# EXPERT DECISION SYSTEM FOR ROBOT SELECTION

As research fields in artificial intelligence (AI) accelerate and a greater number of experts are demanded by industry, expert systems play an important role in meeting the technological sophistication required in today's competitive world. Industries are demanding the assistance of human experts in solving complicated problems. However, there is a shortage of experts due to this demand. Expert systems are rapidly becoming one of the major tools to solve engineering and manufacturing related problems. They have been implemented for

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

several practical applications in many decision-making problems. Expert systems are helping major companies to diagnose processes in real time, schedule operations, maintain machinery, and design service and production facilities.

Robots are an integral part of today's manufacturing environment. New tasks are being defined for robots in order to meet the challenges of flexible manufacturing systems. Robots are entering every facet of manufacturing. Along with this growth there is an increasing variety of robots from which to choose. One of the major problems facing the potential robot user will be the choice of the right robot for a particular task. Various parameters should be considered and the user should choose an industrial robot whose characteristics satisfy the requirements of the intended task.

This article will present a viable solution to the problem of selecting an optimum robot, by building an expert system using a LEVEL5 shell. The system will ask the user several questions regarding the function and requirements of the desired robot. It uses its knowledge base and the developed rules to determine and select an optimum robot for the operation. If this analysis leads to more than one robot, then a test for economic feasibility of the suggested robots is performed and ranked. Based on this, the robot with the most economical characteristics will be selected.

Automation is a technology concerned with the application of mechanical, electronic, and computer-based systems to operate and control production. Table 1 lists the levels associated with automation technology.

The tactical and strategic advantages associated with the application of automation may include: (Engelke, 87).

Enterprise tactical objectives:

- Increased productivity and consistency
- High process quality
- Less lead time
- Cost reduction

Enterprise strategic goals

- Be adaptive to environmental change and make the enterprise more competitive
- Provide in-time and high quality information, which will help with the decision making process
- Cultivate global optimism within the organization
- Increase the market share and give back more profit

**Table 1. Automation Categories**

| Automation Levels | Description |
|---|---|
| Fixed automation | Suitable for high-volume and low-variety production. Equipment is specially designed without flexibility for a specific job |
| Programmable automation | General equipment that can accept different configurations. Different parts settings can be accomplished by program stored in computer |
| Integrated automation | This kind of automation includes every department in a manufacturing firm, from designing, producing, to testing and marketing |

Computers have had a dramatic impact on the development of production automation technologies, as illustrated in Fig. 1. Today, all modern production systems are computer-based and use computers as the control and supervisory system (1). Table 2 lists these applications.

## ECONOMIC JUSTIFICATION OF AUTOMATED SYSTEMS

Three approaches are used for economic justification and analysis of automated systems. These are accounting (economic), analytic and strategic approaches. These models are further developed into categories and methods (2). This is illustrated in Figure 2. The economic method focuses on the short-term objectives and returns. They can be generalized by the equation:

$$\text{Cash flow} = \text{Benefits} - \text{Costs} \tag{1}$$

This approach focuses only on the cost versus benefit analysis and it is often used for single-objective analysis. The results generated could provide the economic results that are used as the indicator for the selection of the automated equipment. Although these methods provide simplicity in analysis, the economic approach has some disadvantages:

- It is unable to capture the noneconomic factors. These "hidden" factors are critical in the selection of automated systems. (e.g., long-term competitiveness).
- Decision is based on a single value. More information may be required to support or reject a proposal. Real-world problems not only require decision making, which may include multiple objectives, but also these objectives may be conflicting.

Comparing with the economic approach, the analytical approach is more complex and is capable of considering factors, which could also have subjective characteristics. It could reflect more realistic scenario which are easier to understand by managers (2). The results are quantitative, while the inputs are often qualitative (e.g., reliability, flexibility). These qualitative terms are the objective(s) that a project is to accomplish. The analytic approach converts degree of fulfilling these objectives into numbers and, based on these values, the best project (or several projects, named "candidates") can be determined. There are three categories of analytic approach. These are:

1. *Value Analysis.* Value analysis is often used in evaluating technical innovations. It is a two-step process composed of Pilot and Build stages (2). In the pilot stage, a small but complete scale of the innovation is evaluated. Based on the analysis results generated from the pilot stage, a decision will be made to initiate the build stage or not. In build stage, full development of system is considered. Both costs and additional benefits are determined carefully and benefits are compared with costs to see if the system is economically feasible. Value analysis provides an incremental approach toward system justification, thus reducing risks.
2. *Portfolio Analysis.* The portfolio analysis is categorized into three methods. These are nonnumeric methods,

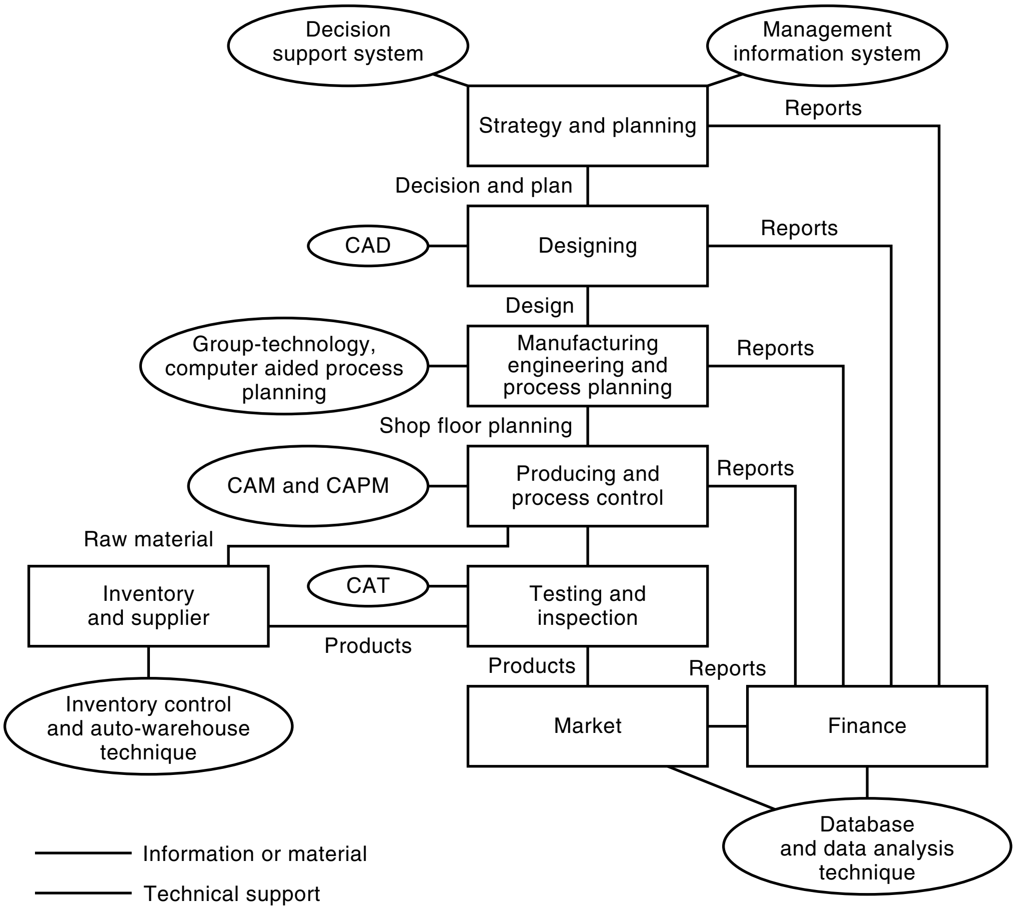

**Figure 1.** Business flow in manufacturing systems.

scoring methods, and programming methods. The nonnumeric methods are often based on the subjective opinion of senior officials (“sacred cow” method) or the necessity by operation condition (e.g., If the machine is not purchased, the whole production line will shut down). In the scoring method, a set of factors are selected as objectives. Each objective is rated indicating to what level each should be achieved. Each system or candidate will be measured against these objectives and a score for each objective is generated. For unweighted methods, the sum of these score will provide the final score of a candidate. For weighted methods, each objective is given a weight, and the final score is calculated as follows:

$$V_j = \Sigma W_i X_{ij} \tag{2}$$

**Table 2. Computer Applications at Different Levels**

| Levels | Computer Techniques | Hardware Required |
|---|---|---|
| Operation level | CNC, Robotics, CAT | PC, single chip computer |
| Middle level | CAD, CAPP, Group Technology, MRP | PC, workstation |
| Management level | MIS, DSS | PC, workstation, sometimes mini- or mainframe computer |

where

$V_j$ = score for the $j$th alternative (candidate)
$W_j$ = weight assigned to the $i$th decision criterion (objective)
$X_{ij}$ = rating assigned to the $i$th criterion, which reflects the performance of alternative $j$ relative to maximum attainment of the criterion

The analytical hierarchy process (AHP) is a complex scoring method. This method allows pairwise comparison between objectives. This comparison is also performed for candidates. Hence, the often called “human judgment inconsistency” (inconsistency emerged in comparing more than two terms, say, $A>B$, $B>C$, $A<C$) is eliminated.

Programming methods are based on scoring methods. Integer programming represents each candidate in a 0–1 variable. The candidate that has the highest score subject to certain constraints is the one selected. In goal programming, multiple and conflicting goals are used for selection. By using an ordinal priority for these goals, the conflicts are resolved. The goal programming method is widely used because of its robustness.

3. *Risk Analysis.* Risk analysis is a statistical method. It simulates the candidate project considering the benefits, costs, capacity, and so forth, and gives out the cu-

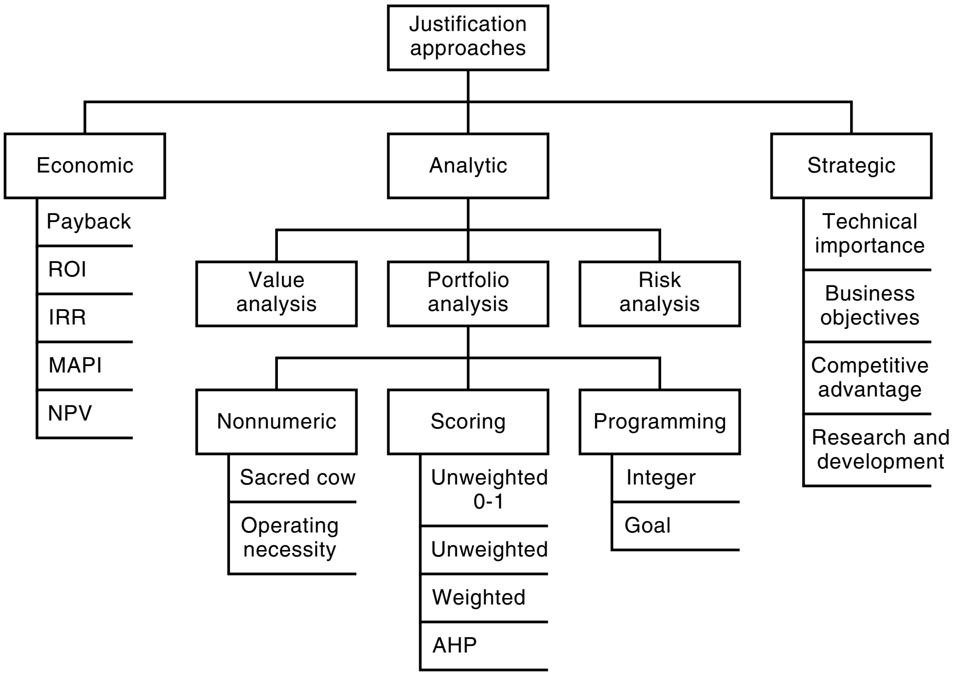

**Figure 2.** Justification techniques and methods.

mulative distributions of these variables. Using the stochastic procedure, inferior candidates will be eliminated (2).

Strategic approach is concern toward the goal of the whole organization. It is considered less technical; sometimes it overlooks the economic aspects. There are a number of methods in this category. These are Technical Importance, Business Objectives, Competitive Advantage, and Research and Development.

Different automation technique will require different justification approaches. Systems could be divided into three categories (2):

1. Stand-alone systems (e.g., robots or NC tools)
2. Linked systems (e.g., robots and NC tools, CAD/CAM)
3. Integrated systems (e.g., FMS, CIM)

Stand-alone system usually apply the economic approach. The critical point associated with applying the economic approach is how to establish and collect the parameters required in the analysis formulas. Linked systems are more complicated, often requiring the analytic approach so that different objectives can be coordinated and different projects could be evaluated. Integrated systems mainly focus on the goal of the whole enterprise and, therefore, the strategic approach is suitable.

Portfolio methods are most common in the analytic approach. Among them, the weighted evaluation method and AHP are recommended, since objectives are sometimes conflicting and should be handled in priority order. AHP can eliminate the inconsistency and promote accuracy. AHP can be used in implementing different technologies in linked system.

The strategic approach is applied at the top executive's level. The methods in this category are nonmonetary. The strategic approach is often combined with the economic approach. An investment slow in return, from any point, is not a good one.

As a whole, justification is a difficult and in some cases a subjective task. There are a number of general guidelines for performing this task.

1. Evaluation should be geared toward the whole system, not just part (3). The whole system's justification will provide a clear view of the global optimum, streamlining accomplishments.
2. Get a thorough analysis of the manufacturing operation. Discover hidden costs and savings by evaluating all possible variables.
3. Understanding the system. Different systems require different methods. Advantages and disadvantages of different methods should be considered.
4. Traditionally the economic analysis was performed by consultants. Engineers and users were not part of this cycle. A thorough understanding of the task requires knowledge of both engineering and accounting. A multidisciplinary team should be formed in the early stages of justification.

## PROBLEM STATEMENT

Industrial robots are major contributors to the automation technology. An industrial robot is a general-purpose, programmable machine, possessing certain anthropomorphic characteristics. However, RIA, the Robot Institute of America, has defined a robot as "A re-programmable multi-functional manipulator designed to move material, parts, tools, or special devices through variable programmed motions for performance of a variety of tasks". According to this definition, robots can be classified as a programmable automation device, where the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations. There is no industry standard for the classification of robots. Although, in general, robots have been classified based on the basic configuration of the manipulator, which includes the body, arm, and wrist, they have also been categorized by their reach, controller capability and its intelligence, load-carrying capacity, applications, drive systems, and the operation's ease and speed of programming. The direct impact of technology on robotics has introduced other means of classification for robotic systems. These may include on-board computers, on-board memory storage devices, and devices for outside interaction and interlocks which add to the robot's intelligence.

As manufacturing turns more toward automation in order to reduce costs and improve productivity, there will be more aggressive implementations of computers and artificial intelligence (AI) capabilities. Artificial intelligence is associated with the application of computers in performing problem-solving and real-time decision making. This discipline began in the early 1950s and requires computers to perform logical reasoning and scientific manipulations. At the early stages of development, AI was applied to solve pure academic problems such as inferring math theorems. But later on it was used in medical diagnosis, natural language comprehension, and pattern-recognition problems. Reasons that AI could be well adapted as a decision-making tool into industry are:

1. *Scarcity of Expertise in a Certain Domain.* Often an expert will be unavailable in the future and the company requires to retain and maintain that expertise.
2. *Decision Complexity and Timeliness.* Companies are becoming larger and more complicated. This issue brings a large number of decision-making problems to each level (e.g., engineers have to choose how to design new products; managers have to choose how to plan and schedule).
3. *Information.* The vast amount of information which must be processed and analyzed every day. Data-mining techniques could facilitate this issue.

Expert systems (ES), an AI branch, has begun to prove its potential for solving important problems in engineering and manufacturing environments. Many applications of ES can be found in manufacturing areas. ES can provide assistance during the scheduling of activities in a job shop, detailed planning of machine operations and facility layouts, the monitoring of thousands of process variables, maintenance, and fault diagnosis of equipment. Implementing advanced technologies such as AI and ES is challenging and difficult, as outlined by the following:

- Economical feasibility—Can the company afford the new technology?
- Function analysis—Will the new technology fulfill the expected function?
- Evaluation criteria—How to evaluate the new technology (top managers) so that it will bring great benefit in the long run?
- Expertise—When the new technology is implemented, there will be a need for technical maintenance and administration people.

In a factory robots are assigned a certain job and utilized in ways that increase productivity, quality, and safety. The selection of a particular robot from the wide variety of what is available should be well planned and structured. The selection process may also have to accommodate some multiple conflicting objectives such as economic issues, simplicity, and flexibility. A well-designed expert decision support system could provide the potential for resolving such issues.

## ROBOTICS AND INDUSTRIAL ROBOTS

Robotics is the scientific discipline associated with the design, development, and application of robots. It includes:

1. *Mechanics.* Design and implementation of hardware. This includes the configuration, the material of which it is composed, the actuator and power. The mechanics' role in robotics science is to convert design ideas of a robot into a concrete entity.
2. *Applied Mathematics.* The movement and control for a robot are always based on the same mathematics model. This mathematical model is implemented using vector algebra and trigonometry. It indicates the position and interrelationships among different parts within the robot.
3. *Automated Control.* The discipline of control theory plays an important role in robotics. Control methods depend on the specific mathematical model used.
4. *Computer Science.* Computers are used due to speed and high memory capacity. Hardware and software are both considered. Hardware is rapidly changing from single computer chip to minicomputers and software is becoming more sophisticated and user friendly.

The robotics concept was introduced in the early twentieth century. During the 1960s, robots begun to be used in industry as laborers. They were selected to perform simple tasks in hazardous conditions. With further development of computer science and technology, robots now could carry out different and complex activities that could consist of intelligent thinking and reasoning. Robots are different in their appearance, function, and operation mechanics. Yet they all belong to the family of automatic machinery. They consist of common components. A general form of any machine is presented in Fig. 3 (4).

Energy represents the driving force of the machine and the tool portion and the control section of this structure provide the means for executing instructions. The tool portion of the

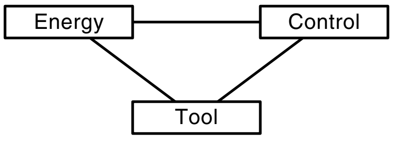

**Figure 3.** Components for machines.

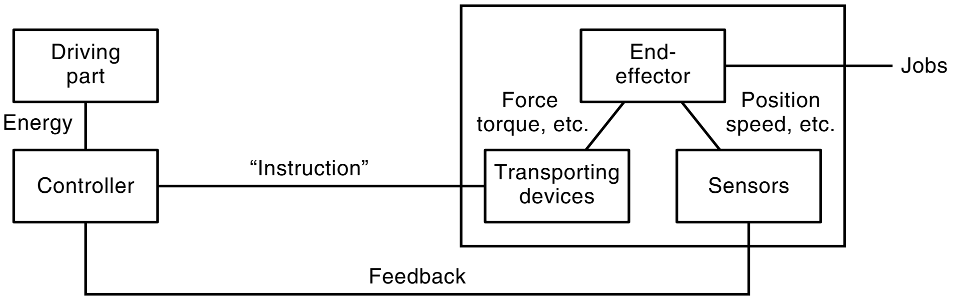

**Figure 4.** Components of a simple robot.

structure follows the controlled instructions. Figure 3 is further detailed in Fig. 4, illustrating robot structures and components.

### Manipulator and Anatomy

The basic robot's manipulator consists of the body, arm, and wrist. An extension to the wrist of the manipulator is used for the orientation of the end-effector, which consists of either grippers or tools. The volume of the area that these components will cover is known as the "work envelope," and it consists of the area in which the robot is capable of performing the required task. The shape of this area varies with the robot's configuration. This difference in shape is important in the selection of the appropriate robot for a given task. A description of an industrial robot's anatomy focuses on the physical structure of the robot, which includes the size of the robot, type of joints, and links. A joint in an industrial robot provides relative motion between two parts of the body. Each joint will create a degree of freedom for the robot and provide the robot with the capacity to move its end-effector to the desired position (5). Robots are often classified according to the total number of degrees of freedom they possess. The mechanical joints commercially available for robots fall into four categories.

1. *Linear and Orthogonal Joints.* The linear joint involves a sliding motion or translational motion of the connecting links. The axes of the input and output are parallel in linear joints. The motion of the axes is achieved by a telescoping mechanism or relative motion along a linear track or rail.
2. *Rotational Joint.* In a rotational joint, the axis of rotation is perpendicular to the axis of the two connecting links.
3. *Twisting Joint.* This type of joint requires a twisting motion between the input and the output links. The axis of rotation is parallel to the axes of both links.
4. *Revolving Joint.* In a revolving joint, the input link is parallel with the axis of rotation of the output link, and the output link is perpendicular to the axis of rotation.

The robot's wrist provides the end-effector the required orientation of the part and consists of three degrees of freedom. These are: *Roll* (rotation of the wrist about the arm axis), *Pitch* (up-and-down rotation of the wrist), and *Yaw* (right-and-left rotation of the wrist).

The shape of the work space (work envelope) depends on the type of robot's configuration. Industrial robots are classified into five categories based on their physical configurations (6). These are:

### Configurations

1. *Cartesian or Rectangular Configuration.* All the motions performed by this type of robot are along three linear and orthogonal axes. These robots are also known as pick-and-place robots. Due to their configuration, they have been used for assembly operations that require high accuracy for the positioning of components. The work volume of these robots describes a rectangular box within which work is performed.
2. *Articulated or Jointed Arm Configuration.* A series of revolving and rotary motions is used in order to move the manipulator in this type of robot. This robot's configuration is similar to the human arm and its motion. The work volume of robots with this configuration is irregular, which makes it possible for these robots to perform a variety of tasks. Due to the flexibility provided by this type of configuration, the manipulator can also reach over and under objects to perform tasks. Robots of this type are used for process operations such as coating and welding. In some cases, they have also been used for assembly and material handling.
3. *SCARA (Selective Compliance Assembly Robot Arm) Configuration.* This configuration is similar to the jointed arm with the exception that the shoulder and the elbow rotational axes are in the vertical position. This robot is used for insertion-type assembly operations in which the insertion is made from above.
4. *Cylindrical Coordinates.* These robots have two linear and orthogonal motions with a rotary base. This provides the robot with rapid motion for operations. The work envelope of this robot is cylindrical, and the maximum and minimum reach of the robot determines the maximum and minimum size of the work volume. This type of robot has been used for material handling operations mostly in the area of machine loading and unloading. They have also been used for applications such as assembly and pick-and-place.
5. *Spherical Configuration.* The work volume generated by this robot describes a sphere. These robots consist of two rotational axes and one linear axis. Robots of this type have the lowest weight and the shortest joint travel compared with the other forms of robot configuration. They have been used for material handling operations due to the large area that they can cover.

### Drive Systems

Joints of industrial robots are moved by actuators powered by a particular form of drive system. The drive systems are of three types: (1) pneumatic, (2) electric, and (3) hydraulic.

1. *Pneumatic Drives.* These are the simplest and cheapest of the drive systems used in robotics. Due to their lack of accuracy and repeatability, and lack of control within intermediate positions, pneumatic drives are used in the simplest robotics applications, such as pick-and-place operations. The advantages of using pneumatic drive systems are their low cost and low maintenance requirements.
2. *Electric Drives.* dc-servo (direct current) and stepper motors are the two types of electric drive systems used in robots. These drive systems can provide precise positioning with high torque. These motors are reliable and clean. Due to the low cost associated with electrical devices, these drives will be the principal system used for the robotics of the future. Stepper motors are manipulated by a series of electric pulses which control the number of revolutions made by the motor's shaft. This type of motor is not as sophisticated as the dc-servo motor and has limited performance capabilities. The advantages of electric drive systems are their high accuracy, repeatability, low cost, smaller size, and ease of maintenance.
3. *Hydraulic Drives.* These types of drive systems are designed for heavy-duty tasks since they can provide high power which results in high strength and speed. Hydraulic-drive systems were used in early robots. They are still in use, but they are criticized for their high noise level, large size, and high maintenance cost. After time, these drive systems tend to leak and the chemical compound in the fluid may be hazardous to the operator and the working environment.

### Programming Techniques

In order for the robot to perform a desired task, information such as operating coordinates and conditions must be provided. This information must be taught by a programmer and recorded by the controller. Most robots are equipped with a teaching module which assists the programmer during this task. Two methods of programming are used.

1. *On-line Programming Approach.* The on-line approach, also known as teaching by showing, is a process in which the robot is manually manipulated by the operator through the desired task while recording the coordinates and conditions. Teaching using this approach will require the programmer to take the robot off the production line, which results in loss of production time. The on-line programming technique is further divided into manual and lead-through programming.
   - In the manual technique, the manipulator is maneuvered through the desired points using a teach box, also known as teach pendent. A series of buttons and joysticks is used to control the robot's motion and to direct the end-effector through the desired path.
   - Lead-through programming requires the operator to physically grab the robot's arm and maneuver the robot through the desired path. In this form of teaching, the path of the required task is being recorded by the controller. This method of programming has been used for applications such as spray painting and welding, where the operator has the knowledge and the experience of the proper path and operating conditions. The speed of operation is controlled during the teaching phase in order to provide the required safety for the operator.
2. *Off-line Programming Approach.* In this approach, the program is written and developed without the presence of the robot. Programs are developed while the robot is still in operation, therefore the down-time of the robot is reduced. This method of programming is beginning to receive the attention of system designers and programmers, due to the increased complexity of the robot's controllers and tasks.

### Controller Unit

The main function of the controller unit is to direct the manipulator and the end-effector through a defined position, while maintaining the required orientation and speed. This unit is capable of controlling the robot's motion either in point-to-point or point-to-point with continuous path (7). The trajectory of the robot's path in the point-to-point method is defined and planned by the controller. The programmer cannot define the trajectory, although a set of intermediate points can be used to define an approximate path. Speed of operation relative to accuracy and repeatability is an advantage of using this form of control.

In point-to-point with continuous path control, the trajectory of the robot's motion can be defined by the operator. This technique is also known as walk-through continuous path, in which the robot emulates the motion of the operator's hand. This technique is required for tasks such as painting and arc-welding. The controller's path is achieved by recording while the operator is leading the end-effector through the desired path.

The advent of technology has enhanced the capability of the robots by providing new functions with which the operator can both teach the coordinates and define the trajectory of the motion. This method is known as the controlled path, where a series of mathematical tools are provided to the robot's controller. In this situation, the operator defines a series of points, and the required path of motion is generated by the computer.

### Precision of Movement

As a measure of performance for industrial robots, the precision of movement is used (8). The precision of movement is classified and defined as the following functions:

1. *Accuracy.* Accuracy is defined as the robot's ability to position its wrist end at a desired target point within the work volume. It relates to the robot's capability to be programmed in order to achieve a given targeted point.
2. *Repeatability.* Repeatability of a robot is defined as the robot's ability to position its wrist or an end-effector attached to the wrist at a point in space that had pre-

viously been taught to the robot. Repeatability is usually considered more important than accuracy.

3. *Load Capacity.* Load-carrying capacity of a robot is dependent on its physical size, configuration, construction, and drive system. This capacity ranges from 1 pound to several hundreds of pounds. Robots usually work with tools or grippers attached to their wrist, hence the net load carrying capacity of the robot is reduced by the weight of the gripper. The manufacturer's specification of this feature is the gross weight capacity.
4. *Speed.* The speed determines how quickly the robot can accomplish a given work cycle. The speed capabilities of current industrial robots range up to a maximum of 5 ft/s.

Other factors considered important in robotic systems are their hardware capabilities, which include:

1. *Memory Capacity.* Some robots have slow access time memory devices such as cassette tapes and disk drives. The advent of new technology has provided robotics systems with on-board processors and high-speed memories such as ROM, RAM, and EPROM. Use of high-level languages and operating systems could provide very efficient utilization of available memory capacity.
2. *Interface (input / output) Capacity.* Interfaces are the robot's connections to the external world for integration and communication. Signals must be received from auxiliary equipment, computers, and sensors. Often, the robot is required to signal the completion of a task or motion, so other actions can take place. The major provision in I/O communication is the provision of correct interfaces to ensure the compatibility of signals and control information to and from the device attached to the system. A standard interface widely used in robotics is the RS-232 line.

## ROBOT APPLICATIONS AND CHARACTERISTICS

Industrial robots can be considered as substitutes for human labor under the following conditions (9):

- *Hazardous Work Environment for Human Operator.* Robots can substitute for human operators when the work environment is unsafe and hazardous for people. Hazardous work situations may include spray painting, welding, and forging.
- *Repetitive Work Cycle.* Another situation that normally promotes the use of industrial robots is a repetitive work cycle. If the steps involved in the work cycle are simple, the robot is often more suitable for the task than is a human operator.
- *Difficult Handling.* Handling operation tools and heavy loads are other situations in which an industrial robot can be considered as a good substitute for the human operator.
- *Multi-shift Operation.* When a firm operates on multi-shifts, finding qualified operators is often a time-consuming task. An industrial robot can easily be used for these situations.

Robotic applications are classified into the three categories. These include (1) material handling operations, (2) processing operations, and (3) other applications such as assembly and inspection.

### Material Handling Operations

The material handling task can be divided into two categories: material transfer, and machine loading/unloading. Material transfer applications are defined as operations in which the primary objective is to move parts from one location to another location.

- *Pick-and-Place.* In pick-and-place operations the robot picks up the part at one location and moves it to another. These operations are usually considered as the most straightforward robot applications.
- *Palletizing and Related Operations.* In palletizing operations, the robot picks up individual cartons or other containers and places them on a pallet. The pallets are then handled mechanically within the plant using some form of material handling device.
- *Depalletizing.* In this operation, the robot picks up cartons and places them onto a conveyor. The operation of inserting parts into cartons from a conveyor is very similar to palletizing, and the operation of removing parts from cartons is similar to depalletizing.
- *Stacking and Unstacking.* In this operation the objects, usually flat pieces such as metal sheets, are stacked on top of each other.
- *Machine Loading.* In machine loading applications, the robot loads the raw material into the machine, but the part will be ejected from the machine by some other means. An example of this situation is the press working operation.
- *Machine Unloading.* In this group, the machine is loaded without robot assistance, and the robot is used only for unloading the machine. Examples for this group may include die casting and plastic molding operations.

### Processing Applications

In processing applications, robots perform some form of operation on the part. For this group of applications, robots are equipped with tools rather than grippers. The processing operations are divided into the following categories:

- *Spot Welding.* In this operation two sheet metal parts are fused together at localized points by passing a large electric current through the parts where the weld is to be made.
- *Continuous Arc Welding.* Arc welding is a continuous welding process. In this form of welding, continuous weld joints are provided rather than the individual welds at specified contact points as in spot welding. The long welded joints made in this operation often form an airtight seal.
- *Spray Coating.* Spray coating is the most common form of robot application. The spray coating process makes use of a spray gun to apply the coating to the object. The fluid flowing through the nozzle of the gun is applied over the surface of the object. The use of robots with such

characteristics and features as continuous-path control, hydraulic drive system, manual lead-through programming method, and multiple program storage, is recommended for spray-coating operations.

## ECONOMIC JUSTIFICATION FOR ROBOTICS

To perform an economic analysis for an industrial robot, information must be gathered by engineers, users, and managers. This information must include the type of project, the costs associated with installing the robot, and the project life cycle. The installation of robotic systems in a company can be of two cases: (1) new application (i.e., in which no facility exists, and there is a need for a new facility. The use of industrial robots may be considered as one alternative approach to satisfy this need); and (2) substituting the existing production method with one or several robots and automated systems (i.e., in which operations are performed manually and the use of robots is somehow considered to be desirable. The usual approach in this case is to demonstrate that the current method is costly and economically inefficient).

To perform the economic justification and analysis, the analyst should gather two types of cost data. These costs include investment costs and operating costs. A list of investment and operating costs encountered in robot installation projects is summarized in Tables 3 and 4 (6).

Economic methods are used in industry to justify and evaluate the economic feasibility of robot installation and application. These methods may include Net Present Value Analysis (NPV), Internal Rate of Return (IRR), Benefit Cost Ratio (B/C), and the Payback Period (PP). From these methods, the payback period is still considered an effective approach and used by many industries to justify the feasibility of their projects. In this method, the length of time required for the net accumulated cash flow to equal the initial cost is determined. A project is considered acceptable if the payback period is equal to or less than some predetermined time set by the management.

## ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) is no longer simply an emerging technology that is *in* one day and *out* the other. It is, in fact, a reality which not only has the ability to provide a major impact on industry, but also is doing so on a daily basis. As AI assumes characteristics of intelligence which involve reasoning, understanding, learning, and deduction, it also assumes the ability to replace the human decision-maker. This aids in realizing levels of automation and CIM as well as providing solutions to specific tasks and problems.

**Table 3. Investment Costs in a Robot Project**

| Cost | Characteristics |
|---|---|
| Robot purchase | Basic price of the robot needed to perform the desired application (The end-effector must be excluded from this price) |
| Engineering | Costs of planning and design by the user company's engineering staff to install the robot |
| Installation | Includes the labor and materials needed to prepare the installation site |
| Special tooling | Includes the cost of the end-effector, parts positioners, and other fixtures and tools required to operate the work cell |
| Miscellaneous | Covers the additional investment costs not included in any of the above categories |

**Table 4. Operating Costs in a Robot Project**

| Cost | Characteristics |
|---|---|
| Direct labor | Direct labor cost associated with the operation of the robot cell. Fringe benefits are usually included in the calculation of direct labor rate, but other overhead costs are excluded |
| Indirect labor | Indirect labor costs that can be directly allocated to the operation of the robot cell. These costs may include supervision, set-up, programming, and other personnel costs not included in category 1 |
| Maintenance | Includes the indirect labor (maintenance crew), parts, and service calls. It is recommended that annual maintenance cost in the absence of better data should be estimated on the basis of 10% to 15% of the purchase price |
| Utilities | Cost of utilities to operate the robot cell. This may include electricity and air pressure |
| Training | Cost of employees‘ training may be included in investment costs table. It is often said that training should be a continuing activity and, hence, it shall be included in operation costs |

There are many definitions of AI, but one which has been commonly accepted is that “AI deals with programming computers to carry out tasks that would require intelligence if carried out by humans.” Another definition of AI could be that it deals with tasks considered to require knowledge, perception, reasoning, learning, understanding, and other cognitive abilities. The goal of AI is a qualitative expansion of computer capabilities and, regardless of its precise meaning, it has been agreed that AI’s applications and its usefulness to industry have a definite and growing impact.

Programs which characterize AI are considered mostly symbolic processes that involve complexity, uncertainty, and ambiguity. On the other hand, conventional programming consists of algorithmic solutions that are primarily numeric. AI deals with more qualitative issues that are typical of human problem-solving and decision-making. In AI architecture a heuristic search approach is taken in order to arrive at the correct solution, and the solution steps are *implicit;* this is due to the large number of solution paths. However, in conventional programming, the solution steps are *explicit.*

One important element of AI is its ability for heuristic search, which encompasses the idea that once a decision has been made, the situation has changed, thus giving rise to new opportunities for further analysis and decision-making. This process is modeled using decision trees as representing the decision-making process with an initial condition and a subsequent branch for every decision thereafter. By further analyzing this chart, it is apparent that as one continues down the various branches of the tree, the number of decision possibilities increases greatly. For problems that require many solution steps, the number of branches can be enormous.

The problem-solving task is a set of actions taken in order to achieve a goal. The elements of a problem solver are the initial situation, a goal or a desired situation, a control strategy or generalized actions that can be used for changing situations, and a control strategy applied to the procedure for achieving the desired goal. Another important element of AI is knowledge representation. Researchers have determined that intelligent behavior depends more on the knowledge one has to reason with, rather than the method of reasoning. Therefore, methods to model knowledge efficiently are important. One method which has been practiced in developing and representing the knowledge is use of the production rules which provide a simplified modular technique to represent knowledge. Production rules have been considered as the basis for expert systems. The entire production system consist of the production rules, a global database which represents the system status, and a rule interpreter or control structure for choosing the rules to execute. The production rules consists of the domain facts as well as the heuristic for search. Knowledge is critical to high-performance intelligent systems. Two methods of knowledge representation are declarative or object-oriented (fact and representation) and procedural (actions).

## KNOWLEDGE-BASED EXPERT SYSTEMS

In the manufacturing environment, the need for expert systems arises due to the limitations offered by conventional programming and decision-making. Even though computers are a power source of information, they cannot provide human-like expertise. A method of distinguishing knowledge-based systems (KBE) from conventional programming follows:

$$\begin{aligned} \textit{Knowledge based system} &= \textit{Knowledge base} \\ &\quad + \textit{Reasoning engine} \\ \textit{Traditional program} &= \textit{Data} + \textit{Algorithm} \end{aligned}$$

KBS is sometimes called KB-Expert System. There are a number of reasons why the KBES is desired (10):

1. Once knowledge is captured into a KBS, it becomes permanent. Human experts are always prone to be unavailable; their knowledge and skills will vanish on this unavailability. Yet knowledge in KBS can be safely stored.
2. KBES can combine knowledge from different experts, and thus goes beyond the scope of a single expert.
3. KBES is always available and accessible, while human experts can be in remote places or otherwise occupied.
4. KBES can deal with a large amount of data. The speed and efficiency of KBES definitely outgo those of humans.
5. KBES has the interface to explain the procedure of reasoning and conclude the results. Hence it is a good tool for training personnel.

Expert systems offer an environment where the right and proper capabilities of humans and the power of computers can be incorporated to overcome many limitations offered by conventional decision-making tools. The major advantage of choosing expert systems lies in the fact that the manipulation of knowledge is possible using the expert systems, whereas the manipulation of data is possible with conventional programming.

Expert systems derive their name from the fact that the system contains the expertise required to solve specific, domain-related problems. The role of the program is to act as an intelligent consultant in the field of interest, capturing the knowledge of one or more experts. The nonexperts can then interface with the expert to answer questions, solve problems, and make the required decisions. The major strength lies in the fact that the presence of the expert is not needed. Like all artificial intelligence software, expert systems are knowledge-based systems containing facts, data, and relationships that are applied to solve a problem. What distinguishes expert systems from other AI software is heuristic knowledge and real-world data. Expert systems are organized in four unique components: (1) knowledge-base, (2) inference engine, (3) database, and (4) the user interface.

There are two methods of collecting and developing knowledge:

1. The conventional method, interviewing the experts or collecting information from technical books and other scientific publications, is composed of:
   - Develop the question sheet.
   - Interview the experts with the question sheet and collect the information.
   - Determine the knowledge representation format.
   - Transform the information gained to this format.

   There are two issues associated with this method. First is how to design the interview. The interviewers should have enough necessary background knowledge in order to collect and ask proper questions. Second, experts may also have some difficulty of expressing their expertise. Some decision may come out of intuition, rather than logic inference, which is also an important part of the development of the KB.
2. The random method of generating initial knowledge and more matured knowledge is developed by using procedures in learning and updating. The knowledge base is the core of the system. The knowledge base is not to be confused with the database. This module is created by the knowledge engineer, who translates real knowledge into rules and strategies. Depending on the problem scenario, these rules and strategies will change accordingly. For expert systems, knowledge can be represented through problem-solving rules, facts, predicate calculus, lists, frames, scripts, semantic nets, or intuitions that a human expert might use in solving a given problem domain. Through considerable experience, it has been determined that production rules are the most effective method used for representing knowledge for the expert systems. The IF-THEN rule format facilitates development of the rules in the knowledge base and, in turn, creates an impressive knowledge base quickly. Moreover, by applying production rules, modification and additions can be easily done. Once all the rules have been developed, they are stored in the computer memory, and the knowledge-base becomes the search space in which the inference engine works.

The self-learning approach in the knowledge-based system has the same goal as the learning feature of human. (In fact, self-learning is internal knowledge acquisition.) Learning is a complicated and psychological term. In practice, self-learning in a knowledge-based system will attempt to achieve one or more of the following goals (11):

1. Provide more accurate solutions
2. Cover a wider range of problems
3. Obtain answers more economically
4. Simplify codified knowledge

There are a number of self-learning methods available. A large portion of these methods concentrates on rule learning and generation. All self-learning engines have feedback mechanisms used for the evaluation of environment. Choosing the evaluation style is subject to system's goal.

The inference engine is a software that implements a search and pattern-matching operation. The inference engine is also known as the rule interpreter due to its operation which behaves similarly to a software interpreter. However, major differences exist. A language interpreter looks at each line of code in a program and then implements the operations specified, whereas the rule interpreter examines the rule in a specified sequence looking for matches to the initial and current conditions given in the database. As rules matching these conditions are discovered, the rules are executed, in turn initiating the actions specified by the rules.

As the execution of the rules continues, the rules will reference one another to form an inference chain. Each time a new rule is examined, it is checked against the current status of the problem solution stored in the database, new information is added, and the next rule is selected until a solution is reached. The inference engine also functions as a hypothesis testing station. When a hypothesis is given to the expert system, the inference engine first checks to see if the hypothesis is stored in the database. If it is, the hypothesis is considered to be proven fact and no further operation or action is required. However, if the hypothesis is not found, which is usually the case, it must be proven by inferencing. Two methods used by the rule interpreter to search for answers are forward chaining and backward chaining. Forward chaining starts with axioms and definitions and derives as many conclusions as possible. It is a data- or fact-driven approach. The rules in forward reasoning are of "IF condition THEN conclusion" format. Backward reasoning, however, starts with a goal and tries to accumulate enough facts to substantiate the goal. Therefore, it is a goal-driven approach. The rules in backward reasoning are of the form "conclusionl IF condition."

Another important part of an expert system is the database. The database is referred to as a global database due to its broad range of information about the current status of the problem being solved. Known facts are stored in the database initially. New facts are added to the database as the problem-solving process proceeds. Other data such as the initial conditions are also stored here. The inference engine begins its search by matching the rules in the knowledge base against the information in the database.

The final element of expert systems is the user interface. User interface is a software that allows the user to communicate with the system. With the use of questions and menus, the user interface allows the user to enter the initial information in the database. In general, the user interface serves as a communication channel between the user and the system. Figure 5 illustrates an overview of a KBE system

The problem of selecting an industrial robot using expert systems has been analyzed using a number of approaches. Some examples are:

*ROBOTEX—Choosing the Right Robot for the Job.* This technique requires that the user have an expert knowledge of the manufacturing processes to be automated using robots. This is an interrogative system which requires no knowledge of robotics. This system asks the user a series of questions about the manufacturing environment regarding subjects such as temperature, access, power supply, safety, and then the specific process itself. The system will evaluate the feasibility of robot usage, and then make the selection (12).

*TOWILL—A Production Engineering Approach to Robot Selection.* This methodology presents the production engineering approach to robot selection with the emphasis on the role of production engineer as systems designer. The types of available robots and the robot time and

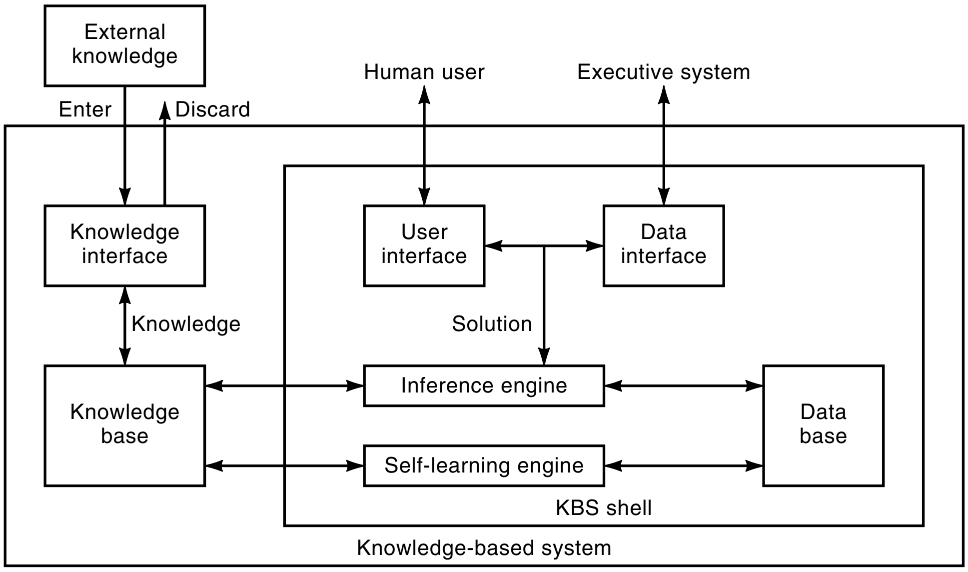

**Figure 5.** Overview of a KBE system.

motion study concept are provided along with the pitfalls faced by the production engineers in their specifications. This system further recommends an approach for throughput time estimation (13).

*ROSE—Robot Selection Expert.* This method requires the user to construct the environment in which the robot will be operating and conform to it by using 3-D modeling techniques. The user will choose from a menu and place the various objects with which the robot will have to interface. The system will query the user as to the characteristics of the desired robot and the expert systems will choose an optimum robot from the available choices in the database (14).

*ROBOSPEC.* This expert system is developed in OPS5 and designed for the selection of industrial robots based on the production system architecture. The system asks the user to select the proposed implementation of the robot and then searches through the encoded knowledge and provides the user with a broad outline of the specifications which a particular robot requires to perform a specific task. The system carries out the analysis and then provides the desired robot, based on the specifications set by the user (15).

*SPECIFICATION AND ROBOT SELECTION.* This model presents a methodology which addresses the robot selection problems by proposing a two-phase decision model that promotes the analysis and matching of robot technologies to tasks. An integer programming model and a rule-based expert system are developed for this task. The first phase (analysis) identifies the best set of robotics technologies that are required to perform the considered task. In the second phase (matching), a particular robot and accessories are chosen from a set of given options. The goal of this phase is to determine the best available robot to fulfill the required technology (16).

## SELECTION OF INDUSTRIAL ROBOTS

A knowledge-based expert system is developed to assist the expert user in the selection of an industrial robot for a particular task. This system takes into account the parameters specified by the user and performs the selection of industrial robot based on the specified parameters. The system is implemented using LEVEL5. An overview of the system architecture is illustrated in Fig. 6. The system architecture is as follows:

**Knowledge Acquisition.** The first step in the process of creating a knowledge base is to evaluate the issues involved in choosing an industrial robot. It is necessary to consult an expert and to review the literature in order to accomplish this task. Much of the information for this work was obtained from *International Robotics Industry Directory* and *Robotics Engineering Handbook* (17,18). As a result, the prototype expert system knowledge base consists of robots from companies all over the world. An important objective in data collection is ensuring that the information collected is accurate. When, for a given robot, a given piece of data could not be obtained, the robot was excluded from the relevant analysis.

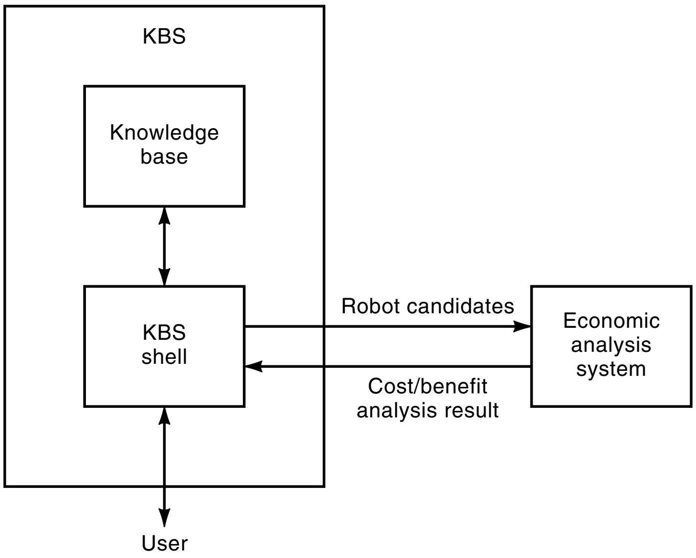

**Figure 6.** Overview of knowledge-based expert system architecture.

**Decision Tree.** The next step in creating a knowledge base is prioritizing the necessary criteria involved in choosing a robot. General information should be evaluated first, such as the type of application and load-carrying capacity, followed by more specific information, such as the memory capacity and type of programming requirements. The order of criteria has been summarized into a decision tree. The parameter Application is the general criterion and thus it is placed at the top of the decision tree. Branching down in the tree will increase the number of specifications, which, in turn, leads to a series of results which corresponds to the applications with the required specifications. A parameters listing used in a decision tree for palletizing and stacking tasks is illustrated in Fig. 7.

**Knowledge Base Development.** The third step in creating a knowledge base is translating the hierarchy of information from the decision tree into a language that the expert system's inference engine understands. This task is accomplished through the development of rules and parameters. Accompanying each parameter are possible choices that correspond to a characteristic of an industrial robot. Thus the expert system will ask the user a series of questions and will provide a selection of choices. An example is the parameter Load Carrying Capacity. The system will ask the user to specify the required load-carrying capacity, which requires a user response. The list of choices provided to the user is as follows:

```
Desired Load Carrying Capacity
   ?      Below 50 pounds
          50-100
          100-150
          150-200
          Above 100
```

Rules are lists of if-then-else statements that define the criteria that lead to the choosing of an industrial robot. Following directly from the ordering of the parameters contained in the rule, the user is prompted with the question that corresponds to the first parameter (in this case, application is the first

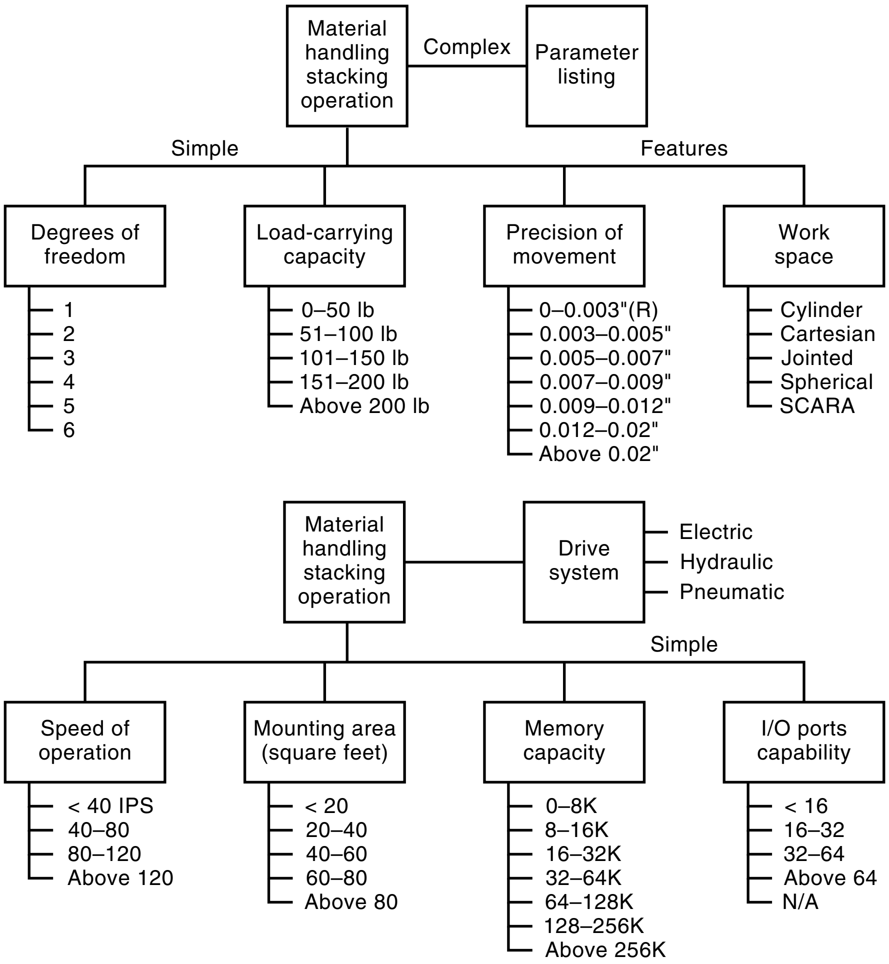

**Figure 7.** Parameters listing in a decision tree for palletizing and stacking tasks.

parameter). Then, based on the user's response, the system scans all the rules and eliminates those rules that do not contain this response. The expert system then asks the question related to the next parameter from the remaining rules. This process terminates once all of the if-then-else conditions for the specific problem have been satisfied, and displays the recommended industrial robot to the user. In some cases, the analysis may not lead to the recommendation of a robot. In such a case, the user is informed of the blockage and is requested to provide a different value for the factor where the blockage occurred and thus the analysis continues. In other instances, the analysis recommends more than one robot that will satisfy the user needs. In this case, an economic feasibility analysis is performed to select the most feasible robot.

The parameters discussed in the overview of robot technology in this article are used by the expert system for the selection of industrial robots. For this work, performance data for 250 robots was obtained. The chart shown in Fig. 8 illustrates the characteristic accuracy and repeatability exhibited by the population of industrial robots surveyed. Some 24% of the robots had repeatability ranges of 0 in to 0.003 in, and another 24% had repeatability ranges of 0.02 in and above. A good percentage (18%) of the robots had repeatability ranges of 0.003 to 0.005 in and 0.007 to 0.009 in each.

The load-carrying capacity of the robots examined varies between a few pounds to several hundred pounds. Figure 9 displays the maximum load capacities of the robots. Clearly the 0 to 50 lb range of load-carrying capacity was found to be the most popular, with approximately 64% of the robots falling in that range and approximately 12% of the robots falling in the 200 lb and above range. From this analysis, it was also seen that small robots requiring mounting areas in the range of 0 to 20 sq. ft, were found to predominate (64%) followed by 10% of the robots requiring an area in the range of 20 to 40 sq. ft.

## SAMPLE SCENARIO

Once the user has decided on the type of application, the knowledge-based system can be used as an essential tool to assist in selecting the appropriate robot. For example, consider a situation in which the user intends the robot for the palletizing task. The following illustrates the sequence of questions and corresponding responses as they appear on the screen. The first screen is the required application.

```
         Select Application
     >     Material Handling
           Processing Operation
           Assembly
           Inspection
```

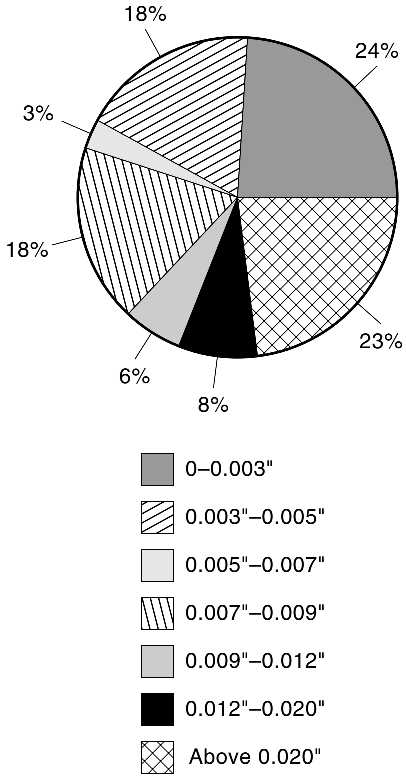

**Figure 8.** Chart of robot performance data for characteristic accuracy and repeatability shown by 250 industrial robots surveyed.

The user selects the first option, material handling, and the system responds by asking the next question which addresses the specific job within the material handling application.

```
        Select the Specific Job for the
         Material Handling Application
           >     Pick-&-Place
                 Palletizing
                 Machine Load/Unload
```

The user is then prompted with the specific characteristics associated with the palletizing task and the type of product which is to be palletized.

```
    Select the Palletizing Task Requirements
          >      No Stacking Required
                 Stacking Required
```

and

```
   Select the Product Geometry Specification
          >     Simple Geometry
                Complex Geometry
```

At this stage, the following rule is fired, which is the indication of the minimum number of requirements for the degrees of freedom necessary:

```
                   {Rule 1}
      IF       Question appl\Choice MH
      AND      Question job\Choice PAL
      AND      Question stck\Choice STACK
```

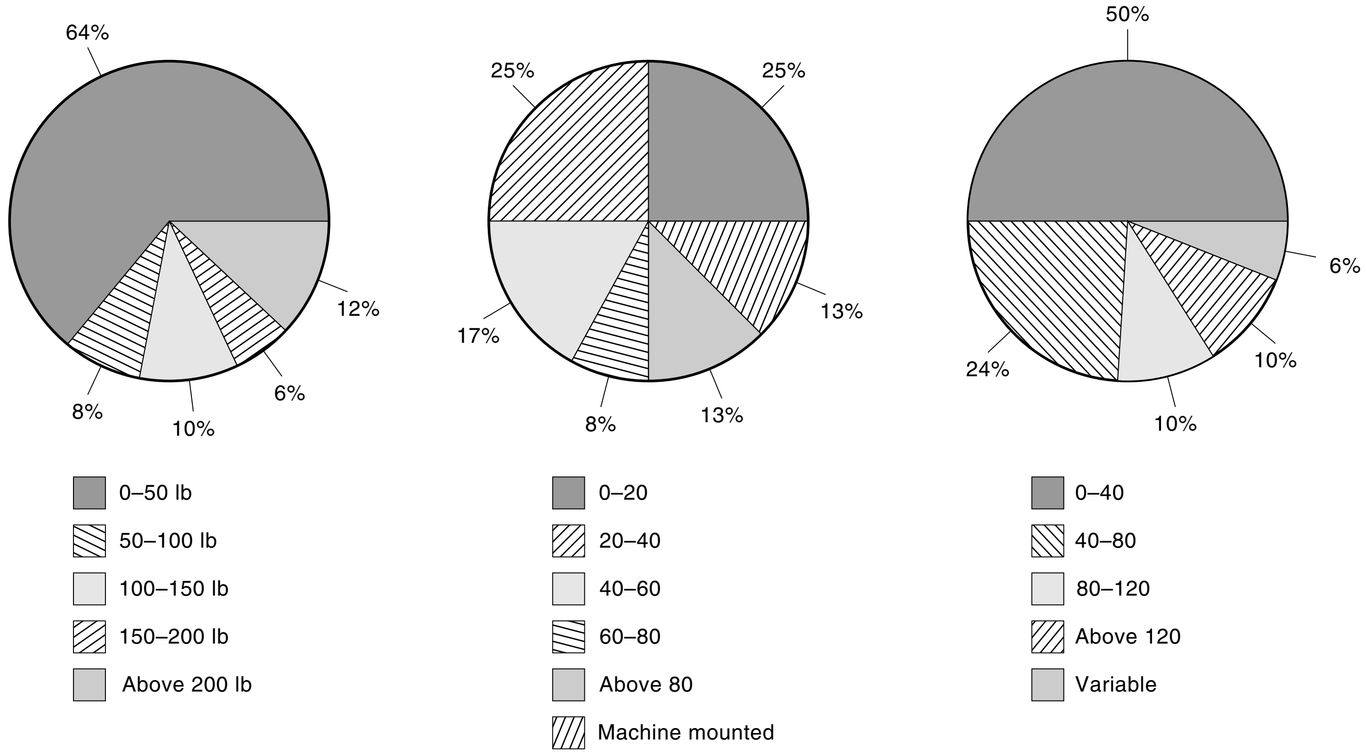

**Figure 9.** Illustration of maximum load capacities of 250 industrial robots in survey.

```
AND      Question part\Choice Simple
THEN     min num of DOF is 4
```

This result which is generated by this rule eliminates a number of rules from further analysis. The remaining parameters can assist the user in the selection of a specific robot. The user is prompted with the following set of questions which will collect the required specifications on the load-carrying capability and repeatability performance:

```
Desired Load Carrying Capability
          Below 50 Pounds
          50-100
          100-150
          150-200
   >      Above 200
```

and

```
Select the Desired Repeatability
          Below 0.003
          0.003-0.005
          0.005-0.007
          0.007-0.009
          0.009-0.012
          0.012-0.20
   >      Above 0.020
```

The following rule is used to capture these specifications:

```
               {Rule 21}
IF        min num of DOF is 4
OR        min num of DOF is 5
OR        min num of DOF is 6
AND       Question load\Choice VERY HIGH
AND       Question repy\Choice VLOW
THEN      we have ROBOTS4
```

ROBOTS4 is used as a temporary parameter which illustrates the result of the fired rule, based on the set of specifications determined by the designer. The next stage is the selection of the work space configuration, speed, and the required mounting area. The user is prompted with a list of options which illustrates these specifications, and the result from the selected options is the fired rule which also uses a temporary parameter.

```
Select the Work Space Configuration
          Cartesian
          Articulated
          Spherical
    >     Cylindrical
          SCARA

       Desired Speed Range
    >     Below 40
          40-80
          80-120
          Above 120
```

and

```
Select the Desired Mounting Area
         Below 20
  >      20-4040-60
         60-80
         Above 80
```

The following rule is used to capture these specifications;

```
                {Rule 49}
IF        we have ROBOTS4
AND       Question space\CYLIN
AND       Question speed\SLOW
AND       Question area\SMALL
THEN      recommended ROBOTS 4a
```

The system continues with the list of questions regarding memory capacity, input/output capabilities, and programming technique. The following rule illustrates this situation, which results in the identification of robots capable to perform the required application.

```
                {Rule 58}
IF        recommended ROBOTS 4a
AND       Question memy\Choice a (0-8k)
AND       Question input\Choice 1 (0-16)
AND       Question prog\Choice tp
THEN      Robot is Found
AND       DISPLAY ROBOTS 4a
```

At this point, the expert system displays the robots model(s) and provides descriptions of their features. The specifications of the selected robots for this sample are illustrated in Appendix 1. The selected robots are models FB and FC by Prab Robotics Incorporated. These robots possess all the characteristics required by the user, but the price for the FB model is $80,000, while the price for the FC model is $125,000. This price contrast clearly indicates the advantage of using this system for robotic system implementation. Further economic analysis is possible using the software interface to the knowledge base.

The rest of the applications follow the same order of questions, with the exception that the criteria used for the selection of the robot are different. For example, in the above sample scenario, the drive system was not a deciding factor, but in a spray-painting application, the drive system would be pivotal.

## CONCLUSION

A solution to the problem of selecting an optimum robot using a decision support expert system is presented. The system is designed to ask the user questions regarding the usage and requirements of a desired robot and then by using the knowledge base and knowledge rules provided, a solution for the optimum robot(s) is given. If this analysis leads to more than one robot, then a test for economic feasibility of the suggested robots is performed and the result is ranked. Based on the ranking, the robot which is the most economical will be selected.

## APPENDIX 1. Sample Robots Specifications

### Model: FB

| | |
|---|---|
| Company | Prab |
| Control system | Microcomputer |
| Coordinate system | Cylindrical or rectilinear |
| Power | n/s |
| Weight | 2,300 |
| Number and type of axis | 3–7 |
| Resolution | 0.012 |
| Accuracy | n/s |
| Repeatability | 0.050″ |
| Load-carrying capacity | 600 lbs |
| Velocity range | 0–36 ips |
| Velocity programmable | Yes |
| Floor space required | 48″ * 48″ |
| End-effectors | Mechanical, vacuum, magnetic |
| Sensors | As required |
| Synchronized operation | Yes |
| Mass storage available | Yes, cassette, RS 232 |
| Standard input devices | Computer, cassette, I/O |
| Standard memory size | 128 programs/7000 points |
| Memory devices | Varies with control option |
| Number of steps or points | 7000 |
| Actuators available | Servo-hydraulic or electric |
| Control inputs supported | Hand-held teach unit, cassette recorder |
| Languages supported | n/a |
| Language | n/a |
| Applications supported | Spot welding, die casting, investment casting, forging machine tool load/unload, parts transfer, plastic molding, machining, palletizing, stacking/unstacking |

Cost—$80,000

### Model-FC

| | |
|---|---|
| Company | Prab |
| Control system | Same as FB |
| Coordinate system | Same as FB |
| Power | 220/440 |
| Weight | 2000 |
| Number and type of axis | 5 |
| Resolution | 0.012 |
| Accuracy | n/s |
| Repeatability | 0.080″ |
| Load-carrying capacity | 2000 lbs |
| Velocity range | Same as FB |
| Velocity programmable | Yes |
| Floor space required | 60″ * 60″ |
| End-effectors | Same as FB |
| Sensors | Same as FB |
| Synchronized operation | Yes |
| Mass storage available | Same as FB |
| Standard input devices | Same as FB |
| Standard memory size | Same as FB |
| Memory devices | Same as FB |
| Number of steps or points | 7000 |
| Actuators available | Same as FB |
| Control inputs supported | Same as FB |
| Languages supported | n/a |
| Language | n/a |
| Applications supported | Forging, investment casting, parts transfer, palletizing, welding, stacking/unstacking, spot welding |

Cost—$125,000

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