The Application of Expert Systems to Automated Strange and Retrieval

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THE APPLICATION OF EXPERT SYSTEMS TO AUTOMATED STORAGE AND RETRIEVAL

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ABSTRACT

This report discusses the major functions, decisions, and strategies of automated storage and retrieval systems (AS/RS). The report surveys the essential features of expert systems and discusses how they can be applied in automated warehousing environments. A blackboard expert system architecture was examined and found to be a flexible and responsive control system for automated warehousing applications. A simple AS/RS expert system was constructed using an expert system software package. A warehousing simulation was performed which compared the expert system's performance to a typical AS/RS control system. The expert system produced increased efficiency of operation because of the intelligent rules programmed into the system.
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INTRODUCTION

The modern manufacturing environment is one of continual change and dynamic interaction between its component parts. This dynamic environment creates complex decision problems that require a continual review of the changing status of the system (Bullers, Nof, and Whinston 1980). The warehousing function, as part of the total manufacturing system, is consequently faced with operating in a climate of complex and unstructured decision problems.

In the factory of today many of these complex decision problems are analyzed and solved by rational and flexible human beings (Beavers 1982). Computer technology can quickly process large amounts of data, but many necessary decisions must wait for humans to examine the data, become familiar with the system, and implement proper action (Bullers, Nof, and Whinston 1980). Human intelligence operating in the dynamic manufacturing environment brings order and efficiency to daily operations and planning. A key element for the factory of the future will be the ability to capture human intelligence in machine form.

In recent years great strides have been made in automated warehousing technology. Computer controlled
storage and retrieval systems have become an integral part of many manufacturing facilities. These technological advances have made the warehousing function a more productive and cost effective component of production systems. But the primary focus of recent technological advances has been in the area of hardware development. Little effort has been devoted to developing realistic predictive/optimization algorithms (Phillips 1980).

We discuss the use of expert systems technology in optimization/control applications for automated storage and retrieval systems (AS/RS). An expert system is an embodiment within a computer program of an expert skill in a form that outputs intelligent advice or decisions (Forsyth 1984). The purpose of this research was to demonstrate the usefulness of expert systems technology to provide flexible and efficient control systems for AS/RS applications.

We discuss current AS/RS operation and control systems and how expert systems can be used in these areas. A blackboard expert systems model was examined as a structure for AS/RS decision control. A simple expert system was constructed using an expert system software package. A simulation was performed to determine the system's effectiveness.
AS/RS OPERATION AND CONTROL

The warehousing function encompasses storing raw materials needed for production, in process storage and retrieval, and storing finished goods for later shipment. The basic warehousing processes involved are: (1) receiving and sorting of incoming materials, (2) moving materials to storage, and (3) retrieving of materials from storage (Salvendy 1982).

Automated systems for warehousing generally are complex arrangements of control subsystems including sensors, on board microprocessors, supervisory minicomputers, and host computers (Kulwiec 1982). Automated storage and retrieval systems work basically as follows: (1) incoming items are assigned to pallets, (2) the contents of pallets are assigned open locations in the warehouse and stored, and (3) requested items are located by accessing computer memory to find physical locations, and then a retrieval is performed (Hausman, Schwarz, and Graves 1976).

The essential hardware components of an automated warehousing system are the pick up and delivery station, the storage and retrieval shuttles, the storage structure, and the control system. The pick up and delivery
station's function is to process incoming and outgoing loads and support the loads in a manner suitable for handling by the storage and retrieval shuttles. The storage and retrieval shuttles are the mechanical carriers that transfer loads to and from the pick up and delivery stations to the storage structure. The storage structure's function is to support multiple levels of loads received from the storage and retrieval shuttles (Material Handling Institute 1977). The control system's function is to direct all storage and retrieval activity within the warehouse.

The design of automated warehousing strategies depends upon the influence of several major factors. Consideration must be given to the characteristics of the material flowing into and out of the warehouse. Both the frequency and distribution patterns of input and output streams of materials must be evaluated and considered in designing effective warehousing strategies.

The physical organization of the warehouse must also be examined as to its effect on storage and retrieval strategies. Two common organization methods are randomized storage and dedicated storage. Randomized storage allows a given stockkeeping unit to be stored in any available location in the warehouse. Dedicated storage assigns each stockkeeping unit a specific storage
location in the warehouse. Dedicated warehouse arrangements tend to maximize material throughput, but increase storage space requirements. Randomized storage requires less overall storage space, but tends to decrease material throughput. Organization of the warehouse in a manner that combines randomized and fixed arrangements may also be used (Salvendy 1982).

Consideration must also be given to various other factors in designing effective warehousing strategies. The interface of other related operations such as general inventory control, in-process manufacturing, and inspection/quality control functions must be examined for their effect on warehousing decisions and control (Material Handling Institute 1977).

There are four major decision areas for processing items in an automated warehousing system. The first decision point involves the sequencing of storage and retrieval requests. This decision involves determining for each cycle whether a storage or a retrieval will be performed. The second decision point involves determining which items will be assigned to a given storage or retrieval cycle. The third decision point involves determining the specific storage locations in the warehouse which will be used to store or retrieve items on a given cycle. The fourth decision point involves
determining the order and physical path by which items will be stored or retrieved on a cycle (Hausman, Schwarz, and Graves 1976).

The overall goal for warehousing strategies is to plan and control the flow of materials in and out of the warehouse in the most efficient and cost effective manner possible. Practical storage and retrieval strategies will involve a tradeoff between system goals. Effective decision strategies should be designed to: (1) maximize space utilization in the warehouse, (2) maximize accessibility of materials, and (3) maximize throughput of materials (Thompkins and White 1984).

Current approaches to decision strategies for automated storage and retrieval systems range from simple operating algorithms to complex research approaches involving math modeling and simulation. A major difficulty experienced in developing practical AS/RS control strategies is that problems actually encountered do not always present themselves in standard forms for analysis by established methods (Hew 1981). Unstructured problems and dynamic variations encountered in real world situations create difficult problems for researchers to accurately model. Integrating warehousing decisions into the overall manufacturing system also presents a difficult problem in developing AS/RS control strategies.
Many of the algorithms for automated warehousing surveyed in the literature addressed certain aspects of storage and retrieval decisions, but no comprehensive model was discovered. Several of the algorithms for optimal order selection for a storage or retrieval trip produced results under certain conditions and orders, but tended overall to be data-dependent (Elsayed 1981).

Some of the major warehousing strategies that have been considered and used in AS/RS control are:

1. Zoned warehouses, in which the warehouse is divided into different zones with faster moving items stored progressively closer to the front

2. Closest open location rule where an incoming load is stored in the closest available storage location and an outgoing load is retrieved from the closest available stock location

3. Turnover based assignment models where the highest turnover items are assigned to the closest locations in a warehouse configured for randomized storage (Hausman, Schwarz, and Graves 1976)

4. Order picking methods where item similarity is the basis of assigning orders to a storage or retrieval group (Elsayed 1981)

5. Mathematical models for sequencing storage and retrieval requests in an optimal manner (Han, McGinnis, Shieh, and White 1984)

Other strategies and models have also been developed that address the different decision areas involved in automated warehousing.
EXPERT SYSTEM FEATURES

The decision problems created by the dynamic and often unstructured environment of automated warehousing present a significant challenge to system designers. A promising technology for solving these types of decision problems is a field of artificial intelligence known as expert systems. Much of the knowledge needed to make effective decisions in the complex manufacturing environment is expert knowledge that exists in the minds of humans. Expert systems that can capture this knowledge can therefore provide effective planning and control systems that will increase productivity in automated systems (Bullers, Nof, and Whinston 1980).

An expert system is an embodiment within a computer program of an expert skill in a form that outputs intelligent advice or decisions. They are computer programs that are based on expert knowledge about a specific problem area. The expert knowledge may include factual, procedural, or heuristic types of knowledge. Expert systems are often structured as a collection of rules with which the system draws conclusions and makes decisions based upon given data (Forsyth 1984).
Expert systems differ from conventional computer programs in several ways. Expert systems are able to deal with imprecise, uncertain, or missing information without defaulting. To facilitate real world problem solving, expert systems contain mechanisms for dealing with data and situations that are less than certain. An expert system, like a human expert, is able to continue a problem solving process even though exact information may not be available (Forsyth 1984).

Program control is separated from domain knowledge in an expert system. Expert systems are modular in that the same general control system can be used to direct problem solving activities for different problem domain areas (Fisher 1985).

Execution in an expert system program does not follow a definite sequential path as is the case for conventional computer programs. The rules and facts about the problem area can be used in any order. The general problem solving control portion of the expert system applies the appropriate rules and knowledge as needed for problem solving activities (Fisher 1985).

The first essential component of an expert system is the system's knowledge base. The knowledge base is that portion of the system which contains the knowledge and expertise for a given problem area. The knowledge base
contains both facts and rules that are relevant to the problem area. Facts are those items of short-term information that may change in a given problem solving session. Rules in the knowledge base are the encoded form of those heuristics and decision methods that a human expert uses in problem solving. Rules are long-term information in the program that generate new facts and direct problem solving activity (Forsyth 1984).

There are several different ways that knowledge bases can be structured within an expert system program. Production rules are one common method of organizing a knowledge base. A production rule structure consists of a set of IF...THEN... type rules called productions and a data structure called the context. The context represents the current situation in a problem solving session. The IF...THEN... rules are situation-action pairs. The IF clause represents a condition that must be present in the current problem context for the rule to execute. The THEN clause represents an action that is to be performed. A simple storage and retrieval example is: IF there are two items having the same turnover rate in the storage queue THEN select these two items for the next storage (Barr and Feignebaum 1981).

Production systems operate in a three step cycle. In step one the system identifies all possible individual
productions whose IF conditions are true in the current context. In step two the system selects one of the productions to execute. In step three the action of the production is executed. On each cycle the action of the production that is executed changes the context. This results in other productions having their IF clauses satisfied for the next cycle. The system executes as many cycles as are necessary until the goal of the problem solving session is accomplished (Hayes-Roth 1985).

Another method of structuring a knowledge base is a frame-based system. Frames are data structures that represent the current problem solving context or situation. Each frame consists of two basic parts. The first part represents permanent features of a problem situation. The second part, called a slot, represents the variable features that are to be filled in during a problem solving session. Procedures are also attached to a slot to direct the problem solving actions of the system (Barr and Feigenbaum 1981).

A frame-based reasoning system operates by selecting a particular frame to represent the current problem situation. The variable feature slots are filled in to describe the specifics of the situation and direct the system to problem solutions. If in the reasoning process a frame is determined to be inappropriate for a problem
situation, procedures in the frame will transfer control to another frame. The problem solving process continues until a solution is determined (Barr and Feigenbaum 1981).

Production rules and frames are two common ways of representing knowledge in expert systems. Other artificial intelligence techniques that have been used to represent knowledge include decision trees, semantic nets, and predicate calculus (Graham 1979).

The second essential component of an expert system is the inference engine. The inference engine is the control mechanism of the expert system. Because the different heuristics contained in an expert system apply only to specific situations, a control mechanism is needed to determine which heuristics are useful at each point in the problem solving process (Graham 1979). The inference engine directs problem solving activity by evaluating and selecting useful rules for execution. An inference engine often has some built-in mechanism to evaluate and rate the potential usefulness of the expert system rules.

The three basic types of inference engine techniques used in expert systems are: (1) forward chaining, (2) backward chaining, and (3) sideways chaining. Forward chaining systems work by searching for rules whose condition parts are true and then executing their action portion. This process adds new information to the context
and leads to further execution of other rules. This process continues until a solution is obtained. Backward chaining systems select a problem hypothesis and work backwards seeking evidence to support the hypothesis and thereby reach a problem solution. If a hypothesis cannot be proved, the system examines other lines of reasoning in search of a solution. Sideways chaining systems assign values to the different rules and seek to select rules that will contribute most to obtaining problem solutions. Working expert systems use a combination of inference engine techniques and are not purely of one type or the other (Forsyth 1984).
USE OF AN EXPERT SYSTEM FOR AS/RS CONTROL

Development of application expert systems requires determining which types of inference engine techniques and knowledge bases will best suit the domain to be modeled (Winston 1977). A general purpose inference engine that is suitable for use in automated storage and retrieval systems is a blackboard control architecture. A blackboard control model would be useful for the automated warehousing domain because: (1) the model provides an effective control system for multiple-task planning problems similar to those encountered in the storage and retrieval environment, (2) the model provides features for dealing with uncertainty, which often occurs in the warehousing decision environment, and (3) the model provides general purpose control features that would be useful in AS/RS control (Hayes-Roth 1985).

An effective knowledge representation scheme for the storage and retrieval domain is a production rule structure. Production rules provide an effective method of representing expert knowledge and are useful for expressing the type of decisions involved in automated warehousing. Production rules are the best choice for knowledge representation in the storage and retrieval
domain for several reasons. Production rule systems provide a more natural and effective framework for representing procedural knowledge than frame-based or other knowledge representation schemes that were examined (Barr and Feigenbaum 1981). Production rules are a proven method used in working, large scale expert systems. Production rules are also a compatible method of knowledge representation for use with blackboard control architectures (Ham 1984).

The four basic elements of a blackboard control architecture are knowledge sources, knowledge source activation records (KSARs), the system blackboard, and the system scheduling mechanism. Knowledge sources are data structures that are used to represent expert knowledge in the blackboard control architecture. Each knowledge source has a production rule, condition-action format. The condition portion describes the conditions under which a particular knowledge source can contribute to solving a problem. The action portion describes the particular problem solving actions that the knowledge source will perform. Inferencing methods used within knowledge sources may be forward chaining, backward chaining, or sideways chaining methods. The various knowledge sources contained in a blackboard system are independent of one another and communicate indirectly through means of the
system blackboard. Figure 1 shows the basic structure and attributes of a knowledge source (Hayes-Roth 1985).

A knowledge source activation record represents a particular knowledge source whose conditions are fulfilled in the current problem situation. KSARs are recorded on the system blackboard and are available for execution by the system scheduling mechanism (Hayes-Roth 1985).

The system blackboard is a global data base which records all current problem data and actions that occur during problem solving sessions. The blackboard data structure is part of the system's working memory and is continually modified during problem solving activities. New information is generated and recorded on the blackboard each time a knowledge source is executed in the current blackboard context (Hayes-Roth 1985).

The system scheduling mechanism directs problem solving activity with three basic control knowledge sources. One knowledge source identifies all KSARs whose conditions are fulfilled in the current blackboard context. A second knowledge source chooses one KSAR for execution. This choice is made based on current problem data, problem characteristics, and the scheduling indices listed in Figure 1. A third knowledge source executes the actions of the chosen KSAR and records the results on the system blackboard. Figure 2 shows the basic problem solving loop for blackboard control (Hayes-Roth 1985).
<table>
<thead>
<tr>
<th>ATTRIBUTE</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Label that identifies knowledge source</td>
</tr>
<tr>
<td>Description</td>
<td>Knowledge source behavior represented in production rule format</td>
</tr>
<tr>
<td>Pre-condition</td>
<td>Current blackboard data required for a KSAR to be eligible for execution</td>
</tr>
<tr>
<td>Scheduling indices</td>
<td>Values that indicate: (1) the system's confidence in pre-conditions &amp; (2) expected problem solving value of knowledge source actions</td>
</tr>
<tr>
<td>Action</td>
<td>Changes that will be made to the system blackboard when a KSAR is executed</td>
</tr>
</tbody>
</table>

Figure 1. Basic knowledge source attributes.

Figure 2. Basic blackboard control loop.
A blackboard control model for an automated warehousing application requires representing basic warehousing data and decision structures with knowledge sources. Knowledge sources are needed to represent and make available information for each stockkeeping unit and information about the current warehouse condition. The information contained in these knowledge sources is shown in figures 3 and 4.

<table>
<thead>
<tr>
<th>ITEM XYZ</th>
<th>Description</th>
<th>Physical Characteristics</th>
<th>Relationship Data</th>
<th>Forecast data</th>
<th>Location data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Name, identification number</td>
<td>Size, weight</td>
<td>Production relationship to other items</td>
<td>Expected quantity over time, expected distribution pattern over time</td>
<td>Current locations in stock</td>
</tr>
</tbody>
</table>

Figure 3. Stockkeeping unit information.

<table>
<thead>
<tr>
<th>WAREHOUSE CONDITION</th>
<th>Item content</th>
<th>Open locations</th>
<th>Warehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quantity and types of items currently in stock</td>
<td>Location and size/weight category of all current warehouse locations</td>
<td>Current system configuration of the warehouse in terms of fixed locations, random locations, and zone set-up</td>
</tr>
</tbody>
</table>

Figure 4. Warehouse condition information.
The purpose of these two types of knowledge sources is to make current item and warehouse information available to other knowledge sources. The condition for their execution is an indirect call from other knowledge sources via the system blackboard. The action of these two types of knowledge sources is: (1) to record their information on the system blackboard when executed, and (2) to calculate and keep track of their respective information on a real-time basis. Predictive data concerning expected quantities and expected distribution patterns for stockkeeping units is calculated through those functions within the knowledge sources that are dedicated to this purpose.

Knowledge sources are also required for the different warehousing decision areas. The six basic types of knowledge sources needed are ones that will be used to: (1) determine goals, (2) determine warehouse configuration, (3) determine storage and retrieval sequence, (4) determine cycle load assignment, (5) determine locations, and (6) determine item order sequence and path. Each knowledge source contains expert decision rules in a production rule format for the particular decision area. The individual knowledge sources operate using both current and predictive data provided by other knowledge sources via the system blackboard.
The 'determine goals' knowledge source is responsible for determining comprehensive warehousing goals and strategies to achieve these goals. This knowledge source uses expert rules to develop warehousing strategies that are supportive of inventory goals, manufacturing goals, and other warehousing related goals. If manufacturing goals require a high processing volume for certain items, strategies will be developed to handle these items in a manner to meet these goals. Strategies are developed on a real-time basis to meet changing requirements and needs.

The 'determine warehouse configuration' knowledge source determines the optimal warehouse configuration based on current and expected future conditions. The warehouse could be configured in a fixed, random, or combination structure. An example of a rule in this knowledge source is: IF a stable input/output distribution is expected AND the physical storage capabilities will not be exceeded THEN configure the warehouse in a fixed manner. The 'determine warehouse configuration' knowledge source would operate in real-time and continually evaluate and determine the optimal configuration to achieve system goals.

The 'determine storage and retrieval sequence' knowledge source uses item data, warehouse condition data, and system goals to determine whether a 'store' or
'retrieve' will be performed for each cycle. This knowledge source makes decisions that fulfill current system goals. If current system goals require maximum material throughput, the sequencing decisions will reflect this. If current system goals require retrievals to have priority, the sequencing decisions will reflect this.

The 'determine cycle load assignment' knowledge source determines which items in the storage or retrieval queue will be selected for a cycle. Expert order picking rules are applied in this knowledge source based on knowledge about items available for selection, the condition of the warehouse, and current system goals. An example of a rule in this knowledge source is: IF the queue contains items of like popularity AND warehouse space is available to store the items together THEN select these items for the cycle.

The 'determine location' knowledge source makes decisions concerning the specific storage locations in the warehouse which will be used to store or retrieve items on a given cycle. Decisions are based on knowledge of items selected for the cycle, current warehouse configuration, warehouse item content, and system goals. In a problem context in which the warehouse is configured in zones based on item popularity, an example of a knowledge source rule would be: IF a medium volume item is to be stored
AND a storage space is available in the medium volume zone THEN store the item in the closest open space in the medium zone. Specific location decisions are determined for each item in a manner that will best fulfill current system goals.

The 'determine item order sequence and path' knowledge source determines the order in which items are stored or retrieved on a cycle and the actual path traveled by the storage and retrieval shuttle. This knowledge source uses information about the current warehouse condition to determine the order and path that will minimize storage or retrieval cycle time.

Blackboard control architectures also provide powerful control features that are useful in automated warehousing applications. The blackboard architecture provides control knowledge sources that focus on problem solving actions that are useful in the current problem situation (Hayes-Roth 1985). If material throughput is a current system goal with high priority, these control knowledge sources will select domain knowledge sources whose actions maximize material throughput. If warehouse space utilization is a priority, heuristics will be executed to achieve this goal.

Control knowledge sources in blackboard models select and discard control heuristics in response to changing
problem situations (Hayes-Roth 1984). In the dynamic warehousing environment these knowledge sources would direct decision making based on current needs and goals. If material flow and production goals change, the warehousing control system responds by adopting new goals and heuristics. Blackboard models intelligently adjust problem solving activity rather than continuing in fixed patterns derived from past data.

The blackboard control loop for an automated warehousing system consists of (1) executing basic storage and retrieval decisions and (2) constructing and implementing comprehensive warehousing goals. Figure 5 shows the essential decision structure and control loop.

A blackboard model would provide an effective control system for increased efficiency and performance for automated warehousing systems. A blackboard system provides a flexible and responsive control system for the dynamic warehousing environment. The system is designed to intelligently respond to changing data and goals, and continually develop efficient operating strategies. Blackboard systems also provide a flexible and modular structure for developing application expert systems. Knowledge sources can be created, modified, or removed independently when developing an application system (Hayes-Roth 1985).
Disadvantages of blackboard systems are their complexity and high computational and storage costs. These features make them inappropriate as a final version for some high performance application systems. The usefulness of blackboard systems is in providing a flexible and modular environment for developing an application expert system. The developed expert system can later be compiled for use as an efficient application system (Hayes-Roth 1985).

Figure 5. Blackboard control loop for automated warehousing.
A SIMPLE EXPERT SYSTEM AND A SIMULATION

To examine the use and efficiency of expert systems for AS/RS control, a simple expert system was constructed and a simulation performed. The expert system was constructed using EXPERT-EASE, a microcomputer based software package. EXPERT-EASE uses a spreadsheet format that allows users to input problem examples from which the system deduces its operating rules. EXPERT-EASE also allows individual expert system files to be developed and linked together to facilitate larger, multiple decision problems. After the expert system has been developed, the system queries the user for needed information and outputs decision advice (Derfler 1985).

The simulation involved the operation of one storage and retrieval shuttle with the capability of storing or retrieving two items per cycle. The storage and retrieval shuttle serviced one side, one row of a three-high vertical storage bay. The shuttle operated on a single command cycle which limited each cycle to either a storage or a retrieval. A storage cycle began at the pick up and delivery station. The shuttle picked up its loads, traveled to the storage locations, deposited the loads, and returned empty to the pick up and delivery station. A
retrieval cycle also began at the pick up and delivery station. The shuttle traveled empty to the retrieval locations, picked up its loads, and returned to the pick up and delivery station to deposit the loads (Salvendy 1982).

The storage and retrieval shuttle travel was a separate vertical and horizontal operation. A constant horizontal velocity of 350 fpm and vertical velocity of 60 fpm were assumed (Thompkins and White 1984). The cycle travel distance was from the pick up and delivery station to the bottom middle of each storage location, and back again to the pick up and delivery station. A constant allowance of 0.2 minutes was added to each cycle to allow for pick up and deposit of loads. The total time required for a cycle was therefore:

$$T_h + T_v + T_c$$

where

$$T_h = \text{time required to travel horizontally from the P/D station to both storage locations and back again}$$

$$T_v = \text{time required to travel vertically from the P/D station to both storage locations and back again}$$

$$T_c = \text{time required on each cycle for pick up and deposit of loads}$$

This formula was used to compute cycle time for both storage and retrieval operations (Salvendy 1982).

Twelve different items of three different size/weight categories and three different turnover rates were used in
the simulation. High turnover items occurred with twice the frequency of medium turnover items and medium turnover items occurred with twice the frequency of low turnover items. Four pairs of the twelve items were related to one another in the sense that they would occur together in the flow of incoming and outgoing materials. The number of items available on each cycle for storage or retrieval randomly varied between two and six. Figure 6 shows the warehouse layout used for the simulation.

Figure 6. Warehouse simulation layout.
The expert system was constructed with multiple types of rules that addressed the different warehousing decision areas. Rules used for determining the warehouse configuration were:

1. Configure the warehouse in three zones, one for each item turnover rate

2. Let the closest zone be for high turnover items, the middle zone for medium turnover items, and the far zone for low turnover items

The purpose of the warehouse configuration rules was to provide an organization strategy that allowed faster moving items to be stored progressively closer to the front of the warehouse.

Rules used for sequencing storage and retrieval requests were:

1. IF two items in the storage queue can be stored in zones that correspond to their turnover rate THEN select a store for the cycle

2. IF rule 1 cannot be executed AND two items in the retrieval queue can be retrieved from zones that correspond to their turnover rate THEN select a retrieve for the cycle

3. IF rules 1 and 2 cannot be executed AND the storage queue contains the most items THEN select a store

4. IF rules 1 and 2 cannot be executed AND the retrieval queue contains the most items THEN select a retrieve; break ties by selecting the opposite of the last cycle

The purpose of these sequencing rules was to select a sequencing order that would maximize items being stored in their respective zones and thereby increase throughput.
Rules used for selecting specific items to be stored on each cycle were:

1. IF two high turnover items are available for storage THEN select these two items to store
2. IF rule 1 cannot be executed AND two medium turnover items are available for storage THEN select these two items to store
3. IF rules 1 and 2 cannot be executed AND two low volume items are available for storage THEN select these two items to store
4. IF two items that are related to each other are available for storage THEN select these two items for storage
5. IF rules 1, 2, 3, and 4 cannot be executed THEN select the two items that require the least cycle time to store in the warehouse

The purpose of these storage selection rules was to select item pairs for storage that were related or of the same turnover rate. When this was done, these items could be stored together in the same zone and cycle travel time was minimized.

Rules used for selecting items to be retrieved on each cycle were:

1. IF two high turnover items are available for retrieval THEN select these two items to retrieve
2. IF rule 1 cannot be executed AND two medium turnover items are available for retrieval THEN select these two items to retrieve
3. IF rules 1 and 2 cannot be executed AND two low volume items are available for retrieval THEN select these two items to retrieve
4. IF two related items are available for retrieval THEN select these two items to retrieve
5. If rules 1, 2, 3, and 4 cannot be executed THEN select the two items that require the least cycle time to retrieve

The purpose of these retrieval selection rules was to select item pairs for retrieval that were related or of the same turnover rate. These types of item pairs would have been previously stored together when the storage selection rules were executed. When a retrieval occurred, the items were retrieved together from the same zones they were previously stored in. This combination of storage and retrieval rules resulted in decisions that increased system throughput.

Rules used for selecting storage and retrieval locations on each storage cycle were:

1. Store each item in the closest open location in its corresponding zone

2. IF rule 1 cannot be executed THEN store each item in the closest open location in the warehouse

3. Retrieve each item from the closest available stock location in the warehouse.

The purpose of the storage location selection rules was to keep stored items in their corresponding zones whenever possible. Total system throughput was increased by storing items in zones that corresponded to their turnover rates. The purpose of rule 3 for retrieval location selection was to minimize retrieval cycle time.

The above decision rules were input to EXPERT-EASE and eighteen linked files were developed to drive the
expert system. The system queried the user on each cycle for the current warehouse condition data, the length of the storage and retrieval queues, and information concerning the items available for storage or retrieval. The expert system output was: (1) the store or retrieve decision for each cycle, (2) which items to store or retrieve, and (3) the specific places in the warehouse in which to store items or from which to retrieve items.

A simulation was run to compare the expert system's performance with a typical AS/RS control system that stores items in the closest open location in the warehouse, and retrieves items from the closest available stock location. In an actual control system, a system bit map is maintained in which full and empty locations are designated for each aisle. The system selects the location requiring the least travel time based on precalculated tables (Hartman Material Handling Systems 1985). The system used for the simulation selected a store or retrieve based on servicing the queue that contains the most items. The system selected the first two items in the queue that can be stored or retrieved on each cycle.

A BASIC program was written to display the current warehouse condition, to display the storage and retrieval queues, to input data for each cycle, and to compute cycle
time. The measure of performance used to compare the two systems was material throughput, the number of items that could be processed through the system in a period of time. Throughput is a key performance measure in warehousing systems and is considered the bottom line for system success (Kulwiec 1982).

Three separate trials were run to compare the two systems. The warehouse was filled to eighty percent capacity at the beginning of each trial. One hundred items from identical, randomized streams of storage and retrieval materials were processed through the warehouse on each trial. The results of the three trials comparing the two systems are shown in Figure 7. System 1 (S1) refers to the AS/RS control system using closest locations for storage and retrieval. System 2 (S2) refers to the AS/RS expert system.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Total time S1 (minutes)</th>
<th>Total time S2 (minutes)</th>
<th>Percent throughput increase S2/S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24.28</td>
<td>22.07</td>
<td>9.10</td>
</tr>
<tr>
<td>2</td>
<td>23.95</td>
<td>21.79</td>
<td>9.02</td>
</tr>
<tr>
<td>3</td>
<td>24.49</td>
<td>22.04</td>
<td>10.00</td>
</tr>
</tbody>
</table>

Figure 7. Simulation results.
The AS/RS expert system produced a significant increase in throughput for each of the three trials. An average percent increase of 9.37 was obtained by the expert system for the three trials. The AS/RS expert system produced increased efficiency of operation because of the intelligent rules programmed into the system. Throughput was increased due to: (1) the system's ability to sequence storages and retrievals in a manner that minimized cycle times, (2) the system's ability to store items in a manner that kept them oriented in the warehouse according to their turnover rate and relationship to other items, and (3) the system's ability to effectively respond to changing data by means of its multiple rule structure.
FUTURE RESEARCH AND CONSIDERATIONS

Automated warehousing systems are an important component of the total manufacturing system and will play a key role in the development of the completely automated factory of the future. Because of the complex problems that exist in the warehousing environment and the strategic place of the warehousing function, there is a great need for research in this area.

Expert systems technology offers the potential for solving the types of decision problems encountered in the dynamic warehousing environment. Development of a large scale expert system for AS/RS control is needed to fully test the potential and usefulness of expert systems technology in the warehousing environment. A large scale expert system would enable simulation and testing of different expert warehousing strategies under a broad range of data and performance criteria.

A large scale expert system model would provide a means of developing and testing advanced warehousing features. New warehousing techniques and strategies are needed to keep pace with ever increasing advances in factory automation. Research and development of advanced
Warehousing technologies is needed for the factory of the future to become a reality (Thompkins and White 1984).

Several problem areas exist for future advances and development of expert systems. Better methods are needed for efficient transfer of expert knowledge to computer programs. Identifying and encoding expert knowledge is one of the most complex and difficult tasks in constructing an expert system. Present methods of transferring knowledge are often very time consuming. Better programming languages are also needed for representing and capturing the intricacies of expert knowledge (Duda and Shortliffe 1983).

Further advances are needed in computer technology to extend the usefulness and application of expert systems. Fifth generation computers with parallel processing capabilities give promise of increased computational speed needed for efficient operation of large scale expert systems. More powerful computers will enhance the development of efficient application expert systems with large knowledge bases (Hayes-Roth 1985).
CONCLUSION

Expert systems technology provides an effective tool for decision making in the dynamic environment of automated warehousing. These intelligent computer programs can capture human knowledge and expertise for use as efficient planning and control systems. A blackboard architecture provides a flexible and responsive control system for the dynamic warehousing environment. A blackboard model provides a control loop for executing basic warehousing decisions and for constructing comprehensive warehousing strategies. The AS/RS expert system constructed using an expert system software package produced increased material throughput in a simulation when compared to a typical AS/RS control strategy. The increased throughput resulted from the multiple intelligent rules programmed into the system.
LIST OF REFERENCES


Han, Min-Hong; McGinnis, Leon F.; Shieh, Jin Shen; and White, John. On Sequencing Retrievals in an Automated Storage/Retrieval System. Atlanta: Georgia Institute of Technology, [1984].


