries equipped with a fully-perforated floor and located near Winnipeg. If the bin is either filled to the peak or if a partially-perforated floor is used, the results of the drying simulation will not be accurate. The program can easily be used for other western Canadian locations with the addition of their weather files and minor modifications.

Cooling considerations If the grain is dry and the storage life is still less than the intended storage period, the grain should be cooled. Some cooling of the grain near the wall and top surface occurs when the outside air turns cold. Unfortunately, this conductive cooling may not be sufficient to cool an entire grain bulk because grain bulks have low thermal diffusivities (Muir et al. 1989).

Yaciuk et al. (1975) ran a series of computer simulations to determine the length of time required to cool a bin of warm grain in Winnipeg below $20^{o}C$ without aeration. Their results indicated that grain stored in large bins (>4 m diameter) should be cooled by some external means. The data from Yaciuk et al. (1975) were used in the GSIS to predict an approximate cooling time if aeration was not used.

Farmers often cool their grain by aeration because conductive cooling is slow when grain is stored in large bins. Aeration refers to the process of forcing ambient air [1-2 $L \bullet s^{-1} \bullet m^{-3}$] through the bulk of grain by a fan. As long as this operation occurs when the ambient air temperature is lower than the average grain temperature, cooling will take place.

When it is determined that the grain should be cooled and the storage bin is equipped with aeration equipment, the GSIS user can run an aeration simulation model. The simulation runs with an airflow of 1.5 $L \cdot s^{-1} \cdot m^{-3}$. The initial grain temperature is assumed constant throughout the bin. The temperatures within the bin are simulated from the specified harvest date until November 15 for three years of historic weather data (1965, 1968, 1969). When the simulations stop, the temperature 1 m below the surface at the centre of the bin is shown to the user for each of the three separate simulation years. This location was selected because it is the most likely location of the maximum temperature in fall and winter (Muir et al. 1989).

Insect control considerations Even when grain is safe from fungal deterioration, stored-product insects can still invade the grain. If insects are present, the GSIS will suggest some possible actions to kill the insects because it is illegal in Canada to knowingly sell grain infested with live grain-feeding insects. From the list of all possible actions, the most probable ones are identified. The GSIS provides information on the various actions, explaining how they work, but the decision of which action to select is left to the user.

The most appropriate control method depends on the type of insects that are present. The GSIS has an insect identification module which helps the user identify the insect species. The insect identification screens contain a picture and information about the species (Fig. 2). The GSIS also emphasizes the difference between grain and fungus feeding species.

Risk of future insect infestations Even when insects are not currently present in the grain sample, there is no guarantee that the grain will remain free of insects. The likelihood of an insect infestation depends on many factors. These factors interact with one another, making it difficult to determine the overall risk of a future infestation. The risk of a future insect infestation is calculated by:

$$PI = \{ F_{mc} F_T F_{MD} F_{SD} F_{LP} F_{SP} F_{GS} F_P F_{HD} F_B \} \times 100 \tag{6}$$

where:

PI = potential infestation factor,
F_{mc} = moisture content factor,
F_T = grain temperature factor,
F_{MD} = mechanical damage factor,
F_{SD} = sprouting damage factor,
F_{LP} = large dockage particles factor,
F_{SP} = small dockage particles factor,
F_{GS} = granary sanitation factor,
F_P = previous insect infestation factor,
F_{HD} = harvest date factor, and
F_B = bin size factor.

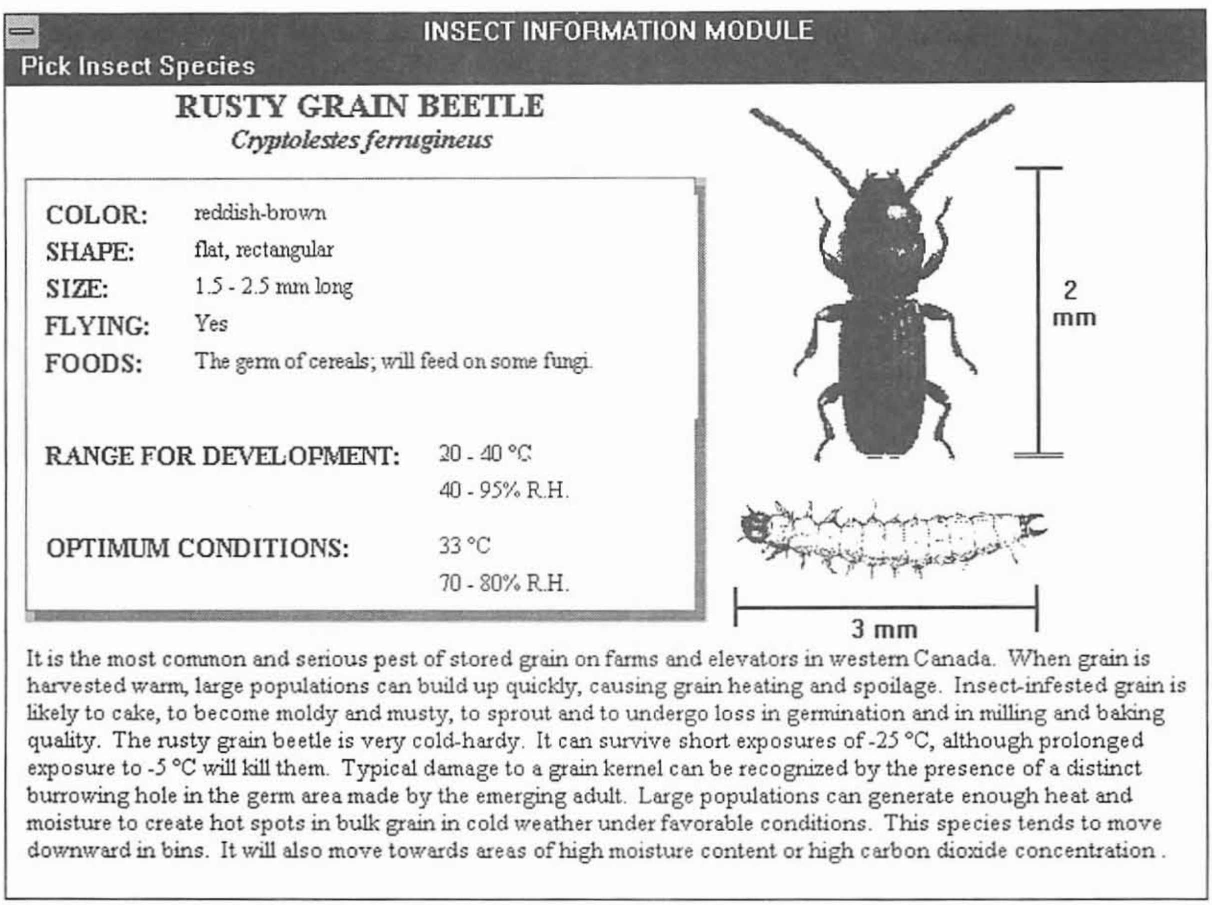

Fig. 2. An example of an insect identification screen from the GSIS.

Each factor is given a value less than or equal to one (Table I). The value assigned to each factor depends on the initial grain conditions specified by the user. In an ideal case, each factor would have a value of one. This would yield a *PI* of 100 corresponding to a negligible risk of a future insect infestation. When some of the factors are less than one, the *PI* decreases below 100. The lower the number, the greater the risk of a future insect infestation. A *PI* less than 10 indicates a high risk. A *PI* between 10 and 25 indicates an intermediate risk and values greater than 25 indicate a low risk of a future insect infestation. The form of Eq. 6 was chosen because when two factors interact with each other the effect is multiplicative not additive.

Information screens The GSIS is designed to be an information system. Throughout a consultation, the user is presented with an abundance of grain storage information. Many of the display screens contain pieces of information that do not contribute to the functioning of the GSIS, but do provide the user with additional help (Fig. 3). This is an excellent way to transfer research findings to the farmer.

In addition to the information contained in the main program, the GSIS also contains four separate **Information Modules**. These modules give the user information on insect identification, grain sampling, granary sanitation, and other grain storage topics. Only the insect identification module is referred to during a consultation. A user does not have to read these modules, but they have been included for those who want to learn more about grain storage management.

Table I: Insect infestation factors for various grain conditions

Parameter	Parameter value	Numerical factor
F_{mc}	very dry	1.0
	dry	0.9
	tough	0.7
	damp	0.5
	wet	0.6
F_T	cold	1.0
	cool	1.0
	warm	0.7
	hot	0.5
F_{MD}	yes	0.7
	no	1.0
F_{SD}	yes	0.9
	no	1.0
F_{LP}	significant numbers	1.0
	none	1.0
F_{SP}	significant numbers	0.8
	none	1.0
F_{GS}	yes	1.0
	no	0.6
F_P	yes	0.9
	no	1.0
F_{HD}	early	0.9
	normal	0.9
	late	1.0
F_B	small	0.9
	intermediate	0.7
	large	0.5

Conclusions of the GSIS Once the end of the consultation is reached, the GSIS briefly summarizes the most important information that was given throughout the consultation. The GSIS does not tell the user what to do. Rather, the situation is explained and some possible courses of action are discussed. The user must then decide what will be done.

Comparisons Throughout the consultation, the user is able to make changes to the initial grain conditions and available storage equipment. This allows the user to explore different options and compare the effects of different actions. Observing the effects of these changes is a good way to learn about grain storage management.

TESTING OF THE GSIS

Types of testing

The testing of an expert system consists of two parts: validation and verification. Validation refers to the process of determining whether a chain of correct inferences leads to the correct conclusion. Verification refers to the process of determining whether the information contained within the expert system is correct. In other words, validation is concerned with building the right product, whereas verification is concerned with building the product right (Giarratano and Riley 1994).

Validation may be viewed as taking an overall view of the program. Is the program being built according to the conceptual design? Does the program meet the needs of the intended users? Questions such as these must be answered to validate the program.

Verification requires a more detailed inspection of the program. Is the information within the program correct? Are the recommendations correct? Verification is necessary because it ensures that the information provided to the user by the program is the same as would be given by a human expert.

Testing criteria

The GSIS was designed to be an educational tool for farmers in Western Canada. A prime objective of the testing procedure was to determine the adequacy of the program as an educational tool. To be effective, the GSIS should facilitate learning and be easy to use. Information should be presented in a logical manner so that it is understandable and considered reasonable by farmers. Presenting the information as it would be in a scientific paper may not be suitable. A second important function of testing was to verify the accuracy of the information contained in the program.

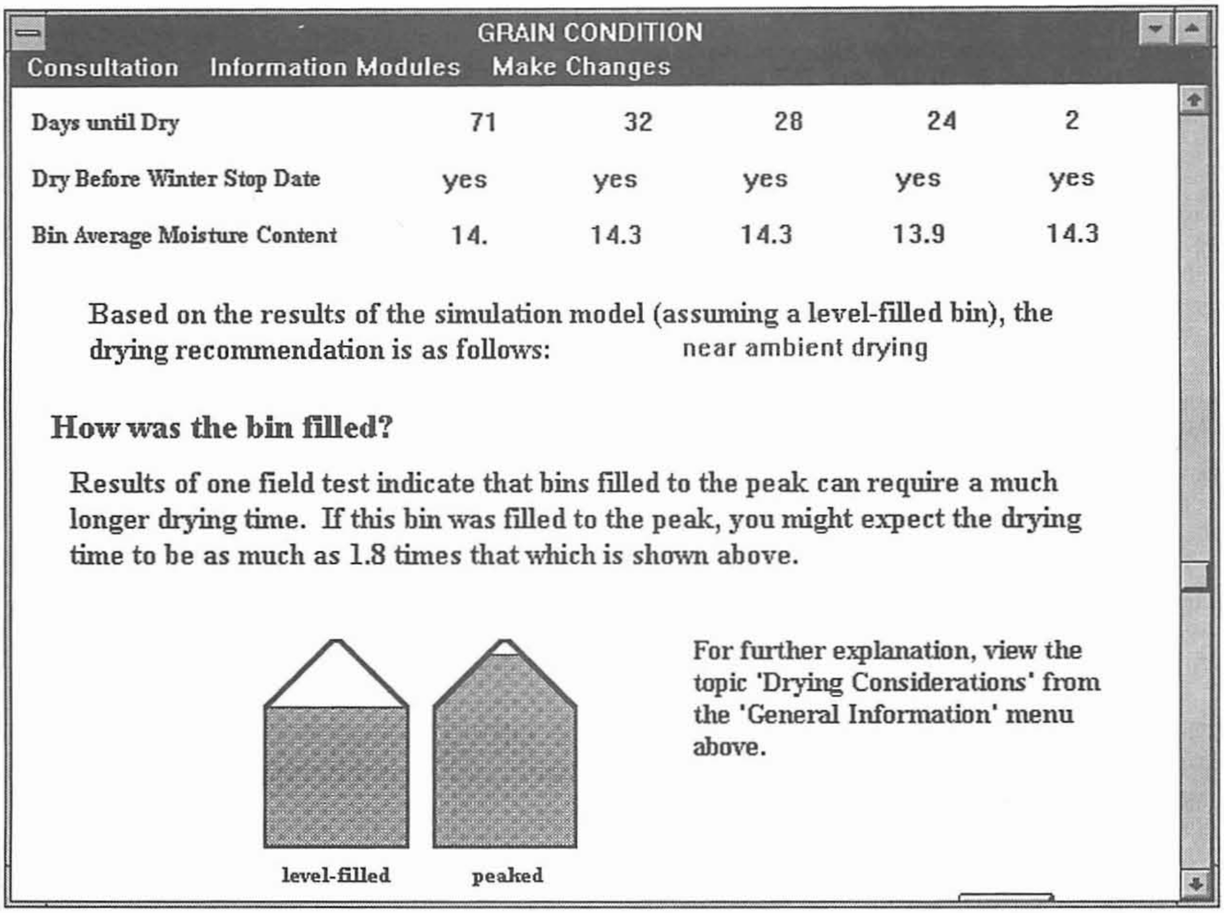

Fig. 3. A typical display screen from the GSIS depicting the extra information that is helpful to the user, though not vital to the functioning of the program.

Validation

To validate the GSIS, the adequacy of the program as an educational tool was based on the user-friendliness of the program and its ability to convey information. A class of engineering students enrolled in a grain storage course were asked to use the GSIS to answer a sample problem after which they were asked to complete a questionnaire on the use of the GSIS. Only 1 out of 18 survey respondents described the GSIS as being "very difficult" to use.

On a further question, 15 out of 17 survey respondents indicated they had learned something new about grain storage during their consultation. Twelve out of the 17 also stated that the GSIS has potential as a teaching tool for university students and farmers.

For the sample problem, the students were required to assume a grain temperature to complete the consultation. Because the temperatures selected by the students covered a wide range, the recommended storage management procedures also covered a wide range. This sensitivity to grain temperature is the result of the storage life equations and not the GSIS. In this way, the GSIS can be used to illustrate the importance of carefully determining grain temperatures.

Verification

To verify the GSIS, it was necessary to ensure that the information contained in the program was accurate. The verification has been limited and unstructured. The three domain experts involved in the project have used the current version and are satisfied with the information contained within the GSIS. These experts were also involved throughout the development, so they are familiar with the program.

Much of the information used in the GSIS was gathered from previously published scientific papers. To ensure that the information within the program describes actual grain storage situations, structured field testing of the GSIS is required, but is cost prohibitive.

SUMMARY AND CONCLUSIONS

The GSIS is designed to be a source of grain storage information. Rather than simply informing the user how to protect grain from spoilage, the program teaches the user why certain actions are more effective than others. If the GSIS functions well as a teaching tool, it will earn the confidence of the users.

Based on responses to a survey completed by 17 GSIS users who were engineering students, the program does function well as a teaching tool. The survey indicated that the program is easy to use and provides useful information. The domain experts are satisfied with the accuracy of the information contained in the GSIS, although field testing is required.

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REFERENCES

Buchanan, B.G. and E.H. Shortliffe. 1984. *Rule-Based Expert Systems. The MYCIN Experiments of the Stanford Heuristic Programming Project.* Don Mills, ON: Addison-Wesley Publishing Company.

Feigenbaum, E.A. 1982. *Knowledge Engineering in the 1980's.* Department of Computer Science, Stanford University, Stanford, CA.

Flinn, P.W. and D.W. Hagstrum. 1990. Stored Grain Advisor: A knowledge-based system for management of insect pests of stored grain. *Artificial Intelligence Applications* 4:44-52.

Fraser, B.M. 1979. Solar grain drying in Canada: a simulation study. Unpublished M.Sc. thesis. Department of Agricultural Engineering, University of Manitoba, Winnipeg, MB.

Friesen, O.H. and D.N. Huminicki. 1987. Grain aeration and unheated air drying. Manitoba Agriculture Publication No. Agdex 732-1. Manitoba Agriculture, Winnipeg, MB.

Giarratano, J. and G. Riley. 1994. *Expert Systems. Principles and Programs.* Boston, MA: PWS Publishing Company.

Holt, D.A. 1989. The growing potential of expert systems in agriculture. In *Knowledge Engineering in Agriculture*, eds. J.R. Barrett and D.D. Jones, 1-11. St. Joseph, MI: ASAE.

Huminicki, D.N., C.I. Kitson, O.H. Friesen and W.E. Muir. 1986. Computerized design of ventilation systems for stored grain. ASAE Paper NCR-86-604. St. Joseph, MI: ASAE.

Kreyger, J. 1972. Drying and storing grains, seeds and pulses in temperate climates. Publication 205. Institute for Storage and Processing Agricultural Produce, Wageningen, The Netherlands.

Longstaff, B.C. 1994. Decision support systems for pest management in grain stores. In *Proceedings of the 6th International Working Conference of Stored-Product Protection, Volume 2*, eds. E. Highley, E.J. Wright, H.J. Banks and B.R. Champ, 940-945. Canberra, Australia.

Muir, W.E., D.S. Jayas, M.G. Britton, R.N. Sinha and N.D.G. White. 1989. Interdisciplinary Grain Storage Research at the University of Manitoba and Agriculture Canada. *Powder Handling Proceedings* 3(1): 281-295.

Muir, W.E. and R.N. Sinha. 1986. Theoretical rates of flow of air at near-ambient conditions required to dry rapeseed. *Canadian Agricultural Engineering* 28:45-49.

Ndiaye, A. and F. Fleurat-Lessard. 1994. Research on an expert system for appropriate management of the quality of stored grain for food and feed processing. *'94 International Symposium & Exhibition on New Approaches in the Production of Food Stuffs and Intermediate Products from Cereal Grains and Oil Seeds.* Beijing, China.

Sanderson, D.B., W.E. Muir, R.N. Sinha, D. Tuma and C.I Kitson. 1989. Evaluation of a model of drying and deterioration of stored wheat at near-ambient conditions. *Journal of Agricultural Engineering Research* 42:219-233.

Wilkin, D.R. and J.D. Mumford. 1994. Decision support systems for integrated management of stored commodities. In *Proceedings of the 6th International Working Conference of Stored-Product Protection, Volume 2*, eds. E. Highley, E.J. Wright, H.J. Banks, and B.R. Champ, 879-883. Canberra, Australia.

Yaciuk, G., W.E. Muir and R.N. Sinha. 1975. A simulation model of temperatures in stored grain. *Journal of Agricultural Engineering Research* 20:245-258.