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Object-oriented Methodology for Analyzing and Allocating Resources for Field Operations

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ABSTRACT

An object-oriented methodology for machinery management was developed by combining knowledge system techniques with conventional problem solving techniques. The methodology developed here, if incorporated into a machinery management tool, provides the farmer with the ability to evaluate the physical feasibility of an overall farm plan (regarding field operations) being considered for the future and to identify possible solutions when the farmer is unable to complete this overall farm plan using current resources. The developed methodology also provides the farmer with the ability to assess the progress being made toward completion of the defined calendar as a result of changes in the farm's physical resources (time, labor, and machinery) at any point during the season and to identify possible corrective actions if the progress is behind schedule.
KEYWORDS. Machinery management.

INTRODUCTION

Farm machinery planning and management tools using proven modeling techniques exist (e.g., Rotz et al., 1983; Freesmeyer and Hunt, 1985; Ozkan and Edwards, 1986; Chen, 1987; Siemens et al., 1988; Kline et al., 1988). The amount of detailed data required to use them and the analytical complexities and underlying assumptions of the tools themselves have limited their use outside of research environments. These tools often require modeling experts to implement them and to accurately interpret and explain the results they produce. The scarcity of, and the expense associated with, these experts have restricted the use of these tools by farm-level decision makers. Knowledge system techniques can be combined with conventional problem solving techniques to provide the farmer with a usable tool that provides useful information allowing the farmer to make more informed decisions when faced with difficult problems.

The farm manager or producer does not need a machinery management tool capable of completely duplicating his/her decision making process: "simplicity is more important than total automation of the decision" (O'Neal, 1989). They are not interested in spending a great deal of time learning to use a complex tool, especially if the tool is based on detailed data which they cannot easily supply or will have to estimate. Additionally, a machinery management tool is not necessary for making everyday decisions involving well-established, successful practices. A machinery management tool capable of aiding the farmer's decision making process when confronted with difficult whole-farm problems, both long-term problems and within-season problems, while requiring a limited amount of data was needed.

BACKGROUND

In agriculture, the primary facilitator of knowledge transfer has been the Agricultural Extension Service through the use of mass media formats ranging from radio and television to extension bulletins, specialized magazines, and journals. There are two primary problems with this approach (Lal et al., 1987). First, it assumes that the farmer or producer has both the time and the knowledge to be able to sort through the vast amount of information in order to gather the specific information which is most applicable to the problem at hand. This is not always the case. Secondly, mass media formats are brief one-way communication platforms. Space limitations often prevent authors from presenting the full extent of their knowledge on a subject. This can lead to unanswered questions for which the user has no convenient avenue to seek clarifications or additional information. Knowledge systems enhance and ease the transfer of knowledge from the experts to the users who will benefit most from the knowledge.

To ensure the success of this knowledge transfer, a domain expert was chosen with years of experience working with producers to solve long-term and within-season machinery management problems. The methodology described in this study is based on the expert's knowledge and experience in the domain area and in interacting with producers. This approach of using a domain expert was also useful for recognizing the limitations and underlying assumptions of the methodology, as well as the development of an algorithm that farm managers and producers will be comfortable using.

Simulation has frequently been used to analyze single machinery components (e.g., Turner et al., 1985) and used to model whole-farm systems (e.g., Kjelgaard et al., 1985; Chen and McClendon, 1985; Edwards and Boehlje, 1980). Simulation has also been used effectively in hybrid systems. For example, a networked simulation model was combined with mathematical optimization (Tsai et al., 1987). Bender (1984) combined simulation and risk

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analysis with a multi-stage linear program. Kline (1987) and Kline et al. (1988) describe a system which also combines simulation with linear programming. This system, however, uses a knowledge-based expert system to help automate the model formulation and to interpret the results of the system. Knowledge-based techniques offer an ideal environment to enhance simulation and mathematical models.

In the machinery management area, expert system applications range from hybrid systems that look at whole-farm questions (Kline et al., 1988) to specific machinery selection (Freeman and Ayers, 1989). Kotzabassis et al. (1989) uses an object-oriented data structure for an implement-tractor matching expert system. This system is part of a larger machinery management software package which combines tractor and implement databases, an on-concrete tractor analysis model, and an in-soil tractor performance prediction model with information describing the farm, crop scheduling, and the weather. This package allows the farmer to utilize detailed tractor performance models which previously required an expert's knowledge.

Using an object-oriented approach for knowledge-based simulation allows a large model to be decomposed into smaller pieces. This allows for a more natural representation of the knowledge involved in the system, much in the same manner that the expert perceives the system: as a group of inter-related pieces. Lal et al. (1990 b) uses this type of approach in a hybrid system which analyzes a field operations simulator. The object-oriented structure used for this system is detailed in Lal et al. (1990 a). This system which combines a simulation model of field operations with a knowledge-base interpretation of the results is closely related to the work done in this study. However, Lal et al. (1990 a, 1990 b) does not use object-oriented programming concepts for the simulation (only the data structure). Additionally, the system requires a great deal of information from the farmer and is geared toward a different target audience "... a planning and/or management tool for researchers, educators, and perhaps farmers..." (Lal et al., 1990 b).

The methodology described in this study was implemented using an object-oriented algorithm written in LISP. Although object-oriented data structures have been described in the literature, this implementation is the first attempt at using a full object-oriented programming paradigm for machinery management decision making. The object-oriented paradigm was chosen for its ability to represent the farm in a more natural manner. The particular LISP dialect chosen allowed for the implementation of this methodology in a standard DOS environment.

Objectives

The primary goal of this project was to develop a machinery management methodology to aid the farmer in evaluating the physical feasibility of an overall farm plan being considered for the future, as well as, the consequences of changes in the farm's physical resources (time, labor, and machinery) resulting from within-season decisions or changes. To accomplish this goal the following objectives were set forth:

- To develop a calendar of operations representing the farm. This calendar would include information on the field operations to be performed as well as the time and labor constraints involved in production.
- To develop an object-oriented algorithm to analyze the physical feasibility of the defined calendar and rules to recommend possible solutions when the calendar cannot be completed within the defined constraints.
- To provide the farmer with the ability to evaluate the physical feasibility of an overall farm plan being considered for the future.
- To provide the farmer with the ability to assess the progress being made toward completion of the defined calendar as a result of changes in the farm's physical resources (time, labor, and machinery) at any point during the season and recommend possible corrective actions if the progress is behind schedule at that point.

Methodology

Knowledge Acquisition

The knowledge acquisition process consisted of five main phases: a) background search of current methods; b) problem definition and identification of a domain expert; c) identification of the methodology to be used; d) refinement of problem definition and identification of the tool's limits; and e) tool development. While these phases also identify the general order of progress during this study, they existed simultaneously during the majority of the project.

It was important to develop a methodology, which if incorporated into a machinery management software package, the producer would be comfortable using. It was decided that the best way to develop this type of methodology was to approach the problem in the same manner as these types of machinery management problems are currently being solved. This was done by working with a domain expert, Henry O'Neal (Texas Agricultural Extension Service, retired), who was chosen for his years of experience in helping producers solve these long-term and within-season machinery management problems.

Knowledge acquisition is defined by Jones (1989) as being the process of extracting, structuring, and organizing knowledge from an expert source in a manner such that it can then be used in a program. This is a concise definition that hides the complexity of application. Knowledge acquisition is a difficult task at best. With this in mind, the following paragraphs will briefly discuss this study's knowledge, acquisition process, and the major contributions made by Mr. O'Neal.

The knowledge acquisition process with Mr. O'Neal began with unstructured interviews. This allowed Mr. O'Neal to become familiar with the goals of the project and to decide if he was interested in serving as the domain expert for the study. (In addition to having established expertise within the domain, the most important characteristics of a good domain expert are enthusiasm toward the project and a willingness to spend the time and effort needed to see the project to a successful completion. Mr. O'Neal met these criteria.) These initial unstructured interviews were concerned with the limitations of the tool, the underlying assumptions which must be made, and the best approach to meeting the requirements of the tool.

Subsequent interviews were more structured. It was during these sessions that the knowledge that was incorporated into the methodology was obtained. A number of different knowledge acquisition approaches were used including prepared questions, written questionnaires, and a mock consultation. Additionally, the sessions were recorded to facilitate interaction with Mr. O'Neal since concentration could be focused on the expert and not on trying to write down everything he said. This resulted in the ability to closely follow Mr. O'Neal's responses, to immediately ask more specific questions about areas that were unclear, and to keep the interview more closely focused on the goals established for the session.

Mr. O'Neal aided in determining the general guidelines and assumptions to be used in the development of the algorithm associated with this methodology. From the interviews with Mr. O'Neal, it was decided that the two most important aspects of the algorithm should be: a) a methodology based on a calendar of operations representing the farm; and b) simplicity (which he considered to be more important than total automation of the decision). Mr. O'Neal's experience in working with farmers led to the following major assumptions of the methodology: a) a successful farmer can be considered an expert on local conditions (e.g., general operation scheduling and the approximate number of good field days available at different times during an average year); and b) the unit of time used should be a day. (Farmers can more easily relate to and are more comfortable in establishing what they can usually do in a day.) Lastly, Mr. O'Neal helped establish the decision tree for making recommendations to the producer on how to correct an infeasible calendar if some of the field operations in the defined calendar could not be completed with the current physical constraints.

Algorithm Characteristics

The key to this methodology is the calendar of operations and the algorithm which checks the feasibility of the defined calendar. The database for the calendar consists of two parts. One is concerned with the field operations and the other consists of the labor and time constraints. A description of the input data that is needed from the farmer concerning each field operation is listed in Table 1 and that concerning the time and labor constraints for each one half month time period is listed in Table 2. (Note: The data supplied by the farmer is in English units because that is what they are more familiar with.) The algorithm used to check the physical feasibility of the calendar neither involves formal optimization procedures, nor does it try to schedule operations for the farmer. It does, however, ensure that all of the field operations can be completed by the defined ending dates without violating any of the resource constraints (time, labor, and machinery) defined by the farmer. The calendar simulation is used to determine if all of the work is completed during a normal operating year, with normal operating procedures. If the work cannot be completed under normal conditions, then changes in operating procedures are suggested.

The algorithm is portable from region to region because the farmer supplies the percentage of good working days in each half of a month. This percentage takes into account the number of working days per week, as well as the local

TABLE 1. Description of field operation data supplied by the farmer for each operation

Data	Description of Data
Operation Name	The name of the field operation.
Crop	The name of the crop involved with this operation.
Number of Acres	The total number of acres involved with this operation.
Starting Date	The beginning of the time window for this operation (i.e., the earliest date that work on this operation can be started in a normal year).
Ending Date	The end of the time window for this operation (i.e., the date that work on this operation must be completed by in a normal year to avoid timeliness losses).
Operating Rate	The normal operating rate in ac / day (i.e., the number of acres that are completed by a full day's work on this operation under normal operating conditions).
Tractors	The ordered list of tractors to be considered feasible resources for this operation (e.g., "JD4040, JD4340" would indicate that the John Deere model 4040 is the primary resource for this operation, but if it is being used elsewhere the John Deere model 4340 is an acceptable resource substitution which may be used for this operation).
Implements	The ordered list of implements to be considered feasible resources for this operation. (Similar to the explanation given for tractors above.)

TABLE 2. Description of time and labor data supplied by the farmer bimonthly

Data	Description of Data
Percentage of Good Working Days	This is the percentage of the days in this time window which the farmer expects to be able to do field work during a normal year. This percentage will account for the local weather and for the farmer's personal preferences (e.g., number of days the farmer is willing to work that week, vacation time, holidays, etc.).
Number of Main Shift Workers	This is the number of workers available daily, throughout this time window, to work on field operations during the main shift. If during certain times of the year a worker is busy doing other work and is unavailable for field work (e.g., devoting a worker full time to the management of a harvesting crew, thus making that worker unavailable to do other field work), even though being a full-time employee, that worker should not be included in this number.
Number of Other Shift Workers	This is the number of workers available daily, throughout this time window, to work on field operations during all other shifts. These workers are grouped together because in most situations the farmer will not have more than two shifts. It is assumed that these workers are capable of doing the same amount of work as main shift workers.

weather. To avoid the variance in the number of hours worked per day, the day is the basic unit of time throughout the algorithm. The farmer is also (by his estimated percentages) able to take risk into account. For example, if the farmer is very conservative towards risk taking, this is reflected in a smaller estimated percentage of good working days, thus incorporating a safety margin into the time constraints.

The question of timeliness is approached in a similar manner. When the farmer defines the field operations, the inputs include the starting date and the ending date. The experienced farmer has a good idea of the optimal time window for each operation. However, if the farmer is adverse to risk, this attitude would be reflected by a shorter time window. In this manner, the calendar simulation verifies that during a normal year the operation can be accomplished by the ending date supplied by the farmer.

Similarly, the operating rates are provided by the farmer in acres per day. Since the farmer has a good idea of how much work is usually done in a day, this approach is more accurate than asking for speed and width and trying to estimate field efficiency and the number of hours in a day that are actually spent doing field work (i.e., hours spent in the field, excluding maintenance and travel time to and from the field). Since farmers are more comfortable with this approach, they will have more confidence in their supplied data which will lead to more confidence in the methodology itself.

The system is able to help the farmer with within-season problems that arise during production. These within-season problems might include the loss of labor due to injury, the loss of equipment due to machinery breakdown, and/or the loss of time due to adverse weather conditions. For eample, if field operations are delayed due to weather or machinery breakdown, it helps the farmer assess the consequences of the delay. The algorithm proceeds from the day the field work is expected to be continued and checks to see if the work can still be accomplished by the desired ending dates.

The algorithm is also able to help with long-term problems. These long-term problems may include renting or purchasing additional land, the loss of a labor source, and/or a change in the machinery complement [tractor(s) and/or equipment]. For example, if additional acreage is being considered, the farmer needs to know the difference between an increase in acreage that can still be farmed with the farm's current machinery and labor resources and one that will require a change in these resources. The farmer can also use the system to determine the impact of increasing the acreage of particular crops in order to recognize which crop will allow the largest increase before additional machinery and/or labor is required.

Algorithm Development

The programming environment for this algorithm was selected based on the needs of the target audience. Since the intended users are farmers and farm managers, the hardware platform must not only support DOS, but DOS without any extended memory or any other enhancements. The programming language chosen for the algorithm is a dialect of LISP, muLISP-87 (Soft Warehouse, Inc., 1989).

One of the reasons for choosing LISP was to take advantage of object-oriented programming techniques. This paradigm was ideal for modeling the calendar of operations. It allowed the components of the whole-farm plan to be represented more closely to the manner in which the farmer or farm manager thinks of them. Object classes were set up for field operations and for time periods. Each field operation is defined to be a particular instance of the field operations class. The instance variables associated with the field operations class are listed in Table 3. Similarly, each bimonthly time period is defined as an instance of the time period class. The instance variables associated with the time period class are shown in Table 4. In addition to instance variables, each class has several methods associated with them. A description of the methods associated with the field operations and the time periods are given in Table 5 and Table 6, respectively. It would have been possible to make additional object classes for smaller components of the model (e.g., tractor, implement, worker, etc.) (Lal et al., 1990 a). However, these additional classes would not have changed the results of the algorithm and would have greatly added to the computational overhead of the program and the data required.

Additionally, dynamic memory allocation provides the ability to handle more variations of the problem. The program is not limited in the number of operations that can be simulated. Similarly, the length of the time window being considered does not have to be constant, but may vary as the particular situation which the farmer is interested in dictates. This allows the program to be much

TABLE 3. Description of instance variables associated with the class: field operations

Variable	Description of Variable
Operation Name Crop Number of Acres Starting Date Ending Date Operating Rate Tractors Implements	The values for these variables are part of the database defined by the farmer as part of the description of the whole-farm plan. A complete description of these variables is given in Table 1.
Time Used	This variable keeps track of the labor (in days) which has already been allocated to this operation.
Time Left	This variable keeps track of the labor (in days) which must still be allocated to this operation in order to complete it.
Unused Main	This variable keeps track of all unused labor from the main shift throughout this operation's time window. This number accounts for all labor from the main shift that could not be allocated to an operation (because of resource conflicts) in addition to any excess labor.
Unused Other	This variable keeps track of all unused labor from the other shift throughout this operation's time window. This number accounts for all labor from the other shift that could not be allocated to an operation (because of resource conflicts) in addition to any excess labor.

TABLE 4. Description of instance variables associated with the class: time period

Variable	Description of Variable
Starting Date	This variable defines the beginning of this time period.
Ending Date	This variable defines the end of this time period.
Percentage of Good Working Days Number of Main Shift Workers Number of Other Shift Workers	The values for these variables are part of the database defined by the farmer as part of the description of the whole-farm plan. A complete description of these variables is given in Table 2.
Unused Main	This variable keeps track of all the unused labor from the main shift throughout this operation's time window. This number accounts for all the labor from the main shift that could not be allocated to an operation because of resource conflicts in addition to any excess labor.
Unused Other	This variable keeps track of all the unused labor from the other shift throughout this operation's time window. This number accounts for all the labor from the other shift that could not be allocated to an operation because of resource conflicts in addition to any excess labor.

TABLE 5. Description of methods associated with the class: field operation

Method	Description of Method
Length	This method defines the length of this operation's time window in days.
Time Required	This method defines the total labor (in days) that is required to complete this operation using the normal operating rate as defined by the farmer.
Rate Increase*	This method defines the increase in the normal operating rate (in ac / day) that would be required to complete this operation using the amount of labor which the algorithm allocated to this operation.
Required Rate*	This method defines the new operating rate (in ac / day) that would be required to complete this operation with the labor allocated by the algorithm.
Percent Done*	This method defines the percentage of this operation which was completed at the end of the algorithm's time period.
Acres Done*	This method defines the number of acres of this operation that were completed at the end of the algorithm's time period.
Acres Left*	This method defines the number of acres of this operation left to be completed at the end of the algorithm's time period.

* These methods are only used by operations that the algorithm was unable to complete under the user-defined constraints.

TABLE 6. Description of methods associated with the class: time period

Method	Description of Method
Percentage of Main Shift Labor Which Was Idle	This method defines the percentage of available main shift labor that was not allocated to a field operation during this time period.
Percentage of Other Shift Labor Which Was Idle	This method defines the percentage of available other shift labor that was not allocated to a field operation during this time period.

more efficient whether it is: a) analyzing the feasibility of whole-farm plans for the next several years to investigate a long-term investment; or b) analyzing only the next two weeks to evaluate the consequences of a change in the weather. Similarly, the number of tractor and implement resources that may be considered for an operation is not limited to any fixed number.

ALGORITHM DETAILS

The calendar algorithm (see fig. 1) is not an optimization algorithm, it determines if all of the defined operations can be completed using current operating procedures defined by time, labor, and machinery constraints. Similarly, the algorithm does not schedule operations per se; therefore, the times when a particular operation is performed are not required in order to determine if the operations are being completed by their defined ending dates.

The first step of the algorithm is to build an operation instance for each operation in the data and to build a time

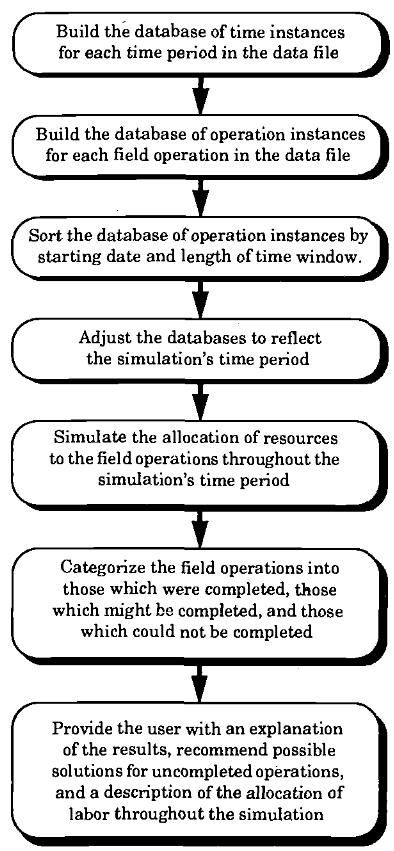

Figure 1–The basic structure of the simulation algorithm.

instance for each two-week period in the data. This database of operations is sorted by starting dates and time window length. Operations having earlier starting dates occur first. If the time windows for two operations start on the same date, the operation which has to be completed by the earliest date is ordered first. Once the operations have been sorted, a calendar of field operations describing the farm has been developed which naturally organizes and prioritizes the scheduling of the field operations.

Next, the program adjusts the database of time instances and the database of operation instances to include only those which occur within the time period the algorithm is considering. All time instances outside the range of the problem's time period are discarded. The time instance which includes the starting date of the problem is adjusted to start on the same day as the problem. For example, if the problem's starting date is 7 May, the time instance for the first half of May would be adjusted to start on the 7th rather than the 1st. Similarly, the time instance which includes the problem's ending date is adjusted to end on the same day as the time period the algorithm is considering. If the ending date of an operation is less than the starting date of the problem, then this operation is not considered as part of the problem. Likewise, if the starting date of the operation occurs after the ending date of the problem, then it does not need be included as part of the problem. However, if an operation's time window started before the starting date of the problem, but its ending date occurs on or after the starting date of the problem, then the program will ask the user for the number of acres that have already been completed on that operation by this starting date and make the appropriate adjustment to that operation instance in the database.

At this point, the program has a calendar of field operations defined for the specific test situation that the user wants to consider and checks whether the operations can be completed with current operating procedures under the defined constraints. To do this check, the algorithm does a daily search taking the possible resource conflicts of labor, available tractors, and available implements into account. (See fig. 2.)

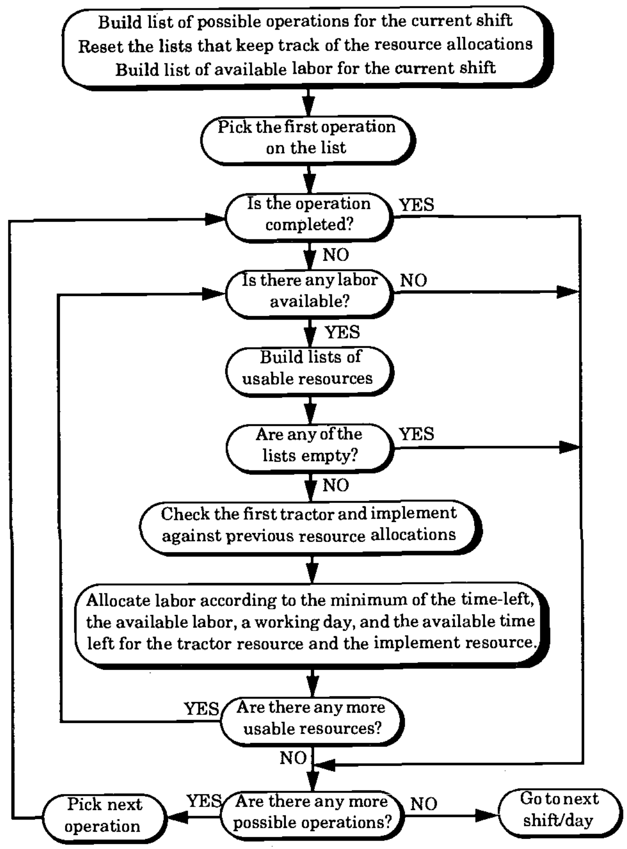

Figure 2–The basic structure of the resource allocation algorithm employed daily for each shift.

For this daily search, the program first builds a list containing all of the operations whose time windows include the particular day in question. The program also creates a list of the available main shift labor for the day in question. If there is an operation that is not completed by that day and there is labor available, then labor is allocated to that operation. If the time left toward completion of the operation is less than a working day, then only labor for the time left is allocated to the operation, otherwise a full working day of labor is allocated to the operation. A working day is defined by the percentage of good working days for the time period which covers the day in question. For example, if the day is in a time window where the farmer expects 90% of the days to be good field days, then a working day for one worker would be defined as 0.9 days. Regardless of how much labor is allocated to the operation, the amount is added to the time-used slot of the operation's instance and subtracted from the time-left slot of the operation's instance. This amount of labor is also allocated to the tractor and implement involved. These latter allocations are local to the particular shift for the current day and allow the simulation to ensure that a resource is not used for more than a working day during that particular shift. The first operation on any day which is allocated labor does not need to be checked for resource conflicts since no equipment has yet been allocated.

The algorithm then proceeds to subsequent operations. If there is another operation that is not completed, the available labor list is searched for any additional labor. If there is labor available, resource conflicts between this operation and the resources that have already been allocated to any previous operations are checked. The algorithm allocates labor to this operation according to the minimum value of: a) the labor still available for the specific shift; b) a working day; c) the time left which may still be allocated to the operation's primary tractor; and d) the time left which may still be allocated to the operation's primary implement. For example, if the operation's primary tractor has already been used for a working day during that shift, then the time left which can still be allocated to that particular tractor is zero (i.e., there is a resource conflict) and this being the minimum value, no labor is allocated to the operation. At this point, the algorithm would search the lists of available resources for this operation for any additional resources. This process will continue until the operation runs out of available resources or until the shift runs out of available labor. When either of these conditions are met, the algorithm then proceeds to the next possible operation for the particular day in question and the process of allocating labor is repeated. This process proceeds until there are no more operations.

Checking for resource conflicts in this manner makes the algorithm more robust. Since the algorithm does not automatically proceed to the next operation after some labor is allocated to the current operation, there is no wasted labor or resources. For instance, more than one working day may be allocated to a particular operation during the same shift if there are enough resources available. In a different case, if an operation's primary resource has only part of a day available, that part will be used before the algorithm looks for alternative resources. In this manner, the resources are always used to their fullest potential.

If there is any unused labor at the end of the shift (i.e., when there are no more possible operations to consider), the algorithm updates the unused-main slot (see Table 3 for a detailed definition) for each possible operation for that particular day and the unused-main slot (see Table 4 for a detailed definition) for the time instance which includes that particular day. After the main shift has been completed for the day, the algorithm then considers the other shift for that day. This process is identical to that of the main shift. All of the operations that were possible during the main shift are possible during the other shift and all resources are again available for allocation. The only change may be the labor available. After considering the other shift, the algorithm proceeds to the next day and starts over in the same manner as described above. This process continues until the defined ending date is completed. Once the entire time period in question has been considered, the program analyzes the results to determine if the calendar of defined field operations was feasible and makes recommendations if necessary.

The program evaluates each field operation instance in the database and separates them into three categories: 1) those operations which were completed; 2) those operations which might be completed; and 3) those operations which were not completed. The operations which were completed are those which had no time left for completion. An operation falls into the "might be completed" category if the operation was not completed by the end of the time period being considered by the algorithm, but it's time window extended beyond this ending date. The operations which were not completed are those having time left for completion greater than zero. The calendar of operations is considered to be feasible if there are no operations in the not completed category. In addition to reporting whether or not the calendar is feasible, the program will also give: a) a list of the operations which were completed; b) an explanation for each operation which might be completed; c) recommendations for completing each operation which was not completed; and d) a summary of the allocation of labor throughout the problem defined time period. For a detailed explanation of the algorithm and the decision tree used for making recommendations see Freeman (1990).

If an operation is not completed, the farmer is provided with suggestions for completing the operation. In allowing the algorithm to maintain its simplicity and yet still provide useful information with the least amount of input data, it was necessary for these recommendations to be fairly general in nature. This generality allowed the recommendations to be made using a decision tree structure without requiring any inferencing techniques. These recommendations are made based on the following:

- Any unused labor during the operations time window.
- The increase in the normal operating rate required to complete the operation with the currently defined constraints of available labor, available equipment, and available time.
- A comparison of the time left required for completion of the operation at the current operating rate with the total time required to complete the operation with the current operating rate and the unused time from each shift during the operation's time window.

Results of Case Studies

The following sections will discuss the results of the algorithm for various situations. These scenarios will demonstrate how the methodology can be applied, by a farm manager or producer, both as a long-term planning decision aid and as a within-season planning decision aid. The example situations described and discussed in the following sections use an actual farming enterprise as a basis.

Base Case

The subject farm is located in Weld County on Colorado's eastern slope. The farm consists of both dryland acres and irrigated acres, as well as a cow-calf operation. The available labor for the farming operation consists of two partners and an additional full-time worker during the summer. Data concerning 50 field operations for the farm starting with the land preparation operations in the fall of 1989 and proceeding through the fall of 1990 were obtained from the farm managers. While the time windows for the field operations, the number of workers, and the percentage of good working days are taken to be for a normal year, the specific acres involved are for the current

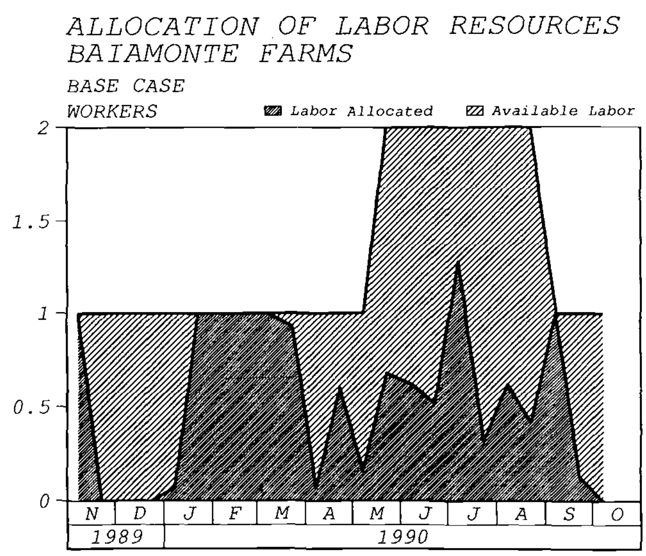

Figure 3–A summary of the allocation of labor resources for the subject farm, base case.

operating year. Livestock operations and custom harvesting operations were ignored. It was also assumed that during a normal year, one of the partners would consistently be busy working on things other than field operations. Thus, only one full-time labor source from the two partners is considered an available labor for field operations. As expected, the base case (November 1989 through October 1990) was feasible under normal operating conditions. Figure 3 shows the allocation of labor throughout the time period. As shown, there is excess labor throughout most of the year. In fact, the time instance representing the first half of July is the only time period that required more than one full-time worker to complete the field operations. However, there is very little idle time on the subject farm. There are several reasons for this.

The most likely reason is that on a dryland farm in eastern Colorado, the farmer will try to complete an operation as soon as possible once the operation is started. However, the starting date may vary several weeks depending on the weather. For example, the time window in which the wheat-fallow should be chiseled is given to be from the middle of May until the end of June. Experience has established that the operation will be done some time within this window, yet it is not practical to narrow the time window because of the large variance in when the operation should be done. Additionally, operations on irrigated land take precedence over dryland operations. Thus, the time windows for dryland operations need to reflect the possibility of being delayed until the more time critical irrigated operations are completed. Therefore, in practice two workers may be allocated full time to field operations (where the algorithm showed that one would have been sufficient) in order to complete them in a timely manner.

Another possible reason is in the definition of field operations. The field operations used by the algorithm are those directly related to the production of each particular crop. However, on most farms, and on the subject farm in particular, "tractor work" is only a small part of the labor required for crop production. There is a constant need for labor applied to maintenance chores, livestock operations, and work not related to any particular crop. Examples of which include: preparing irrigation ditches for the start of the season, and within season spraying and burning to keep weeds and grass out of the irrigation ditches. In addition, on a large row-crop farm, irrigation itself may require a full-time labor source.

It was mentioned above that only one of the partners was listed as a possible labor source for field operations in order to account for these additional labor requirements. It appears that this assumption was inaccurate and likely an underestimation of the actual labor required. This problem points out the underlying assumption of the methodology which has the most potential for developing inaccurate results — the fact that labor required for non-field operations is ignored. For example, from the output of the base case, it would appear that the additional worker during the summer is only needed during the first part of July. However, in practice the additional worker is allocated throughout the summer, though not always to a field operation. Since the managers of the subject farm recognize this, figure 3 may be used to schedule non-field work when it is least likely to cause delays in the timely completion of field operations. Thus, the labor used by the algorithm is labor which is available for field operations, but not restricted from allocation to other types of work. With this in mind, if all of the available labor was being allocated consistently throughout the year, the farm in question would be in trouble if situations varied from the base case scenario. In reality, since many of the factors affecting the farming enterprise are stochastic in nature, it would be better to have a slight abundance of available labor during a normal year to provide a buffer capable of handling different situations if they should arise during the growing season.

A potentially more accurate approach would be to allocate all available labor while accounting for field operations and all additional labor requirements. However, this approach may not be feasible in application. This would require a large amount of additional data from the users which they will not be able to easily supply. Additionally, the algorithm would have to be able to handle completely different types of operations. It would be necessary to consider operations which must be done daily, but only require a small portion of a working day. This would mean abandoning the idea of using the "working day" as the basic unit of time, and thus, abandoning all of the simplifications and advantages for choosing the "working day" to start with. It would also become necessary to consider operations which would essentially have an infinite time window, but would only be worked on when there are no other operations which could be allocated labor. These changes would be possible, but for the intended use of the algorithm are not necessary and if implemented, the algorithm's simplicity would be lost and the likelihood of this algorithm becoming another research tool, unused by farm-level decision makers, would increase.

Weather Examples

Now that the base case for subject farm has been proven technically feasible, it is possible to consider the results of operating under different conditions. For example, if the subject farm experienced an unusually wet fall and none of the normal fall land preparation could be done, could the land preparation still be completed in a timely manner? To answer this question, two variations of the base case were examined.

In the first case, it was assumed that the land preparation operations which usually start the beginning of November could not be started until the middle of January. This case proved to be feasible. The significant difference in the two calendars (other than the fact that no work was done in November) is that the land preparation operations which are usually completed in March were pushed into April. However, the time windows for these operations were long enough to allow for the delay in completion and the operations were still completed in time to avoid delaying any of the spring planting operations.

In the second case, land preparation was not allowed to start until the middle of March. This case turned out to be infeasible under the current operating constraints. The simulation was only run through the time in which all the spring planting needed to be completed, but this was long enough to evaluate the consequences of such a late start. The results show that some of the preparation and planting operations for corn and barley were not completed, but that all of the operations associated with preparing and planting the bean ground were completed. This indicates that there was not enough labor available to complete the operations required for the earlier crops, but that there was enough labor available later in the spring to allow all of the operations associated with the pinto beans to be completed in a timely manner. The results show that the one available labor source worked continuously from mid-March until the end of April when the time windows for the uncompleted operations were exhausted. In this case, since there was a large difference between what was done and what needed to be done, the algorithm recommended that the user should hire an additional worker for the main shift or for the other shift. For convenience, an example of the recommendations suggested by the algorithm is given in figure 4.

It should be noted that a similar situation was experienced on the subject farm during the spring of 1990 due to an unusually wet period in March. A large portion of the land preparation was done in the fall and during a warm spell (which allowed the ground to thaw) in January. However, the wet period prevented field operations during March. In April, when field operations could continue, both partners worked on them in order to complete them in a timely manner. Thus, they did essentially what the algorithm would have recommended. That is, an additional full-time labor source was used during that time period in order to complete the operations.

Figure 5 compares the allocation of labor for these two example cases to the base case. The primary point of interest is shown during the months of March and April. The example with no fall land preparation extends the allocation of labor through March and into April, but by the middle of April is back on track with the base case. The example considering an even longer delay extends the complete allocation of all the available labor all the way through April and does not get back on track with the base case until the first part of May when the time window for the land preparation operations had already passed (with five of them being uncompleted).

Thus, these two example cases have shown how the methodology developed in this study can be used to assess the effects of delays in allocating labor both for long-term planning and within-season assessments. The examples use delays due to weather conditions, but any situation which results in delaying field work could be evaluated in a similar manner.

Additional Land

The next two example cases will evaluate the consequences of leasing or purchasing an additional 40.5 ha (100 ac) and planting it in corn. (Since no economics are involved, the method of obtaining the additional acreage is not important, only that acreage of the other crops remain the same.)

For the first example, 40.5 ha (100 ac) of corn was added to the base case. The contract for the land became effective on the first of January, 1990; thus, no fall land preparation was possible on the additional acreage. Everything else stayed the same as in the base case. This example case was feasible. The second example case is a combination of the additional 40.5 ha (100 ac) of corn with the first weather example case in which no fall land preparation was done. The algorithm evaluated this scenario to be infeasible with the current operating constraints. In this case, there was not enough labor available in the first part of April to plant barley. In addition, there was not enough labor available in the second part of April to plant all of the corn. Similar to the example case involving the delay of field work due to the scenario of a long winter, the algorithm recommended that an additional worker be hired for one of the shifts during the time period involving both planting operations.

Figure 6 shows a comparison of the labor allocation for the two additional acreage example cases to the base case. In the first example (nominal fall land preparation for the other crops), additional labor is needed in March and April for the land preparation and planting of the additional

The operation: PLANT CORN
When the program reached the ending date, 51% of the work was completed with the following statistics:
acres completed: 52
acres left: 50
To complete this operation within the present time constraints the current operating rate of 30 acres/day needs to be increased 28 acres/day to meet the required rate of 58 acres/day
During the time window for this operation, there was not enough labor available to complete all the field operations The time required to complete this operation is greater than 10% of the total time required
Therefore, WORKING LONGER HOURS may not be sufficient to complete the operation Thus the solutions you may wish to consider first are:
1 HIRE AN ADDITIONAL WORKER FOR THE MAINSHIFT
2 HIRE AN ADDITIONAL WORKER FOR THE OTHERSHIFT
Additional solutions you may wish to consider are:
3 CUSTOM HIRE PART OF THE OPERATION
4 INCREASE YOUR FIELD CAPACITY (see note)
5 DECREASE YOUR AMOUNT OF ACREAGE
6 ENLARGE THIS OPERATION'S TIME WINDOW

NOTE: increase field capacity implies larger equipment and possibly a larger tractor as well

Figure 4–An example of the recommendations suggested to the user to correct an uncompleted operation.

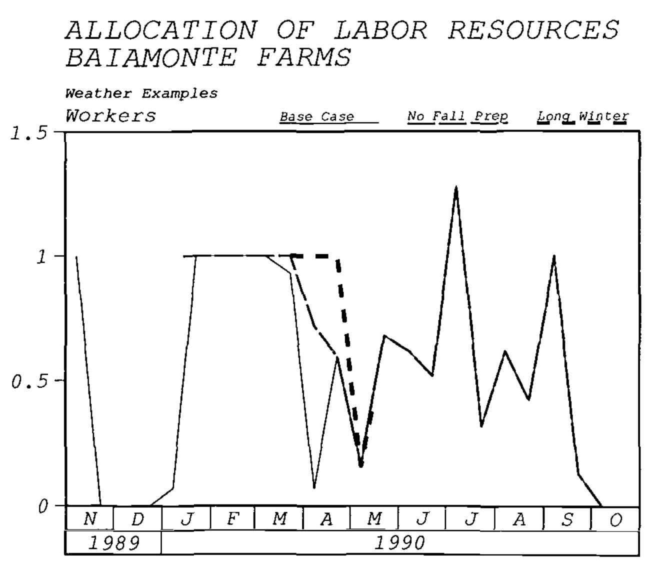

Figure 5–A comparison of the effects on the allocation of labor resources due to the delay of field operations because of weather.

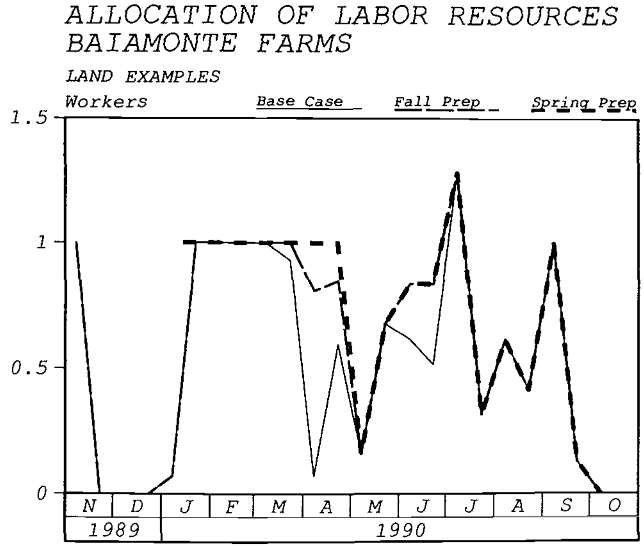

Figure 6–A comparison of the effects on the allocation of labor resources due to an additional 40.5 ha (100 ac) of corn.

acreage and in May and June for the cultivation and ditching of the additional acreage. Since corn harvesting is a custom operation on the subject farm, no additional labor is required at the end of the season for harvesting. As mentioned above, the additional labor required by this scenario was available, and thus, the additional 40.5 ha (100 ac) of corn resulted in a physically feasible investment alternative to the base case.

The example in which no fall land preparation was done follows the above example starting in the first part of May. Figure 6 shows that all of the available labor was allocated through April. However, there was not enough labor available in April to make this scenario feasible. While this scenario needed an additional worker early in the spring, it should be noted that during the summer, the required labor was very similar to the base case. Even with the additional 40.5 ha (100 ac) of corn, the first half of July is the only time period in which more than one worker was needed to complete the required field operations.

These two example cases have shown how the methodology can be used to assess how the physical feasibility of a farm is affected by additional acreage. For the subject farm, the additional acreage required no changes during normal years; however, in years of adverse weather, the current resources were insufficient to complete the required operations. The user, in such a case, (if the additional acreage is economically feasible in normal years) would have to assess the risks involved to determine whether the additional acreage should be obtained. The results of these two cases also indicate that the need for additional labor occurs earlier in the spring than additional labor is currently available. Thus, if an additional worker was available toward the beginning of spring, a year of adverse weather might have less of an effect on the feasibility of the proposed calendar.

Additional examples of the how the algorithm can be used to assess long-term and within-season problems such as a change in the available machinery complement, adding additional field operations, or a change in the available labor sources are given in Freeman (1990).

Summary

A calendar of operations representing information on the field operations to be performed as well as the time and labor constraints involved in production has been developed which allows the producer to more clearly represent his management style. This methodology was developed to use a limited amount of input data from the farm manager or producer. The amount of data required was reduced by: a) allowing this algorithm to be a decision support system, not a decision making system; and b) considering the successful farmer to be an "expert" on local conditions (e.g., operations scheduling, and normal weather conditions). In addition, an object-oriented simulation algorithm has been developed to allocate available resources to the required field operations in order to analyze the physical feasibility of a whole-farm plan (i.e., the analysis determines if the whole-farm plan of required field operations can be completed with the current resources of available time, labor, and machinery). A decision tree has also been developed to recommend possible solutions to the user when the calendar is infeasible (i.e., it cannot be completed within the defined physical constraints of machinery, labor, and time).

During the process of trying to successfully transfer expert knowledge and experience into a form that farm-level decision makers can understand and apply, a good deal was learned about the process of knowledge engineering and the following descriptive statements can be made:

- A new approach has been successfully developed which could potentially be applied to an area of machinery management where previous efforts were generally unsuccessful for farm-level decision making (outside of research projects).
- It was shown that object-oriented algorithm using LISP is both feasible and possible in a standard DOS environment. An object-oriented environment is ideal for the representation of a farm since farm components can be represented in different levels of detail as unique interactive objects. While previous research in this area has taken advantage of an object-oriented data structure by using PROLOG, this is the first attempt at a full object-oriented implementation using inheritance and methods.
- The methodology developed has no regional specific data or biases. Traditional machinery management tools have required specific regional data (e.g., yield reduction due to timeliness losses and detailed weather information). All of the regional specific data required by this methodology is of a form which the farmer can readily supply.
- The methodology in its current form has the following limitations:
  - Only field operations are considered for resource allocation.
  - No prioritizing exists for the field operations beyond the starting date. However, since no scheduling is done, this will not effect the feasibility of the farm on a yearly basis.
  - All labor resources are considered to be equal.
  - All possible machinery resources for an operation work at the same rate.

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