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# Design of a web-based integrated material handling system for manufacturing applications

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**Design of a web-based integrated material handling system  
for manufacturing applications**

by

**Chiwoon Cho**

A dissertation submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of

**DOCTOR OF PHILOSOPHY**

**Major: Industrial Engineering**

**Program of Study Committee:  
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**2001**

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## LIST OF NOMENCLATURE

$a_{ij}$  = alternative MHE j for  $m_i$

$A_{ij}$  = a measure of membership function for the applicability aspect of alternative MHE j for move i

$A_{Ej} = 1$  if MHE j is acceptable to the user in terms of the economical aspect  
 0 otherwise

$A_{Ij} = 1$  if MHE j is acceptable to the user in terms of the integratability and applicability aspects  
 0 otherwise

$A_{Mj} = 1$  if MHE j is acceptable to the user in terms of to the maintenance and safety aspects  
 0 otherwise

$A_{Oj} = 1$  if MHE j is acceptable to the user in terms of the other aspect  
 0 otherwise

$A_{Pj} = 1$  if MHE j is acceptable to the user in terms of the applicability aspect  
 0 otherwise

$AS$  = expected annual saving

$b_{ij} = 1$  if MHE j can be used for move i  
 0 otherwise

$B$  = available budget

$C$  = total purchase costs of all  $f_i$ ,  $\sum_{i=1}^m p_i$

$C_i^b$  = basic fixed cost of the interface equipment

$C_j^b$  = basic fixed cost associated with MHE j. This cost includes initial installation charges

$C_j^d$  = cost of rail per unit length

$C_{ij}^e$  = change effect value for move i, where j is the set of feasible alternatives for move i

$C_j^l$  = guide path cost per unit distance for AGV or monorail j

$C_j^p$  = cost of the instrument for guiding AGV j

$C_j^{pt}$  = cost per pallet

$C_j^r$  = cost per pallet position (PP)

$C_j^s$  = cost of control system including computer system and interface

$C_j^u$  = cost per unit load capacity of the interface equipment

$C_j^v$  = cost per unit load capacity

$C_j$  = operating cost of MHE j per unit time

$CE$  = coefficient value and it represents the number of possible values of each condition

$d_i^a$  = distance associated with move i considering network aisle and shared aisle with other AGVs

$d_i$  = distance associated with move i

$d_{ij}$  = distance for transporting the unit load between MHE and the workstation

$DC$  = the average dual command cycle time

$DR$  = applicable discount rate

$E_{ij}$  = a measure of membership function for the economic aspect of alternative MHE j for move i

$EL$  = expected economic life

$f_i$  = the final solution for move i

$F_j = 1$  if MHE j is chosen in the MHE types

0 otherwise

$H_j$  = overall height of rack

$H(V_{ij})$  = height of load pattern used on which  $V_{ij}$  items are transported using MHE j

$i$  = move (material flow link) identifier,  $i = 1$  to  $m$

$IC_{ij}$  = interface cost of MHE j for move i

$j$  = MHE identifier,  $j = 1$  to  $n$

$k_i$  = frequency of move i

$K_j$  = width needed for MHE j

$l$  = list of moves identifier, 1 to  $p$

$l_j$  = load carrying capacity of MHE j

$L_l$  = load carrying capacity of the interface equipment

$L_j$  = overall length of rack

$m_i$  = MHE type selected for move i by the knowledge-based rules

$M$  = a very large positive number

$M_{ij}$  = a measure of membership function for the maintenance & safety aspects of alternative  
MHE j for move i

MARR = minimum attractive rate of return

$N_{ij}$  = number of units of MHE j required for move i

$N_j$  = number of units of MHE j required for all moves

$N_{sr}$  = number of SR machines

$N_w$  = number of working days per year

$NNC$  = number of nondeterministic conditions

$NRNC$  = number of rules dealing with nondeterministic conditions

$O_t$  = available operation time

$O_r$  = operation time of the MHE per day

$OC_{ij}$  = annual operating cost of MHE j for move i

$p$  = total number of pallets



$P_i$  = purchase cost of  $f_i$

$PC_{ij}$  = purchase cost per unit of MHE j for move i

$PD$  = the required time to pick-up or deposit the unit load

$P(V_{ij})$  = longer side of load pattern used on which  $V_{ij}$  items are transported using MHE j

$Q_{ij}$  = a measure of membership function for other aspects that are user specified, if any, of alternative MHE j for move i

$r$  = total number of pallet positions (PP)

$R$  = annual rental cost per unit space

$s$  = span for the crane

$s_j$  = velocity of MHE j

$S_i$  = normalized evaluation value for  $f_i$

$S'_{ij}$  = normalized evaluation value for alternative MHE j for move i

$S_{ij}$  = space occupied by MHE j for move i

$SC$  = the average single command cycle time

$SC_{ij}$  = annual cost of space related to MHE j for move i

$S(V_{ij})$  = shorter side of load pattern used on which  $V_{ij}$  items are transported using MHE j

$t_{ij}$  = annual operating time of MHE j for move i

$T_a$  = the annual working time

$T_{ij}$  = total operating time for move i if handled by MHE j

$TC$  = total cost of an alternative MHE

$TN$  = total number of rules in the FDT

$TR$  = applicable tax rate

$U$  = acceptable utilization level of MHE

$U_i$  = utilization of  $f_i$

$U_{ij}$  = utilization of MHE j by the move i

$V_1$  = measure of the economic aspect of an alternative MHE

$V_2$  = measure of the applicability aspect of an alternative MHE

- $V_3$  = measure of the adaptability and integratability aspect of an alternative MHE
- $V_4$  = measure of the maintenance and safety aspect of an alternative MHE
- $V_5$  = measure of the other aspect of an alternative MHE
- $V_i$  = flow-volume (jobs) per year associated with move i
- $V_{ij}$  = a measure of membership function for the adaptability & integratability aspects of alternative MHE j for move i
- $w$  = width of the unit load
- $w_i$  = width of the unit load of material handled in move i
- $w_{ij}$  = width satisfying the requirement for the unit load related move i and MHE j
- $W^a$  = weighted value for applicability factor specified by the user
- $W^e$  = weighted value for economic factor specified by the user
- $W^i$  = weighted value for adaptability & integratability factor specified by the user
- $W_{ij}$  = total number of trips required by MHE j for move i
- $W_j^1$  = overall width of AS/RS including the width for S/R movement
- $W_j^2$  = overall width of the rack
- $W^m$  = weighted value for maintenance & safety factor specified by the user
- $W^o$  = weighted value for other factor specified by the user
- $W(V_{ij})$  = weight of load pattern used on which  $V_{ij}$  items are transported using MHE j
- $x_{ij} = 1$  if MHE j is assigned for move i
- 0 otherwise
- $Y_i$  = total number of unit items required to be handled in move i
- $Y_{ij}$  = number of units in each load (each trip) transported by MHE j for move i
- $\alpha$  = a possible highest cost of alternative MHE for a material flow link
- $\alpha_j$  = load length limit for MHE j
- $\beta$  = a specified value for budget feasibility check
- $\beta_j$  = load width limit for MHE j

$\gamma_j$  = load height limit for MHE j

$\delta_j$  = load weight limit for MHE j

$\mu(V_j)$  = a membership function (degree) for  $V_j$

$\mu(V_j)/V_j$  = a fuzzy set containing exactly one element  $V_j$  with a degree of membership function  $\mu(V_j)$ .

## **CHAPTER 1. INTRODUCTION**

In this research, an approach for the design of a Web-based integrated material handling system is addressed. The design of a material handling system usually involves the selection of material handling equipment (MHE), the type of unit load, and the assignment of the MHE to the moves. To improve the efficiency of the MHE and the application of manufacturing information for operations such as job scheduling and inventory control to material handling, the system integration between MHE control system and host system must to be considered. Manufacturing information and system control rules are generally maintained by a host computer or distributed set of computers. The objective of this research is to develop a system executable on the Web to design integrated material handling systems that consider the integration of MHE and a host system. Knowledge-based rules are developed to search for alternative MHE. A decision algorithm is developed to find the most suitable solutions to problems in material handling system design. The concept of fuzzy logic is employed in the knowledge-base rules and the decision algorithms developed. The modules for economic analysis, performance measure analysis, AS/RS design analysis, and system integration analysis for automatic MHE are also developed to provide system users with useful data for the material handling system design and decision on investment in MHE.

### **1.1. Statement of the Problem**

In material handling systems (MHS) design, the selection of MHE type and the specification of the selected MHE are important parts. However, because of the wide variety of MHE available, MHE selection is an extremely difficult and time-consuming task. The

other important factors contributing to the complexity of MHE selection are constraints imposed by the structural environment of the facility, the combination and characteristics of the materials to be handled, and the uncertainty in the operational environment. In this research, both technical and non-technical factors are considered in determining the best design for instances of material handling systems design problems in manufacturing. The focus of the developed system is the design of material handling systems for manufacturing facilities.

### **1.2. Research Motivation**

Few tools other than checklist tables are available to assist material handling engineers in the selection of appropriate and cost-effective MHE. Because of this lack of decision-making aids, some knowledge-based systems have been introduced to solve the problem of MHE selection. Nevertheless, there are some problems with these approaches when they are implemented in real situations. The drawback associated with knowledge-based rules is that they consider a limited number of equipment types and characteristics, and also tend to ignore storage equipment and integration for computer control requirements. A number of quantitative approaches have also been developed to solve this problem. However, there are some limitations to the application of quantitative measures to the design and selection of MHE. The use of quantitative measures often requires the acceptance of questionable assumptions.

There are several limitations to the existing approaches for MHE selection as mentioned above. Most are incomplete prototypes that consider only a limited number of MHE types and the essential attributes required. They also ignore the system integration

requirement between the selected MHE and the host computer system to operate the MHE automatically. To be useful in practice, MHS design must consider not only quantifiable factors such as cost and aisle space but also technical and strategic factors such as the environmental condition of the facility, the nature of the operations, and the expected production trend. The systems currently reported in archival journals tend to ignore these factors. The work undertaken in this research not only extends the scope of previously reported MHS design tools but also represents the first MHS design platform designed for the Internet. The deployment of a design system on the Internet can be made available worldwide to prospective users. Based on the above reasons, the design and development of a Web-based integrated material handling system is potentially an important contribution to the overall effort of building a universal and science-based design for manufacturing systems.

### **1.3. Research Objective**

The objective of this research is to develop a web-based system for the integrated MHS design for a manufacturing environment. The scope of the system is to produce a design that meets the entire requirements of a facility and to recognize applicable MHS designs that are eligible to operate a facility most efficiently. Users of the integrated design system are expected to provide information regarding the characteristics of the materials to be handled, the physical environment of the facility, the routing of the materials, volume of flow, and budget constraints. Based on the information specified by the user, the system provides an appropriate system design suitable to meet the needs of the material handling problems that is described. The output of the system includes the MHE recommended, the MHE specifications, performance measures and cost analysis for the MHE, information on

system integration for automatic MHE, and AS/RS design analysis when an AS/RS is suggested.

The final outcome of the MHS design system is the minimization of the total cost of the material handling system selected subject to satisfying operational constraints. The sources of cost considered in the system include equipment cost, operating cost, space cost associated with equipment operation, and the interface cost between workstations and the material handling system. The integrated design system also considers multiple design factors that include economics, applicability, adaptability and integratability, maintenance and safety, as well as other factors that the system user identifies to impact the final decision.

An integrated set of tools is used in identifying the suitable MHS design for an application. The techniques employed in the design platform for finding solution to MHS design problems include both quantitative and qualitative approaches that consist of mathematical modeling, knowledge-based rules, a decision-making algorithm using normalized evaluation values, the concept of fuzzy logic, and analysis modules. Each applicable approach is described in Chapter 3.

#### **1.4. Principles of Material Handling**

Material handling is well described by Tompkins et al. (1996) as an activity that uses the right method to provide the right amount of the right material at the right place, at the right time, in the right sequence, in the right position, and at the right cost. This description conveys the message that one needs to look at material handling system design broadly instead of as a simple moving activity. Designing a material handling system is a complex task because there are many factors that need to be considered. There are no unique rules to

be followed for achieving a successful material handling system. However, there are several basic guidelines available to reduce the total cost and enhance the efficiency of MHS. These guidelines are known as the principles of material handling. In 1966, the College-Industry Council on Material Handling Education (CICMHE) proposed 20 basic principles for material handling. These were modified in 1981 to reflect changes in industrial operations. The 20 basic principles of material handling are as listed in Table 1.1.

Designing a material handling system includes the selection of material handling equipment, the specification of unit load sizes, and the application of design methods to assign equipment to moves. These components of design can be expressed as  $\text{Material} + \text{Moves} + \text{Methods} = \text{Best suitable MHS}$ .

### **1.5. Problem Assumptions**

Certain assumptions were made in developing the system designed in this research.

They include the following:

1. The application environment for the system developed is manufacturing.
2. The user of the system provides all requested information on material handling.
3. The purchase cost of each MHE type can be different based on the model and make.
4. The operation cost of each MHE can be different based on operational environment.
5. The performance measures of suggested MHE can be different based on the operating conditions.



**Table 1.1. The twenty material-handling principles**

<b>Principle</b>	<b>Description</b>
<b>Orientation</b>	Thoroughly study the problem and identify problem areas, constraints, and goals.
<b>Planning</b>	Develop a plan that meets our basic requirement, is flexible, and includes desirable features.
<b>Systems</b>	Integrate various activities such as receiving, shipping, production assembly, and so on.
<b>Unit load</b>	Make the unit load size as large as possible.
<b>Space utilization</b>	Use the cubic space as effectively as possible.
<b>Standardization</b>	Where possible, standardize equipment and methods.
<b>Ergonomic</b>	Design equipment and methods that allow effective interaction between humans and machines.
<b>Energy</b>	When evaluating handling equipment, examine energy requirements and costs.
<b>Mechanization</b>	Where possible, mechanize methods to achieve efficiency.
<b>Flexibility</b>	Use methods and equipment that provide the greatest flexibility.
<b>Simplification</b>	Simplify, combine, or, if possible, eliminate unnecessary moves or equipment.
<b>Gravity</b>	Use gravity as much as possible to transfer material, keeping in mind safety and product damage.
<b>Safety</b>	Use safe handling equipment and methods.
<b>Computerization</b>	To the extent possible, computerize to achieve better material and information control.
<b>System flow</b>	Integrate material and information flows.
<b>Layouts</b>	Evaluate each alternative layout and select the most effective and efficient one.
<b>Cost</b>	Evaluate each alternative solution and select one based on cost per unit handled.
<b>Maintenance</b>	Perform preventive maintenance.
<b>Obsolescence</b>	Develop an equipment replacement plan based on after-tax life cycle costs.

### **1.6. Contribution of the Research**

The cost of material handling is a key factor in the facilities design process for new shops as well as for the redesign of existing shops. If the material handling activities are well

analyzed and examined, it is possible that more than 30 percent of the manufacturing cost can be eliminated (Eom & Trevino, 1992).

Many manufacturing operations have changed or have considered changing their manufacturing environment to computer-oriented manufacturing. Therefore, the integration of systems, including MHE and control computer systems for information flows, is a vital factor in a successful material handling system. However, small and medium-sized companies still rely on stand-alone MHS solutions. Even larger firms that can afford to invest in integrated and automated MHE spend substantial sums of money on stand-alone equipment (Chu et al., 1995). Therefore, the development of a Web-based system for the design of integrated material handling system is very attractive in the sense that it can provide opportunity for the design of a integrated material handling system to a wider group of manufacturers. This is possible because of the wider accessibility of a Web-based design platform. Hence, the benefits derived from this research include:

- An Internet-based integrated MHS design environment and platform that is widely accessible is developed. Therefore, the potential for wider application is significantly higher.
- The scope of the system in solving material-handling systems design problems is broader than those previously reported in the literature.
- The system suggests the proper integration guidelines for automated MHS for information flows.
- The system considers both qualitative and quantitative factors for MHE selection and design.

- A wide variety of MHE types for movement, storage, positioning, and computer control are considered. There is no known system reported to date in the literature that explicitly considers computer control.
- An integrated set of algorithms for MHS design and selection deployable on the Internet is developed. No such platform with the same scope of capability has been previously reported.

### **1.7. Organization of the Thesis**

The remainder of this thesis is organized into three chapters. In Chapter 2, the literature related to material-handling system design is reviewed. Chapter 3 describes models of material handling costs, a mathematical model that considers the problem constraints while attempting to minimize the overall material handling costs, and knowledge-based rules to search for alternative solutions. A decision algorithm for the selection of the best design, fuzzy logic applications to material-handling systems design, and analysis modules are presented in Chapter 3. System integration for automatic MHE and implementation of DESIGNER are also described in Chapter 3. An example of MHS design on DESIGNER is given to illustrate the use of the system in this Chapter. In Chapter 4, the conclusions and recommendations of the research are described. General information and specifications of material handling equipment types considered in the research, questions associated with extracting attributes of material flow links, and fuzzy evaluation matrices for equipment alternatives are provided in the appendices.

## **CHAPTER 2. LITERATURE REVIEW**

This chapter reviews previous research work on the selection of in-plant material handling equipment (MHE). Previous research work in MHE selection can be classified largely into three categories: (a) optimization model; (b) knowledge-based rules; and (c) combination of knowledge-based rules and optimization modeling approach.

### **2.1. Optimization Models**

The optimization modeling approaches reported in previous research are focused on the improvement of the utilization of MHE. A minimum cost MHE is selected first and then some moves are assigned to the MHE until its utilization meets an acceptable level.

Mohsen et al. (1985) formulated the selection problem as an integer program with the objective of minimizing the total operating and purchasing costs of the selected MHE. Two sets of constraints are specified. The first set of constraints ensures that every move is assigned to only one MHE type. The second set ensures that the time required by all moves does not exceed the available operating time of the selected number of units of the equipment. The problem is solved using a heuristic algorithm. The interesting aspect in the heuristic is that when the MHE types are considered one at a time it reveals some similarities between the MHE selection problem and both the loading and knapsack problem.

A mixed-integer linear programming model was developed by Johnson et al. (1993) to obtain the proper equipment configuration, particularly for conveyors and industrial trucks. The primary objective of the model is cost (operating and initial) minimization. There are also some secondary objectives such as maximizing the utilization of the selected MHE and minimizing the variation in the selected equipment types. A heuristic method is applied

to solve the problem. The algorithm also considers the equipment types one at a time. Moves are assigned to a unit of the selected equipment until it is fully utilized or until no other move can be assigned to it.

Sunderesh Heragu (1997) introduced a deterministic optimization model to help material-handling designers select the required MHE. The objective function of the model minimizes a cost function subject to some specified constraints. The model makes some assumptions that are worth mentioning. First, it assumes that a move between workstations includes only the loaded trip, but no direct consideration is given to the possible unloaded or empty trip in the opposite direction. Second, the time for transporting a unit part between workstations using an MHE cannot be determined exactly because it can be different due to flow congestion and repair or maintenance of the MHE. Third, the purchase cost of an MHE is the cost of the equipment amortized over its economic life, measured in years.

Optimization approaches have also been used for selection problem of manufacturing equipment. Bard et al. (1991) proposed a nonlinear cost minimization model that can be used by facility planners to analyze the general manufacturing equipment selection. The objective is to determine how many of each machine type to purchase, as well as what fraction of time each machine has to be charged to a particular type of operation. A depth-first branch and bound routine is used to solve the problem and it employs a greedy set covering heuristic to find good feasible solutions. Velury et al. (1992) employed mixed integer programming to select bulk material-handling equipment. The research focuses on the selection of relevant factors that need to be considered in the design of a bulk material handling system and on the selection of equipment once these factors have been considered. The objective function of the model is the minimization of the total cost that is the sum of two factors, handling cost and

transportation cost. The handling cost is incurred at each location where there is a transfer of material. The model requires several inputs such as the capacity of the equipment, equipment costs, demand, budget and compatibility. The compatibility constraints the compatibility of a particular equipment type with the system, the compatibility of equipment type at material transfer points, and the compatibility with the types of material being transported.

An integrated optimization model was proposed by Noble et al. (1998). The research presents a model that integrates material handling equipment selection and specification, including material handling interface equipment and path/load dependent unit load size. The problem is solved using the meta-heuristic procedure of tabu search. The objective function minimizes the operation and capital cost of material handling and the necessary interface equipment resulting from either similar or dissimilar material handling equipment types. Several constraints are specified to ensure integrality of the decision parameters. Due to the complexity of the problem structure and the lack of precision in the data, a metaheuristic method is applied to solve the problem more efficiently. The method chosen is tabu search due to its success on a variety of problem types.

## **2.2. Knowledge-based Rules**

The MHE selection problem is difficult and knowledge-intensive because there are several feasible solutions of varying efficiency, and numerous and conflicting objective functions. Thus, the use of a knowledge-based rule approach has been proposed in solving the problems of MHE selection. This approach emulates the decision-making process of a human expert in a given area. Even though the decision procedure is complicated and not

well understood, knowledge-based rules have been used to a limited extent in some problem areas (Heragu, 1997).

Park (1996) proposed a knowledge-based expert system called ICMESE for the selection and evaluation of MHE to transport materials between workstations. Fifty types of MHE and 29 attributes were identified from the available literature. The equipment types were classified into two groups based on their functions, namely, equipment for movement and equipment for storage. The attributes were also classified into four sub groups: (1) the move attributes; (2) the attributes of the material to be handled; (3) the operation requirement attributes; and (4) the area constraint attributes. To improve the efficiency of the system, decision trees were used to design the knowledge-based rules. Each rule has the following basic format:

Rule name

If <condition> THEN <conclusion>

[Confidence Factor <number>]

BECAUSE "<text>";

Park (1996) also suggests multicriteria decision-making procedures to acquire more reliable solutions in future work. An expert system was also developed to solve the selection problem of material handling and storage systems by Kim et al. (1997). The paper proposes and describes an expert system called MAHSES which is composed of two modules. The first module selects material handling alternatives as well as storage systems for electronics assembly. The second module suggests a proper assembly flow and layout, including single-linear, parallel, multi-parallel, circle-U, and S-shape. The following parameters are used for the selection rules: material type, product mix, complexity, accuracy, volume, and storage.

Several questions are presented to the user during consultation. The paper considers several material handling alternatives such as fixed-path AGV, free-ranging AGV, conveyor, carousel, etc.

Matson et al. (1992) described a knowledge-based approach for addressing the major factors that influence MHE selection. The work involves two major activities. One aspect of it involves the modification of the traditional material handling design checklists and some knowledge bases. The other is the development of a prototype expert system for MHE selection. The paper mentions computer control and high levels of automation but these are not addressed explicitly. According to the paper, even larger firms that can install integrated and automated systems spend substantial amounts of money on individual equipment options. Thirty-five equipment types selected from the available literature and 28 attributes are considered in the system. Inference chains were developed for the 35 equipment types considered. They include the attributes that should be considered, the sequence in which these attributes should be considered, and the equipment options suitable for a set of attributes. The knowledge rule type used in this paper is of the form:

**Rule**

If ATTRIBUTE 1 has VALUE 1

\*

\*

\*

and ATTRIBUTE n has VALUE n

Then EQUIPMENT TYPE is OBJECT k

Fisher (1988) developed a rule-based expert system called MATHES which selects appropriate types of MHEs for in-factory moves of materials. The equipment types are



suggested by applying heuristic selection rules acquired from a human expert to the requirements of a user. Associated with each suggested MHE type is a certainty factor that can be used to rank the selected MHE as to each MHE type's degree of suitability relative to other selected types of equipment for a certain movement. Twenty-four equipment types and 12 attributes were considered in the system. All of the knowledge in MATHES are expressed in the form of IF premise-Then consequent rules. The structure of MATHES consists of three modules: the knowledge base, the inference engine, and the cache. The knowledge base is composed of statements of the goal and all of the rules used by the system. The inference engine is the control mechanism that directs the backward search through the rules. The cache is the working memory of the system. Uncertainty matrix and parameter matrix rules are used to provide some representation over a range of values permitted to parameters having discrete values and infer parameter values, respectively.

Chu et al. (1995) proposed a computer-aided MHE selection system called ADVISOR. ADVISOR models the MHE selection process and contains information on 77 different types of MHE. They classified MHE into four categories: equipment for material transport, equipment for positioning, equipment for unit formation, and equipment for storage. The system identifies an appropriate MHE through two stages. At the first stage, through the use of physical requirements of the material handling activities provided by users, potential equipment are compared and ranked based on their normalized accumulated rating and are then placed in an alternative equipment list. Next, an economic analysis for each eligible equipment is performed in the second stage. They used data matrices containing the ratings associated with design factors to determine the best equipment or alternative.

Other applications of knowledge-based rules have been used in MHE selection. Malmberg et al. (1987) studied a prototype expert system for industrial truck selection. The work considered five types of industrial truck: front-loading straddle trucks, side-loading trucks, order-picking trucks, reach trucks, and low-lift and no-lift trucks. Seventeen categories of data were used by this system to identify truck types and samples of five rules for each type of truck were derived. General environmental factors such as aisle space restrictions, terrain/floor surface, presence of dockboards/ramps and structural building limitations that are necessary in material handling problem were also considered. Luxhoj et al (1992) used a prototype of an expert system to find proper AGV types suitable for given MHS design instances. The system has three main parts: a knowledge base, an inference engine, and a user interface. The knowledge base includes facts, rules based on facts, heuristics, uncertainty factors, and methodologies for making educated guesses. The rules used were in the format of "if-then" statements. The inference engine is the logical unit that extracts information from the user and applies the facts to the knowledge base. The user interface is provided to make the expert system easier to use by the user. The paper also mentions several limitations of expert systems. The key point is that all expert systems are limited by the information in their knowledge bases and that even though the expert system was implemented well, including all models of a certain product, the system still can be outdated.

A prototype knowledge-based system called MAHDE was developed by Gabbert et al. (1989) to generate acceptable material handling system designs. In MAHDE, knowledge-based rules and a heuristic algorithm were combined to provide a solution for this problem. The paper suggests a hybrid system to solve the kinds of problems similar to that used in

**MAHDE. Because the heuristic rules that guide the design process can be easily changed without modifying the control structure, knowledge-based rules can be represented in a domain where expertise is diminishing.**

**Abu et al. (1985) and Malmborg et al. (1986) summarized the field of knowledge-based systems and their possible applications to MHE selection. They noted that knowledge-based systems can be very useful when a large number of alternatives and information sources are available, and uncertainties are present regarding the appropriateness of the available alternatives. They summarized the limitations of these kinds of systems as follows: (1) such systems can only be as effective as the information on which they are based; (2) expert systems cannot be expected to recognize if a given problem belongs to the domain the system can manage; and (3) expert systems are nothing more than computer programs for executing logical relationships.**

### **2.3. Combined Knowledge-based Rules and Optimization Approach**

**Because of the complexities involved in the problem of selection of MHE, knowledge-based rules seem to have great potential for this problem. However, a general limitation of knowledge-base approaches is that they commonly suggest feasible alternatives based on certain requirement and no attempts are performed to optimize the overall material-handling system. Even though hybrid knowledge-based rules and optimization approaches have been rarely applied in MHE selection problems until now, they have great potential (Welgama & Gibson, 1995, 1996).**

**Welgama and Gibson (1995, 1996) studied a combined methodology for automating the determination of material handling systems and layouts. The knowledge-based system**

consists of rules and facts to determine the possibility of using a MHE type for a material flow link specified by users. The optimization part suggests the layout of machines to minimize the material-handling costs and the dead space in the given layout using a multi-criteria optimization model. The optimization procedure consists of two stages in which concepts in Abdou (1989) and Hassan (1985) are incorporated into a modified algorithm. During the first stage, the procedure finds the minimum cost MHE for each move without trying to maximize the utilization of the MHE. During the second stage, the algorithm attempts to maximize the utilization of MHE. The objective function of the optimization model minimizes material handling cost, aisle space usage, and dead space in the layout. They use penalty cost values per unit area of aisle space to measure the cost of aisle space. These papers proposed models for the calculation of material handling cost that include both the investment cost and operating cost of MHE. The domain of the knowledge-based rules was limited to heavy industrial equipment situations.

Several other papers also related to MHE selection use different approaches. Zhao et al. (1996) used a genetic algorithm for robot selection and workstation assignment problem. They combined a genetic algorithm with a heuristic bin-packing algorithm to solve the problem. The objective function of their algorithm minimizes total cost of resources and satisfies the capacity constraints of selected robots. A fitness function and genetic operators, such as selection, crossover, and mutation to represent the problem, are used.

A concurrent engineering approach was applied to product design and material handling system selection by Atmani et al. (1996). The basis for a concurrent approach to product-process system design lies in making a connection between product design and manufacturing logistics design. The manufacturing logistics involves both the internal

logistics within the manufacturing shop and the external logistics after the product left the shop. This paper focused on internal logistics functions to construct a mathematical model using index sets for products, material handling systems and operations. Through these parameters, the model can manage the time available for the equipment during the planning period and overall number of MHE available.

Cho et al. (1996) proposed a real example of the construction of an integrated material-handling system called HMHS. The system consists of several types of MHE and includes AS/RS, electric wire-guided AGV, laser-guided AGV, and an electric monorail system. The host computer system and the material control computers are interfaced and each automatic MHE communicates with the material handling system control computer in real time. Cho et al. also suggested some ideas for system integration of the MHE, the material handling system control computer, and the host computer

There are several limitations related to the problem of MHE selection in the set of reported work. Most are incomplete prototypes that consider only a limited number of MHE types and attributes. The studies also ignore the system integration factors among the MHE selected, a host computer, and the MHE control computer to operate the MHE automatically and share the material flow information. To be useful in practice, an MHS design not only must consider quantifiable factors such as cost and aisle space but also technical and strategic factors such as the environmental conditions of the facility, the operations, and the expected production trend of the manufacturing facility. The proposed approaches in archival research papers tend to ignore these factors. Furthermore, there are no reports of the deployment of such MHS design tools or platforms on the Internet to make it widely accessible to potential

**users. The work undertaken in the current research addresses these limitations and provides a truly integrated system for MHS design.**

## **CHAPTER 3. SYSTEM DEVELOPMENT**

This chapter describes the systematic computer-assisted methodology for the design of an integrated material handling system on the web along with a mathematical model, knowledge-based rules, a decision-making algorithm, Fuzzy logic applications, and analysis modules. An example is provided to demonstrate the use of the newly developed Web-based system called DESIGNER.

### **3.1. System Architecture**

DESIGNER is composed of database module for three MHE types, an MHE selection module using knowledge-based rules and decision-making algorithm, a graphical user interface (GUI) and processor module, and four analysis and design modules for performance measures, economic analysis, automated storage/retrieval system (AS/RS) design, and system integration (see Figure 3.1). The database for the three MHE types includes a table for moving equipment, a table for storage equipment, and a table for positioning equipment. The general information and specification for 45 MHE are used in constructing the databases in DESIGNER. The MHE selection module searches for a feasible set of MHE for each material flow link using knowledge-based rules and determines the final solution using a decision-making algorithm. The GUI and processor module includes sub modules for user input and system output. The module for user input provides the interface between the system and the user. Through the module for system output, users can obtain the final solution for the design problem. The system output includes economic analysis, performance measures, equipment specification, system integration guides, and AS/RS design analysis if an AS/RS is suggested.

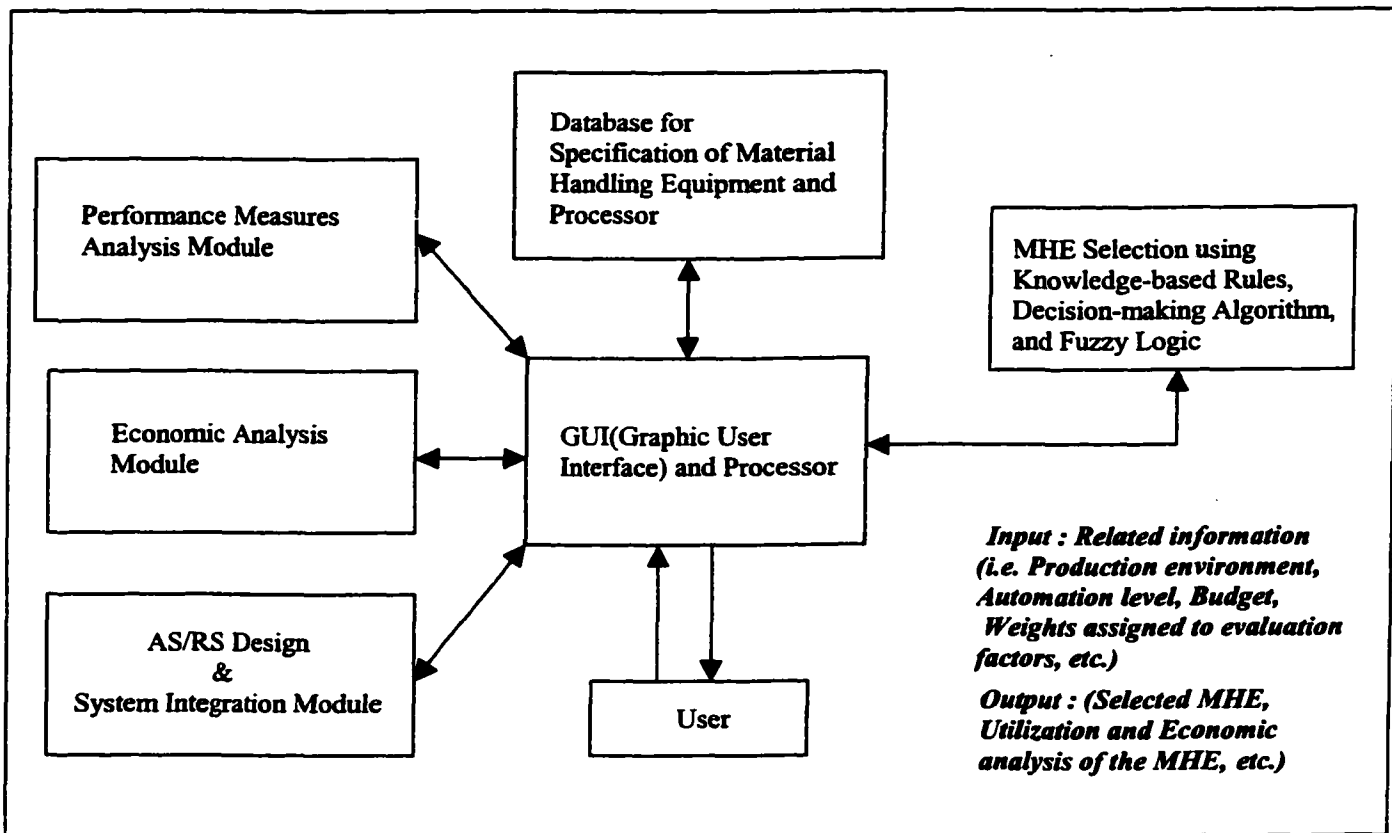


Figure 3.1. System configuration for DESIGNER

The economic analysis module provides economic information that allows users to determine the approximate cost of the MHE. The module for performance measures analysis calculates several performance indicators or values, including the utilization of the MHE, and outputs the results to the users. The AS/RS design and integration module provides design data associated with the design of an AS/RS - such output data include the number of storage/retrieval (S/R) machines needed and the rack design. It also provides general information related to the system integration with other equipment, MHE control computers, and a host computer to operate automatic MHE such as AS/RS, AGV, and electric monorail system (EMS) and share the information related to material flow.



### **3.2. Modeling the MHE Selection Problem**

In this section, a mixed-integer linear programming model is presented to obtain the optimal selections of MHE for move activities. It minimizes the total system cost which includes purchase cost, operating cost, space cost, and interface cost between workstations and MHE.

#### **3.2.1. Problem constraints**

The model for MHE selection problem has several constraints. The general constraints to be satisfied are:

1. All moves have to be assigned a MHE.
2. A move has to be assigned to only one type of MHE.
3. A MHE type can be assigned to more than one move if it is acceptable in terms of the feasibility and utilization limit of the MHE.
4. The maximum allowable utilization level for each MHE must consider the time for maintenance and break down of the equipment.

The constraints associated with the feasibility of selecting a MHE for a move are as follows:

1. The MHE chosen must be technologically feasible and capable of handling the move.
2. The load carrying capacity of the MHE selected must be greater than or equal to the weight of the unit loads associated with the move considered.
3. The MHE selected must satisfy the environmental condition of the facility (truss height, available space for MHE moves, etc.).
4. The total investment on the solution MHE must satisfy the budget constraint specified by the user.

5. The MHE selected must satisfy all compatibility and interfability requirements associated with the move.

### **3.2.2. Model of the material-handling cost**

A key objective of MHE selection tasks is to minimize the total system costs, which includes MHE purchase cost and operating cost, space cost, and interface cost between the workstations and the MHE. To satisfy the objective of the problem, accurate models of costs are needed. The cost model studied by Welgama and Gibson (1995, 1996) are too simplistic for real life applications. They calculated the investment costs of the MHE by adding the fixed cost and the cost required for load-carrying capacity specified by the user for variable-path equipment such as AGV, fork-lifts, tow-tractors, and mobile cranes. They also added a fixed cost to the cost for the span for fixed path equipment such as a bridge and gantry crane. For the investment cost of conveyor, they used the width of the unit load and distance associated with a move. However, to be useful, costs for the installation of the MHE, special accessories, and additional functions must be considered. For example, the purchase cost of an AGV system can vary based on the AGV type employed because each type of AGV uses a different guidance method and requires special attachments for guide-path recognition. Furthermore, they did not consider the cost of the space occupied by the MHE and the interface cost between workstations and the MHE. In addition, the operating costs of storage equipment such as AS/RS and mobile racks were not considered. The model developed in the current research addresses the limitations of the Welgama and Gibson (1995, 1996) models.

### 3.2.2.1. Purchase cost of MHE

Actually, the purchase costs are dependent on many factors such as load carrying capacity, distance associated with a move, and speed of a MHE. For automated procedures to calculate the purchase costs, the appropriate costs are estimated with the assumption that the purchase costs are linearly proportional to some main factors associated with MHE. The purchase cost  $PC_{ij}$  of an MHE  $j$  for move  $i$  can be summarized as shown in Table 3.1. Seven equipment types are given along with their associated expressions for calculating their purchase costs.

The purchase cost  $PC_{ij}$  of industrial trucks such as a counterbalanced lift truck, tractor trailer, and a pallet jack can be estimated in proportion to the carrying capacity. For AGV, the purchase cost can vary based on AGV type and load-carrying capacity. The cost of the instrument  $C_j^p$  for guiding AGV is not necessary for monorail.

The purchase cost of conveyors is proportional not only to the load-carrying capacity but also the width of the unit load and distance related to the move. For cranes, the cost is related to the load capacity and the span of the crane(s). In addition, the costs of the pallet, rack, S/R machine, and control system, including interface cost of the equipment and host computer system for information flows have to be considered for determining the cost of an AS/RS. The purchase cost of a general rack such as pallet rack, minirack, and cantilever rack is similar to the cost of an AS/RS except that it does not consider S/R machines and control systems.

Table 3.1. Purchase cost of MHE

Equipment Type	Purchase Cost( $PC_{ij}$ ) Expression
Industrial Trucks	$C_j^b + C_j^u \times l_j$
AGVs	$C_j^b + C_j^p + C_j^l \times d_i + C_j^u \times l_j$
Monorail	$C_j^b + C_j^l \times d_i + C_j^u \times l_j$
Conveyors	$C_j^b + C_j^u \times l_j \times w \times d_i$
Cranes	$C_j^b + C_j^u \times l_j \times s + C_j^d \times d_i$
AS/RS	$C_j^b + C_j^{pt} \times p + C_j^r \times r + C_j^u \times l_j + C_j^s$
General Rack	$C_j^b + C_j^{pt} \times p + C_j^r \times r$

**Key:**

$C_j^b$  = basic fixed cost associated with MHE j. This cost includes initial installation charges.

$C_j^u$  = cost per unit load capacity.

$l_j$  = load carrying capacity of MHE j

$C_j^d$  = cost of rail per unit length.

$C_j^p$  = cost of the instrument for guiding AGV j.

$C_j^l$  = guide path cost per unit distance for AGV or monorail j.

$d_i$  = distance associated with move i

$w$  = width of the unit load.

$s$  = span for the crane.

$C_j^{pt}$  = cost per pallet.

$p$  = total number of pallets.

$C_j^r$  = cost per pallet position (PP)

$r$  = total number of pallet positions (PP)

$C_j^s$  = cost of control system including computer system and interface.

### 3.2.2.2. Operating cost of MHE

Usually energy, operator, and maintenance and spare parts contribute to the operation cost of an MHE. Estimating these costs separately is extremely difficult, but the costs have a proportional relationship to the operation times. Therefore, it is reasonable to apply the model for operation costs configured by Welgama and Gibson (1995, 1996). However, they did not study the operation cost for storage MHE such as AS/RS and mobile rack.

The annual operating cost  $OC_{ij}$  of MHE  $j$  for move  $i$  is calculated as

$$OC_{ij} = t_{ij}C_j$$

where

$t_{ij}$  = annual operating time of MHE  $j$  for move  $i$

$C_j$  = operating cost of MHE  $j$  per unit time

The expressions for annual operating cost  $OC_{ij}$  can be summarized as shown in Table 3.2.

For the annual operating times of MHE which belong to a variable path MHE such as an AGV, monorail, crane, and industrial vehicle, rectilinear distances are used and the loading/unloading time is not considered because the velocity of MHE  $j$ ,  $V_j$ , can be controlled to reflect the loading/unloading time. In addition, the MHE is assumed to be returning empty to the previous location so the multiplication factor of 2 is applied. The annual operating time of AS/RS can be different and depends on the operation mode of MHE, namely, single versus dual command cycle. A single command cycle consists of either a storage or a retrieval, but not both operations, whereas a dual command cycle involves a storage operation and a retrieval operation.

Table 3.2. Operating cost of MHE

Equipment Type	Annual Operating Cost( $OC_{ij}$ ) Expression
Variable Path MHE (AGV, Monorail, Crane, Industrial Vehicle)	$\frac{2 \times d_i \times V_i}{s_j} \times C_j$
Fixed Path MHE (Conveyor)	$\frac{k_i \times d_i \times V_i}{s_j} \times C_j$ : when frequency of a move is too low $T_a \times C_j$ : other
AS/RS	$V_i \times (SC + 2 \times PD) \times C_j$ : For single command cycle $\left(\frac{V_i}{2}\right) \times (DC + 4 \times PD) \times C_j$ : For dual command cycle

Key:

 $s_j$  = velocity of MHE j $V_i$  = flow-volume (jobs) per year associated with move i $d_i$  = distance associated with move i $T_a$  = the annual working time $SC$  = the average single command cycle time $DC$  = the average dual command cycle time $PD$  = the required time to pick-up or deposit the unit load $k_i$  = frequency of move iUtilization,  $U_{ij}$ , of MHE j by the move i can be expressed as:

$$U_{ij} = \frac{t_{ij}}{T_a}$$

### 3.2.2.3. Space and interface costs

The annual cost  $SC_{ij}$  of space related to MHE j for move i is calculated as

$$SC_{ij} = RS_{ij}$$

where

$R$  = annual rental cost per unit space

$S_{ij}$  = space occupied by MHE j for move i

The expressions for  $SC_{ij}$  can be summarized as shown in Table 3.3.

Interface cost is incurred when additional instruments are needed to transfer the unit load between the MHE and the workstations. For example, when an AGV or monorail is used as an MHE to pick up a load from an AS/RS or deposit a load into an AS/RS, a conveyer is required for transporting the material between the MHE and the AS/RS. The purchase cost of conveyors can be assumed to be linearly proportional to the width of the conveyor and the move distance. Therefore, the interface cost of MHE j for move i ( $IC_{ij}$ ) can be estimated as follows:

$$IC_{ij} = C_I^b + C_I^u \times L_I \times w_{ij} \times d_{ij}$$

where

$C_I^b$  = basic fixed cost of the interface equipment

$C_I^u$  = cost per unit load capacity of the interface equipment

$L_I$  = load carrying capacity of the interface equipment

$w_{ij}$  = width satisfying the requirement for the unit load related move i and MHE j

$d_{ij}$  = distance for transporting the unit load between MHE and the workstation

Table 3.3. Cost of space occupied by MHE j for move i

Equipment Type	Cost $SC_{ij}$ of space
Bridge Crane	0
Monorail, Gantry Crane	$RK_j d_i$
AGV	$RK_j d_i^a$
Conveyors	$Rw_i d_i$
Industrial Truck (Riding)	$RK_j d_i$
AS/RS	$RW_j^1 L_j H_j$
Pallet rack, Carousel	$RW_j^2 L_j H_j$

Key:

$K_j$  = width needed for MHE j

$d_i$  = distance associated with move i

$d_i^a$  = distance associated with move i considering network aisle and shared aisle with other AGVs

$w_i$  = width of the unit load of material handled in move i

$W_j^1$  = overall width of AS/RS including the width for S/R movement

$W_j^2$  = overall width of the rack

$L_j$  = overall length of rack

$H_j$  = overall height of rack

#### 3.2.2.4. Model formulation

Given the above cost models, a mathematical model to minimize the total system cost

is given as follows:

$$\text{Minimize } Z = \sum_{i=1}^m \sum_{j=1}^n \{ (N_{ij} PC_{ij} x_{ij}) + (C_j T_{ij} + SC_{ij} + IC_{ij}) x_{ij} \} \quad (1)$$



subject to

$$\sum_{j=1}^n b_{ij} x_{ij} = 1 \quad \text{for } i = 1, 2, \dots, m \quad (2)$$

$$x_{ij} \leq F_j \quad \text{for all } i, j \quad (3)$$

$$x_{ij} \leq b_{ij} \quad \text{for all } i, j \quad (4)$$

$$\sum_{i=1}^m T_{ij} x_{ij} \leq N_j O_i \quad \text{for } j = 1, 2, \dots, n \quad (5)$$

$$(1 - x_{ij})M + Y_{ij}W_{ij} \geq Y_i \quad \text{for all } i, j \quad (6)$$

$$-(1 - x_{ij})M + P(Y_{ij}) \leq \alpha_j \quad \text{for all } i, j \quad (7)$$

$$-(1 - x_{ij})M + S(Y_{ij}) \leq \beta_j \quad \text{for all } i, j \quad (8)$$

$$-(1 - x_{ij})M + H(Y_{ij}) \leq \gamma_j \quad \text{for all } i, j \quad (9)$$

$$-(1 - x_{ij})M + W(Y_{ij}) \leq \delta_j \quad \text{for all } i, j \quad (10)$$

$$\sum_{i=1}^m \sum_{j=1}^n N_{ij} PC_{ij} x_{ij} \leq B \quad (11)$$

$$\sum_{i=1}^m N_{ij} x_{ij} \geq N_j \quad \text{for all } j \quad (12)$$

$$x_{ij} \leq A_{Ej}, x_{ij} \leq A_{Pj}, x_{ij} \leq A_{Ij}, x_{ij} \leq A_{Mj}, x_{ij} \leq A_{Oj} \quad (13)$$

$$F_j = \{0,1\}, N_j \geq 0, N_{ij} = \{0,1\}$$

$$x_{ij} = \{0,1\}, b_{ij} = \{0,1\} \quad \text{for } i, j$$

where

$A_{Ej} = 1$  if MHE  $j$  is acceptable to the user in terms of the economical aspect

0 otherwise

$A_{Ij} = 1$  if MHE  $j$  is acceptable to the user in terms of the integratability and applicability aspects

0 Otherwise

$A_{Mj} = 1$  if MHE  $j$  is acceptable to the user in terms of to the maintenance and safety aspects

0 otherwise

$A_{Oj} = 1$  if MHE  $j$  is acceptable to the user in terms of the other aspect

0 otherwise

$A_{Pj} = 1$  if MHE  $j$  is acceptable to the user in terms of the applicability aspect

0 otherwise

$b_{ij} = 1$  if MHE  $j$  can be used for move  $i$

0 otherwise

$B$  = available budget

$C_j$  = operating cost of MHE  $j$  per unit time

$F_j = 1$  if MHE  $j$  is chosen in the MHE types

0 otherwise

$H(Y_{ij})$  = height of load pattern used on which  $Y_{ij}$  items are transported using MHE  $j$

$i$  = move identifier,  $i = 1$  to  $m$

$IC_{ij}$  = interface cost of MHE  $j$  for move  $i$

$j$  = MHE identifier,  $j = 1$  to  $n$

$M$  = a very large positive number

$N_{ij}$  = number of units of MHE  $j$  required for move  $i$

$N_j$  = number of units of MHE  $j$  required for all moves

$O_t$  = available operation time

$PC_{ij}$  = purchase cost per unit of MHE  $j$  for move  $i$

$P(Y_{ij})$  = longer side of load pattern used on which  $Y_{ij}$  items are transported using MHE  $j$

$SC_{ij}$  = annual cost of space related to MHE  $j$  for move  $i$

$S(Y_{ij})$  = shorter side of load pattern used on which  $Y_{ij}$  items are transported using MHE  $j$

$T_{ij}$  = total operating time for move  $i$  if handled by MHE  $j$

$W_{ij}$  = total number of trips required by MHE  $j$  for move  $i$

$W(Y_{ij})$  = weight of load pattern used on which  $Y_{ij}$  items are transported using MHE  $j$

$x_{ij} = 1$  if MHE j is assigned for move i

0 otherwise

$Y_i$  = total number of unit items required to be handled in move i

$Y_{ij}$  = number of units in each load(each trip) transported by MHE j for move i

$\alpha_j$  = load length limit for MHE j

$\beta_j$  = load width limit for MHE j

$\gamma_j$  = load height limit for MHE j

$\delta_j$  = load weight limit for MHE j

The objective function (1) minimizes the sum of the purchase cost, operating cost, space cost, and interface cost. Equations (2–4) ensure that a move has to be assigned to only one MHE type and that such assignment can only be made to MHE type suitable for the move. Constraint set (5) means that the time required for all moves to be performed by a type of MHE cannot exceed the total available operating time of the assigned number of units of the MHE. Constraint set (6) ensures that the MHE selected has to cover the total requirement in units for move i. Equations (7–10) requires that the length, width, height, and weight of unit load have to be within the MHE dimensional limits. Equation (11) indicates that total investment cost of all MHE selected for all moves has to be less than or equal to the budget specified by the user. Equation (12) means the number of a MHE required for a move could not always be an integer so the number needs to be adjusted. Constraint set (13) ensures that the MHE selected should meet the acceptable levels of economics, adaptability and integratability, applicability, maintenance and safety, and other factors such as noise, and appearance of the MHE.

### 3.2.2.5. Summary of solution steps and information flow between steps

The model presented in the last section is extremely difficult to solve for any reasonable size problem. As a result, a search procedure is used instead. The search procedure includes the applications of knowledge-based rules, decision-making algorithm, and fuzzy logic, etc. The overall decision steps for the search procedure are summarized in Figure 3.2. The information flow between the steps is summarized in Table 3.4. The information summarized in Figure 3.2 and Table 3.4 are presented and discussed in detail throughout the remainder of this Chapter.

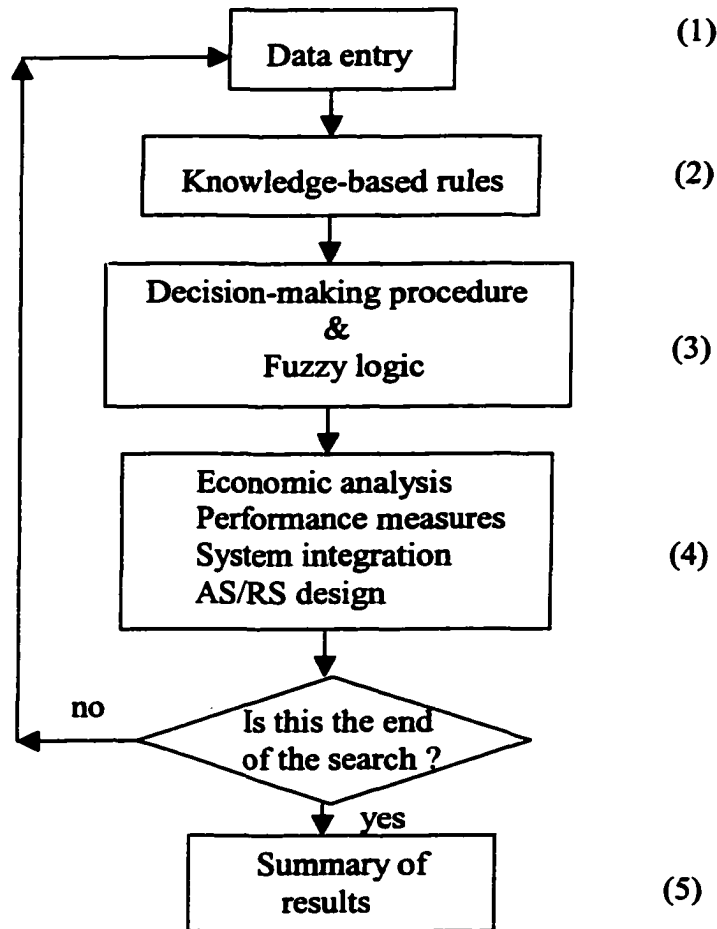


Figure 3.2. Summary of algorithmic steps

Table 3.4. Summary of information flow between algorithmic steps

Block #	Input	Output
1	<ul style="list-style-type: none"> <li>- General attributes (budget, etc.)</li> <li>- Material attributes (weight, etc.)</li> <li>- MHE attributes (operation type, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>- Processed input data</li> </ul>
2	<ul style="list-style-type: none"> <li>- Output of Block 1</li> </ul>	<ul style="list-style-type: none"> <li>- Alternative MHE for moves</li> </ul>
3	<ul style="list-style-type: none"> <li>- Output of Block 2</li> </ul>	<ul style="list-style-type: none"> <li>- The most appropriate MHE for the moves</li> </ul>
4	<ul style="list-style-type: none"> <li>- Output of Block 3</li> <li>- Output of Block 1</li> </ul>	<ul style="list-style-type: none"> <li>- Results of economic analysis (return on investment, etc.)</li> <li>- Results of performance measure (utilization, etc.)</li> <li>- Results of system integration (system configurations)</li> <li>- Results of AS/RS design (dimension of the storage space &amp; number of S/R machines required)</li> <li>- Specifications</li> </ul>
5	<ul style="list-style-type: none"> <li>- Output of Block 3</li> <li>- Output of Block 4</li> </ul>	<ul style="list-style-type: none"> <li>- Summarized results of the search</li> </ul>

### **3.3. Design of the Knowledge-based Rules**

The MHE selection model in subsection 3.2 cannot be solved optimally and efficiently because of the complexity of the problem itself. Therefore, combining knowledge-based rules and a decision algorithm using weighted factors specified by users is an efficient and practical approach to solve the problem. The knowledge-based system searches and generates several alternative candidate solutions for a move using the attribute values specified by the user. The decision algorithm evaluates the alternative solutions to provide a recommended solution. These are the main parts of the developed system, referred to as DESIGNER. In this section, knowledge-based rules are presented to address the major criteria that influence MHE selection. The decision algorithm is described in subsection 3.5.

#### **3.3.1. Compilation of the knowledge base**

The MHE selection problem is a complex task because of the constraints imposed by the facility and materials, and the wide variety of equipment types and models available. New and customized MHE enter the commercial market on a regular basis. The MHE selection problem is made much more difficult by the lack of a systematic approach to equipment selection. Thus, several expert systems have been built for the MHE selection problem (Chu et al., 1995; Fisher et al., 1988; Kim and Eom, 1997; Matson et al., 1992; Park, 1996; Welgama and Gibson, 1996). It is apparent that knowledge associated with material handling is not obtained from one single source or one human expert. Thus, this research effort involved the extraction of knowledge-based rules from several published sources.

### **3.3.2. MHE Types and attributes**

A total of 41 MHE types are considered for the knowledge-based rules in this research. The addition of more MHE types is also possible in future system configurations. Figure 3.3 shows the list of MHE types identified from a survey. These represent the major types of MHE used in in-plant material handling. These MHE were classified into three groups based on their functions: equipment for movement, equipment for storage, and equipment for positioning. Equipment for movement simply move materials from one location to another. This type of MHE consists of industrial vehicles, automatic guided vehicles (AGVs), monorails, conveyors, and cranes. Equipment for storage are used for holding materials in storage over a period of time. Examples of this type of MHE are automated storage and retrieval systems (AS/RS) and general rack systems. Equipment for positioning are generally used at workstations to help position items for machining operations. This type of MHE feeds and brings materials to exact position and holds them until some machining or processing operation is completed. Typical types of MHE that perform this function are robots, turntables, feeders, and load balancers.

Attributes relevant to the 41 MHE types considered were identified and included in the knowledge-based rules. These attributes are used to find alternatives for a move specified by users. Forty attributes were considered from available materials. These attributes were classified into four groups: general attributes related to the manufacturing facility, attributes of the material to be handled, attributes related to the move, and attributes related to the operation and data treatment. The data treatment attribute refers to how operation data are loaded into MHE and how the transaction data are treated by the MHE control system. To be selected as a suitable MHE for a move, extensive matching of these attributes is required.

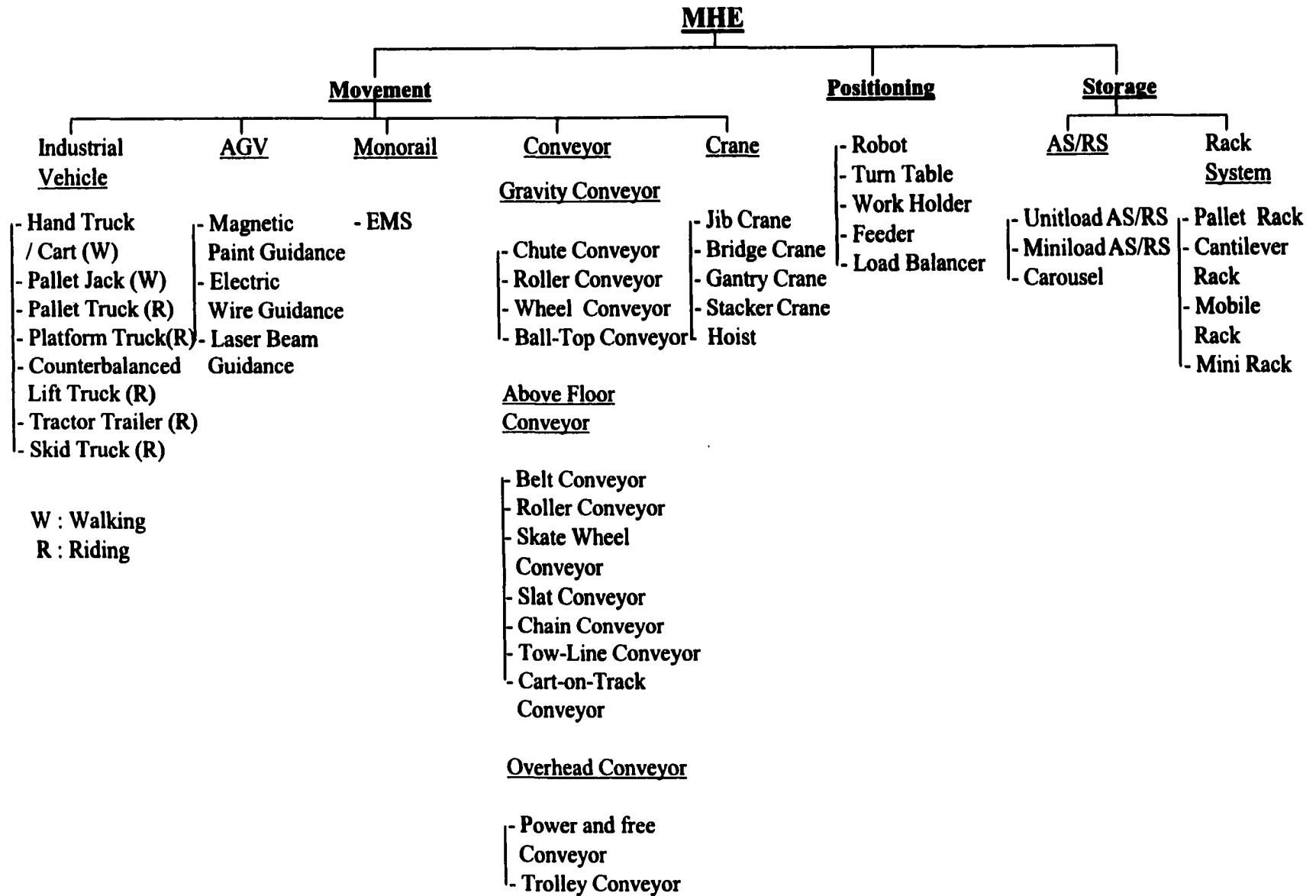


Figure 3.3. MHE types considered in DESINER



The attributes considered and their values are summarized in Tables 3.5 and 3.6. The detail values and explanations are provided in Appendix B.

For general attribute, automation level refers to the overall level of automation of the MHE to be operated in the facility or the desired level of automation for new MHE purchases. For the options, manual implies the MHE is operated manually; semi-programmable implies a powered system in which there is no computer control from the host computer; and programmable implies a powered, computer controlled system. The host computer level refers to the degree of the host computer application in the facility. The host computer manages all activities of the company, including inventory control, scheduling, accounting, purchasing, material handling system control, and management of personnel. As an option, low level indicates the number of operations managed and controlled by the host computer is less than 33% of all activities of the company. Medium level means the number of operations managed and controlled by the host computer is between 33% and 67%. High level means the number of operations managed and controlled by the host computer is greater than 67%.

The selection of suitable material handling equipment must consider several factors such as economics, applicability, adaptability and integratability, maintenance and safety, etc. In DESIGNER, the user is expected to assign weights to these factors. The weights reflect the level of importance assigned to the factor. The weight assigned to economics reflects the importance of cost in the final decision and how economical the equipment is. Applicability reflects how much the MHE meets the production requirements and the constraints of the production environment specified by a user. Adaptability and integratability imply how easy the MHE can be modified to suit a new product or production

Table 3.5. General and material attributes included in DESIGNER

General attributes	Material attributes
<ul style="list-style-type: none"> <li>• Number of material flow links</li> <li>• Budget</li> <li>• Automation level: manual, semi-programmable, programmable</li> <li>• Host computer level: low, medium, high</li> <li>• Expected production trend: increasing, highly increasing, decreasing, highly decreasing, stable</li> <li>• Product mix: high, medium, low</li> <li>• Weights assigned to evaluation factors: for economic (%), for applicability (%), for adaptability &amp; integratability (%), for maintenance &amp; safety (%), other factors (%)</li> <li>• Operation time per day</li> </ul>	<ul style="list-style-type: none"> <li>• Unit load type: in-container, on-pallet, individual, tote box, barstock, bulk</li> <li>• Unit load weight: light, medium, heavy</li> <li>• Length of unit load: short, medium, long</li> <li>• Width of unit load: short, medium, long</li> <li>• Height of unit load: short, medium, long</li> <li>• Unit load volume: small, medium, large</li> <li>• Bottom surface: rigid, not rigid</li> <li>• Quantity of unit loads to be handled</li> </ul>

Table 3.6. Attributes in DESIGNER associated with move, operation, and data treatment

Move attributes	Operation and data treatment attributes
<ul style="list-style-type: none"> <li>• Move type: horizontal (above floor, overhead), inclined, rotational</li> <li>• Move distance : short, medium, long</li> <li>• Move path : fixed, variable</li> <li>• Move speed required : slow, medium, fast</li> <li>• Length of available space for MHE</li> <li>• Width of available space for MHE</li> <li>• Height of available space for MHE(truss height)</li> <li>• Move pattern : continuous, intermittent</li> <li>• Floor surface : smooth, rough</li> <li>• Loading/unloading speed needed at workstation : slow, medium, fast</li> <li>• Loading/unloading(L/U) automation level: manual, machine L/U, automatic L/U</li> <li>• Type of workstations associated with the move : 1:1, 1:several, several:several, several:1</li> <li>• Direction of the move : one-way, two-way</li> <li>• Type of MHE to be connected : manual MHE, semi-programmable MHE, programmable MHE</li> <li>• MHE type transporting into storage : not decided, manual, industrial truck, AGV, Monorail, conveyor, crane</li> <li>• MHE type transporting out of storage : not decided, manual, industrial truck, AGV, Monorail, conveyor, crane</li> </ul>	<ul style="list-style-type: none"> <li>• Type of equipment : movement, storage, positioning</li> <li>• Operation type : manual, semi-programmable, programmable</li> <li>• MHE motion type : transferring, rotating, gripping, feeding</li> <li>• Accuracy required : low, medium, high</li> <li>• Frequency : continuous, intermittent</li> <li>• Weight control needed : yes(load cell), no</li> <li>• Transaction data treatment : manual, semi-auto, automatic(bar code)</li> </ul>

environment and how well the MHE is readily integrated with an existing MHE.

Maintenance and safety mean how economical and safe the MHE is for maintenance and

safety. The other factors imply how attractive or noisy the MHE is. These are additional factors the user may like to consider but are not explicitly included in the other factors. Operation and data treatment refer to how transaction data are loaded and transmitted to the MHE control computer, especially for storage and retrieval operations of the AS/RS.

### **3.3.3. Knowledge organization schemes**

There are no rigid guidelines for constructing decision rules (Matson et al., 1992). One reasonable way to form knowledge is to represent the knowledge rules in terms of the attributes and values specified in Tables 3.5 and 3.6. All possible combinations of attributes and values can be identified for a small size problem. However, this approach cannot be applied to a large problem because it would result in thousands of rule combinations. The rule space will be extremely large for a problem involving 41 MHE types and 40 attributes. It is inefficient and unrealistic to consider a large number of these combinations in the knowledge base. Thus, the problem needs to be solved more appropriately with some more critical attributes in decision making. In the selection of a suitable MHE for a move, a solution can be found in a sequence of a few steps with the critical attributes. Each step directs the search. Therefore, an exhaustive attribute space search and matching are not required to find a fit. This is the general way experts reason about problems and find solutions to them. DESIGNER asks a series of questions associated with the attributes to users. The answers to the attributes are used in finding a solution to the MHE selection problem.

Decision chains are developed to design a knowledge-based system having the features shown in the Figure 3.4 through 3.11. The following approaches were applied to develop the decision chains:

1. Decision chains are designed to select a subgroup of MHE. Thereafter, MHE types within the subgroup are considered as alternatives for the move specified by the user. An appropriate solution can be reached after going through the two stages. For example, if a user specified an MHE for movement, the decision chain for subgroup of movement MHE will find one subgroup of MHE for movement, such as AGV. Once the subgroup AGV is identified, the decision chain for AGV type will delve further to specify an MHE type within the subgroup, such as laser-guided AGV as an alternative for the move.
2. When a solution is suggested by the MHE decision chain, several other alternatives for the move are identified from the database of alternatives. In addition, the decision-making algorithm uses the weights assigned to the five evaluation factors, the factors themselves, and the available budget specified by users to evaluate the alternatives and suggest a final solution along with information regarding specification, economic analysis, performance measures, system integration, and AS/RS design for storage purposes. The optimization algorithm is explained in subsection 3.5.
3. Only the set of attributes important to the selection of each subgroup of MHE and each type of MHE are included in the search path. For example, the longest search path involves 12 attributes for the selection of a belt conveyor from the decision chain for conveyor type.

4. A value or set of values for which an MHE type is suitable for is specified. For example, gravity ball-top conveyors are appropriate for unit loads of up to 100 lbs.

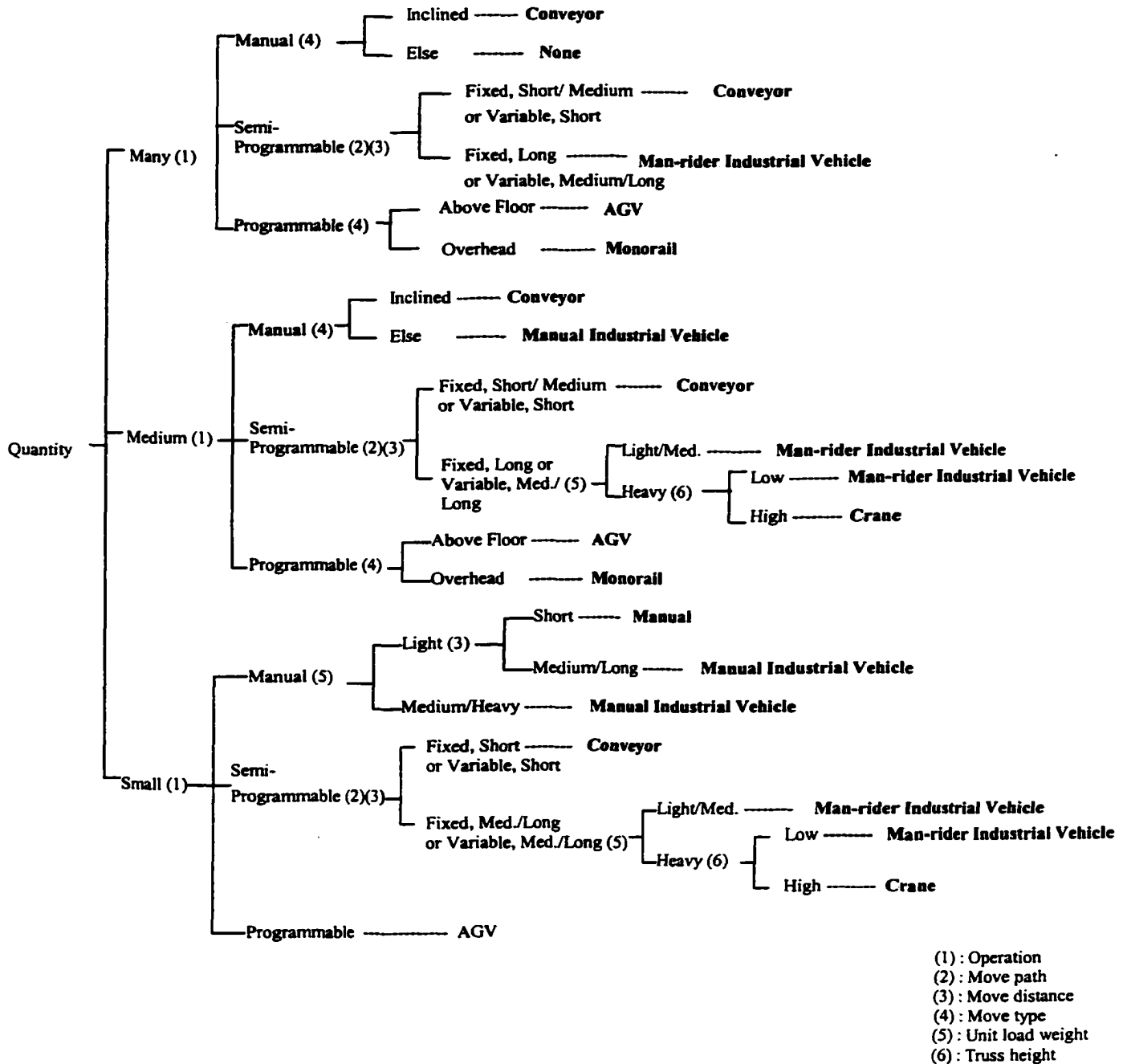


Figure 3.4. Decision chain for subgroup of movement MHE

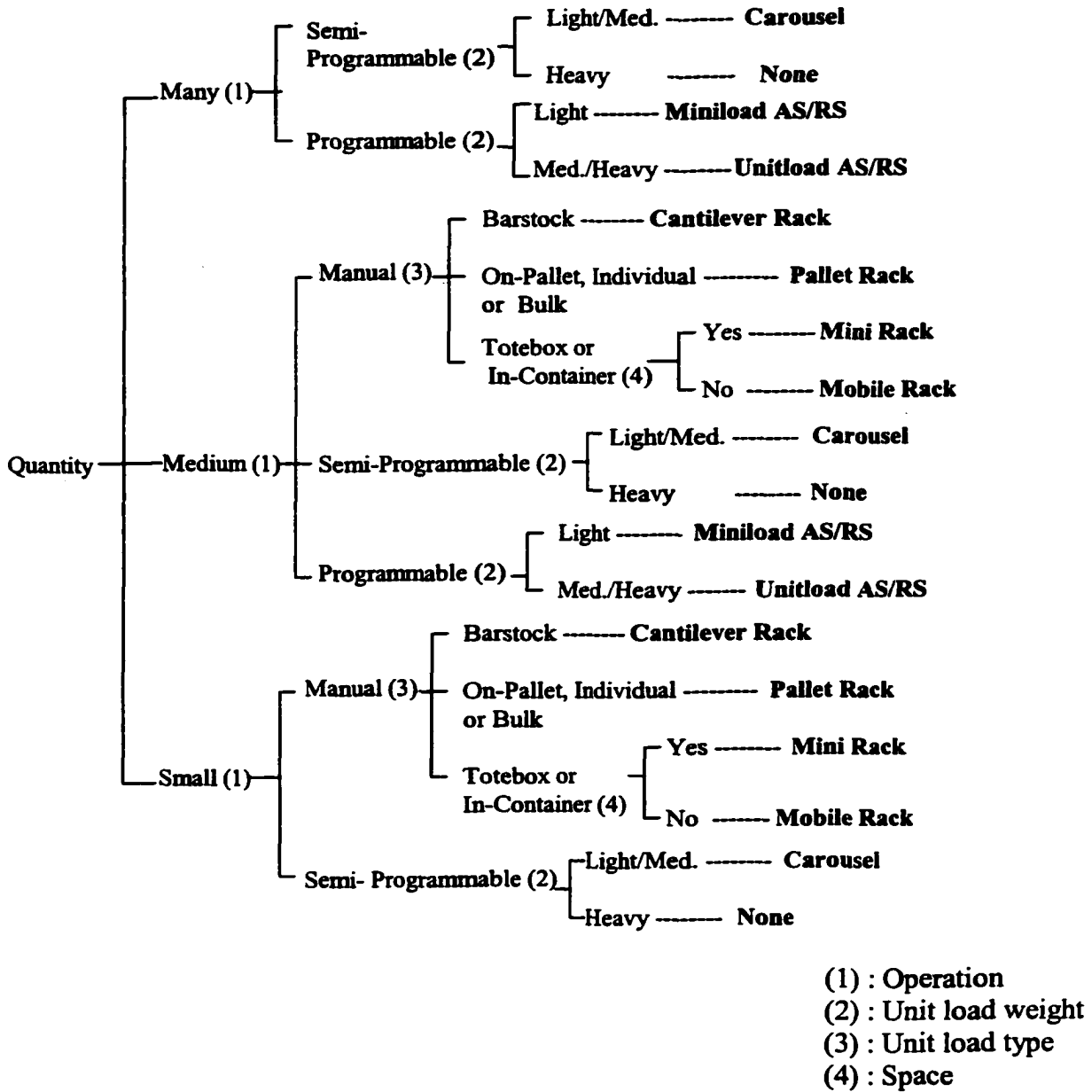
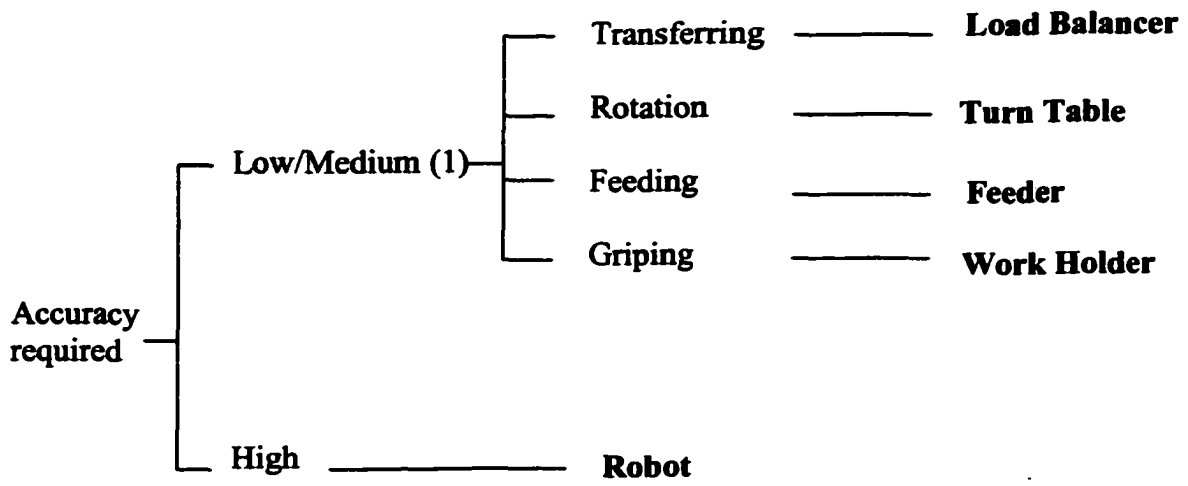
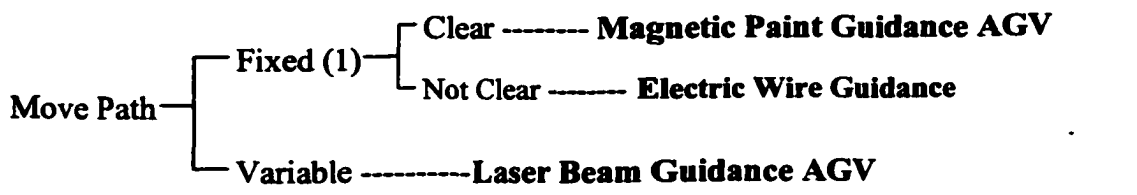


Figure 3.5. Decision chain for subgroup of storage MHE



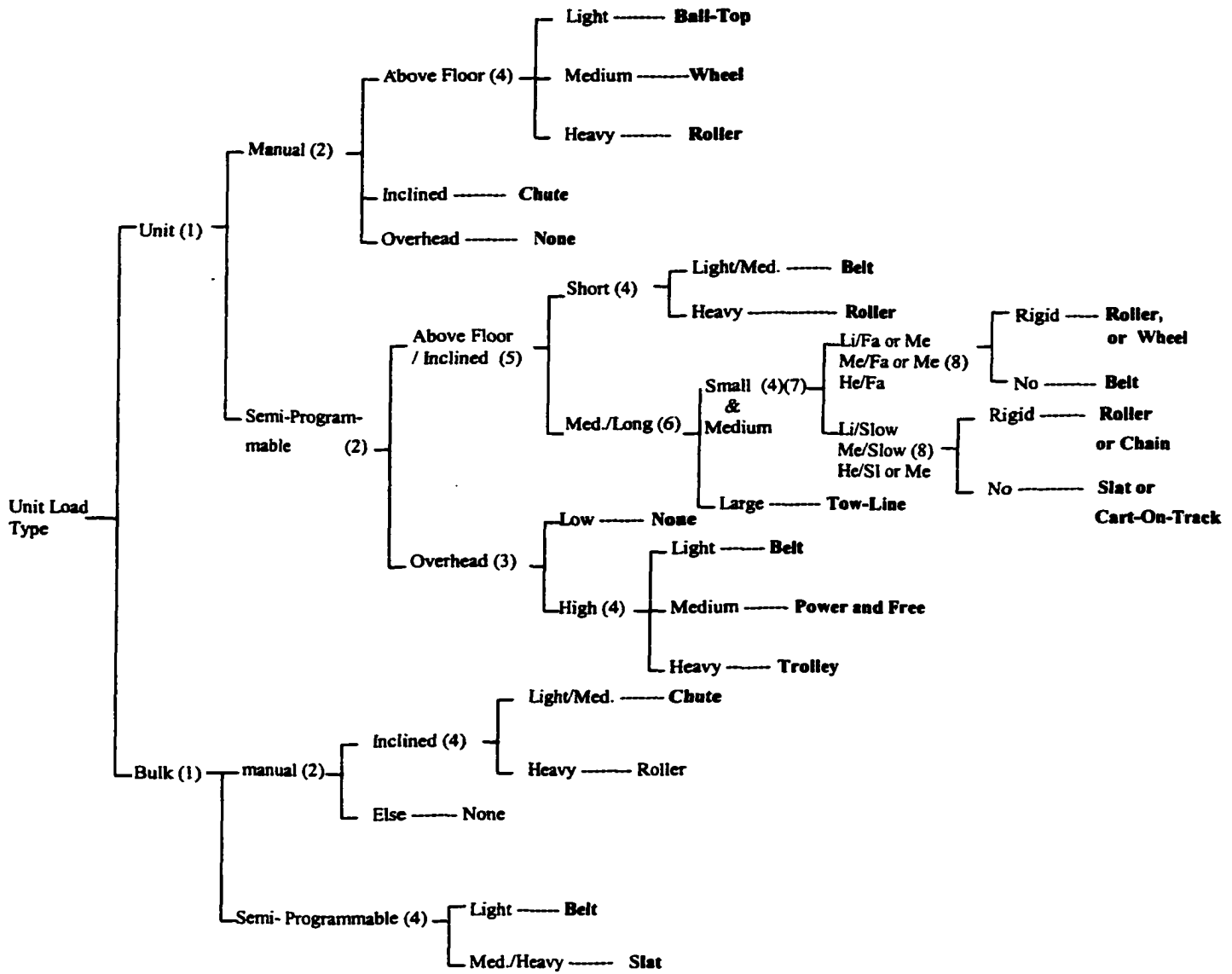
(1) : Motion type

Figure 3.6. Decision chain for subgroup of positioning MHE



(1) : Floor surface

Figure 3.7. Decision chain for AGV type



- (1) : Operation
- (2) : Move type
- (3) : Truss height
- (4) : Unit load weight
- (5) : Move distance
- (6) : Unit load volume
- (7) : Move speed
- (8) : Bottom surface

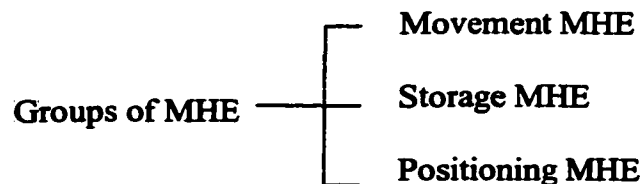
Figure 3.8. Decision chain for conveyor type



Therefore, unit loads whose weight are less than or equal to 100 lbs can be handled by a gravity ball-top conveyor. Thus, “light” is a possible attribute regarding unit load weight for this MHE.

5. When there is no suitable MHE solution, the suggestion of “none” or “manual” is provided.

System users are expected to select one MHE group they are considering from among the three MHE groups below when they initially activate DESIGNER on the web.



The decision chains for MHE subgroups and MHE types are summarized in Figure 3.4 through 3.11. For example, Figure 3.4 shows one segment of the decision chain for subgroup of MHE included in the knowledge-based rules. This decision chain is used if the user chooses the movement MHE as the group of MHE for a move. At this stage, the possible MHE subgroups are conveyor, man-rider industrial vehicle, manual industrial vehicle, AGV, monorail, and crane. Seven different attributes are considered in guiding the search. These attributes include quantity, operation type, move path, move distance, move type, unit load weight, and truss height. If the quantity is many (e.g., more than 300 unit loads per day), the operation type required is semi-programmable, the move path and the move distance are fixed and short/medium or variable and short, respectively. The MHE subgroup suggested is conveyor. After a subgroup selection, Figure 3.8 is used to further search for the type of conveyor most suitable for the task.

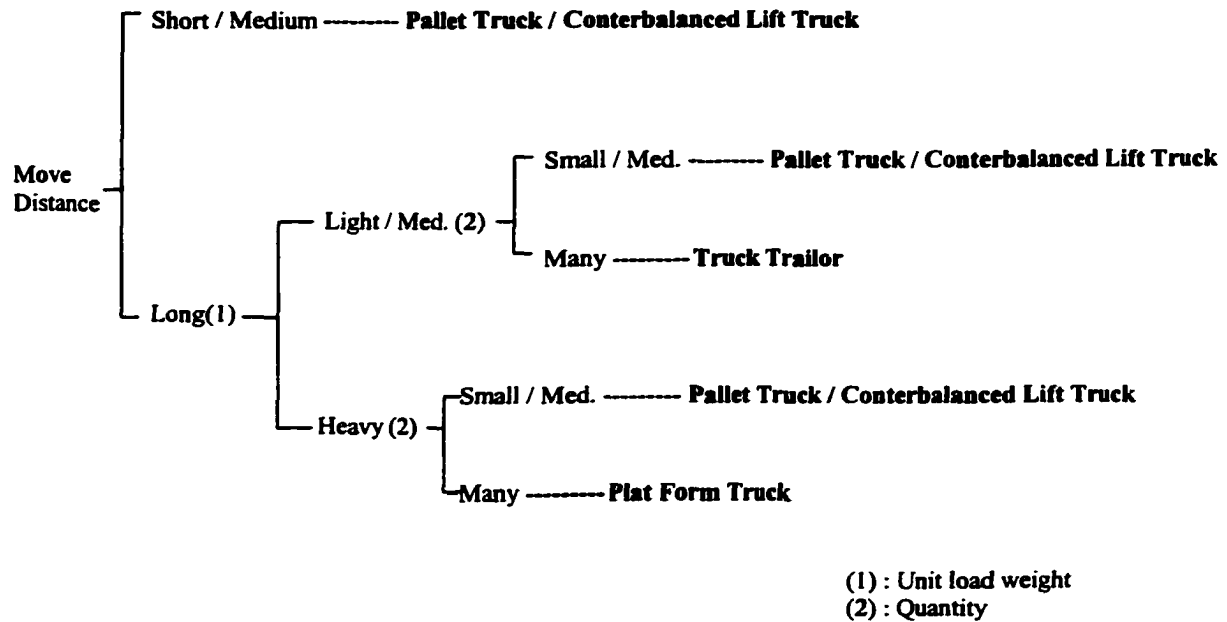


Figure 3.9. Decision chain for man-rider industrial vehicle

Using the decision chain in Figure 3.8, nine attributes are used to select an alternative MHE for the move. Early in the chain, the unit load type is identified as either a unit type or bulk type. If the attribute is “unit” type, then all eight attributes in Figure 3.8 are checked for the MHE type. If it is “bulk” type, then attributes such as operation, move type, and unit load weight are checked. When the user specifies “unit” as the unit load type, semi-programmable as the operation type, above floor or inclined as the move type, short as the move distance, and heavy as the unit load weight, a roller conveyer is recommended as a possible MHE type for the move. The processing logic for each branch in the entire decision chain for the MHE type selected is applied in a similar manner.

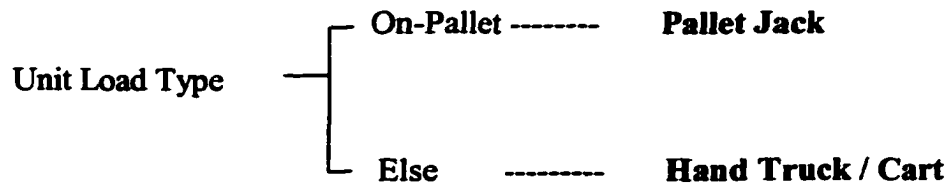


Figure 3.10. Decision chain for manual industrial vehicle

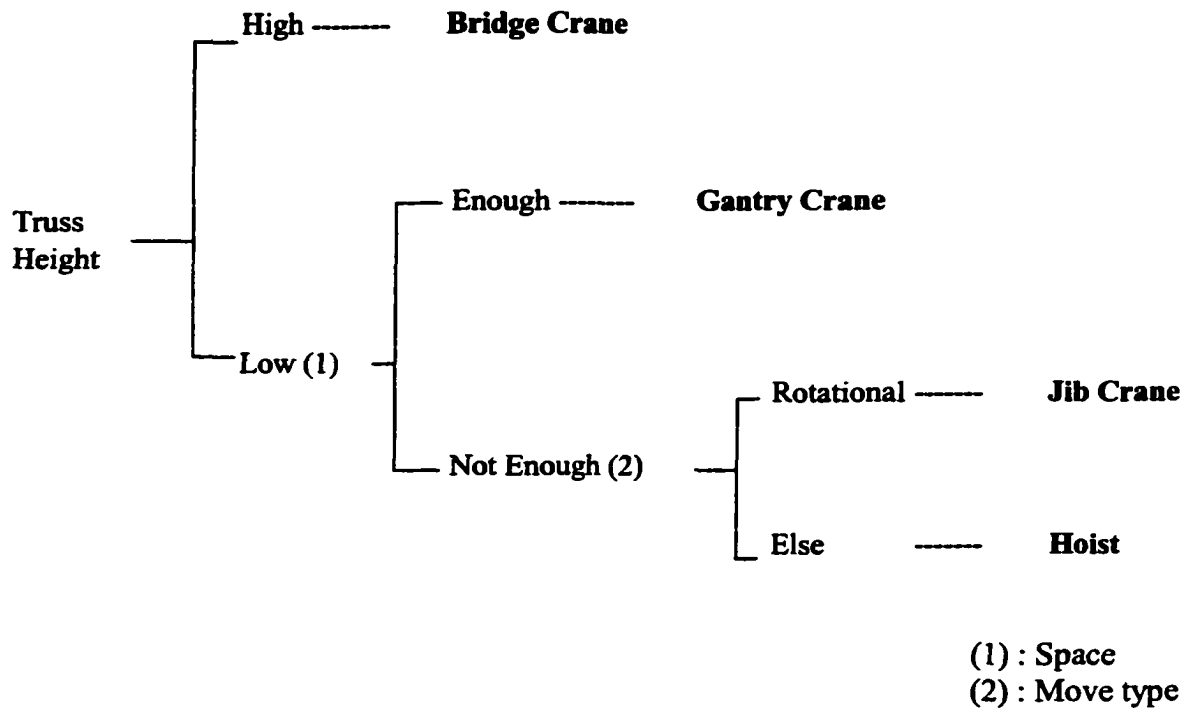


Figure 3.11. Decision chain for crane

### **3.3.4. Knowledge-based rules and the database**

Knowledge-based rules are developed in the form of **if ... then ... format** to represent the problem-solving knowledge. This is one of the oldest techniques for representing domain knowledge in an expert system. Nevertheless, it is also one of the most natural and remains widely used in real applications. Reasoning with knowledge-based rules approach is carried out using forward or backward chaining. Forward chaining is a data-driven reasoning process where a set of rules is used to derive new facts from an initial set of data. It does not employ the resolution algorithm used in predicate logic. It generates new data by the simple and straightforward application or firing of the rules. Backward chaining is often called goal-directed reasoning, because a particular consequence or goal clause is evaluated first, and then goes over the rules. Unlike forward chaining, which uses rules to produce new information, backward chaining uses rules to answer questions about whether a goal clause is true or not. Therefore, a backward-chaining approach was applied in DESIGNER.

The information on decision chains explained in subsection 3.3 was translated into a programmable format for implementation. The total number of rules developed and considered in the research is 370 based on 41 MHE types and 40 attributes. The basic form of each rule is given as follows:

**If Attribute 1 has Value 1**

**and Attribute 2 has Value 2**

•

•

**and Attribute m has Value m**

**Then the suggestion is MHE type 1**

The recommended solution obtained from DESIGNER is dependent on the user's responses to the queries.

A database was designed and constructed to store the specifications for the 41 MHE types, the alternatives for the MHE types that were suggested from the knowledge-based rules, session information associated with Web application, and the results from the analysis modules such as performance measure module and economic analysis module. Table 3.7 summarizes the tables included in the database.

The Microsoft computer package MS SQL was used for the database. Session number, MHE group, and MHE type were identified as primary keys in the database. Number of material flow links and MHE model were used for foreign keys. There were no specific relationship such as relational, hierarchical, or network in the database. Eight MHE type tables, one alternative MHE type table, one processor table, one summary table, and four question tables were included in the database. MHE type tables were constructed to store the specifications and expected purchase cost of the MHE type. An alternative MHE type table was used to contain the information on the alternative MHE for the selected MHE type and the results of the evaluations for the alternatives based on economics, applicability and integratability, maintenance and safety, and other factors as deemed necessary by the user. The process table was constructed for the calculations of normalized evaluation results, operation cost, and interface cost of alternatives. MHE question tables were constructed to store the data specified by the user for each query. The summary table was constructed to

store the optimal MHE type for each material flow link and the normalized evaluation results of the MHE. In addition to previously mentioned data, economic analysis, specification, performance measures, integration guide, and AS/RS design results were also stored in the summary table. Question tables were constructed to contain the general attributes table, the movement attributes table, the storage MHE attributes table, and the positioning attributes table. The query lists and detail explanations of these queries are provided in Appendix B. Figure 3.12 shows the linkages between these tables and Table 3.8 displays the data dictionary for these tables. Table 3.9 shows the critical factors employed in the specification of subgroups of MHE considered in this research.

**Table 3.7. Summary of the database tables**

Input Tables	Output Tables	Internal Working Tables
<p>- Table for general attributes (Gen.Att.)</p> <p>- Tables for MHE &amp; material attributes (Mov.MHE.Att, Stor.MHE.Att., Posi.MHE.Att.)</p>	<p>- Alternative table (Alternatives)</p> <p>- Summary table (Summary)</p>	<p>- Tables for MHE specifications (Conveyor, AS/RS, Robot, etc.)</p> <p>- Tables for internal processing (Process)</p>

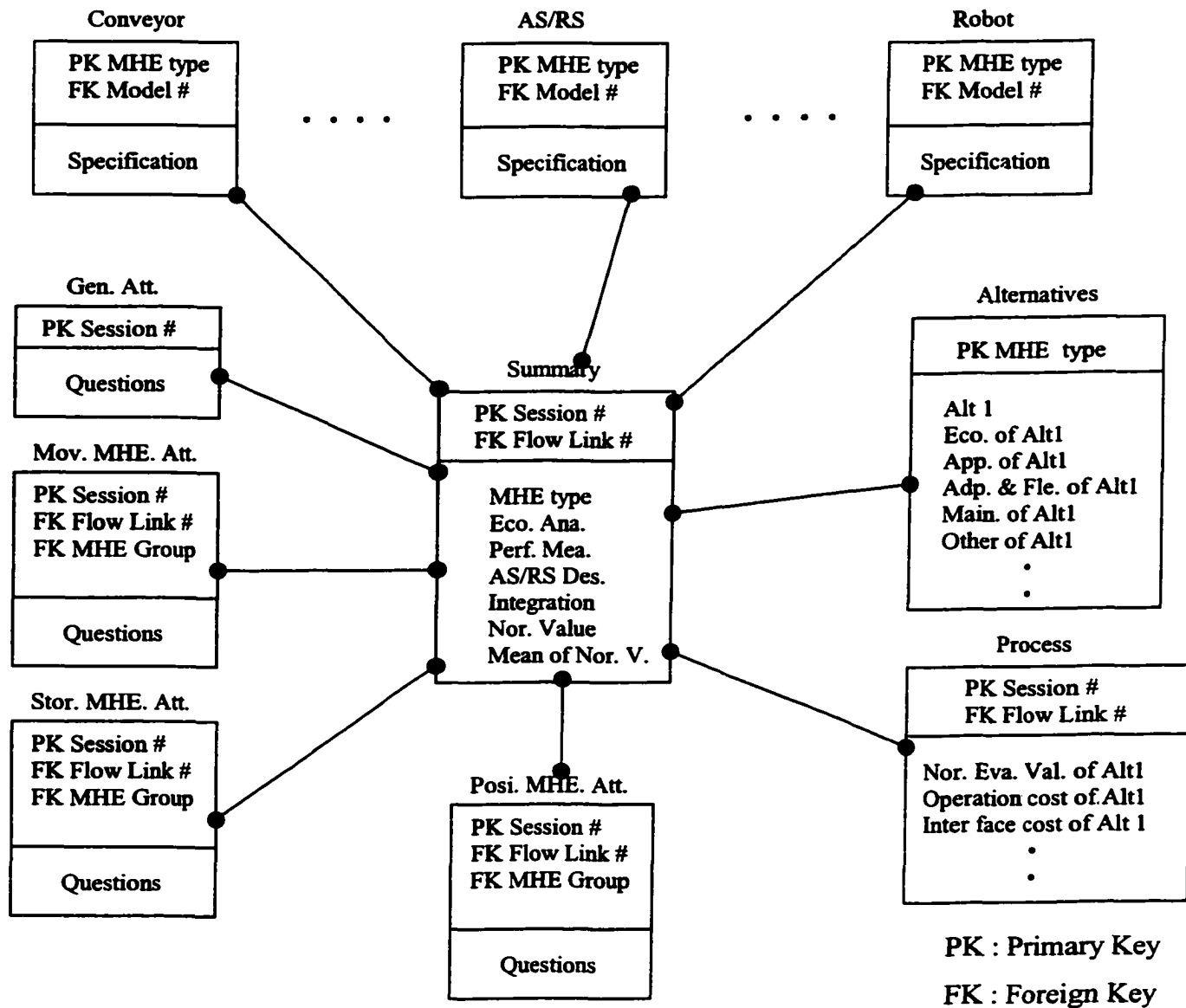


Figure 3.12. Interface diagram of the database in DESIGNER

Table 3.8. Data dictionary for DESIGNER

Table	Description
MHE Group	contains the list of MHE type, model numbers, and the specifications of the MHE types belonging to the group.
Attribute	includes the tables for general attributes, movement MHE attributes, storage MHE attributes, and positioning MHE attributes. Each table has list of queries related to the attributes.
Session #	used to identify the user as a primary key.
Flow Line #	used to identify the material flow as a primary key.
MHE Group	refers to the type of MHE category.
Alternative	stores the alternative MHE type considered and compares evaluation results obtained for the alternatives in terms of the design factors of economics, applicability, adaptability & integratability, maintenance & safety, and any other factors.
Alt1.	alternative number 1 for the material flow link specified by the user.
Alt2.	alternative number 2 for the material flow link specified by the user.
•	Continued to the last alternative.
•	
Process	used in calculating the normalized evaluation results, purchase cost, operation cost, interface cost, and space cost for the alternatives.
Summary	stores the final suggested MHE type and related information, including economic analysis, performance measures, AS/RS design, system integration.

For the specifications of an automated MHE type such as AGV, AS/RS, and monorail, integration with the host computer, the material control computer, and other MHE are considered. The specifications for software and hardware for these MHE are also included. An example of the specifications for a unit load type AS/RS provided as output by DESIGNER is given in Figure 3.13. The output data with respect to system integration will be presented using examples in subsection 3.6.



Table 3.9. The critical factors in the specification of MHE subgroup in DESIGNER

Subgroup	Factors
Industrial vehicle	loading capacity, fork lifting height, travel speed, overall fork dimension, power supply type
AGV	guidance method, travel speed, loading capacity, power supply type, positioning accuracy, overall load carrier size, control system
Monorail	carriage type, loading capacity, speeds of lifting and traveling, positioning accuracy, overall length of rail, control system
Conveyor	travel speed, loading capacity, width of load, distance to move
Crane	loading capacity, travel speed, overall height, overall span
Robot	payload, ranges of motion, moving speed, repeatability, accuracy, loading capacity, degrees of freedom
AS/RS	loading capacity, speeds of horizontal move , vertical move, type of extractor, type of pallet, number of cells, number of S/R machine, overall dimension , data communication method, control system
Rack system	overall dimension, pallet type, number of pallet, loading capacity

**\* S/R Machine**

- Capacity : 4500lbs
- S/R machine height : 60ft
- Horizontal speed : 600fpm
- Vertical speed: 250fpm
- Extractor speed : 200fpm
- Type of hoist : Chain rope
- Type of extractor : Dual telescoping forks
- Minimum aisle width available : 52"
- On-board controller : PLC(CLCV)
- Interface with control computer : Optical units

Price : \$220,000

**\* Rack**

- Available space : 200'L × 70'W × 68'H
- Number of cells : 350
- Type of pallet : Wood

Price of Wood Pallet : \$30/pallet

Price of Rack : \$120/pp(pallet position)

Figure 3.13. Specifications for unit load AS/RS

**\* AS/RS System Controller**

- CPU : IBM PC compatible / Window NT 4.0
- Diskette drive : 3.5", Zip drive
- Printer : Dot printer (10ppm)
- UPS : 3KVA/30min.
- Ports : 3 (one for Printer, one for host interface, and one for extra)
- Database : Oracle 8.0
- Barcode reader : Fixed scanner type
- Barcode printer : 8dots/min
- Load cell
- Communication with S/R machine : Optical Units
- Communication with Conveyor : PLC
- Communication with Host Computer : Ethernet with NetBios calls
- Communication with Printer : RS232
- Communication with barcode scanner : RS422
- Communication with AGV control computer : RS422
- Communication with EMC control computer : RS422
- Sub Program required
  - Storage management module
  - Retrieval management module
  - Host interface (communication) module
  - Inventory management module
  - Report management module
  - Etc.
- Console room required

Price : \$410,000

Figure 3.13. (Continued)

### **3.4. Fuzzy Logic Applications to Material Handling Systems Design**

The theory of fuzzy logic (fuzzy mathematical model), which originated with Zadeh during the 1960s, allows for the existence of a type of uncertainty due to vagueness or fuzziness rather than due to randomness alone. Another word for this type of uncertainty could be imprecision. In a narrow sense, fuzzy logic refers to a logical system that generalizes the classical logic (Boolean logic) for reasoning under uncertainty. In a broad sense, it means all of the theories and technologies that employ fuzzy sets, which are comprised of classes with unclear boundaries. In this research, the concept of fuzzy logic is applied to the knowledge-based rules as sensitivity indexes and to evaluation matrices used for the selection of the most suitable MHE through a fuzzy linguistic approach.

#### **3.4.1. Evaluation of knowledge-based rules**

The knowledge-based rules generated for this research may contain inaccuracies and uncertainties that are inherent in the description of the rules. They are due to the difficulty of representing the facts involved in the conditions and conclusions of the inference rules, which are expressed, in most cases, by ambiguous characterizations (for example, the host computer level is described as “low”, “medium”, or “high”), or by imprecise data (such as quantity of unit loads to be handled per day described as “approximately” equal to 300 units). In order for the knowledge-based rules to be useful, they must associate an actual measure of this uncertainty with each conclusion. This measure is commonly called the certainty factor, and defines how well the knowledge-based rules model human knowledge.

For that, fuzzy decision tables (FDT) and sensitivity indexes are employed. Decision tables can be used in all phases of software engineering, from system planning through the

software design process, down to software maintenance. The concept of decision table was modified in this research so that the values of conditions could be nondeterministic. An FDT is a special form of table that determines a set of decision rules based on a clearly identified set of conditions and conclusions. The FDT consists of four major parts: the condition part and values, and the conclusion part and values. Figure 3.14 shows the general form of an FDT.

Condition Part	Condition Values
Conclusion Part	Conclusion Values

Figure 3.14. Parts of a fuzzy decision table

The condition part contains each condition item to be evaluated, and the condition values have values for each condition item. Similarly, the conclusion part contains conclusion items and the conclusion values have consequences for each conclusion item. The section on condition and conclusion values is divided into columns called rules. Each column specifies values for certain conditions and the conclusion to be taken when those conditions meet the specified values. An example of an FDT using several rules generated to select a suitable conveyor type is shown in Table 3.10.

Table 3.10. An example of an FDT for selection of a suitable conveyor type

Conditions	Rules						
	#1	#2*	#3	#4*	#5	#6	#7
Unit load type <sup>1</sup>	Unit	Unit	Unit	Bulk	Bulk	Bulk	Unit
Operation <sup>1</sup>	Manual	Semi- Prog.	Semi- Prog.	Manual	Semi- Prog.	Semi- Prog.	Semi- Prog.
Move type <sup>1</sup>	Incline	Ab. Fl.	Incline	Incline	Incline	Ab. Fl.	O.head
Truss height <sup>2</sup>	-	-	-	-	-	-	X <sub>1</sub>
Unit load weight <sup>2</sup>	-	-	X <sub>2</sub>	-	X <sub>2</sub>	X <sub>2</sub>	X <sub>2</sub>
Move distance <sup>2</sup>	-	-	X <sub>3</sub>	-	-	X <sub>3</sub>	-
Unit load volume <sup>2</sup>	-	-	X <sub>4</sub>	-	X <sub>4</sub>	-	-
Move speed <sup>2</sup>	X <sub>5</sub>	-	X <sub>5</sub>	-	-	-	X <sub>5</sub>
Surface rigidity <sup>2</sup>	X <sub>6</sub>	-	X <sub>6</sub>	-	-	-	-
Conveyor Type	Chute	Belt	Roller	Chute	Belt	Slat	Trolley

\* This rule deals with only deterministic conditions.

- 1 Deterministic condition
- 2 Nondeterministic condition

The available options for the condition of unit load type are unit and bulk. Manual, semi-programmable, and programmable are the available options for operation. Above floor, overhead, inclined, and rotational are the available options for move type. These three conditions are deterministic because the user is allowed to select only one possible option for these conditions. The other conditions, including truss height, unit load weight, move distance, unit load volume, move speed, and surface rigidity, are nondeterministic because the user can input any values for these conditions.

A sensitivity index is defined as follows to indicate the sensitivity of these knowledge-based rules to the subjective evaluation to the user:

$$\text{Sensitivity Index} = \frac{(NNC)(NRNC)}{(\sum CE)(TN)}$$

Where *NNC* is the number of nondeterministic conditions; *NRNC* is the number of rules dealing with any nondeterministic conditions; *CE* is the coefficient value and represents the number of possible values of each condition, and *TN* is the total number of rules in the FDT. For nondeterministic conditions such as truss height, unit load weight, move distance, unit load volume, move speed, and surface rigidity, 1 is assigned for *CE* to represent one range of values because the possible values for these conditions which a user can specify are infinite. For example, the set of possible values for the first condition is {unit, bulk} so *CE* is 2, whereas the set of possible values for the 4th condition, truss height, is {*s* | *s* can be any value} so 1 is assigned for *CE*.

This makes the sensitivity index  $\in [0,1]$ . When the sensitivity index = 0, it means that the knowledge-based rules are completely deterministic, therefore, the certainty factor of these rules is 1. When the sensitivity index = 1, it implies that the evaluation of the knowledge-based rules can be completely different based on the users, which means the certainty factor of these rules is 0. For the FDT in Table 3.10, 5 rules deal with nondeterministic conditions and the total number of rules in the FDT is 7. The possible set for unit load type is {unit, bulk}; the possible set for operation is {manual, semi-programmable, programmable}; and the possible set for move type is {horizontal above floor, horizontal overhead, inclined, rotational}. Thus the sensitivity index of this example can be calculated as follows:

$$\text{Sensitivity Index} = \frac{(6)(5)}{(2 + 3 + 4 + 1 + 1 + 1 + 1 + 1)(7)} = 0.29$$

The number of nondeterministic conditions in the rule needs to be decreased to reduce the sensitivity index. The sensitivity indices for the knowledge-based rules designed for this research are summarized in Table 3.11. According to the results of Table 3.11, the sensitivity index of the rules for selection of industrial vehicle (riding) is 1 because all conditions are nondeterministic. And the rules for industrial vehicle (manual) and AGV have the smallest value since no nondeterministic conditions were considered. The other rules have lower sensitivity indexes relatively. The sensitivity index using FDT can be interpreted as a certainty factor to evaluate the knowledge rules in expert systems that have some fuzziness. This sensitivity index can also be applied to each rule to evaluate the certainty of it.

Table 3.11. Sensitivity indexes of the knowledge-based rules (refer to Figure 3.4 –3.11)

	Sub-group of Movement MHE	Sub-group of Storage MHE	Sub-group of Positioning MHE	AGV
N.D.* Conditions	- Quantity - Move distance - Unit load weight - Truss height	- Quantity - Unit load weight	- Accuracy	
D.** Conditions	- Operation - Move path - Move type	- Operation - Unit load type - Space	- Motion type	- Move path - Floor surface
Sensitivity Index	0.21	0.14	0.2	0
	Conveyor	Man-rider Indus. Vehicle	Manual Indus. Vehicle	Crane
N.D.* Conditions	- Truss height - Unit load weight - Move distance - Unit load volume - Move speed	- Move distance - Unit load weight - Quantity		- Truss height
D.** Conditions	- Unit load type - Operation - Move type - Bottom surface		-Unit load type	- Space - Move type
Sensitivity Index	0.28	1	0	0.14

\* Nondeterministic, \*\* Deterministic

### **3.4.2. Fuzzy evaluation matrix**

Several evaluation factors must be considered to select the most suitable MHE for a material flow link. While some of the factors such as the economic aspect are objective and easy to quantify, other factors such as applicability, adaptability and integratability, maintenance and safety, and other aspects are subjective and not easy to quantify. In addition, the objective factors can be evaluated in monetary terms, however, the subjective factors merely provide qualitative information. In this research, a fuzzy linguistic approach is used to quantify subjective factors that must be considered for MHE selection problems.

#### ***Basic Idea***

Let us define a set “suitable MHE” which describes the degree of satisfaction of an MHE for a given material flow link by a user. The set “suitable” has the boundaries yes and no to indicate the appropriateness of an MHE. The boundary yes means that the MHE is suitable while the boundary no indicates the MHE is not suitable. An appropriate MHE is indicated by a response with a membership function value that approximately equals 1 (yes) in the set “suitable”. An unsuitable MHE is indicated by a response with a membership function value that approximately equals 0 (no) in the set “suitable”, whereas a value with a membership function of 0.5 represents a crossover point. Both subjective and objective factors influence the membership function value of “suitable MHE”. The measures of all subjective and objective factors form the element of the universe of discourse for “suitable MHE”.



### ***Quantification of Subjective Factors***

Let us propose that the universe is represented as:

$S = \{V_1, V_2, V_3, V_4, V_5\}$ , and  $V_1, V_2, V_3, V_4$ , and  $V_5$  are the measures of 5 evaluation factors constituting the elements of  $S$ . Element  $V_1$  represents the measure of the economic aspect of an alternative MHE;  $V_2$ , the applicability aspect;  $V_3$ , the adaptability and integratability aspect;  $V_4$ , the maintenance and safety aspect; and  $V_5$ , the other factors. The fuzzy set “suitable MHE” of a universe  $S$  is characterized by a membership function  $\mu(V)$  and this notion of membership in fuzzy sets becomes a matter of degree, which is a number between 0 and 1. This means that a number in  $\mu(V)$  in the closed interval  $[0,1]$  is associated with each element of  $S$ . The closer the value  $\mu(V)$  is to 1, the higher is the indication that the alternative MHE is more suitable for the material flow link based on the factor.

The fuzzy set “Suitable MHE” can be defined through enumeration using the following expression:

$$\begin{aligned} \text{Suitable MHE} &= [\mu(V_1)/V_1, \mu(V_2)/V_2, \mu(V_3)/V_3, \mu(V_4)/V_4, \mu(V_5)/V_5] \\ &= \sum_j \mu(V_j)/V_j \end{aligned}$$

where the summation operator refers to the union (disjunction) operation and the notation  $\mu(V_j)/V_j$  refers to a fuzzy set containing exactly one element  $V_j$  with a membership degree  $\mu(V_j)$ . Some elements in a fuzzy set may represent objective factors, for example, the economic aspect. In this case, the membership function would represent the total cost of an alternative MHE, including the purchasing cost, operation cost, interface cost, and space cost; and the function can be modeled as a linear function. The alternative MHE whose total cost

(TC) is the same as the possible highest cost ( $\alpha$ ) that would be assigned a membership function value of 0, implying least suitable, while the alternative MHE whose TC is \$0 would be assigned a membership function value of 1, implying most suitable, as shown in Figure 3.15. The membership function regarding the economic aspect can be described as follows.

$$\mu(V_1) = \begin{cases} \frac{(\alpha - TC)}{\alpha} & 0 \leq TC \leq \alpha \\ 0 & TC > \alpha \end{cases} \quad (3.1)$$

where  $\alpha$  = total cost of most expensive MHE alternative or the reference MHE alternative

$TC$  = total cost of an alternative MHE

$\mu(V_1)$  = a function that maps the fuzzy specification to a membership degree

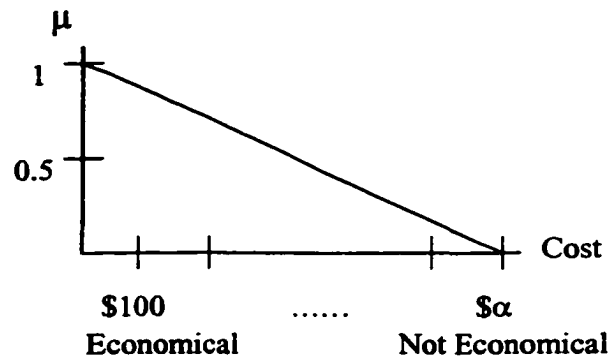


Figure 3.15. Membership function for the economic aspect

When a factor yields qualitative information, its membership value in “suitable MHE” needs to be determined differently. In order to build the membership function for such factors, an estimation method of membership functions called exemplification can be

applied. For example, to derive the value of the membership function, “roller conveyor is good in maintenance and safety aspect”, one may ask experts of an MHE whether roller conveyors are good from the view point of maintenance and safety aspect. To answer, an expert has to use one among several possible linguistic truth-values, e.g., true, more or less true, borderline, more or less false, false. Then these linguistic levels can be translated into numerical values such as: 1, 0.75, 0.5, 0.25, 0, respectively. A discrete representation of the membership function is thus obtained by repeating the query for different MHEs. In this research, information from published papers, other related materials, and experience is used to estimate the value of the membership function for qualitative factors instead of an actual survey since conducting such a survey is nearly impossible.

Four qualitative factors that include applicability, adaptability and integratability, maintenance and safety, and other aspects are used in this research. For these factors, the linguistic variable, which is an important concept in the fuzzy logic, can be applied. A linguistic variable enables its value to be described both qualitatively by a linguistic term (i.e., a symbol serving as the name of a fuzzy set) and quantitatively by a corresponding membership function. Linguistic terms are used to express concepts and knowledge in human communication, whereas membership functions are used for processing numerical input data. The maintenance and safety factor, for instance, cannot be measured quantitatively like the economic factor above but it can be expressed by linguistic terms such as good, average, and poor. These linguistic terms can be defined by giving each a fuzzy representation on a universe of discourse such as  $w$ :

$$w = [0, .1, .2, .3, .4, .5, .6, .7, .8, .9, 1]$$

with the membership intervals [0, 1] as follows:

$$\text{good} = [0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, .125/.7, .5/.8, .875/.9, 1/1] \quad (3.2)$$

$$\text{average} = [0/0, 0/.1, 0/.2, .7/.3, 1/.4, .7/.5, 0/.6, 0/.7, 0/.8, 0/.9, 0/1] \quad (3.3)$$

$$\text{poor} = [1/0, .875/.1, .5/.2, .125/.3, .0/.4, 0/.5, 0/.6, 0/.7, 0/.8, 0/.9, 0/1] \quad (3.4)$$

In the expressions (3.2)-(3.4), the numerators indicate the degree of membership whereas denominators depict the degree of satisfaction of a MHE based on the maintenance and safety aspect.

Nevertheless, the definitions of these linguistic terms are subjective and need to be verified experimentally. In this research, two types of membership functions commonly used in practice are employed. The Gaussian membership function is used for the linguistic term of average because the shape of the function (thin or flat) can be controlled by adjusting the parameter  $\delta$  [Yen & Langari, 1999]. The S membership function is used for the linguistic terms of good and poor because this membership function is a smooth function with two parameters,  $a$  and  $b$ , and the shape is well-fitted to the terms of good and poor [Yen & Langari, 1999]. These two membership functions are available in the Membership Editor of the Fuzzy Logic Toolbox for MATLAB. A Gaussian membership function as shown in Figure 3.16 is specified by two parameters  $\{m, \delta\}$  as follows:

$$\text{Gaussian}(x : m, \delta) = \exp\left(-\frac{(x - m)^2}{\delta^2}\right)$$

where  $m$  and  $\delta$  denote the center and width (standard deviation) of the function, respectively.

Adjusting the parameter  $\delta$  can control the shape of the function. A small  $\delta$  will generate a thin membership function, while a big  $\delta$  will lead to a flat membership function.

The S membership function is a smooth membership function with two parameters,  $a$  and  $b$ .

The shape of the function is shown in Figure 3.17. The membership value is 0 for points below  $a$ , 1 for points above  $b$ , and 0.5 for the midpoint between  $a$  and  $b$ .

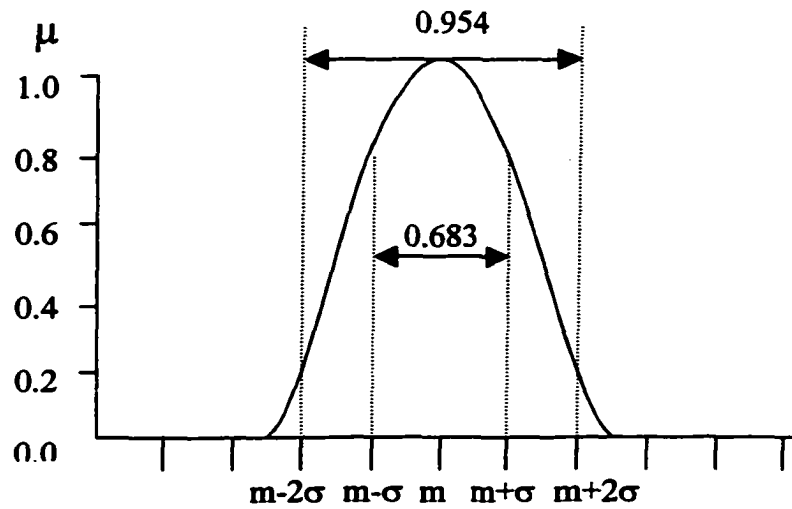


Figure 3.16. Gaussian membership function with  $\{m, \sigma\}$

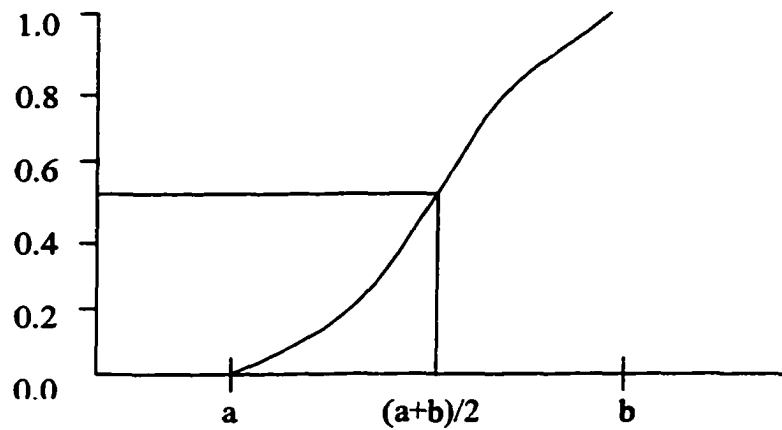


Figure 3.17. S membership function with  $\{a, b\}$

$$S(x : a, b) = \begin{cases} 0 & x < a \\ 2\left(\frac{x-a}{b-a}\right)^2 & a \leq x \leq \frac{a+b}{2} \\ 1 - 2\left(\frac{x-b}{b-a}\right)^2 & \frac{a+b}{2} \leq x < b \\ 1 & x \geq b \end{cases}$$

The linguistic terms given in expressions (3.2)-(3.4), in conjunction with hedges, can be modified as follows :

$$\begin{aligned} \text{Very good} &= [\text{good}]^2 \\ &= [0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, .016/.7, .25/.8, .076/.9, 1/1] \end{aligned}$$

Similarly, for other linguistic variables, such as applicability, adaptability and integratability, and other aspects can be defined quantitatively or converted to quantitative measures. For applicability, the highest degree of satisfaction, 1.0, is given to the MHE suggested by the knowledge-based rules for a material flow link. Figures 3.18 to 3.21 show the membership functions of these aspects.

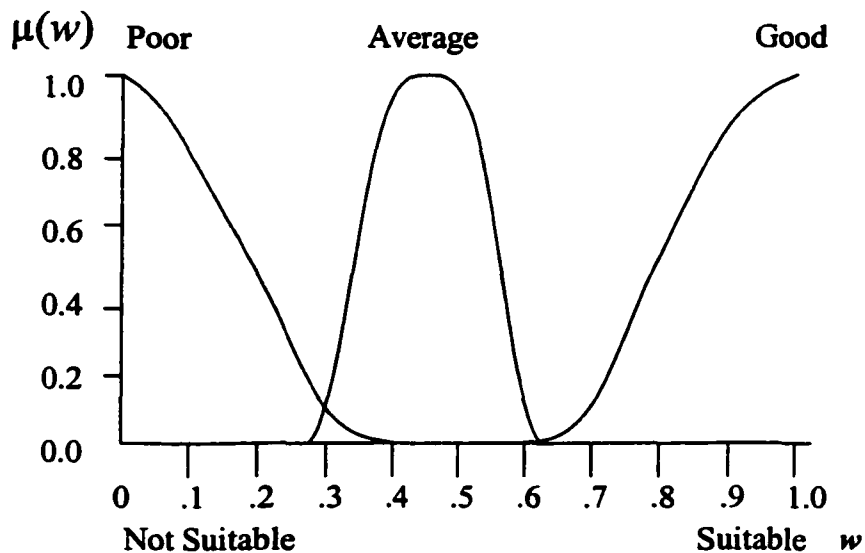


Figure 3.18. Membership function for applicability aspect

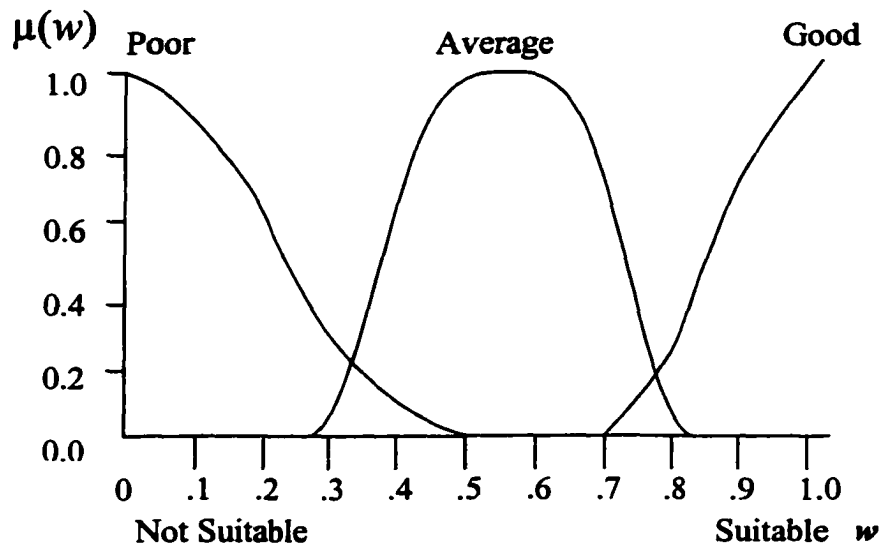


Figure 3.19. Membership function for adaptability and integratability aspect

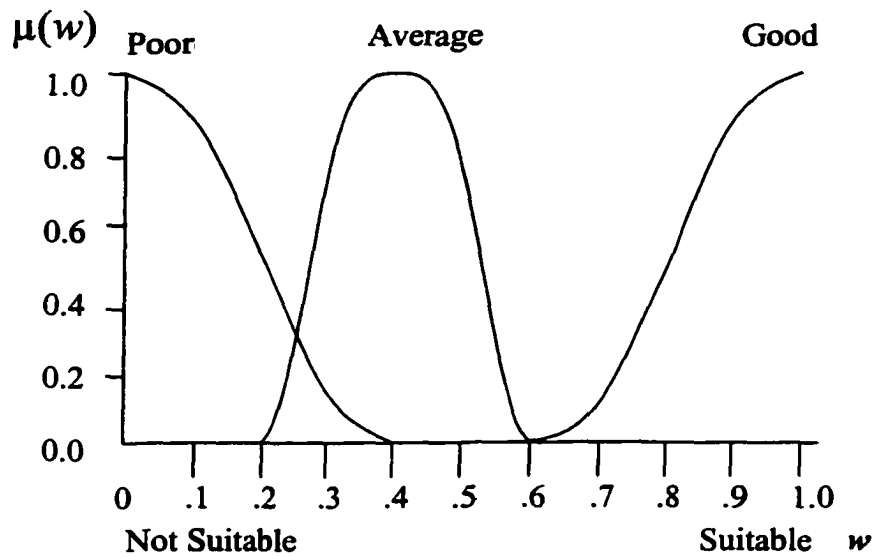


Figure 3.20. Membership function for maintenance and safety aspect

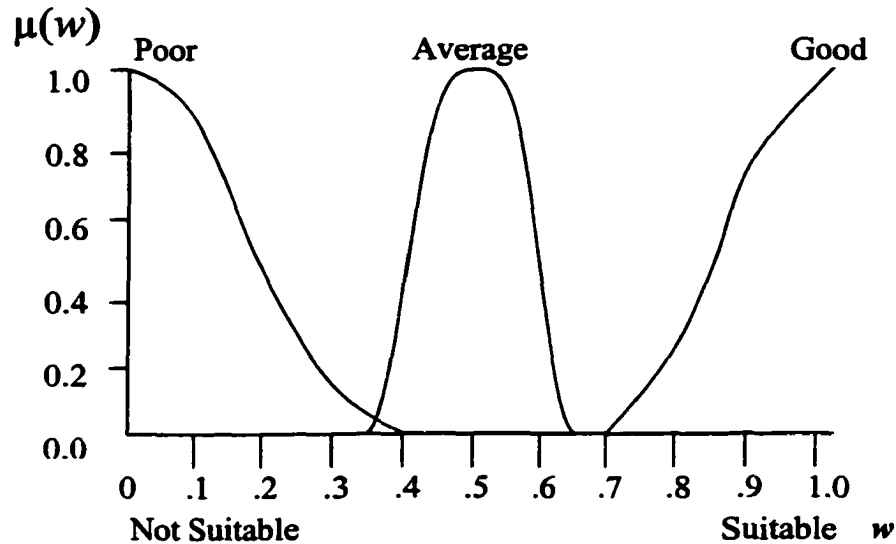


Figure 3.21. Membership function for other aspects

Once all aspects involved are quantified, “suitable index for a MHE” can be expressed as a mixed fuzzy numerical set.

$$\begin{aligned}
 \text{Suitable} = & [ \mu(V_1) / V_1, (0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, .125/.7, .5/.8, .875/.9, 1/1) / V_2, \\
 & (0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, 0/.7, .22/.8, .78/.9, 1/1) / V_3, \\
 & (0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, .125/.7, .5/.8, .875/.9, 1/1) / V_4, \\
 & (0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, 0/.7, .22/.8, .78/.9, 1/1) / V_5 ] \quad (3.5)
 \end{aligned}$$

Equation (3.1) is used to calculate the measure of membership function for the economic aspect  $\mu(V_1)$ . For the other quantitative measures, the membership functions for the linguistic term of good as shown in Figures 3.18 to 3.21 are used.

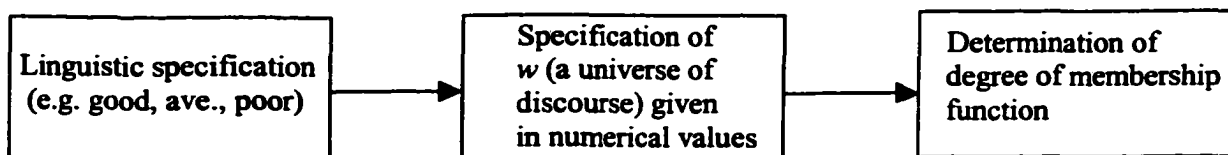
As an example, consider a scenario for an MHE where the expected total cost in the economic aspect is \$75,000,  $\alpha$  is \$150,000, the applicability aspect is good, adaptability and



integratability aspect is poor, maintenance and safety aspect is good, and other aspects are good. The fuzzy set will express a suitable index and this expression can be written as below based on the equation (3.1) and (3.5).

$$\text{Suitable} = [.5/V_1, .875/V_2, 0/V_3, .5/V_4, 1/V_5]$$

The entire process of specifying the ‘suitability’ of an MHE using linguistic terms (e.g. good, average, poor) based on qualitative aspects to determining the degree of membership function can be expressed as below.



However, since all aspects are not equally important, the contribution of each aspect can be adjusted in proportion to its importance. Therefore, the expression of “suitable index for an MHE” needs to be modified as follows to include the weighting values specified by the users and to get a numerical value that can be compared with other MHE.

$$\text{Suitable} = [(W_1)\mu(V_1) + (W_2)\mu(V_2) + (W_3)\mu(V_3) + (W_4)\mu(V_4) + (W_5)\mu(V_5)] \quad (3.6)$$

where  $W_1, \dots, W_5$  are the weighting values given by users for each aspect.

### **Example**

To illustrate the method for mapping linguistic terms into quantitative measures, consider the example shown in Table 3.12. Given the discrete universe of discourse,  $w = \{0, .1, \dots, .9, 1\}$ , *Goods* are fuzzy subsets of  $w$  characterized by the following membership functions as shown in Figures 3.18 to 3.21.

**Good for applicability factor** = [ 0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, .125/.7, .5/.8, .875/.9, 1/1]

**Good for adaptability and integratability factor** = [ 0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, 0/.7, .22/.8, .78/.9, 1/1]

**Good for maintenance and safety factor** = [ 0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, .125/.7, .5/.8, .875/.9, 1/1]

**Good for other factors** = [ 0/0, 0/.1, 0/.2, 0/.3, 0/.4, 0/.5, 0/.6, 0/.7, .22/.8, .78/.9, 1/1]

**Table 3.12. Total costs for the economic factor and  $w$  values for other factors of alternatives**

	Economic factor	Applic. factor	Ada. & Int. factor	Main. & Safe. factor	Other factors
EMS	average	good	good	good	good
Chain conveyor	good	average	average	average	good
Bridge crane	poor	average	average	poor	poor
Mag. guided AGV	average	good	good	average	good

↓  
**Conversion from  
 Linguistic Terms to Total Cost &  $w$**

	Total cost (\$)	$w$ for App. factor	$w$ for Ada. & Int. factor	$w$ for Ma. & Sa. factor	$w$ for Other factors
EMS	60,000	1	.9	.9	1
Chain conveyor	24,000	.8	.8	.7	.9
Bridge crane	254,000	.7	.8	.4	.5
Mag. guided AGV	85,000	.9	.9	.8	1

Suppose EMS is selected as the suitable MHE type for this move by the knowledge-based rules and  $\alpha$  is \$100,000. The total costs can be calculated by the cost models described in subsection 3.2.

Using equation (3.1) and fuzzy subsets of  $w$  defined previously, the values in Table 3.12 are mapped into the measures in Table 3.13, respectively. For example, the total cost (TC) of the EMS is \$60,000, thus the measure of membership function of economic factor for EMS  $\mu(V_1)$  is obtained as follows:

$$\mu(V_1) = \frac{(\alpha - TC)}{\alpha} = \frac{40000}{100000} = 0.4$$

The value of  $w$  for the applicability factor of the EMS is 1, therefore it is mapped into 1 by the fuzzy subset of *Good* for the applicability factor. Other  $w$  values can be mapped into measures of membership functions for other factors in this manner. The measures of the membership functions of the alternatives are summarized in Table 3.13. This table is used as a fuzzy evaluation matrix in the decision algorithm explained in subsection 3.5.

Table 3.13. Measures of the membership functions of the alternatives for a move

	$\mu(V_1)$	$\mu(V_2)$	$\mu(V_3)$	$\mu(V_4)$	$\mu(V_5)$
EMS	0.4*	1	0.78	0.875	1
Chain conveyor	0.76	0.5	0.22	0.125	0.78
Bridge crane	0	0.125	0.22	0	0
Mag. guided AGV	0.15	0.875	0.78	0.5	1

\* Elements of this table represent the degrees of membership functions based on the entries in Table 3.12 and using the membership functions for the mapping.

Let us say the weighting values that are specified by the user for each factor are 30%, 20%, 10%, 25%, and 15%, respectively. By substituting these values in equation (3.6), the

suitable indices for the alternatives can be calculated and compared to select the most appropriate MHE for the move:

$$\text{Suitable index for the EMS} = [(.3)(.4) + (.2)(1) + (.1)(.78) + (.25)(.875) + (.15)(1)] = 0.77$$

$$\text{Suitable index for the Chain conveyor} = [(.3)(.76) + (.2)(.5) + (.1)(.22) + (.25)(.125) + (.15)(.78)] = 0.5$$

$$\text{Suitable index for the Bridge crane} = [(.3)(0) + (.2)(.125) + (.1)(.22) + (.25)(0) + (.15)(0)] = 0.05$$

$$\text{Suitable index for the Magnetic guided AGV} = [(.3)(.15) + (.2)(.875) + (.1)(.78) + (.25)(.5) + (.15)(.1)] = 0.438$$

These results indicate the EMS is the most suitable MHE for the move.

### **3.5. Decision-making Procedure and Analyses**

To select the final suitable MHE type for each material flow link, not only does the system consider the economic aspect of the equipment but also their applicability, adaptability and integratability, maintenance and safety, and other factors the user deems worthy of consideration. The main elements of the factors are summarized in Table 3.14. Figure 3.22 is a graphical illustration showing how the evaluation factors are jointly considered to arrive at the final selection of the appropriate equipment. Alternatives for a move are obtained from the knowledge-based rules.

The final measure indicating the evaluation score of each candidate piece of equipment is obtained by using the normalized values of the evaluation factors. The MHE type whose normalized evaluation score is the highest is selected as the final solution for the move in question. A further reduction of cost can be achieved if any excess capacity is identified and it can be eliminated without introducing design infeasibility. Excess capacity is eliminated by assigning a unit of each equipment to multiple flow links and thereby reducing the total number of units of the equipment that is recommended. In addition, operating systems for automatic equipment, such as AGV, EMS, and AS/RS, are checked if these can be combined to reduce the total number of the operating systems. The total purchasing cost for all the MHE types selected for all material flow links must be less than or equal to the budget available. Finally, a decision algorithm is developed to implement the procedure described previously.

Table 3.14. Evaluation factors for each aspect

Aspect	Evaluation factors
Economic	How economical is the MHE? The purchase cost, operation cost, space cost, and interface cost are considered.
Applicability	How well does the MHE meet the production requirements and the constraints of production environment specified by a user?
Adaptability & integratability	How easy can the MHE be modified to suit a new product or production environment and how well can the MHE be readily integrated with the existing MHE?
Maintenance & safety	How economical and safe is the MHE for maintenance and safety? Spare parts supply, easiness of repair, safety device design, after service, and ergonomic design can be considered.
Other	How much acceptable is the MHE for the factors the user deems worthy of consideration such as noise, beauty, etc.?

### 3.5.1. Decision algorithm

The decision algorithm to select the final suitable MHE type among alternatives for each move (material flow link) after considering the selection factors described in the previous section is developed. To consider and compare the MHE alternatives based on the selection factors, fuzzy evaluation matrices (described in subsection 3.4) and normalized evaluation values are employed. An example of fuzzy evaluation matrices is shown in Table 3.15(the meanings of table entries are described in subsection 3.4.2.).

The fuzzy evaluation matrices used for this research are summarized in Appendix C. The alternative whose normalized evaluation score is the highest is selected as the final solution for a move. By assigning or sharing an earlier selected MHE to adjacent moves, if it is possible, the overall system design cost can be reduced. The sharing of equipment increases utilization level and reduces the number of units of the MHE needed. The total purchase cost of the set of all final selected equipment is then compared to the available

budget as specified by the user. If the total purchase cost of the set of selected MHE is less than or equal to the available budget, then the selected MHE is approved and adopted.

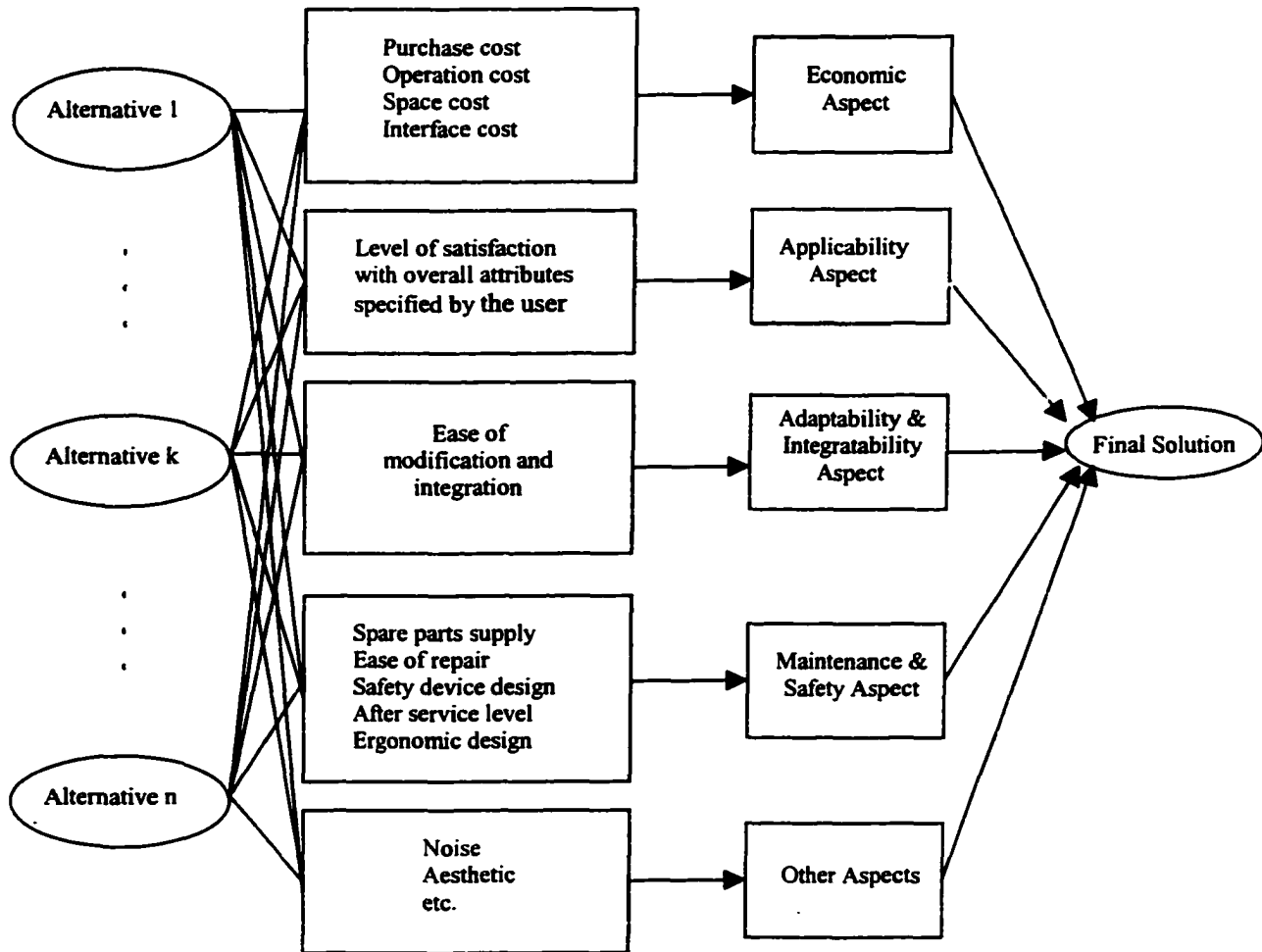


Figure 3.22. Decision chain for the final solution using multi-consideration factors

Otherwise, a search is carried out to replace one of the selected equipment by a less expensive alternative equipment, if one exists, to bring the total cost within budget. The new set of equipment is selected to satisfy the available budget while minimizing the reduction in

total evaluation score. The cost models developed in subsection 3.2.2 were used in calculating the cost for each MHE type.

Table 3.15. An example of a fuzzy evaluation matrix

	$E_{1j}$ $=\mu(V_1)$	$A_{1j}$ $=\mu(V_2)$	$V_{1j}^*$ $=\mu(V_3)$	$V_{1j}^{**}$ $=\mu(V_3)$	$M_{1j}$ $=\mu(V_4)$	$Q_{1j}$ $=\mu(V_5)$
$a_{11}$	0.8	1	0.6	0.5	0.8	0.4
$a_{12}$	0.6	0.5	0.8	0.4	0.5	0.7
$a_{13}$	0.5	0.3	0.4	0.7	0.4	0.2

\* When expected production trend is increasing or highly increasing

\*\* When expected production trend is decreasing or highly decreasing

Key:

$a_{ij}$  : alternative MHE j for  $m_i$

$A_{ij}$  : a measure of membership function for the applicability aspect of alternative MHE j for move i

$E_{ij}$  : a measure of membership function for the economic aspect of alternative MHE j for move i

$V_{ij}$  : a measure of membership function for the adaptability & integratability aspects of alternative MHE j for move i

$m_i$  : MHE type selected for move i by the knowledge-based rules

$M_{ij}$  : a measure of membership function for the maintenance & safety aspects of alternative MHE j for move i

$Q_{ij}$  : a measure of membership function for other aspects that are user specified, if any, of alternative MHE j for move i

The algorithm developed has three phases. In phase I, the procedure finds the MHE type that has the highest normalized evaluation score among the alternatives for each move.



The most appropriate MHE for each move is obtained at this phase. To reduce the overall system cost, in Phase II, the system checks for excess capacity for each type of equipment recommended. It also checks if operating systems for automatic equipment suggested can be combined to reduce the total number of the operating systems. Any excess capacity identified is eliminated whenever it is considered possible without introducing design infeasibility. Excess capacity is eliminated by assigning a unit of each equipment to multiple flow links and thereby reducing the total number of units of the equipment that is recommended. This reduction in equipment capacity does not apply to conveyors and storage devices because of their immobile feature. The reduction process is applicable to mobile equipment that enjoy flexible routing. In phase III, the set of material handling equipment selected is adjusted to satisfy budget constraints if the total cost of the initial set of the selected equipment exceeds the budget.

The following variables and parameters are used in the algorithm to be presented.

***Variables***

- $a_{ij}$  : alternative MHE j for  $m_i$
- $A_{ij}$  : a measure of membership function for the applicability aspect of alternative MHE j for move i
- $B$  : available budget
- $C$  : total purchase costs of all  $f_i$ ,  $\sum_{i=1}^m p_i$
- $C_{ij}^e$  : change effect value for move i, where j is the set of feasible alternatives for move i
- $E_{ij}$  : a measure of membership function for the economic aspect of alternative MHE j for move i
- $f_i$  : the final solution for move i
- $i$  : move (material flow link) identifier, 1 to m
- $j$  : alternatives MHE identifier, 1 to n
- $l$  : list of moves identifier, 1 to p
- $m_i$  : MHE type selected for move i by the knowledge-based rules

- $M_{ij}$  : a measure of membership function for the maintenance & safety aspects of alternative MHE j for move i
- $P_i$  : purchase cost of  $f_i$
- $PC_{ij}$  : purchase cost per unit MHE j for move i
- $Q_{ij}$  : a measure of membership function for other aspects that are user specified, if any, of alternative MHE j for move i
- $S_i$  : normalized evaluation value for  $f_i$
- $S'_{ij}$  : normalized evaluation value for alternative MHE j for move i
- $U$  : acceptable utilization level of MHE
- $U_i$  : utilization of  $f_i$
- $V_{ij}$  : a measure of membership function for the adaptability & integratability aspects of alternative MHE j for move i
- $W^e$  : weighted value for economic factor specified by the user
- $W^a$  : weighted value for applicability factor specified by the user
- $W^i$  : weighted value for adaptability & integratability factor specified by the user
- $W^m$  : weighted value for maintenance & safety factor specified by the user
- $W^o$  : weighted value for other factor specified by the user
- $\beta$  : a specified value for budget feasibility check

**Algorithm:**

Fuzzy evaluation matrices are used to calculate the normalized evaluation values ( $S'_{ij}$ ) and  $E_{ij}$ ,  $A_{ij}$ ,  $V_{ij}$ ,  $M_{ij}$ , and  $Q_{ij}$  are measures of membership functions for selection aspects of MHE alternatives for moves. The selection aspects include economics, applicability, adaptability and integratability, maintenance and safety, and other aspects respectively. Fuzzy evaluation matrices used in this research are summarized in Appendix C.

**Phase I : Preliminary Preferred MHE Selection Stage**

Set move  $i = 1$ .

**Step 0. Initialization**

0a. Set the MHE selected by the knowledge-based rules for move  $i$  to  $m_i$ .

0b. Set  $a_{i1} = m_i$ .

0c. Retrieve all alternatives for  $a_{i1}$  from the alternative table in database and set all alternatives to  $a_{ij}$  respectively, for  $j = 2$  to  $n$ .

**Step 1.** Calculate the purchase cost, operation cost, space cost, and interface cost of each  $a_{ij}$  (refer to subsection 3.2.2 for cost models).

**Step 2.** Calculate normalized evaluation values ( $S'_{ij}$ ) for each  $a_{ij}$  using fuzzy evaluation matrices (refer to subsection 3.4.2 for more detail).

$$S'_{ij} = W^e E_{ij} + W^a A_{ij} + W^i V_{ij} + W^m M_{ij} + W^o Q_{ij}$$

where  $i = 1$  to  $m$  and  $j = 1$  to  $n$

**Step 3.** Select alternative  $(i, j) a_{ij}$  whose normalized evaluation value ( $S'_{ij}$ ) is the highest and

set  $f_i = a_{ij}$  and  $S_i = S'_{ij}$ . If there are more than one  $a_{ij}$  which satisfy the selection rule, then choose the alternative that has also been chosen for earlier material flow links already evaluated.

**Step 4.** Increase  $i$  by 1 and go to Step 0 until all  $f_i$  are found for all material flow links requested by the user.

### ***Phase II : MHE Unit Reduction & Utilization Maximization Stage***

**Step 0.** 0a. Identify the number of unique types of MHE selected in Phase I algorithm for all moves. Let  $L'$  equal to the number of MHE types.

0b. Let the number of unique MHE types be numbered from  $k'$  to  $L'$ .

0c. For all moves that use MHE type  $k'$ , place in list  $l_k$ , where  $k' = 1, 2, 3, \dots, L'$ .

0d. Set  $k' = 1$  and list  $l = l_k$ .

**Step 1.** Obtain list  $l$  of moves that are assigned to the same type of MHE.

**Step 2.** Arrange moves belonging to list  $l$  in descending order of unit load weight.

**Step 3.** Select the MHE  $f_i$  with the heaviest unit load weight capacity among the same type of MHE suggested for moves in list  $l$ .

**Step 4.** Calculate  $U_i$  (refer to subsection 3.2.2 for calculation of utilization level).

**Step 5.** Assign the arranged moves except move  $i$  (because move  $i$  is already assigned to  $f_i$ ) in list  $l$  to  $f_i$  until its new calculated  $U_i$  is greater than the acceptable utilization level of MHE  $U$  or until no further assignment is possible.

If all moves in list  $l$  are assigned to  $f_i$  then go to Step 9, otherwise go to Step 6.

**Step 6.** Select the MHE  $f_i$  whose load capacity is the highest among the MHE suggested for the unassigned moves in list  $l$ .

**Step 7.** Calculate  $U_i$ .

**Step 8.** Assign the remaining moves to  $f_i$  until its new calculated  $U_i$  is greater than  $U$  or until no further assignment is possible.

If all moves are assigned to  $f_i$  then go to Step 9, otherwise go to Step 6.

**Step 9.** Set  $k' = k' + 1$  and  $l = l_k$ :

if  $k' \leq L'$ ,                      go to Step 1

otherwise,                          go to Phase III

### ***Phase III : Budget Feasibility Check and Design Modification Stage***

**Step 1.** Sum the purchase costs of all  $f_i$  suggested and set this value to  $C$ .

**Step 2.** Check the feasibility of the selected equipment in terms of the available budget ( $B$ ).

2a. if  $C \leq B$ ,                      the final solution for each material flow link is obtained; stop

otherwise,                          go to Step 3.

**Step 3.** Calculate  $dif = C - B$ .

3a. if  $(\frac{dif}{B}) \leq \beta$ , go to **Step 4**.

otherwise, advise the user to adjust upward the budget  $B$

**Step 4.** Consider all  $a_{ij}$  for each move  $i$  whose purchase cost is less than the cost of current selected MHE for move  $i$ ,  $P_i$  and calculate the change effect values for move  $i$  ( $C_{ij}^e$ ).

$$C_{ij}^e = \min\left(\frac{S_i - S'_{ij}}{P_i - PC_{ij}}\right)$$

where  $j$  is a feasible alternative for move  $i$  and  $PC_{ij} < P_i$

**Step 5.** Select the  $a_{ij}$  which has the smallest change effect value among the candidates for all moves and change the  $f_i$  for move  $i$  to that of  $a_{ij}$ .

**Step 6.** Perform Phase II again to check the possibility of reduction of the number of units of MHE and control system.

The overall decision algorithm can be summarized as shown in Figure 3.23.

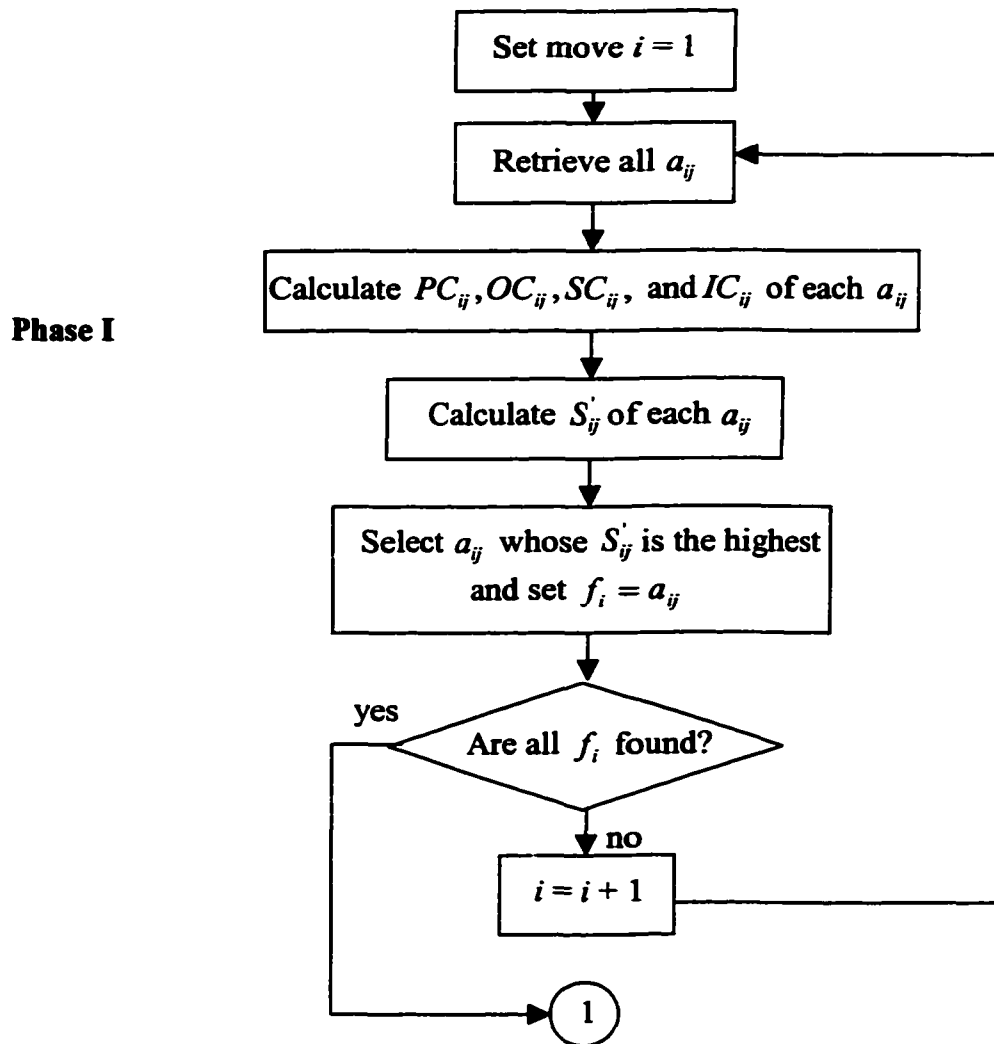


Figure 3.23. Flowchart of the decision algorithm for MHE selection in DESIGNER

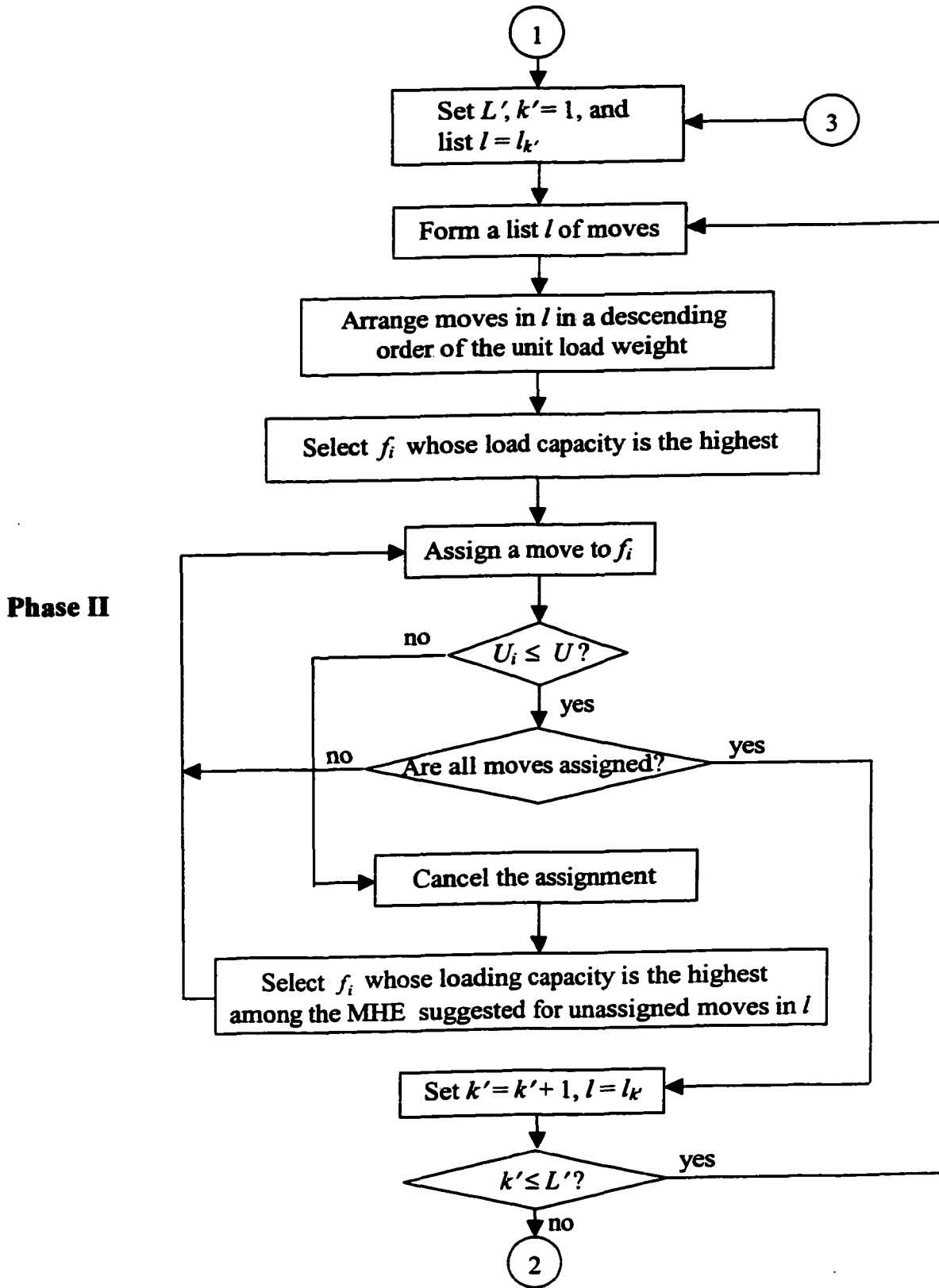


Figure 3.23. (continued)

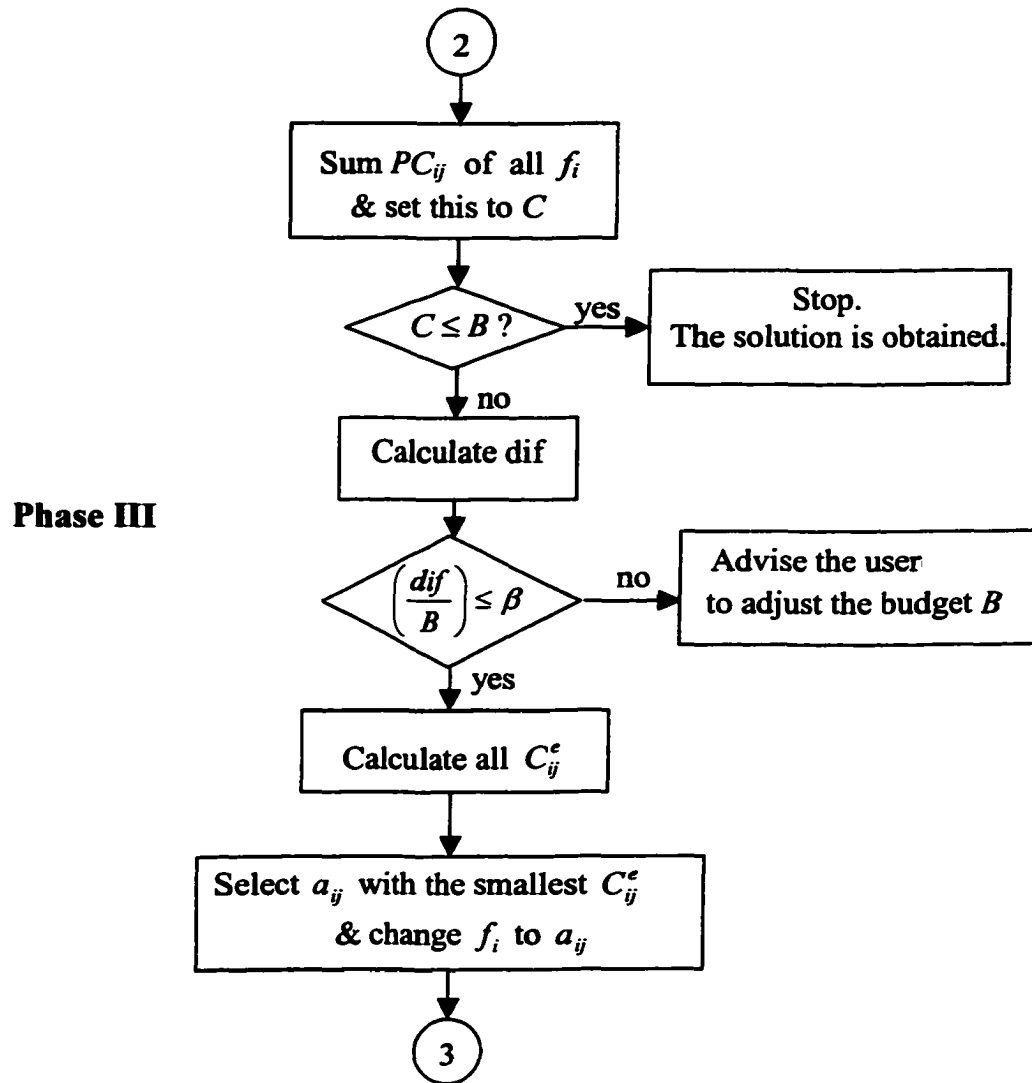


Figure 3.23. (continued)

**Example**

To illustrate the steps of the algorithm, consider the problem described in Table 3.16 to 3.19. The details and meanings of fuzzy evaluation matrix tables are explained in subsection 3.4.2. Suppose minirack, EMS, and electric wire-guided AGV are selected as the suitable MHE type for moves 1, 2, and 3, respectively, by the knowledge based rules. An overall listing of the algorithmic steps follows.



Table 3.16. Alternative matrix for moves from Step 0 of Phase I

	Move 1	Move 2	Move 3
$m_i$	Minirack	EMS	Electric wire guided AGV
$a_{i1}$	Minirack	EMS	Electric wire guided AGV
$a_{i2}$	Miniload AS/RS	Chain conveyor	Gantry crane
$a_{i3}$	Carousel	Bridge crane	EMS
$a_{i4}$	Mobile rack	Magnetic guided AGV	Roller conveyor

Table 3.17. Fuzzy evaluation matrix for move 1

	$E_{1j}$	$A_{1j}$	$V_{1j}$	$M_{1j}$	$Q_{1j}$
$a_{11}$	0.95	1	0.3	0.5	0.35
$a_{12}$	0	0.4	0.8	0.75	0.8
$a_{13}$	0.77	0.7	0.7	0.7	0.7
$a_{14}$	0.89	0.6	0.4	0.65	0.65

Table 3.18. Fuzzy evaluation matrix for move 2

	$E_{2j}$	$A_{2j}$	$V_{2j}$	$M_{2j}$	$Q_{2j}$
$a_{21}$	0.7	1	0.7	0.75	0.8
$a_{22}$	0.88	0.45	0.5	0.5	0.5
$a_{23}$	0	0.3	0.3	0.4	0.4
$a_{24}$	0.58	0.7	0.7	0.7	0.8

Table 3.19. Fuzzy evaluation matrix for move 3

	$E_{3j}$	$A_{3j}$	$V_{3j}$	$M_{3j}$	$Q_{3j}$
$a_{31}$	0.47	1	0.7	0.7	0.8
$a_{32}$	0.66	0.4	0.4	0.4	0.4
$a_{33}$	0.65	0.88	0.7	0.7	0.8
$a_{34}$	0.87	0.5	0.5	0.55	0.55

The weighted values for the evaluation factors specified by the user are 30%, 30%, 20%, 10%, and 10% respectively and the available budget is \$65,000.

### ***Phase I***

Set move  $i = 1$  and this is increased by 1 until  $i$  reaches 3.

*Step 0.* Retrieve all alternatives for move  $i$ . Refer to Table 3.16.

*Step 1.* Calculate the costs of each  $a_{ij}$ .

For an example on cost calculations, bridge crane  $a_{23}$  which is an alternative MHE for move 2 is used. Refer to Table 3.21 – 3.23 for the calculated costs of other MHE.

Let the cost data for the bridge crane be as summarized in the Table 3.20.

Table 3.20. The cost data for the bridge crane

Parameters	$C_j^b$ (\$)	$C_j^u$ (\$)	$l_j$ & $L_l$ (tons)	$C_j^d$ (\$)	$d_i$ & $s$ (')	$C_j$ (\$)	$V_i$ (units)
$a_{23}$	110,000	16,000*	3	300**	150	12	3,000

Table 3.20. (continued)

Parameters	$T_a$ (hr)	$S_{ij}$ (ft <sup>3</sup> )	$C_r^b$ (\$)	$C_r^u$ (\$)	$w_{ij}$ (')	$d_{ij}$ (')	$s_j$ ('/hr)
$a_{23}$	2,080	0	5,500	1,500 <sup>***</sup>	2	10	1,300

\* Unit load capacity is one ton with 50' of span for the crane  $s$ .

\*\* Unit length is 50'.

\*\*\* Unit load capacity is one ton with 20' of travel distance  $d_{ij}$  and 1' of width of a interface conveyor  $w_{ij}$ .

Let's  $B = \$65,000$ ,  $U = 0.8$ , and  $\beta = 0.1$ . Thus the cost calculations for the bridge crane is as follows:

$$\begin{aligned} \text{Purchase cost, } PC_{ij} &= C_j^b + C_j^u \times l_j \times s + C_j^d \times d = 110000 + 144000 + 900 \\ &= \$254,900 \end{aligned}$$

$$\text{Operating cost, } OC_{ij} = t_{ij} C_j = \frac{2d_i V_i}{s_j} C_j = 692 \times 12 = \$8,304$$

$$\text{Space cost, } SC_{ij} = RS_{ij} = \$0$$

$$\text{Interface cost, } IC_{ij} = C_r^b + C_r^u \times L_r \times w_{ij} \times d_{ij} = 5500 + 4500 = \$10,000$$

Table 3.21. Costs of alternatives for move 1

	$PC_{1j}$	$OC_{1j}$	$SC_{1j}$	$IC_{1j}$	Total Cost
$a_{11}$	\$8,500	\$500	\$5,000	\$3,000	\$17,000
$a_{12}$	\$270,000	\$9,500	\$8,000	\$5,000	\$292,500
$a_{13}$	\$45,000	\$6,000	\$6,500	\$4,500	\$62,000
$a_{14}$	\$22,000	\$6,500	\$6,000	\$4,000	\$38,500

Table 3.22. Costs of alternatives for move 2

	$PC_{2j}$	$OC_{2j}$	$SC_{2j}$	$IC_{2j}$	Total Cost
$a_{21}$	\$60,000	\$9,000	\$4,000	\$8,000	\$81,000
$a_{22}$	\$24,000	\$7,000	\$4,000	\$5,000	\$40,000
$a_{23}$	\$254,900	\$8,300	\$0	\$10,000	\$273,200
$a_{24}$	\$85,000	\$9,000	\$4,000	\$8,000	\$106,000

Table 3.23. Costs of alternatives for move 3

	$PC_{3j}$	$OC_{3j}$	$SC_{3j}$	$IC_{3j}$	Total Cost
$a_{31}$	\$90,000	\$9,000	\$5,000	\$1,700	\$105,700
$a_{32}$	\$55,000	\$10,000	0	\$2,400	\$67,400
$a_{33}$	\$60,000	\$9,000	\$5,000	\$1,500	\$75,500
$a_{34}$	\$13,000	\$7,000	\$5,000	\$1,000	\$26,000

Step 2. Calculate  $S'_{ij}$  for each  $a_{ij}$  (refer to Table 3.17 – 3.19).

$$S'_{ij} = W^e E_{ij} + W^a A_{ij} + W^i V_{ij} + W^m M_{ij} + W^o Q_{ij}$$

For move 1:  $S'_{11} = 0.73$ ,  $S'_{12} = 0.435$ ,  $S'_{13} = 0.72$ ,  $S'_{14} = 0.68$

Step 3. Select  $a_{ij}$  whose  $S'_{ij}$  is the highest and set at  $f_i = a_{ij}$ .

For move 1:  $f_1 = a_{11}$  (minirack)

Step 4. Increase  $i$  by 1 and go to Step 0 until all  $f_i$  are found.

For move 2:  $S'_{21} = 0.88$ ,  $S'_{22} = 0.65$ ,  $S'_{23} = 0.27$ ,  $S'_{24} = 0.74$ ,  $f_2 = a_{21}$  (EMS)

For move 3:  $S'_{31} = 0.73$ ,  $S'_{32} = 0.48$ ,  $S'_{33} = 0.75$ ,  $S'_{34} = 0.631$ ,  $f_3 = a_{33}$ (EMS)

### ***Phase II***

***Step 0.*** Set  $L'$ ,  $k' = 1$ , and list  $l = l_k$ .

***Step 1.*** Obtain list  $l$  of moves.

list  $l = \{\text{move 2, move 3}\}$

***Step 2.*** Arrange moves. Unit load weights for moves are 3 tons, 120 lbs and 200 lbs, respectively.

list  $l = \{\text{move 3, move 2}\}$

***Step 3.*** Select  $f_i$  whose loading capacity is the highest.

$f_3$  (EMS) is selected.

***Step 4.*** Calculate  $U_i$ .  $t_{33} = 750\text{hr}$

$$U_{ij} = \frac{\sum t_{ij}}{T_a}, \text{ therefore, } U_3 = \frac{750}{2080} = 0.36$$

***Step 5.*** Assign the moves except move  $i$  in list  $l$  to  $f_i$  until its  $U_i$  is greater than  $U$  or until no more assignment is available. If all moves are assigned  $f_i$  then go to *Step 9*, otherwise go to *Step 6*.

The EMS selected for move 3 is also assigned to move 2 and  $t_{2EMS} = 610\text{hr}$ .

$$U_3 = \frac{750 + 610}{2080} = 0.65 < U, \text{ all moves are assigned.}$$

***Step 9.*** Set  $k' = k' + 1$  and  $l = l_k$ . If  $k' \leq L'$  then go to *Step 1*, otherwise go to *Phase III*

No new list  $l$  is available. Therefore,  $f_1 = \text{minirack}$ ,  $f_2 = \text{EMS}$  assigned to move 3,

$f_3 = \text{EMS}$

**Phase III**

**Step 1.** Sum the purchase costs of all  $f_i$  and set this value to  $C$ .

$$C = \$8,500 + \$60,000 = \$68,500$$

**Step 2.** Check feasibility in terms of  $B$ .

if  $C \leq B$             the final solution for each material flow link is obtained: stop

otherwise            go to *Step 3*.

$\$68,500 > \$65,000$ , therefore, go to *Step 3*.

**Step 3.** Calculate *dif*.

if  $\left(\frac{dif}{B}\right) \leq \beta$         go to *Step 4*.

Otherwise            advise the user to adjust upward the budget  $B$

$$dif = \$68,500 - \$65,000 = \$3,500, \left(\frac{dif}{B}\right) = \frac{3500}{65000} = 0.05 < \beta$$

**Step 4.** Consider all  $a_{ij}$  for each move  $i$  whose purchase cost is less than the cost of current

selected MHE for move  $i$ ,  $P_i$  and calculate the change effect value for move  $i$  ( $C_{ij}^e$ ).

There is no alternative that satisfies the condition for move 1.

$$C_{22}^e = \frac{0.88 - 0.65}{65000 - 24000} = 0.0000056, C_{32}^e = 0.000027, C_{34}^e = 0.0000022$$

**Step 5.** Select  $a_{ij}$  which has the smallest  $C_{ij}^e$  among the candidates and change the  $f_i$  for

move  $i$  to that of  $a_{ij}$ .

$a_{34}$  has the smallest  $C_{ij}^e$  so roller conveyor is newly assigned to move 3, and if we keep the EMS selected in Phase I or II for move 2, the condition  $C \leq B$  will not be satisfied again. So chain conveyor is assigned to move 2 instead of the EMS.

Therefore, for move 1:  $a_{11}$  (minirack), for move 2:  $a_{22}$  (chain conveyor), and for move 3:  $a_{34}$  (roller conveyor) – refer to Table 3.21 – 3.23

*Step 6. Perform Phase II again.*

There is no list of moves available to perform Phase II.

$$C = \$8,500 + \$24,000 + \$13,000 = \$45,500 \text{ and } C \leq B$$

Therefore, the final solution is obtained as follows:

$$f_1 = \text{minirack}, f_2 = \text{chain conveyor}, \text{ and } f_3 = \text{roller conveyor}$$

### 3.5.2 Economic analysis

Economic analysis is an important part of an investment decision after finding eligible equipment. The economic criteria provided by DESIGNER include return on investment (ROI), payback period (PP), and present worth (PW) methods. Before applying these evaluation criteria, the results of costs and cash flow need to be calculated in advance.

For an example of costs and cash flow calculations, a miniload AS/RS (dual command cycle) with 300lbs loading capacity is employed. The cost data for the miniload AS/RS is summarized in the Table 3.24. Let's say  $AS$  (expected annual saving) = \$65,000,  $EL$  (expected economic life) = 7 years, and  $IR$  (applicable interest rate) = 8%.

Table 3.24. The cost data for the miniload AS/RS

Parameters	$C_j^b$ (\$)	$C_j^{pt}$ (\$)	$p$ (units)	$C_j^r$ (\$/pp)	$r$ (pp)	$C_j^u$ (\$/lbs)	$l_j$ (lbs)
	40,000	27	130	100	115	350	300

Table 3.24. (continued)

Parameters	$C_j^s$ (\$)	$V_i$ (jobs)	$DC$ (min)	$PD$ (min)	$C_j$ & R (\$)	$L_j$ (ft)	$H_j$ (ft)	$W_j^1$ (ft)	$IC_{ij}$ (\$)
	60,000	26,000	2.7	0.5	0.5	50	40	20	1,000

Then, the costs of an MHE can be calculated as follows:

$$\text{Purchase cost, } PC_{ij} = C_j^b + C_j^{pt} \times p + C_j^r \times r + C_j^u \times l_j + C_j^s = \$220,010$$

$$\text{Operating cost, } OC_{ij} = \left( \frac{V_i}{2} \right) \times (DC + 4 \times PD) \times C_j = \$30,550$$

$$\text{Annual space cost, } SC_{ij} = RW_j^1 L_j H_j = \$20,000$$

Let's assume, the miniload AS/RS is expected to have a salvagel value of \$22,001 (assumed 10% of the purchase cost) at the end of the expected economic life of 7 years. Table 3.25 shows the results of costs and savings and Table 3.26 summarizes the results of cash flow for the MHE.

As mentioned before, three measures are used to evaluate the economic investment on any MHE. These measures are return on investment (ROI), payback period (PP), and present worth (PW). Equations 3.7 through 3.10 represent the computational expression for these measures.



$$\sum_{t=0}^n f_t (1+r)^{-t} = 0, \text{ solve for } r \quad (3.7)$$

where  $f_t$  = net cash flow in year  $t$ ,  $n$  = life of equipment, and  $r$  = ROI (unknown)

$$\text{Alternative, ROI} = r = \frac{\sum_{t=0}^n f_t^*}{\sum_{t=0}^n f_t^{**}} \quad (3.8)$$

where  $f_t^*$  = saving in year  $t$ ,  $f_t^{**}$  = investment in year  $t$ , and  $n$  = life of equipment

Table 3.25. Costs and savings for the miniload AS/RS

Items	Costs(\$)	Savings(\$)	Year
Purchase Cost	220,010		0
Operating Cost	30,550		1 - 7
Space Cost	20,000		1 - 7
Interface Cost	1,000		0
Saving		65,000	1 - 7
Residual Value		22,001	7

Table 3.26. Cash flow results for the miniload AS/RS

Cash Flow(\$)	Year
-221,010	0
14,450	1-6
36,451	7

$$PP = \frac{\text{Investment costs}}{\text{Average annual cash flow}} \quad (3.9)$$

$$PW = \sum_{t=0}^n f_t (1+i^*)^{-t} \quad (3.10)$$

where  $f_t$  = net cash flow in year  $t$ ,  $n$  = life of equipment, and  $i^*$  = interest rate

The results of economic analysis for this example are summarized in Table 3.27.

Table 3.27. Indexes of economic analysis for the miniload AS/RS

	Return on investment (%)	Payback period (years)	Present worth (\$)
Results	79	6	12,838

### 3.5.3 Performance measures analysis

A number of different performance measures have been used in analyzing material handling system design and operation. A performance measure may be defined as a value quantifying the effectiveness of an MHE. In this research, three performance measures that include MHE utilization, handling time per unit load, and throughput are employed. These performance measures are calculated to analyze an MHE independently.

For the example of the performance measures, the miniload AS/RS used in subsection 3.5.2 is employed again. Let us say  $O_T$  (operation time of the MHE per day) = 8hr,  $N_w$  (number of working days per year) = 260 days,  $N_r$  (number of SR machines) = 1. As mentioned in subsection 3.2.2.2, Utilization,  $U_{ij}$ , of MHE  $j$  for the move  $i$  can be expressed as follow:

$$U_{ij} = \frac{t_{ij}}{T_a}$$

where  $t_{ij}$  = annual operating time of MHE j required for move i

$T_a$  = annual working time

Accordingly, the utilization of the MHE is obtained as below:

$$\begin{aligned} \text{Utilization} &= \frac{(F_i/2) \times (\text{dual command cycle time})}{N_w \times O_T \times 60} \times 100 = \frac{(F_i/2) \times (DC + 4 \times PD)}{N_w \times O_T \times 60} \times 100 \\ &= \frac{13000 \times (2.7 + 2)}{260 \times 8 \times 60 \text{ min}} \times 100 = 49\% \end{aligned}$$

The handling time per job (unit load) is comprised of the time directly associated with material handling. The total handling time per job includes the time from when the MHE gets a job until when the MHE releases the job. The handling time per job of the MHE can be obtained as below:

$$\text{Handling time/job} = \frac{\text{dual command cycle time}}{2} = \frac{DC + 4 \times PD}{2} = 2.35 \text{ min}$$

Throughput is the number of jobs (unit loads) completed in a given period time. This can also be quantified as a rate like number of unit loads handled by the MHE per unit time.

The throughput per hour of the MHE may be calculated as below:

$$\text{Throughput/hr} = \frac{60 \text{ min} \times 0.85 (\text{efficiency of MHE, assumed})}{\text{Handling time per job}} = 21 \text{ jobs}$$

The efficiency of an MHE needs to be considered when the throughput of the MHE is calculated because of breakdown and maintenance time of the MHE. The performance measures of the miniload AS/RS are summarized in Table 3.28.

Table 3.28. Results of performance measures for the miniload AS/RS

Handling time(min)/job	Utilization(%)	Throughput(job)/hr
2.35	49	21

### 3.5.4 AS/RS design analysis

To design an AS/RS system means determining all three dimensions of the physical storage space and total number of SR machines required. For the example of the AS/RS design analysis, let us assume the following case. A user wants to store a unit load on a wood pallet and the unit load characteristics including the pallet are as follows: length, 44 inches, width, 38 inches, height, 44 inches, and load weight, 1000lbs. The available height of the storage building is 60 feet. 50 dual cycle transactions (throughput) are required per hour, and the storage capacity of the system required is 5,000 unit loads.

Based on the above conditions, the number of SR machines can be determined as follows:

For single cycle SR machine:

$$\text{Number of SR machines} = \frac{\text{throughput}}{\left( \frac{60 \text{ min}}{\text{single command cycle time}} \right) \times 0.85 (\text{efficiency})}$$

For dual cycle SR machine:

$$\text{Number of SR machines} = \frac{\text{throughput}}{\left( \frac{60 \text{ min}}{\text{dual command cycle time}} \right) \times 0.85 (\text{efficiency})}$$

$$\text{where single command cycle time} = (SC + 2 \times PD)$$

$$\text{dual command cycle time} = (DC + 4 \times PD)$$

Refer to subsection 3.2.2.2 for more detail of the cycle times.

Let's say  $SC = 1.8\text{min}$ ,  $DC = 2.7\text{min}$ , and  $PD = 0.2\text{min}$ . The numbers of single cycle SR machines and dual cycle SR machines required to handle a throughput of 50 transactions per hour can be obtained respectively as follows:

For single cycle machines:

$$\text{Number of SR machines} = \frac{100}{\left(\frac{60}{1.8 + 0.4}\right) \times 0.85} = 4.31 \text{ or } 5 \text{ (round up)}$$

$$\text{Number of rows} = 5 \times 2 = 10$$

For dual cycle machines:

$$\text{Number of SR machines} = \frac{50}{\left(\frac{60}{2.7 + 0.8}\right) \times 0.85} = 3.43 \text{ or } 4 \text{ (round up)}$$

$$\text{Number of rows} = 4 \times 2 = 8$$

The numbers of stacks that can be accommodated with a 44-inch (3.7-foot) height unit load is (allowing for 6-inch clearance between stacks) is  $\frac{60}{(3.7 + 0.5)} - 1 = 13.3$  or 13 unit

loads (round down). Thus the number of bays required can be calculated as follows:

For single cycle machines:

$$\text{Number of bays} = \frac{5000 \text{ unit loads}}{2 \times 5 \text{ machines} \times 13 \text{ unit load high}} = 38.4 \text{ or } 39 \text{ (round up)}$$

For dual cycle machines:

$$\text{Number of bays} = \frac{5000 \text{ unit loads}}{2 \times 4 \text{ machines} \times 13 \text{ unit load high}} = 48.1 \text{ or } 49 \text{ (round up)}$$

For each bay, the width is 38 inches for the unit load plus 6 inches clearance giving a total of 3.7 feet. The length of the storage can be obtained as follows:

For single cycle machines:

$$\text{Length of AS/RS} = 3.7\text{feet} \times 39\text{bays} + 25\text{feet}(\text{for SR machine clearance}) = 170\text{feet}$$

For dual cycle machines:

$$\text{Length of AS/RS} = 3.7\text{feet} \times 49\text{bays} + 25\text{feet}(\text{for SR machine clearance}) = 207\text{feet}$$

Multiplying the aisle unit by the number of SR machines gives the width of the AS/RS system (Sule, 1994). The aisle unit can be obtained by the depth (length) of a unit load  $\times 3 + 2$  feet (clearance), which is  $3.67\text{feet} \times 3 + 2 = 13\text{feet}$ . The width of the storage can be calculated as follows:

For single cycle machines:

$$\text{Width of AS/RS} = 13\text{feet} \times 5 \text{ machines} = 65\text{feet}$$

For dual cycle machines:

$$\text{Width of AS/RS} = 13\text{feet} \times 4 \text{ machines} = 52\text{feet}$$

Thus the storage dimensions are as follows:

For single cycle machines:  $65 \times 170 \times 60\text{feet}$

For dual cycle machines :  $52 \times 207 \times 60\text{feet}$

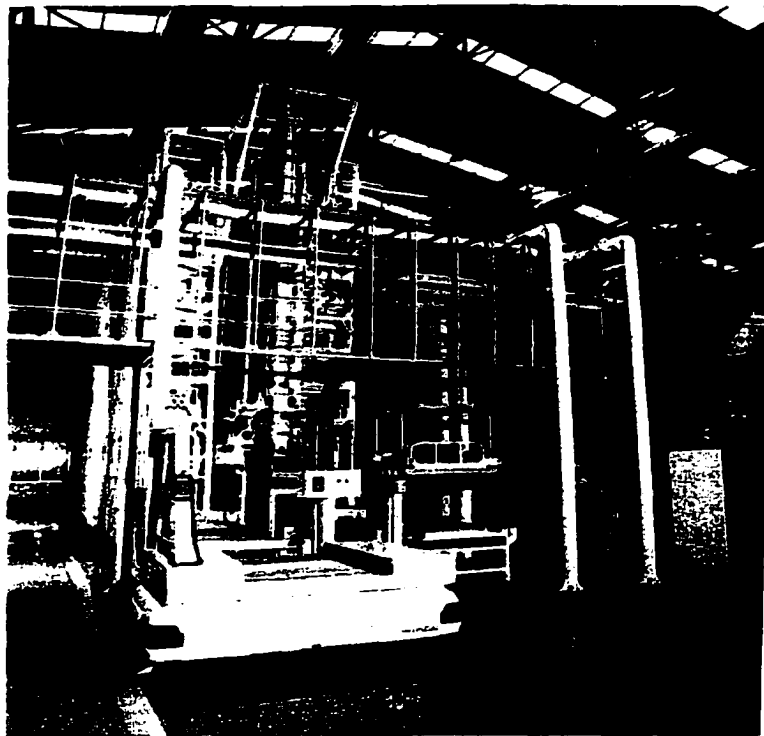
The AS/RS design results are summarized in Table 3.29.

**Table 3.29. Results of the AS/RS design analysis**

	<b>Single command cycle</b>	<b>Dual command cycle</b>
<b>Number of SR machines</b>	<b>5</b>	<b>4</b>
<b>Number of Rows</b>	<b>10</b>	<b>8</b>
<b>Number of Bays</b>	<b>39</b>	<b>49</b>
<b>Width of the AS/RS(ft)</b>	<b>65</b>	<b>52</b>
<b>Length of the AS/RS(ft)</b>	<b>170</b>	<b>207</b>
<b>Height of the AS/RS(ft)</b>	<b>60</b>	<b>60</b>
<b>The Overall Dimension</b>	<b>65 × 170 × 60 feet</b>	<b>52 × 207 × 60 feet</b>

### **3.6. System Integration for Automatic MHE Applications**

An example of an integrated material handling system is designed and described in this subsection. An integrated material handling system is defined as a network of a host computer, MHE control computers, and automated MHE such as S/R (Storage and Retrieval) machines, AGV (Automatic Guided Vehicle), EMS (Electrified Monorail System), and others. MHE control computers effectively monitor the equipment status and control material movement. They regulate the system parts so that the right material is moved at the right time to the right place as required by the process planning and shop floor scheduling. Figure 3.24 illustrates an application of an automated MHE in a material handling system.



**Figure 3.24. Application of an automated MHE in a material handling system**



### 3.6.1. Example of an integrated material handling system

Figure 3.25 depicts an application of an integrated material handling system consisting of a host computer, five AS/RS, two shop floor control systems, and other automated MHE such as electric wire guided AGV, laser guided AGV, and EMS. The host computer and MHE control computers including AS/RS control computers and shop floor control computers are interconnected and each MHE communicates with its control computer in real time. The host computer generates the job schedules, material movement routes, and material retrieval and storage orders.

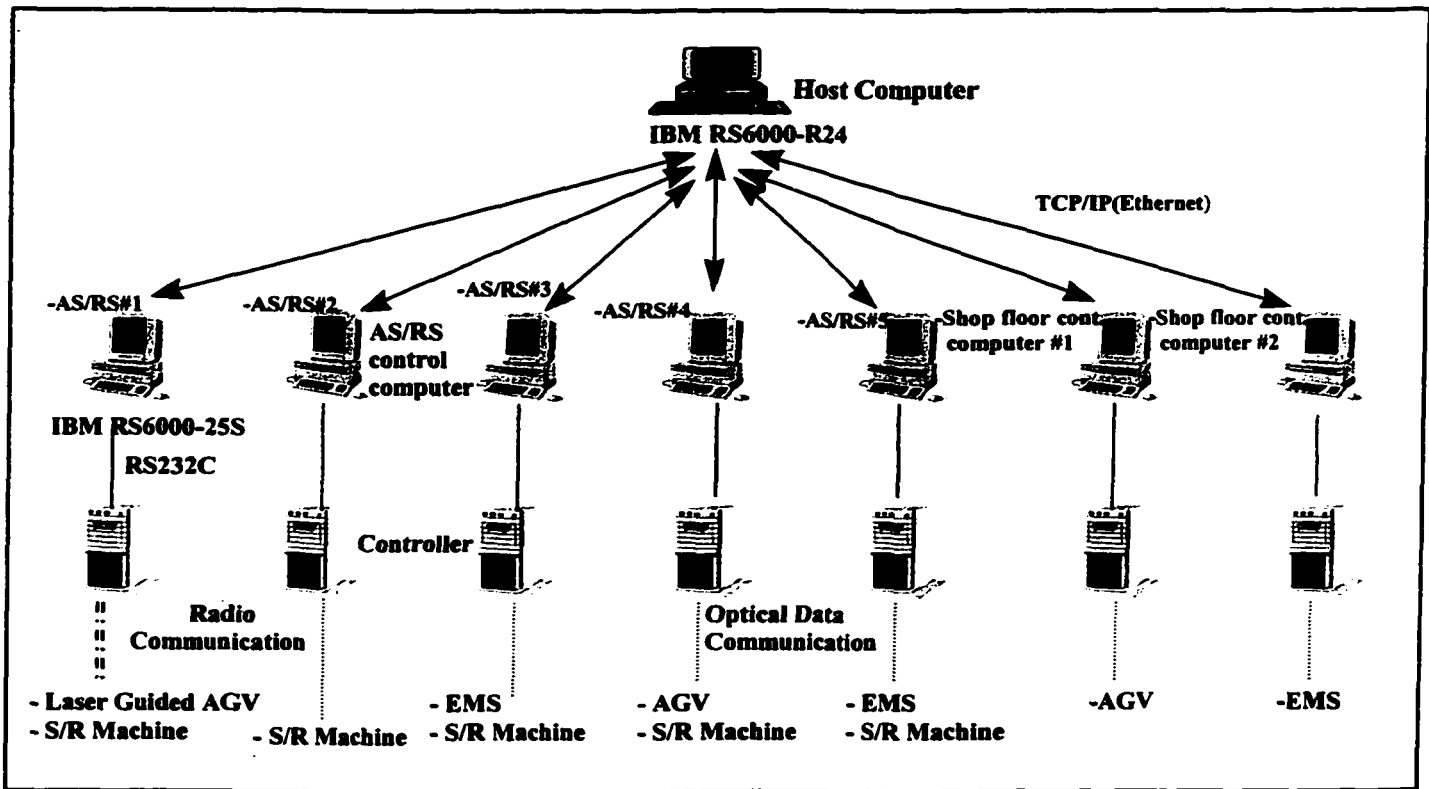


Figure 3.25. The overall system configuration of an application

The host computer is linked to two shop floor control computers and five AS/RS control computers that control the S/R machines. For example, the control computer of

**AS/RS #1 is connected to the host computer for uploading/downloading information and the control computer also manages a laser-guided AGV and SR machine for downloading orders of material transportation. After receiving an order from the AS/RS control computer, the AS/RS controller issues an order for material transport to the AGV. The AS/RS control computer also issues orders for material storage and retrieval to the S/R machine. Radio frequency is used for communication between the AS/RS control computer (controller) and the laser-guided AGV, while optical data are applied for communication between the AS/RS control computer and the S/R machines, and between the AS/RS control computer and the EMS.**

**Figure 3.26 illustrates a configuration of a material handling system. The main host computer is connected to the AS/RS control computer and this computer, in turn, is connected to the AGV (or EMS) control computer. The AS/RS control computer manages the S/R machine and input/output conveyors. This computer also downloads the orders of the AGV operation to the AGV control computer. The sub-modules of the management program of the AS/RS control computer can be summarized as shown in Figure 3.27. The AS/RS control computer uploads the inventory data files to the host computer and the host computer downloads the job schedule files, material order files, and material route files to the AS/RS control computer. The management program consists of four sub-modules, namely, order management, job status, data management, and data status.**

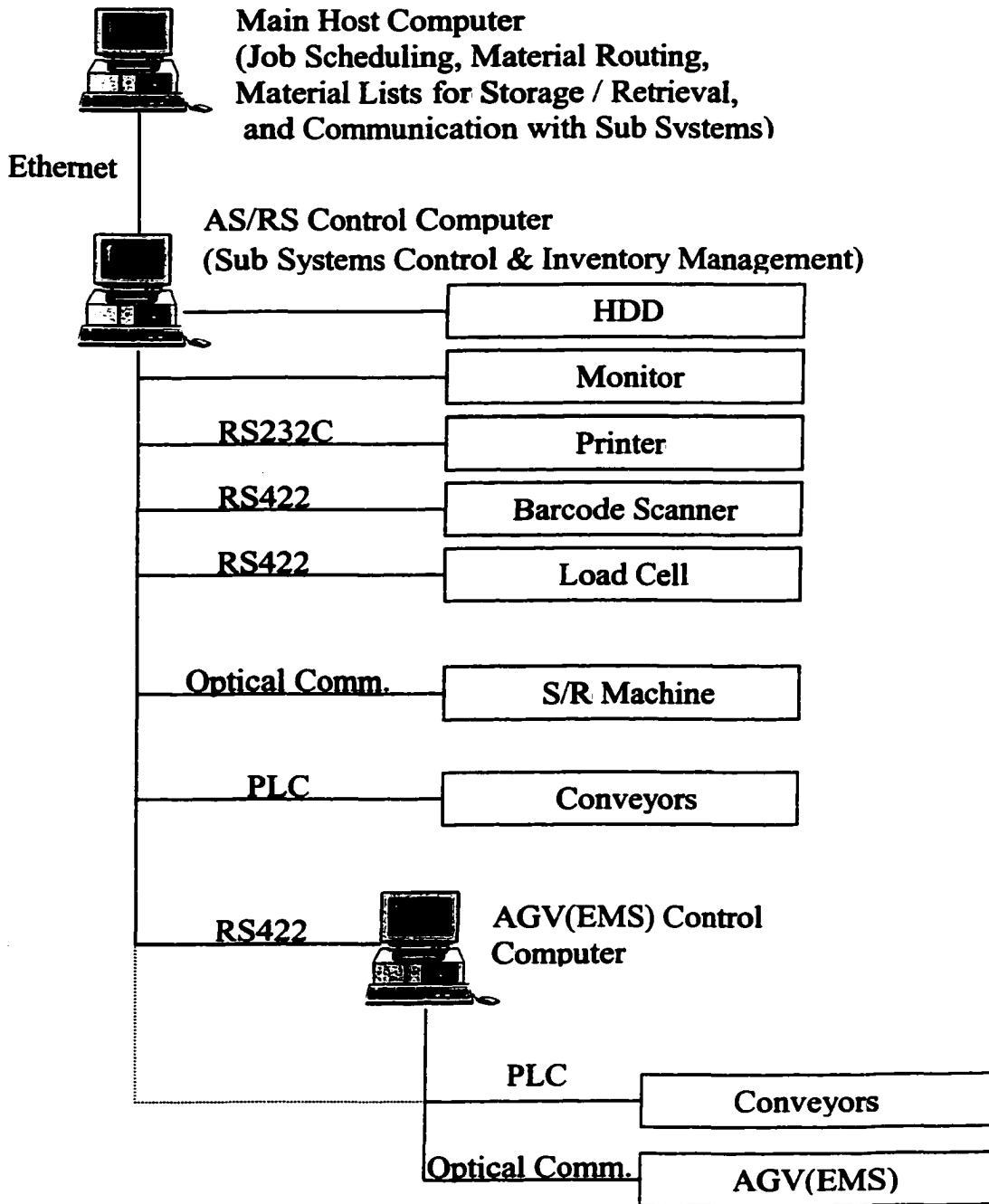


Figure 3.26. Configuration of a material handling system

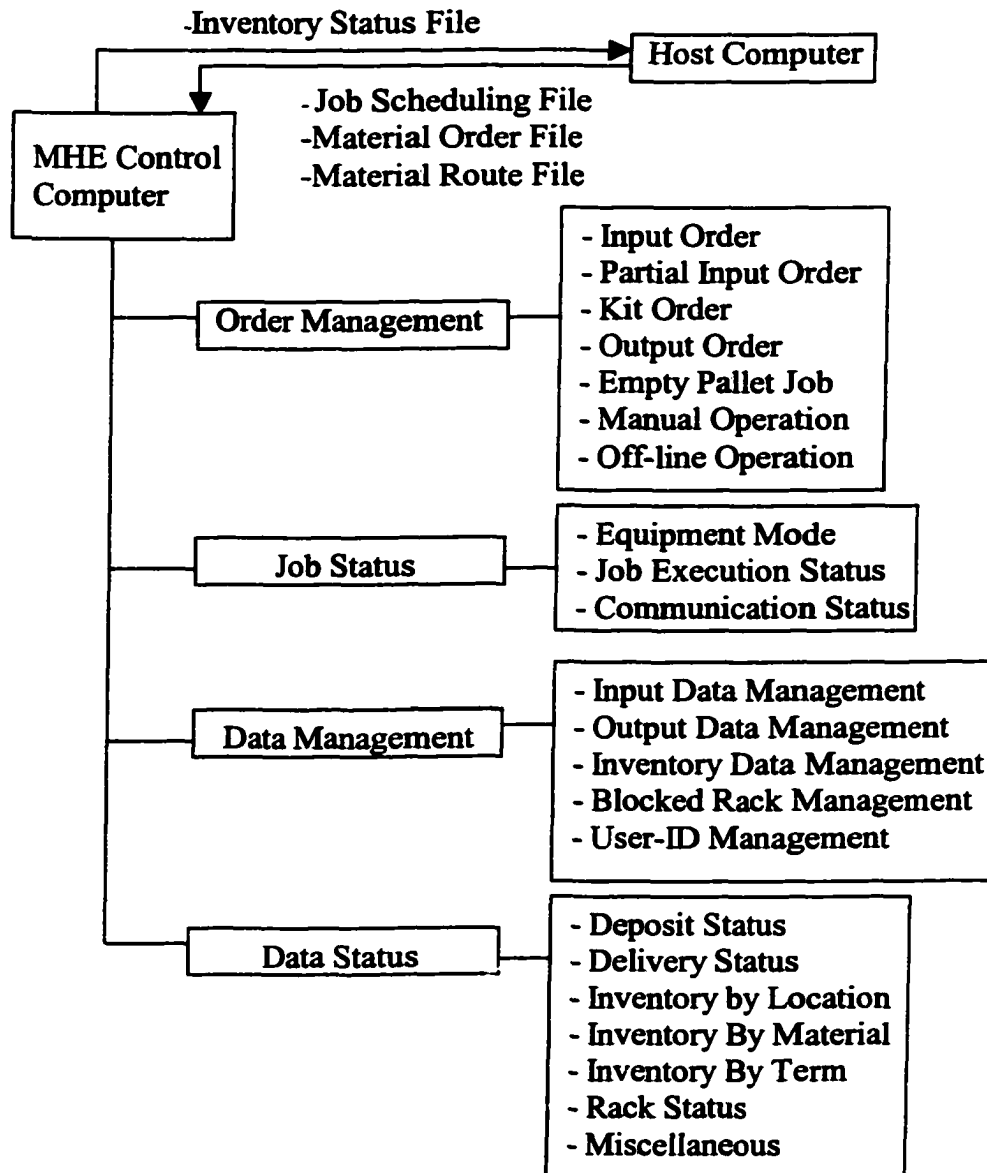


Figure 3.27. An example of a production support program in an AS/RS control computer

### 3.6.2. Application of AGV

The most important factor that separates and defines AGV groups is the guidance method. These groups can be classified into magnetic-guided AGV, electric wire guided

AGV, or a laser-guided AGV. When a magnetic-guided AGV or an electric wire guided AGV is applied to transport materials to conveyors, the information flow diagram to the vehicles can be represented as shown in Figure 3.28. The MHC (material handling computer) controls the AGV's schedules and dispatches the vehicles according to some rules based on the load handling requests and the production schedule downloaded from the host computer. The vehicles begin their travel to the requested workstations upon the receipt of the dispatch signal from the control computer. Communication between the vehicles and the stations is accomplished through the transfer interlock sensors to load or unload their items.

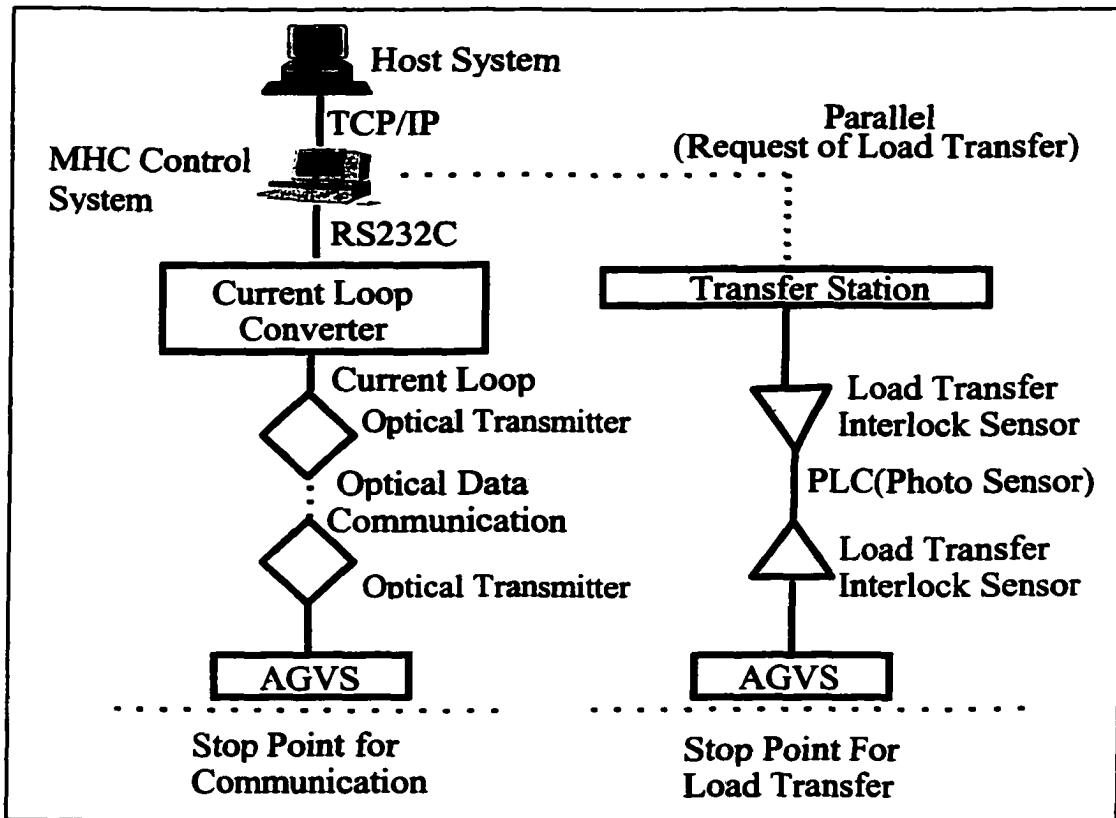


Figure 3.28. Information flow diagram for an AGV

The laser-guided AGV consists of a control computer, a graphic-interface system, an on-board controller, a radio communication system, a laser emitter/scanner, and reflectors. The MHC analyzes signals and builds computer images of the vehicle's surroundings and compares these images with maps that are preprogrammed into the vehicle's on-board system. The system configuration is as illustrated in Figure 3.29. Reflectors in the facility are used to establish the location of vehicles at any point in time. The angular separation between reflectors must be less than or equal to  $108^\circ$  so that the controller of the vehicle can calculate the location of the vehicle 3.33 times per rotation of a laser scanner. Based on the calculated results, the location of the vehicles can be determined.

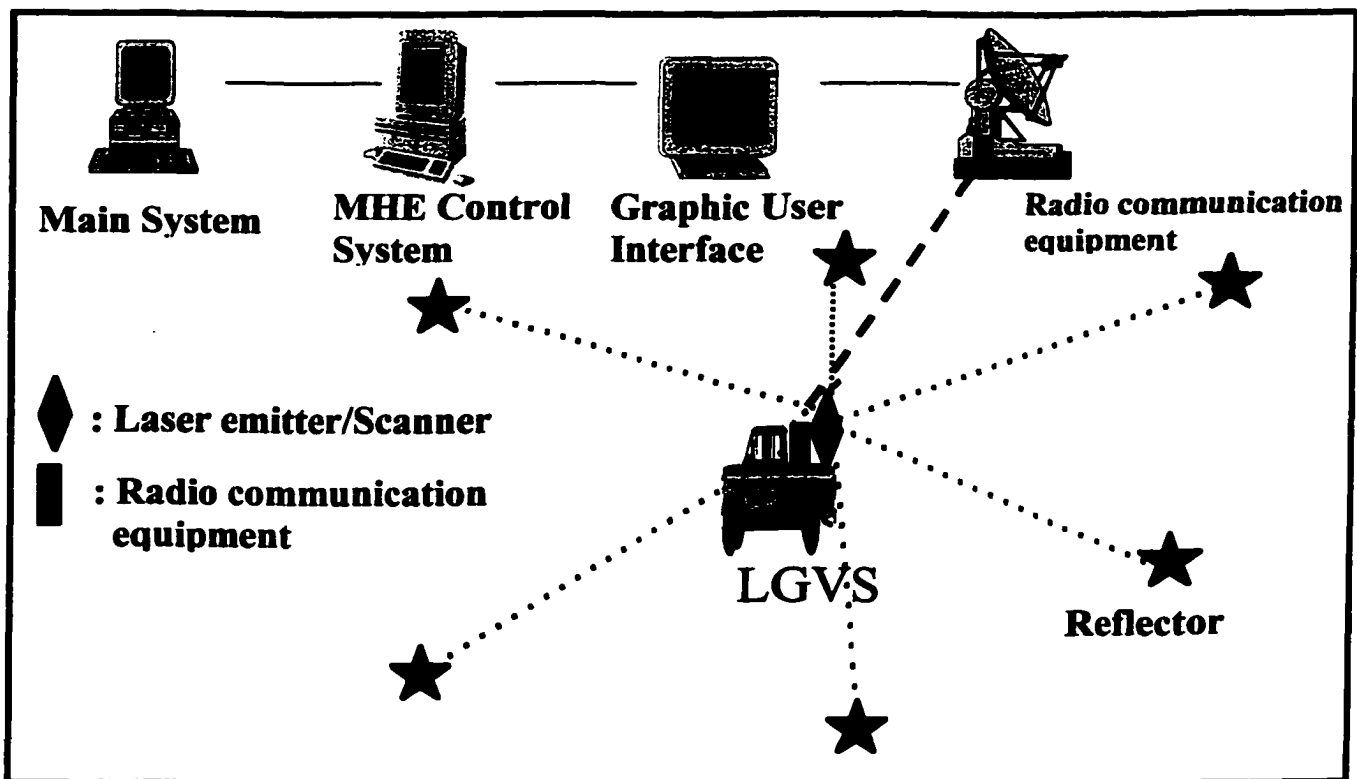


Figure 3.29. System configuration of a laser-guided AGV

### **3.6.3. Application of EMS**

Figure 3.30 illustrates the system configuration of an EMS. The station interlock is important in an EMS and is used to hoist operations in order to prevent collision of loads or other dangerous operations upon loading and unloading at the stations. Four bit photoelectric switches are provided for interlocking with the designated conveyors. When there is a load at a loading station, the Down-Ok signal is transmitted to the EMS. The EMS then lowers the carriage to the specified position. The EMS outputs the Action-Ok signal, which initiates the conveyor to send the load into cage. When the load is completely loaded, the conveyor transmits the Up-Ok signal and the EMS then turns off Action-Ok signal, raising the carriage. The procedures are the same for unloading. Figure 3.31 provides an example of an EMS application. This example consists of one AS/RS, two working stations, and one EMS to transport materials between the workstations and the AS/RS.

### **3.6.4. Application of AS/RS**

An AS/RS is a fully automated warehouse that can be interfaced with AGV system, EMS, and conveyor. The data transactions regarding storage and retrieval of materials can be done automatically. In addition, AS/RS control computer usually stores huge amount of data associated with inventory and operations and needs an operating program. Therefore, the specification for the control system is very important. The following is an example of a typical specification of a control system for an AS/RS:

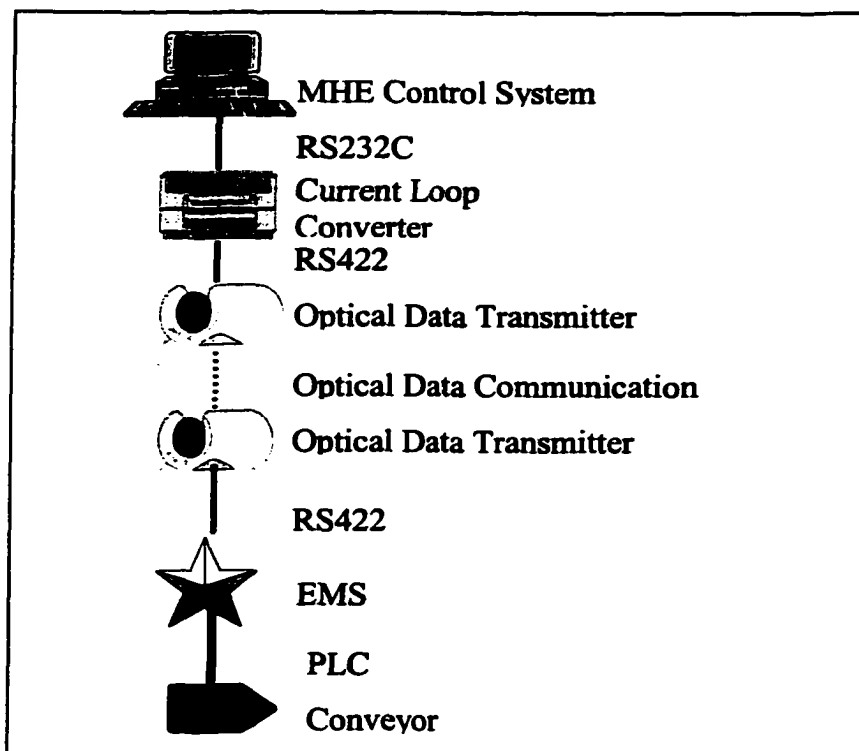


Figure 3.30. System configuration of an EMS

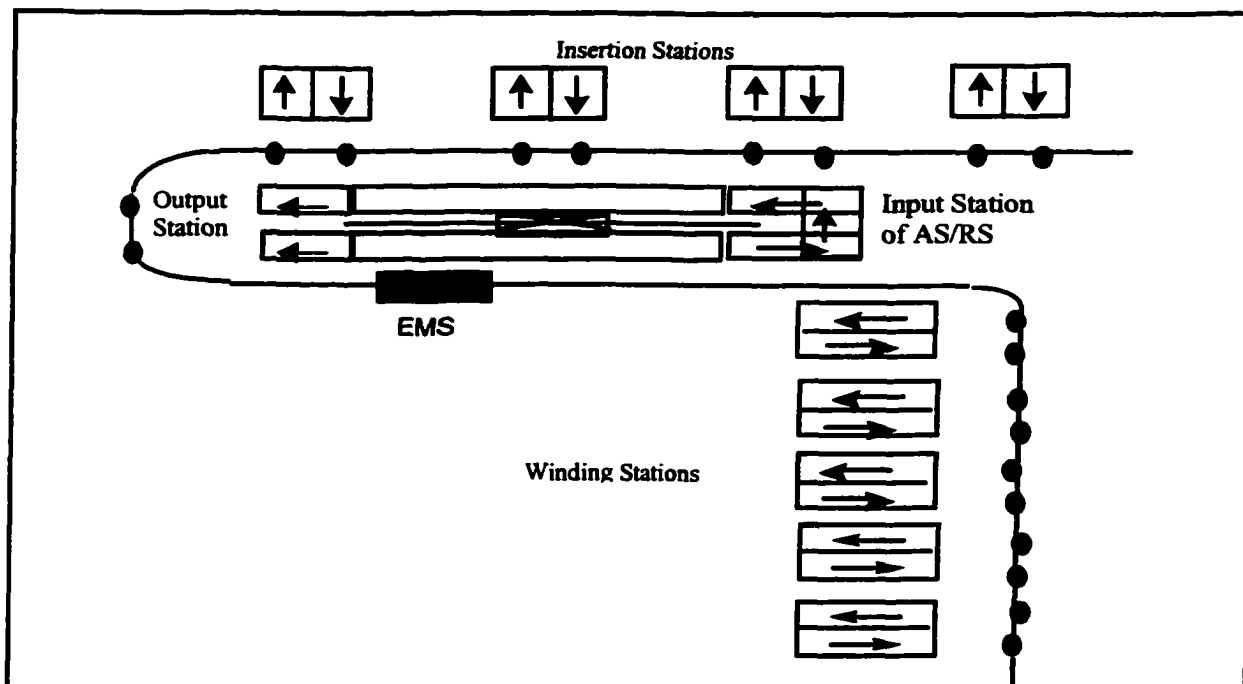


Figure 3.31. An example of an EMS application



- CPU : IBM PC compatible / Window NT 4.0
- Diskette drive : 3.5", Zip drive
- Printer : Dot matrix printer (10ppm)
- UPS : 3KVA/30min.
- Ports : 3 (one for Printer, one for host interface, and one extra part)
- Database : Oracle 8.0
- Barcode reader : Fixed scanner type
- Barcode printer : 8dots/min
- Load cell
- Communication with S/R machine : Optical Units
- Communication with Conveyor : PLC
- Communication with Host Computer : Ethernet with NetBios calls
- Communication with Printer : RS232
- Communication with barcode scanner : RS422
- Communication with AGV control computer : RS422
- Communication with EMC control computer : RS422
- Sub Program required
  - Storage management module
  - Retrieval management module
  - Host interface (communication) module
  - Inventory management module
  - Report management module
  - Etc.
- Console room required

**Database, communication requirements, and operation program have to be specified.**

### 3.7. Implementation of DESIGNER

DESIGNER is written using ASP (Active Server Page), Java Script, and MS SQL. ASP is used to implement the server and client side programs, including GUI (Graphic User Interface) and intermediate processing modules. ASP is also applied to access the MHE databases constructed using MS SQL. The knowledge-based rules, the decision-making algorithm, and the analysis modules are programmed using ASP and Java Script. MATLAB is employed to obtain degrees of membership functions for the fuzzy logic application. The overall system structure is as depicted in Figure 3.1. DESIGNER runs on any computer system with executable Netscape 4.7 and Explorer 4.0. Figure 3.32 is the title page of DESIGNER appears when it is visited.

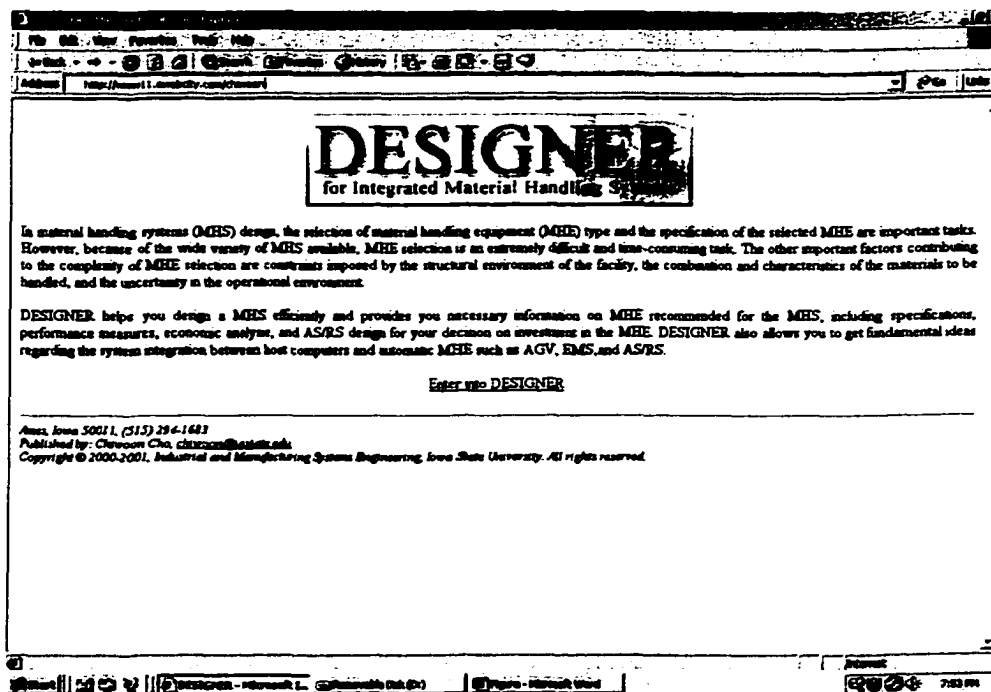


Figure 3.32. Title page of DESIGNER

### 3.8. Example of MHS Design on DESIGNER

Figure 3.33 illustrates the main page of DESIGNER. It is partitioned into three frames. The first frame (A) provides the general information to the user about material handling, MHE, system integration for automated MHE, and related Web sites. This frame also includes the counter on the number of visitors to this Web site. The second frame (B) shows the logo of DESIGNER, and the third frame (C) contains the main part on which all processes are performed and results are shown. A user can obtain help by clicking on the “Click here for HELP” label. Clicking on the “Click here for HELP” label will generate or display the explanation to each question as illustrated in Figure 3.34. To return to the previous page (Figure 3.33), the user will need to click the back button. If the user wants to know more about integration, for example, the user can select integration on the first frame and a new page (Figure 3.35) will appear. The user can click the back button or move the vertical scroll bar down and click “Move to Main Page” at the bottom to return to the main page.

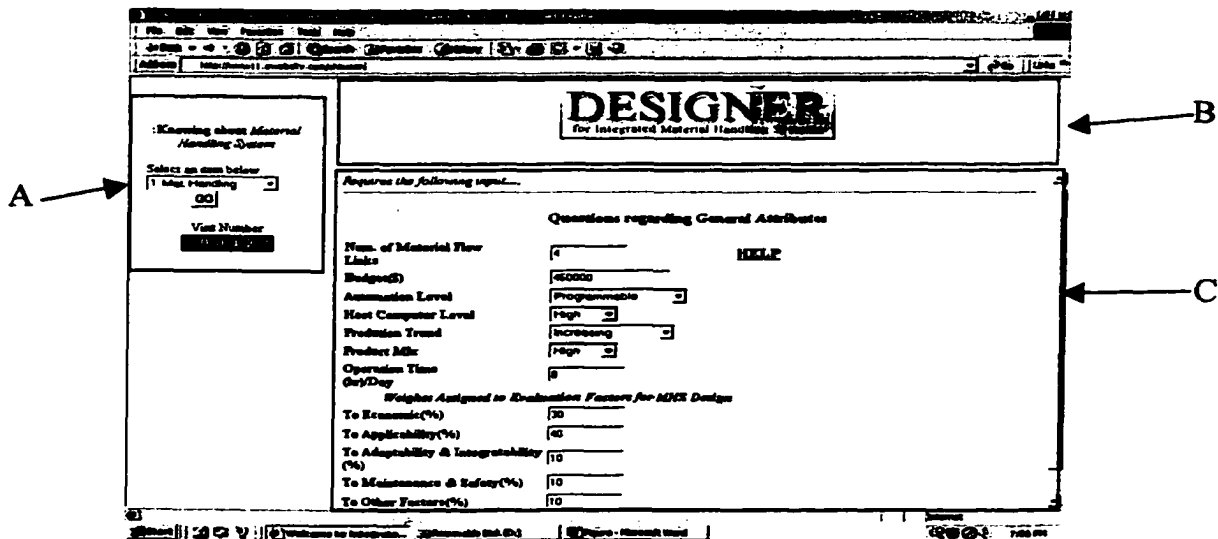


Figure 3.33. Main page of DESIGNER

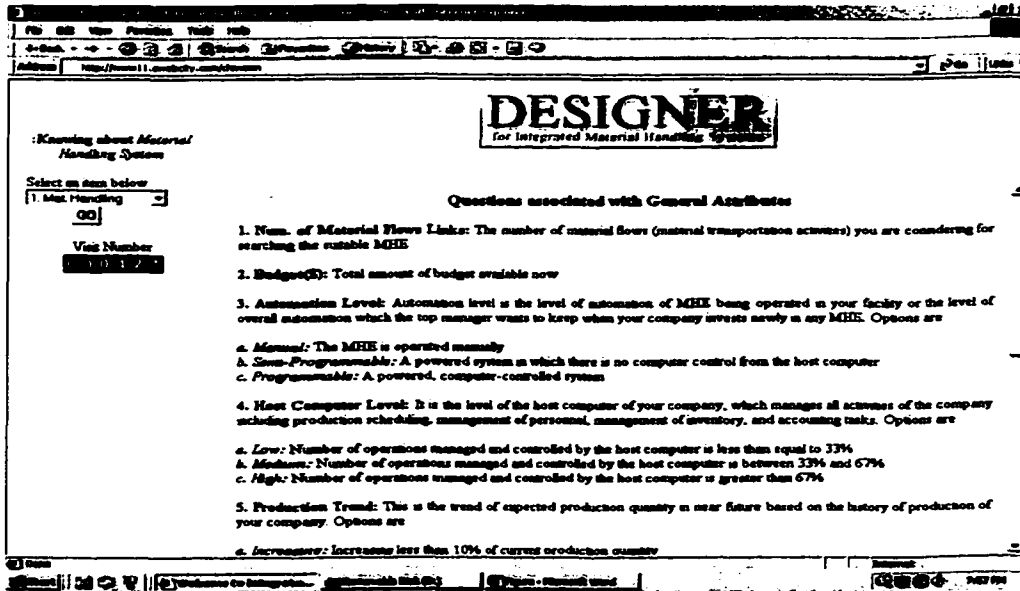


Figure 3.34. Help page for general attributes

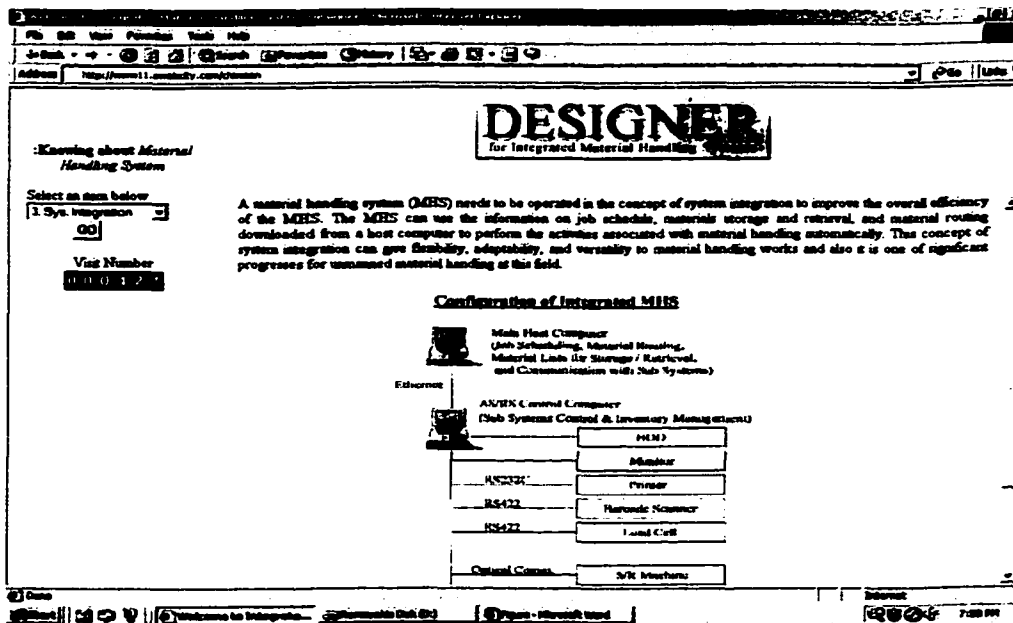


Figure 3.35. System integration guide page

A user can apply DESIGNER to design a material handling system for an application by providing a response to each question as shown in Figure 3.33. Clicking the “Confirm” button at the bottom will process the query.

***Questions associated with general attributes***

The followings are queries issued to system users to extract essential data:

- Total numbers of material flow links required:
- Budget:
- Automation level: manual, semi-programmable, programmable
- Host computer level: low, medium, high
- Expected production trend: increasing, highly increasing, decreasing, highly decreasing, stable
- Product mix: high, medium, low
- Weights assigned to evaluation factors for MHS design:
  - To Economic Aspect (%):
  - To Applicability Aspect (%):
  - To Adaptability & Integratability Aspect (%):
  - To Maintainability & Safety Aspect (%):
  - To Other Aspect (%):
- Operation time per day:

Next the user can choose any type of MHE category from the pull down menu as shown in Figure 3.36. Three MHE categories are available, namely, “For Movement”, “For Storage”, and “For Positioning”. If the user selects “For Movement” as the MHE type category in Figure 3.36, the user is expected to type or provide a response to each question as indicated in Figure 3.37. Help for each question is also available.

DESIGNER  
for Integrated Material Handling Systems

Knowing about Material Handling Systems

Select an item below

3 Integration

GO

Visit Number

001172

Select a MHE Type

Movement MHE

GO

Selection of the Type of MHE you are considering for Material Flow Link#1...

Figure 3.36. MHE group selection page for a material flow link

DESIGNER  
for Integrated Material Handling Systems

Knowing about Material Handling Systems

Select an item below

3 Integration

GO

Visit Number

001172

Questions Regarding Material Flow

General Data

Operation Type

Programmable

HELP

Width available for MHE

Narrow

Quantity to be handled per Day (unit loads)

345

Material Data

Type of Unit Load

In-Container

Weight of Unit Load (lbs)

100

Length of Unit Load

Short

Width of Unit Load (inches)

23

Height of Unit Load

Short

Volume of Unit Load

Small

Bottom Surface

Flat

Figure 3.37. Questionnaire page for movement MHE group

**Questions associated with movement MHE attributes**

- Operation type : manual, semi-programmable, programmable
- Width available for MHE move : narrow, medium, wide

- **Quantity to be moved per day :**
- **Type of unit load : in-container, on-pallet, tote box, barstock, bulk**
- **Weight of unit load(lbs) :**
- **Length of unit load : short, medium, long**
- **Width of unit load(ft) :**
- **Height of unit load : short, medium, long**
- **Volume of unit load : small, medium, large**
- **Bottom surface : rigid, not-rigid**
- **Type of move : horizontal (above floor, overhead), inclined, rotational**
- **Distance of move(ft) :**
- **Path of move : fixed, variable**
- **Floor surface : clear, not clear**
- **Speed of move (ft/min) :**
- **Pattern of move : continuous, intermittent**
- **Truss height : low, high**
- **Available space for MHE move : enough (not critical), not enough (critical)**
- **Loading/unloading speed required : slow, medium, fast**
- **Type of workstations associated with the move : 1:1, 1:several, several:several, several:1**
- **Direction of move : one-way, two-way**
- **Type of MHE to be connected : manual MHE, semi-programmable MHE, programmable MHE**
- **Method of loading/unloading : manual, machine L/U, programmable MHE**

***Questions associated with storage MHE attributes***

- **Operation type : manual, semi-programmable, programmable**
- **Length of the available space for MHE(ft) :**
- **Width of the available space for MHE(ft) :**
- **Height of the available space for MHE(ft) :**
- **Available space for MHE is critical : yes, no**
- **Quantity to be handled per day : small, medium, many**

- Average number of unit loads the MHE needs to store :
- Type of unit load : in-container, on-pallet, tote box, barstock, bulk
- Weight of unit load(lbs) :
- Length of unit load(ft) :
- Width of unit load(ft) :
- Height of unit load(ft) :
- Volume of unit load : small, medium, large
- Transaction rate per hour :
- Bottom surface : rigid, not-rigid
- Transaction data treatment : manual, semi-automatic, automatic (bar code)
- Weight control needed : yes (load cell), no
- MHE type transporting into storage : not decided, manual, industrial truck, AGV, EMS,  
conveyor, crane
- MHE type transporting out of storage : not decided, manual, industrial truck, AGV, EMS,  
conveyor, crane

***Questions associated with positioning MHE attributes***

- Operation type : manual, semi-programmable, programmable
- Quantity to be handled per day :
- Type of unit load : in-container, on-pallet, tote box, barstock, bulk
- Weight of unit load (lbs) :
- Volume of unit load : small, medium, large
- Bottom surface : flat, not flat
- Type of motion : transferring, rotating, gripping, feeding
- Accuracy required : low, medium, high
- Frequency : continuous, intermittent
- Treatment number required per hour :

After obtaining all the information needed from a user, the knowledge-based rule may, for example, recommend magnetic paint-guided AGV as the suitable MHE for a



material flow link. However, DESIGNER may suggest a different MHE from the result of the knowledge-based rule like roller conveyor as the most appropriate MHE (in Figure 3.38, magnetic paint-guided AGV is suggested for that), after analyzing the factors for consideration and their weighted values that the user had specified in Figure 3.33 (refer to Phase I in subsection 3.5.1 for more detail). Users also can obtain information on the overall solution steps, the specification, the economic analysis, the performance measure, and the system integration regarding the MHE selected by clicking on the buttons as illustrated in Figure 3.38.

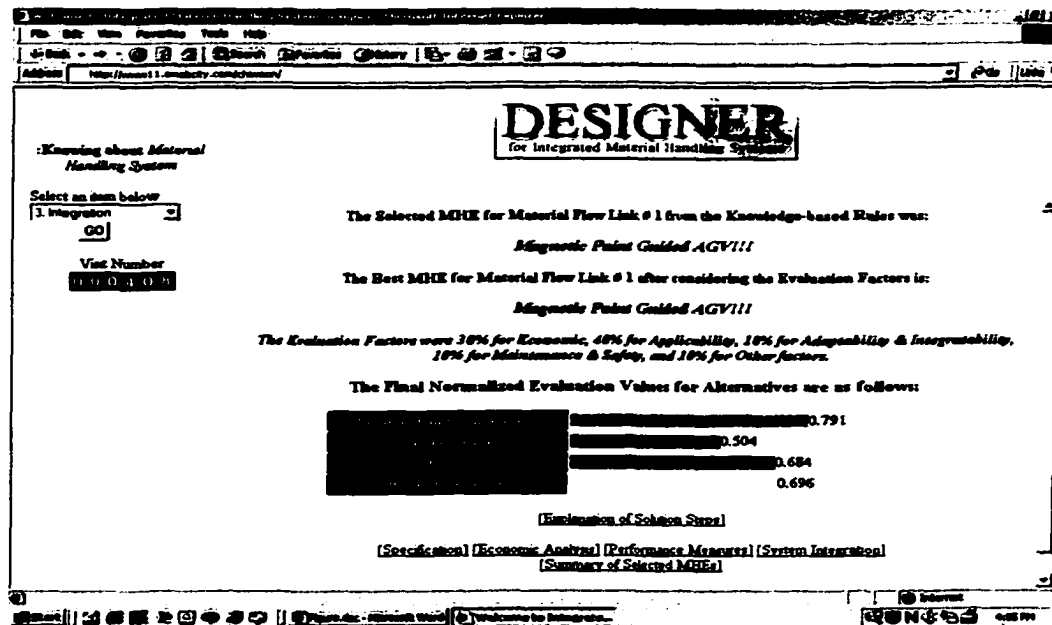


Figure 3.38. Result page for 1<sup>st</sup> material flow link

A user can obtain an explanation about the decision process for the solution and the factors DESIGNER considered for that as illustrated in Figure 3.39 (refer to subsection 3.5.1 for more detail) by clicking on the "Explanation of Solution Steps" button. The information

on the specification of the MHE suggested is provided as shown in Figure 3.40 (refer to Appendix A for more detail) by clicking on the “Specification” button.

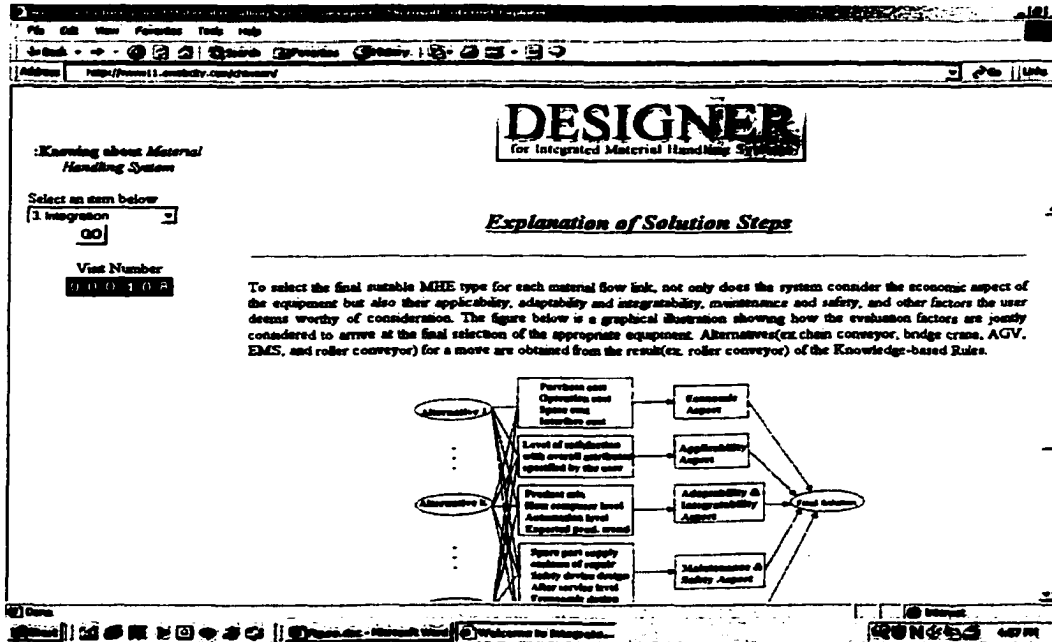


Figure 3.39. Explanation page about decision process for a solution

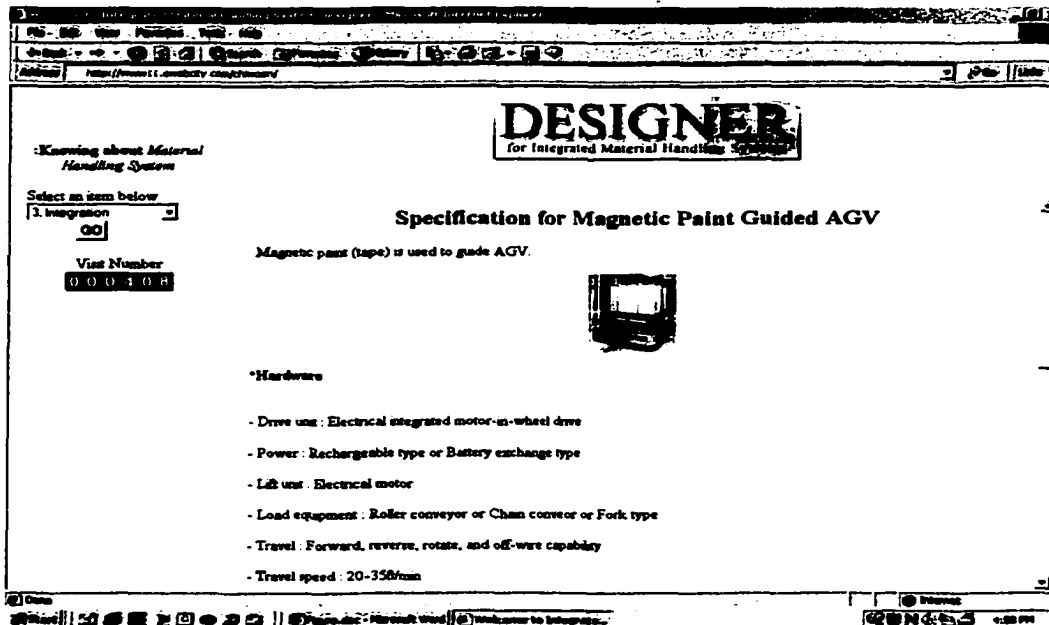


Figure 3.40. Specification page for a solution MHE

A user can obtain the results of economic analysis as illustrated in Figure 3.42 (refer to 3.5.2 for more detail) by typing a response to each question provided and clicking on the “Confirm” button in Figure 3.41 which appears after clicking on the “Economic Analysis” button.

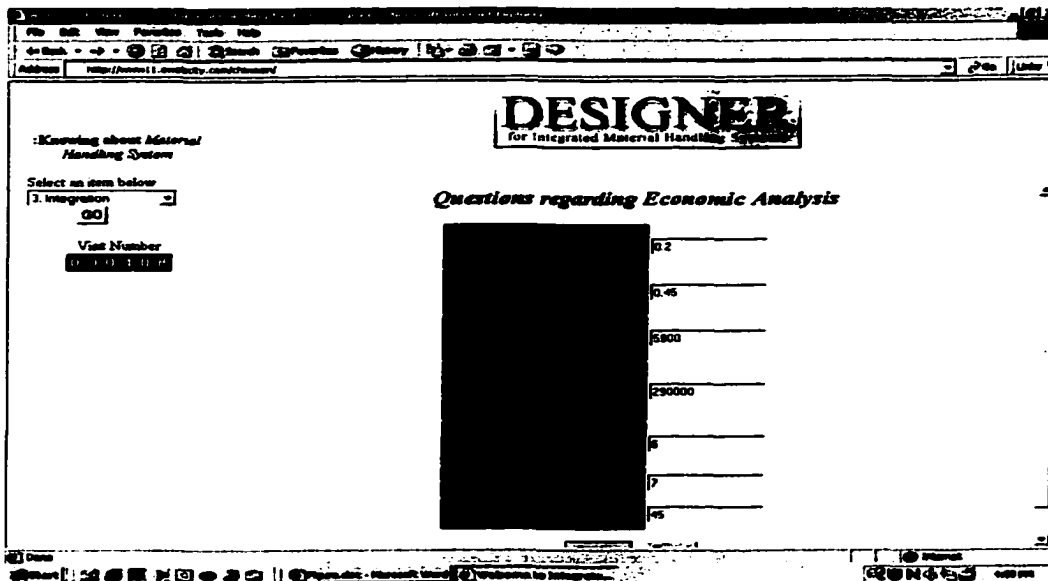


Figure 3.41. Questionnaire page for economic analysis

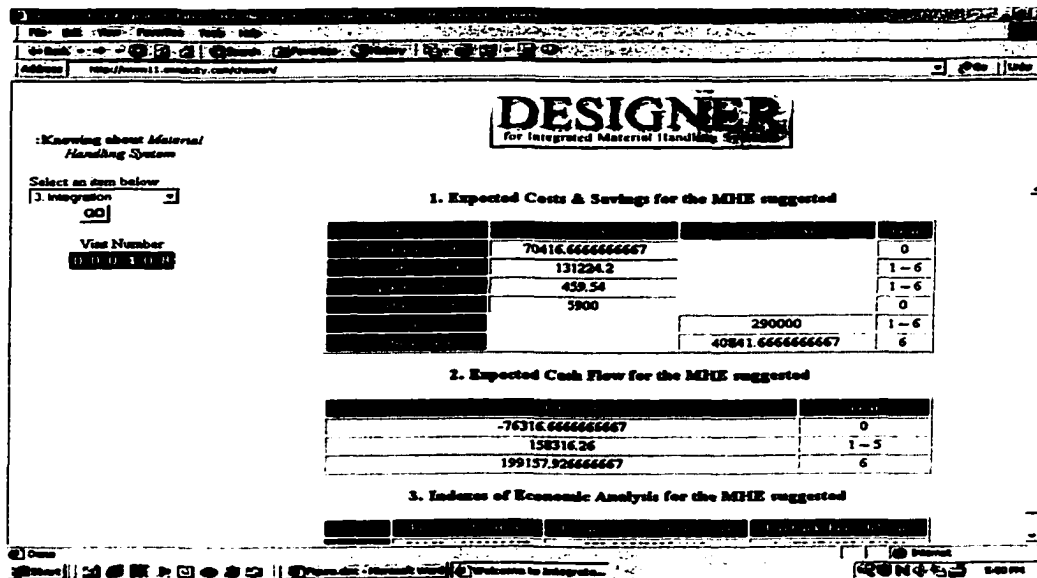


Figure 3.42. Results of economic analysis for a solution MHE

The information on costs, savings, and cash flow regarding the solution MHE is provided.

The results of performance measures of the MHE suggested are obtained as shown in Figure 3.43 (refer to subsection 3.5.3 for more detail) by clicking on the “Performance Measures” button.

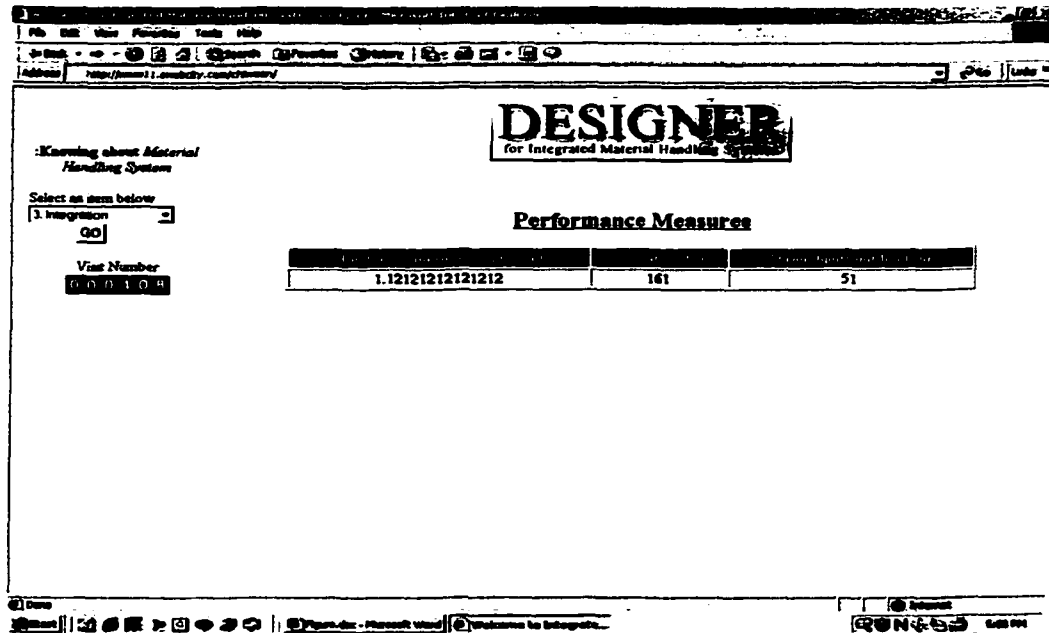


Figure 3.43. Results of performance measures for a solution MHE

When DESIGNER suggests AGV or EMS as the final solution, the user can obtain information on system integration as illustrated in Figure 3.44 (refer to subsection 3.6 for more detail) by clicking on the “System Integration” button. Similar data on system integration and system configuration are also provided if an AS/RS is recommended.

A user can obtain the summarized results regarding the solution MHE suggested for each material flow link as shown in Figure 3.45 by clicking on the “Summary of Selected MHE” button.

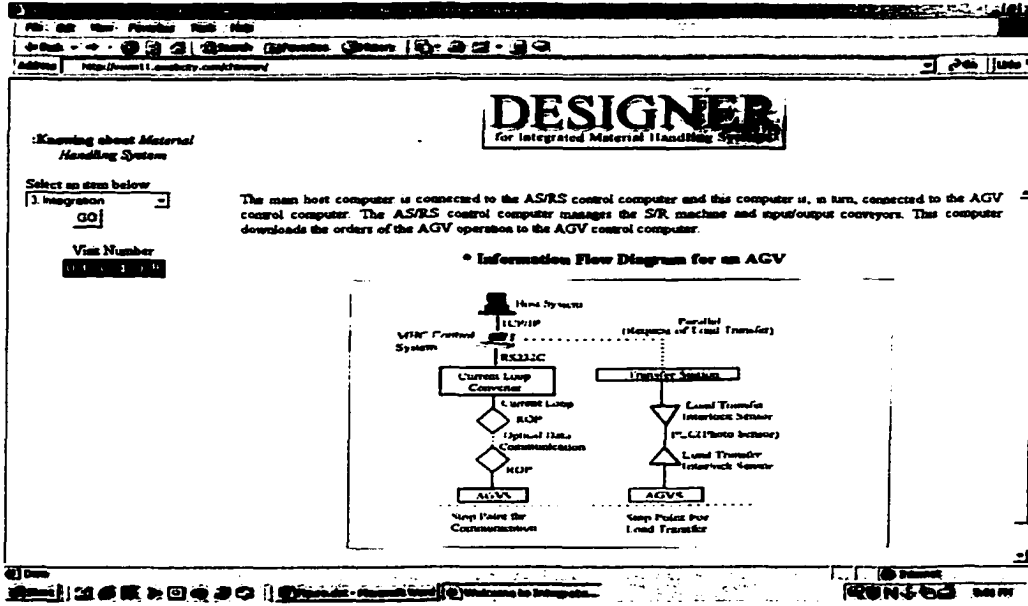


Figure 3.44. Example of system integration and configuration

The screenshot shows the 'DESIGNER' software interface with the title 'DESIGNER for Integrated Material Handling Systems' and the subtitle 'Summary of MHE'. Below the title, it says 'Results of Recommended MHE for the Material Flows'. A table is displayed with the following data:

Flow Link	Recommended MHE	Number of MHE	Flow Link ID	Material Flow ID
1 of 4	Magnetic Pinch Chained AGV	161	70417	0 478474399164054

Figure 3.45. Summarized results regarding the solution MHE

A user can continue the search for an equipment for the next material flow link by clicking on the "Move to Next Material Flow" button at the bottom part of Figure 3.38. DESIGNER searches for MHE solution of one material flow link at a time. Figure 3.46

illustrates the result of the MHE selected for a 2<sup>nd</sup> material flow link by DESIGNER. In this example, an unitload AS/RS is suggested as the solution MHE. When an AS/RS is selected as the solution for a material flow link, a user can obtain the results of the AS/RS design analysis as shown in Figure 3.47 (refer to subsection 3.5.4 for more detail) by clicking on the “AS/RS Design” button in Figure 3.46.

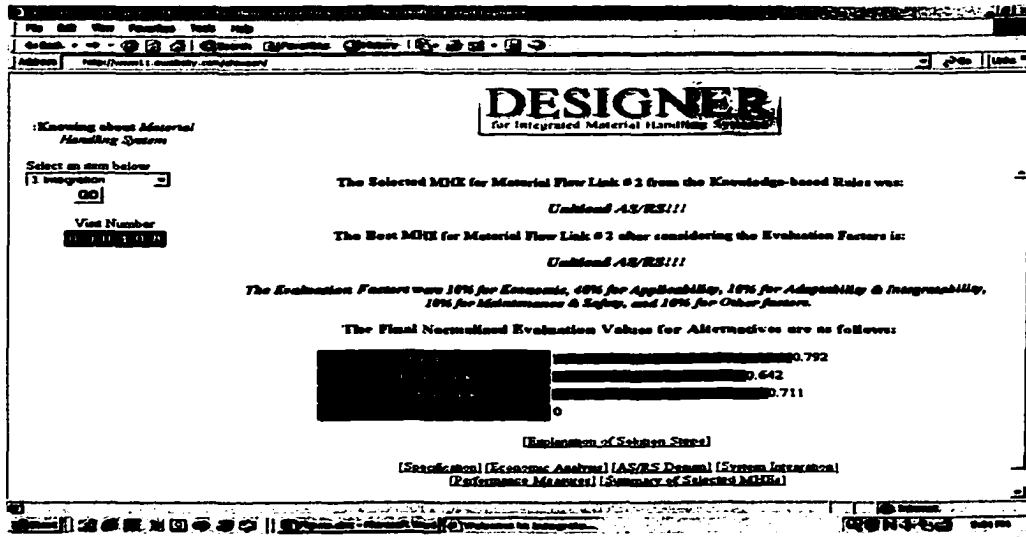


Figure 3.46. Result page for 2<sup>nd</sup> material flow link

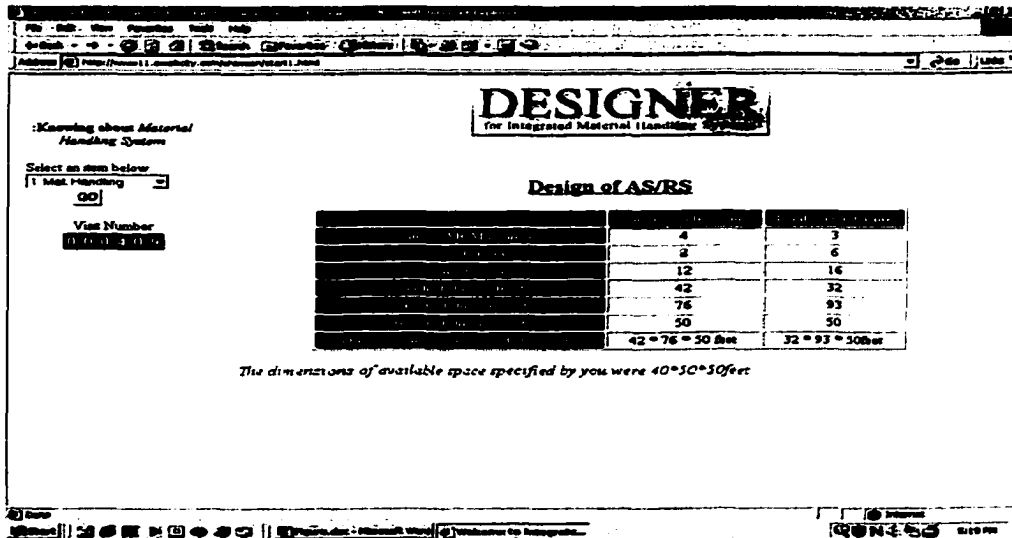


Figure 3.47. Results of an AS/RS design analysis

If a user finishes searching for all material flow links, the user can return to the main page by clicking on the “Move to Main Page” button at the bottom of Figure 3.46 (actually, it means the result page for the last material flow link). And the user also can review the summarized information on MHE suggested for all the material flow links as illustrated in Figure 3.48 (refer to Phase II and Phase III in subsection 3.5.1 for more detail) by clicking “Summary of Selected MHE” in Figure 3.46 (it also means the result page for the last material flow link). At here, the possibility of reducing the numbers of units of each MHE type and control systems is checked and the set of MHE selected is adjusted to satisfy the budget constraint. Actually, the utilization of each MHE selected can not exceed the acceptable level  $U$ , let’s say 80%. The purchase cost of MHE whose utilization is greater than  $U$  includes the total purchase cost of units of the MHE and the cost expected to upgrade the specification of the MHE to meet this requirement. The utilization of MHE for positioning can not easily calculated so the utilization of the MHE is expressed as 0%.

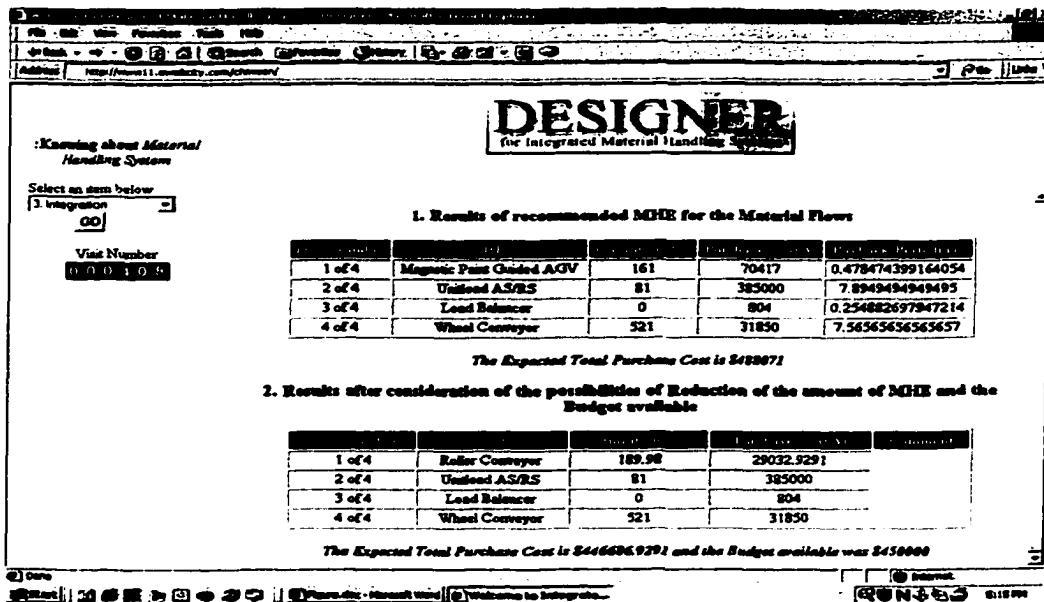


Figure 3.48. Summarized results regarding MHE suggested for all material flow links

## **CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS**

In this research, a Web-based system called DESIGNER is developed to design integrated material handling systems for manufacturing applications. DESIGNER models the material handling system design processes including MHE selection and employs information on the most common MHE types used in material movement, storage, and positioning.

DESIGNER is written using ASP (Active Server Page), Java Script, and MS SQL. ASP is used to implement the server and client side programs, including GUI (Graphic User Interface) and intermediate processing modules. ASP is also applied to access the MHE databases constructed using MS SQL. The knowledge-based rules, the decision-making algorithm, and the analyzing modules are programmed using ASP and Java Script. MATLAB is employed to obtain degrees of membership functions for the fuzzy logic application. DESIGNER runs on any computer system with executable Netscape 4.7 and Explorer 4.0.

The system designs the material handling system for an application through three phases. In Phase I, the procedure identifies the most appropriate MHE type among the alternatives that are suitable for the application. Knowledge-based rules are employed to identify alternative handling equipment for each material flow link. To select the final suitable MHE type for each material flow link, not only does the system consider the economic aspect of the equipment but also their applicability, adaptability and integratability, maintenance and safety, and other factors the user deems worthy of consideration. To compare the aggregate effect of the multiple design attributes considered for the alternatives, fuzzy evaluation matrices and normalized evaluation values are employed. To reduce the



overall system cost, in Phase II, the system checks for excess capacity for each type of equipment recommended. It also checks if operating systems for automatic equipment suggested can be combined to reduce the total number of the operating systems. Any excess capacity identified is eliminated whenever it is considered possible without introducing design infeasibility. Excess capacity is eliminated by assigning a unit of each equipment to multiple flow links and thereby reducing the total number of units of the equipment that is recommended. This reduction in equipment capacity does not apply to conveyors and storage devices because of their immobile feature. The reduction process is applicable to mobile equipment that enjoy flexible routing. In Phase III, the set of material handling equipment selected is adjusted to satisfy budget constraints if the total cost of the initial set of the selected equipment exceeds the budget.

After finding the appropriate MHE for each material flow link, analyzing modules for economic analysis, performance measures analysis, AS/RS design analysis, and system integration are performed. The economic criteria provided by DESIGNER include return on investment (ROI), payback period (PP), and present worth (PW) methods. Before applying these evaluation criteria, the results of costs and cash flow are calculated in advance. A number of different performance measures have been used in the design and analysis of material-handling systems. For the analysis module on performance measures, three performance measures that include MHE utilization, handling time per unit load, and throughput are employed. These performance measures are calculated to analyze MHE independently. In the AS/RS design module, all three dimensions of the physical storage space and the number of S/R machines needed to meet the requirements of a system are

calculated. The information on system integration and system configuration is also provided to a user when AGV, EMS, or AS/RS is suggested as the solution MHE.

In addition, to enhance the capacity and efficiency of DESIGNER and improve its overall performance in the design process, the following recommendations are necessary:

- 1) Additional MHE types can be added to the MHE database tables whenever new or more accurate data on MHE type is available. Furthermore, the system can customize his databases by deleting undesirable MHE types that are not commonly used any more.
- 2) The evaluation factors can be properly modified, added, or eliminated according to the objective viewpoint of the users, and questionnaire can also be modified to reflect any new MHE data incorporated into DESIGNER.
- 3) The knowledge-base rules have to be updated continuously according to new information on MHE type and the objective viewpoint of the users through market surveys and research.
- 4) To obtain more acceptable values of the membership functions for qualitative factors, actual surveys are required. In addition, more research for the selection and design of membership functions is needed to reflect the opinions of experts and experienced people in material handling field.
- 5) In this research, the cost functions are assumed to have proportional relationships to related variables because estimating costs is extremely difficult. Thus the cost functions can be modified to be more realistic.

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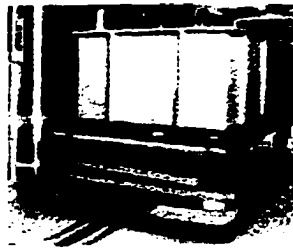
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## **APPENDIX A: GENERAL SPECIFICATIONS OF MHE TYPE**

### **MHE for Movement**

#### **1. AGV**

**1.1 Magnetic Paint Guidance:** Magnetic paint (tape) is used to guide AGV.



#### **\* Hardware**

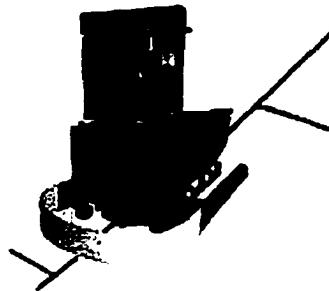
- Drive unit : Electrical integrated motor-in-wheel drive
- Power : Rechargeable type (Battery exchange type)
- Lift unit : Electrical motor
- Load equipment : Roller conveyor
- Travel : Forward, reverse, rotate, and off-wire capability
- Travel speed : 10m/min
- Capacity : 3,500lbs
- Control : Magnetic tape
- Lift capacity : 2,200lbs

**\* AGV System Controller**

- CPU : IBM PC compatible / Window NT 4.0
- Diskette drive : 3.5", Zip drive
- Printer : Dot printer (10ppm)
- UPS : 3KVA/30min.
- Ports : 3 (one for Printer, one for host interface, and one for extra)
- Communication with AGV : Optical Units
- Communication with Conveyor : PLC
- Communication with Host Computer : RS422
- Communication with Printer : RS232C
- GUI required (Menu driven operator interface)

**Approximate Price : \$85,000**

**1.2 Electric Wire Guidance:** Inertial wire is the used method of AGV guidance.

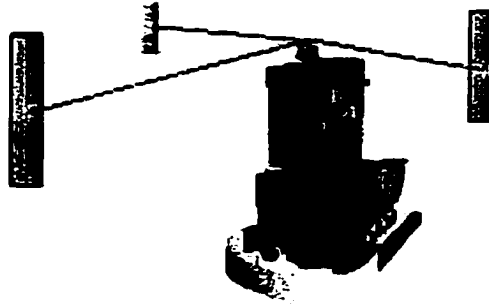


**Almost the same as Magnetic Paint Guidance except**

- Control : Inertial wire

**Approximate Price : \$90,000**

**1.3 Laser Beam Guidance:** A laser scanner which gives out X and Y coordinates and vehicle angle control the AGV



Almost the same as Magnetic Paint Guidance except

- Control : Laser beam
- Navigation control system required
- Number of reflector : 20

Approximate Price : \$140,000

**2. Monorail:** EMS(Electrified Monorail System) is generally used for overhead transfer of material from one point to another automatically.





**\* Hardware**

- Power : Electrified
- Carriage type : Hand Chain
- Capacity : 2200lbs
- Lifting speed : 3m/min
- Travel speed : 15m/min
- Overall length of rail : 100ft
- Distance between monorail supporter : 6ft
- Distance from floor to top of monorail : 5ft

**\* EMS Controller**

- CPU : IBM PC compatible / Window NT 4.0
- Diskette drive : 3.5", Zip drive
- Printer : Dot printer (10ppm)
- UPS : 3KVA/30min.
- Ports : 3 (one for Printer, one for host interface, and one for extra)
- Communication with EMS : Optical Units
- Communication with Conveyor : PLC
- Communication with Host Computer : RS422
- Communication with Printer : RS232C
- GUI required (Menu driven operator interface)

Approximate Price : \$60,000

### 3. Industrial Vehicle

**3.1 Pallet Jack:** It is an economical way for one person to move medium weight pallet

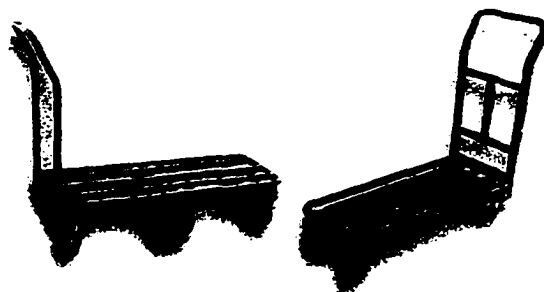


loads without the use of a pallet truck.

- Capacity : 1800lbs
- Overall fork dimension : 48" long and 27" wide
- Fork height : 1-7/8" lowered to 7-1/4" raised
- Space between forks : 6"

Approximate Price : \$475

**3.2 Hand Truck:** Facilitates movement of product over uneven floors and heavy loads.



- Base plate : 7"W × 13"D
- Wheel size/style : 8" × 2" mold-on-rubber
- Capacity : 500lbs

**Approximate Price : Two wheel - \$160**

**Four wheel - \$260**

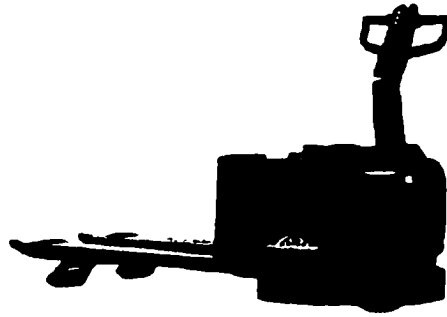
**3.3 Counterbalanced Lift Truck:** desirable for loading, unloading, storing, and retrieving loads together.



- **Power : Battery-Powered / gas or diesel**
- **Capacity : 5000lbs**
- **Travel speed : Empty – 7.5m/min, Loaded – 6.9m/min**
- **Lifting speed : Empty – 101fpm, Loaded – 63fpm**
- **Max. fork height : 250"**

**Approximate Price : \$10,000**

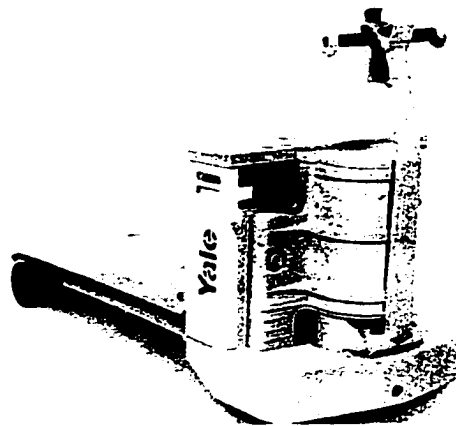
**3.4 Pallet Truck:** Used when the distance to be traveled precludes walking.



- Power : Battery-Powered
- Capacity : 6,000lbs
- Travel speed : Empty – 7.5m/min, Loaded – 6.9m/min
- Lifting speed : Empty – 101 fpm, Loaded – 63 fpm
- Max. fork height : 270"

Approximate Price : \$5,500

**3.5 Platform Truck:** Used for transporting and an alternative method of loading /unloading is needed.



- Power : Battery-Powered

- Capacity : 8,000lbs
- Travel speed : 7m/min

Approximate Price : \$5,000

**3.6 Tractor Trailer:** Used to pull a train of connected trailer to transfer high quantity.



- Power : Battery-Powered
- Capacity : 8,000lbs
- Travel speed : 9m/min

Approximate Price : \$5,300

#### 4. Conveyor

##### \* Gravity Conveyor

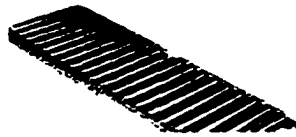
**4.1 Chute Conveyor:** It is one of the most inexpensive methods of conveying material. It is also used to provide accumulation in shipping areas.



- Steel frames
- Width : 12"
- Capacity : 65lbs

Approximate Price : \$3/ft

**4.2 Roller Conveyor:** For applications requiring more uniform conveying surface than provided by wheels.



- Steel channel
- Width : 26"
- Roller diameter : 1.9"
- Center drive
- Capacity : 200lbs
- Space between rollers : 4"

Approximate Price : \$11/ft

**4.3 Wheel Conveyor:** is used for conveying, lightweight package, and cartons by gravity



- Aluminum frame
- Width : 12"
- 15 wheels per ft
- Capacity : 65lbs

Approximate Price : \$9/ft

**\* Above Floor Conveyor**

**4.4 Belt Conveyor:** Provides complete support under materials for moving light and

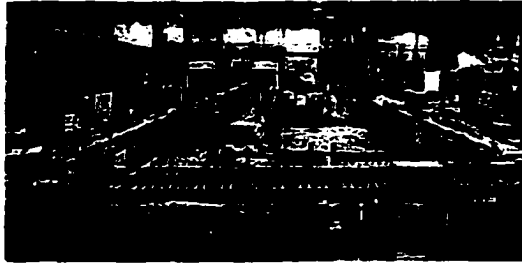


medium weight loads.

- Rugged and heavy-duty bed construction
- Belt width : 12"
- Capacity : 100lbs
- Center drive

Approximate Price : \$60/ft

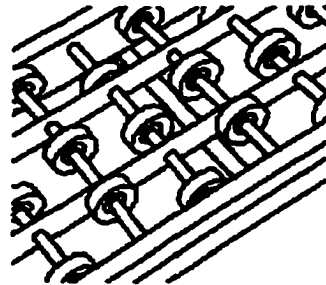
**4.5 Roller Conveyor:** Moves items horizontally and up to 5 to 7 degrees slopes. And special types are used for accumulation.



- Steel Frame
- Width : 22"
- Roller diameter : 2"
- End drive
- Capacity : 350lbs
- Space between rollers : 4"

Approximate Price : \$150/ft

#### 4.6 Skate-Wheel Conveyor

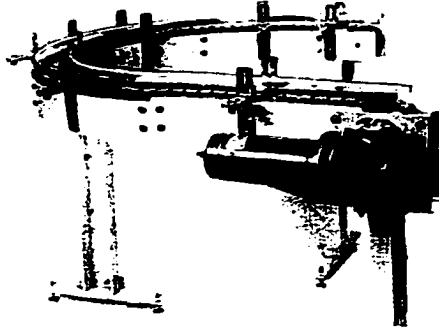


- Steel frame
- Width : 18"
- 15 wheels per ft
- Axles on 3" centers
- Capacity : 120lbs

Approximate Price : \$140/ft



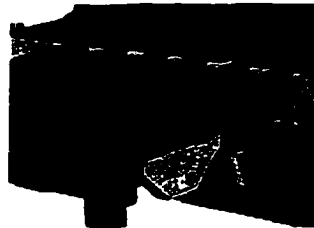
**4.7 Slat Conveyor:** Load-supporting slats are attached to chain and it handles heavy loads with abrasive surfaces.



- Steel slat
- 6" pitch steel bushed roller chain with 6" wide × 24" long slats
- Capacity : 200lbs

Approximate Price : \$600/ft

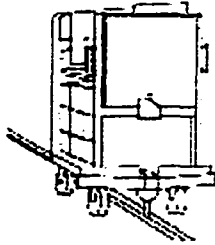
**4.8 Chain Conveyor:** Primarily for transporting heavy materials and single or multiple chains can be used.



- Steel frame
- Rollers form the load-carrying surface
- Chain-on-edge configuration
- Space between rollers : 4"
- Capacity : 1,000lbs

Approximate Price : \$400/ft

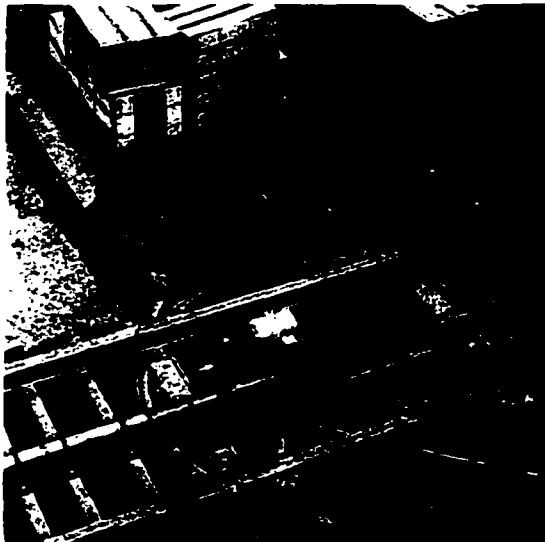
**4.9 Tow-line Conveyor:** useful for transportation of multiple units of products



- Steel frame
- Power-driven chain
- Load-carrying wheeled cart moves combinations of main lines and spurs
- Capacity : 1,000lbs

Approximate Price : \$100/ft

**4.8 Cart-on-track Conveyor:** Similar in design to roller or chain conveyors but capable of handling more heavy loads than those.



- **Steel frame**
- **Width : 22"**
- **Roller diameter : 2"**
- **Center drive**
- **Capacity : 2,000lbs**
- **Space between rollers : 4"**

**Approximate Price : \$470/ft**

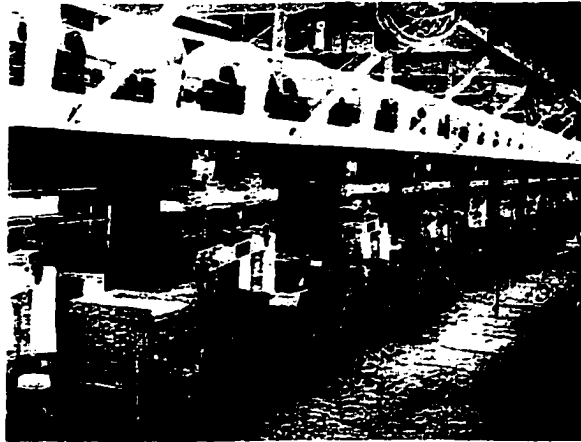
**4.9 Ball-top Conveyor:** Useful for light/medium weight loads with abrasive surfaces.

- **aluminum ball**
- **Number of ball in inch : 8**
- **Space between balls : 3 "**
- **Capacity : 70lbs**

**Approximate Price : \$18/ft**

**\* Overhead Conveyor**

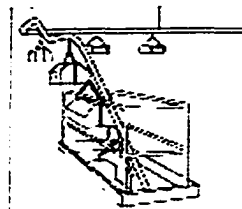
**4.10 Power and Free Conveyor:** suspended from second set of trolley, running on an independent or free track.



- Type of track : I beam
- Type of drive : Caterpillar
- Chain conveyor
- Type of chain : Chain No. 348
- Capacity : 600lbs

Approximate Price : \$650/ft

**4. 11 Trolley Conveyor:** It frees floor space for other use and carriers suspended from individual trolleys.

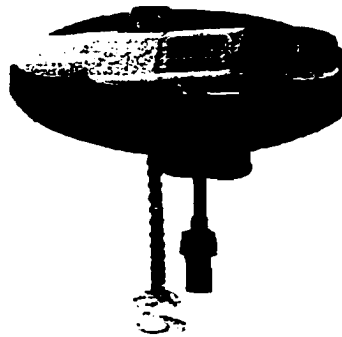


- Type of track : Enclosed
- Type of drive : Sprocket
- Chain drive
- Type of chain : Chain No. 458
- Capacity : 500lbs

Approximate Price : \$190/ft

## 5. Crane

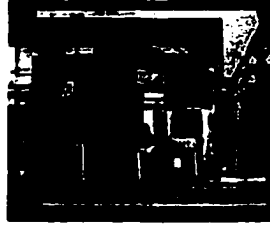
**5.1 Hoist:** It is used to facilitate the positioning, lifting, and transferring of materials within a small area.



- Capacity : 1 ton
- Top hook mount
- Adjustable travel limit
- Travel speed : 50 – 150fpm(single speed / two speed / variable speed options)

Approximate Price : \$2,500

**5.2 Jib Crane:** Jib crane is relatively inexpensive and provides three degrees of freedom;



vertical, radial, and rotary.

- Overall I-beam length : 30'
- Usable I-beam length : 23'
- Overall height : 57"
- Capacity : 15tons

Approximate Price : \$20,000

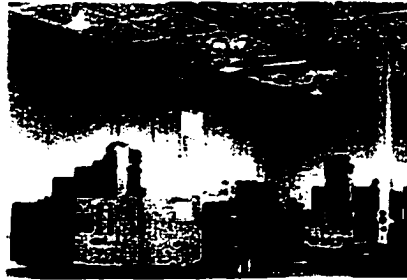
**5.3 Gantry Crane:** It can be primary bay crane in some applications. Wheels on leg bottom move on track.



- Max. length of under I-beam to ground : 12'
- Max. usable span : 50'
- I-beam flange : 33"
- Capacity : 20tons

Approximate Price : \$55,000

**5.4 Bridge Crane:** It works for heavy in-plant material handling. Also this provides full

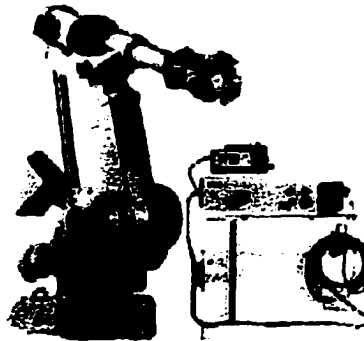


coverage of working area or bay.

- Max. length of under I-beam to ground : 14'
- Max. usable span : 150'
- I-beam flange : 50"
- Capacity : 70tons

Approximate Price : \$200,000

### **MHE for Positioning**



#### **1. Robot**

- Payload : 11lbs
- Axes : 7
- Ranges of motion : 260-720 degrees based on axes

- **Max. speed : 260-720 degrees/sec**
- **Wrist rated torque : 1.6lbs**
- **Wrist rated moment of inertia : 0.02lbs-m-s<sup>2</sup>**
- **Vertical reach : 50"**
- **Horizontal reach : 40"**
- **Repeatability :  $\pm 0.002$ "**
- **Positioning feed back : Absolute encoder**
- **Drive motors : Brushless AC servomotor**

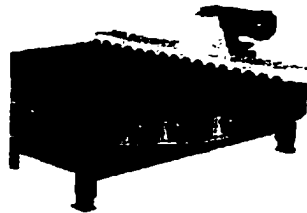
**Approximate Price : \$230,000**

## **2. Work Holder**

- **Capacity : 700lbs**
- **Overall height : 76"**
- **Vertical reach : 20"**
- **Horizontal reach : 30"**

**Approximate Price : \$5,000**

## **3. Turn Table**



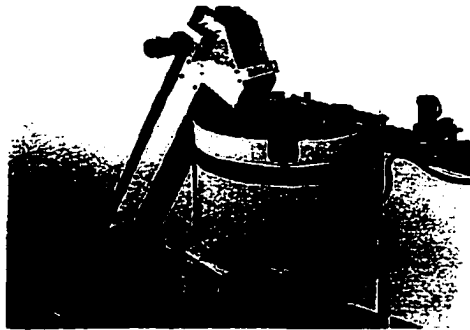
- **Capacity : 6000lbs**
- **Max. outer diameter : 120"**



- Top plate thickness : 1"
- Length of under driving : 14"
- Length of external driving : 10"
- Drive chain : RC80
- Speed : 30fpm

**Approximate Price : \$7,000**

#### **4. Feeder**



- Overall height : 100"
- Discharge height : 35"
- Overall length : 198"
- Overall width : 105"
- Capacity : 50lbs

**Approximate Price : \$9,000**

#### **5. Load Balancer**

- Overall I-beam length : 80"
- Usable I-beam length : 70"

- Overall height : 96"
- Capacity : 350lbs

Approximate Price : \$870

### **MHE for Storage**

#### **\*AS/RS**

1. **Unit load AS/RS:** Pallets containing materials are stocked and retrieved by an automated S/R machine.



#### **\* S/R Machine**

- Capacity : 4500lbs
- S/R machine height : 60ft
- Horizontal speed : 600fpm
- Vertical speed: 250fpm
- Extractor speed : 200fpm
- Type of hoist : Chain rope
- Type of extractor : Dual telescoping forks
- Minimum aisle width available : 52"
- On-board controller : PLC(CLCV)
- Interface with control computer : Optical units

**Approximate Price : \$220,000**

**\* Rack**

- Available space : 200'L × 70'W × 68'H
- Number of cells : 350
- Type of pallet : Wood

**Approximate Price of Wood Pallet : \$30/pallet**

**Approximate Price of Rack : \$120/pp(pallet position)**

**\* AS/RS System Controller**

- CPU : IBM PC compatible / Window NT 4.0
- Diskette drive : 3.5", Zip drive
- Printer : Dot printer (10ppm)
- UPS : 3KVA/30min.
- Ports : 3 (one for Printer, one for host interface, and one for extra)
- Database : Oracle 8.0
- Barcode reader : Fixed scanner type
- Barcode printer : 8dots/min
- Load cell
- Communication with S/R machine : Optical Units
- Communication with Conveyor : PLC
- Communication with Host Computer : Ethernet with NetBios calls
- Communication with Printer : RS232
- Communication with barcode scanner : RS422
- Communication with AGV control computer : RS422

- **Communication with EMC control computer : RS422**
- **Sub Program required**
  - **Storage management module**
  - **Retrieval management module**
  - **Host interface (communication) module**
  - **Inventory management module**
  - **Report management module**
  - **Etc.**
- **Console room required**

**Approximate Price : \$60,000**

2. **Miniload AS/RS:** Bins containing materials are stocked and retrieved by an automated S/R machine.



**\* S/R Machine**

- **Capacity : 900lbs**
- **S/R machine height : 30ft**
- **Horizontal speed : 750fpm**
- **Vertical speed: 350fpm**
- **Extractor speed : 280fpm**
- **Type of hoist : Chain rope**
- **Type of extractor : Dual telescoping forks**
- **Minimum aisle width available : 35"**

- **On-board controller : PLC(CLCV)**
- **Interface with control computer : Optical units**

**Approximate Price : \$160,000**

**\* Rack**

- **Available space : 140'L × 40'W × 35'H**
- **Number of cells : 280**
- **Type of pallet : Wood**

**Approximate Price of Wood Pallet : \$27/pallet**

**Approximate Price of Rack : \$100/pp(pallet position)**

**\* AS/RS System Controller**

- **CPU : IBM PC compatible / Window NT 4.0**
- **Diskette drive : 3.5", Zip drive**
- **Printer : Dot printer (10ppm)**
- **UPS : 3KVA/30min.**
- **Ports : 3 (one for Printer, one for host interface, and one for extra)**
- **Database : Oracle 8.0**
- **Barcode reader : fixed scanner type**
- **Barcode printer : 8dots/min**
- **Load cell**
- **Communication with S/R machine : Optical Units**
- **Communication with Conveyor : PLC**
- **Communication with Host Computer : Ethernet with NetBios calls**
- **Communication with Printer : RS232**

- **Communication with barcode scanner : RS422**
- **Communication with AGV control computer : RS422**
- **Communication with EMC control computer : RS422**
- **Sub Program required**
  - **Storage management module**
  - **Retrieval management module**
  - **Host interface (communication) module**
  - **Inventory management module**
  - **Report management module**
  - **Etc.**
- **Console room required**

**Approximate Price : \$60,000**

3. **Carousel:** Materials are contained in tubs or shelves suspended in revolving carousels. This system saves aisle space and provides rapid access to materials.



- **Overall widths : 50, 64, 86, 100"**
- **Pan widths : 33, 48, 69, 89"**
- **Number of pan : Min. 800**
- **Max. overall height : 20'**
- **Pan capacity : 300lbs**
- **Machine capacity : 8000lbs**
- **Max. number of access windows : 2**

Approximate Price : \$75,000

**\* Rack system**

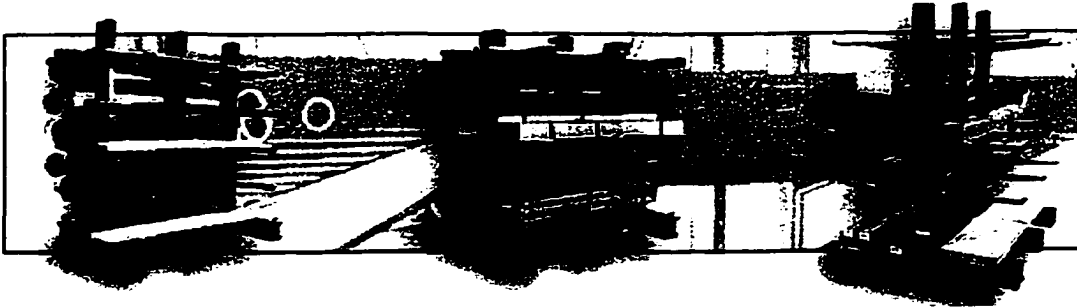
1. **Pallet Rack:** Pallets rest on front and rear horizontal ledges of rack structure, can be readily positioned or retrieved by forklift truck or other industrial vehicles have a fork.



- Upright frames : 20' tall x 4" deep C-channel structure
- Beam frames : 96" long x 3" tall C-channel structure
- Overall length : 40'
- Overall height : 20'
- Pallet : wood

Approximate Price : \$90/pp

2. **Cantilever:** It is used to store long, narrow items such as pipe and tubing.



- Roll formed columns : 12' tall single sided with base included
- Structure arms : 48" long cantilever arm
- Bracing between columns : 28" wide cantilever brace set
- Overall length : 40'
- Overall height : 20'

Approximate Price : \$140/pp

3. **Mobile Rack:** Racks can be moveable in horizontal direction.



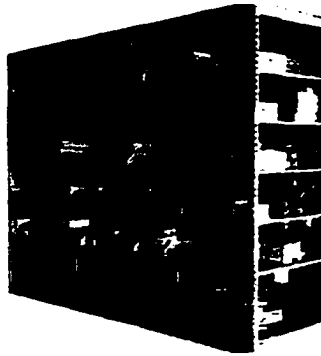
- Overall length : 30'
- Overall height : 15'
- Capacity : 1ton



- Operation : Mechanical type

Approximate Price : \$180/pp

4. **Mini Rack:** Small size of pallets rest on front and rear horizontal ledges of rack structure, can be readily positioned or retrieved by forklift truck or other industrial vehicles have a fork.



- Upright frames : 10' tall × 22" deep C-channel structure
- Beam frames : 45" long × 1.3" tall C-channel structure
- Overall length : 35'
- Overall height : 14'
- Pallet : wood

Approximate Price : \$65/pp

## **APPENDIX B : LIST OF QUESTIONS**

### **Questions associated with general attributes**

1. Total numbers of material flow links required: The number of material flow links (material transportation activities) you are considering for MHE selection.
2. Budget : Total amount of budget available
3. Automation level: The overall level of automation of MHE to be operated in your facility or the desired level of automation for new MHE purchases. Options are
  - a. Manual: The MHE is operated manually
  - b. Semi-Programmable: A powered system in which there is no computer control from the host computer
  - c. Programmable: A powered, computer-controlled system
4. Host computer level: It is the level of the host computer of your company, which manages all activities of the company, including production scheduling, management of personnel, management of inventory, and accounting tasks. Options are
  - a. Low : Number of operations managed and controlled by the host computer is less than equal to 33%
  - b. Medium : Number of operations managed and controlled by the host computer is between 33% and 67%
  - c. High : Number of operations managed and controlled by the host computer is greater than 67%
5. Expected Production Trend: This is the trend of expected production quantity in near future based on the history of production of your company. Options are
  - a. Increasing : increasing less than 10% of current production quantity
  - b. Highly increasing : increasing more than 10% of current production quantity
  - c. Decreasing : decreasing less than 10% of current production quantity
  - d. Highly decreasing : decreasing more than 10% of current production quantity
  - e. Stable: no change

6. **Product mix:** It is the number of products being manufactured through the production line you are considering. Options are
  - a. High: more than 5
  - b. Medium: 2 to 5
  - c. Low: only 1
7. **Weights assigned to evaluation factors for MHS design:** It is the weighting values of the five factors needed for selection of MHE. You can specify the values based on your situation. And the summation of the values has to be 100 and all assigned values must be nonnegative. Options are
  - a. **To Economic Aspect (%):** How economical is the MHE? For that, purchase cost, operation cost, space cost, and interface cost are considered.
  - b. **To Applicability Aspect (%):** How well does the MHE meet the production requirements and the constraints of production environment specified by a user?
  - c. **To Adaptability & Integratability Aspect (%):** How easy can the MHE be modified to suit a new product or production environment and how well is the MHE readily integrated with existing MHE?
  - d. **To Maintenance & Safety Aspect (%):** How economical and safe is the MHE for maintenance and safety? For that, spare part supply, easiness of repair, safety device design, after service, and ergonomic design can be considered.
  - e. **To Other Aspect (%) :** How much acceptable is the MHE for the factors the user deems worthy of consideration such as noise, beauty, etc.?
8. **Operation time per day:**

**Questions associated with movement MHE attributes**

1. Operation type: It is the level of automation of the MHE you want. Options are
  - a. Manual: The MHE is operated manually
  - b. Semi-Programmable: A powered system in which there is no computer control from the host computer
  - c. Programmable: A powered, computer-controlled system
2. Width available for MHE move: Options are
  - a. Narrow: 5ft to 8ft
  - b. Medium: 8ft to 12ft
  - c. Wide: larger than 12ft
3. Quantity to be moved per day:
4. Type of unit load: Options are
  - a. In-Container: Unit load is maintained in container
  - b. On-Pallet: Unit load is maintained on pallet
  - c. Tote Box: Unit load is maintained in tote box
  - d. Barstock: Unit load is long
  - e. Bulk: Unit load is bulk type
5. Weight of unit load (lbs):
6. Length of unit load: Options are
  - a. Short: less than 1ft
  - b. Medium: 1ft to 3.28ft
  - c. Long: more than 3.28ft
7. Width of unit load (ft):
8. Height of unit load: Options are
  - a. Short: less than 1ft
  - b. Medium: 1ft to 3.28ft
  - c. Long: more than 3.28ft

9. Volume of unit load: Options are
  - a. Small: less than 1 cubic ft
  - b. Medium: 1 cubic ft to 35.28 cubic ft
  - c. Large: more than 35.28 cubic ft
10. Bottom surface: The bottom surface of unit load. Options are
  - a. Rigid:
  - b. Not-Rigid:
11. Type of move: The type of movement of the MHE. Options are
  - a. Horizontal (above floor):
  - b. Horizontal (Overhead):
  - c. Inclined:
  - d. Rotational:
12. Distance of move (ft):
13. Path of move: The moving path of MHE. Options are
  - a. Fixed: The moving path is fixed
  - b. Variable: The moving path is changeable
14. Floor surface: The condition of the floor surface. Options are
  - a. Clear:
  - b. Not Clear:
15. Speed of move (ft/min):
16. Pattern of move: The pattern of movement of MHE required. Options are
  - a. Continuous: MHE moves continuously
  - b. Intermittent: MHE does not move continuously
17. Truss height: Options are
  - a. Low: less than 13ft
  - b. High: more than 13ft
18. Available space for MHE move: Options are
  - a. Enough: Space is not very critical point
  - b. Not Enough: Space is very critical point

19. **Loading/Unloading speed required:** The speed required for loading the material from a workstation and unloading the material to a workstation. Options are
- a. **Slow:** The time for loading/unloading is not important. And less than 1 time/min
  - b. **Medium:** 1 time/min to 5 times/min
  - c. **Fast:** The time for loading/unloading is important. And more than 5 times/min
20. **Type of workstations associated with the move:** The format of workstations associated with this material flow link. Options are
- a. 1:1
  - b. 1:Several
  - c. Several:Several
  - d. several:1
21. **Direction of move:** The direction of MHE movement. Options are
- a. One-way
  - b. Two-way
22. **Type of MHE to be connected:** The type of MHE to be connected with this MHE to transfer unit loads. Options are
- a. **Manual MHE:** The MHE is operated manually
  - b. **Semi-Programmable MHE:** A powered system in which there is no computer control from the host computer
  - c. **Programmable MHE:** A powered, computer-controlled system
23. **Method of loading/unloading:** The method (level) of loading and unloading. Options are
- a. **Manual:** Manual or electricity is not needed
  - b. **Machine L/U:** Electricity is needed but not fully automated
  - c. **Programmable MHE:** Electricity is used and fully automated

**Questions associated with storage MHE attributes**

1. **Operation type:** It is the level of automation of the MHE you want. Options are
  - a. **Manual:** The MHE is operated manually
  - b. **Semi-Programmable:** A powered system in which there is no computer control from the host computer
  - c. **Programmable:** A powered, computer-controlled system
2. **Length of the available space for MHE (ft):**
3. **Width of the available space for MHE (ft):**
4. **Height of the available space for MHE (ft):**
5. **Available space for MHE is critical?:** If the MHE can occupy more space than the space you planned? Options are
  - a. **Yes:**
  - b. **No:**
6. **Quantity to be handled per day:** The number of unit loads to be transacted per day. Options are
  - a. **Small:** less than 30
  - b. **Medium:** 30 to 150
  - c. **Many:** more than 150
7. **Avg. quantity of unit loads to store:** The average number of units loads the MHE needs to store
8. **Type of unit load:** Options are
  - a. **In-Container:** Unit load is maintained in container
  - b. **On-Pallet:** Unit load is maintained on pallet
  - c. **Tote Box:** Unit load is maintained in tote box
  - d. **Barstock:** Unit load is long
  - e. **Bulk:** Unit load is bulk type
9. **Weight of unit load (lbs):**
10. **Length of unit load (ft):**
11. **Width of unit load (ft):**

12. Height of unit load (ft):
13. Volume of unit load: Options are
  - a. Small: less than 1 cubic ft
  - b. Medium: 1 cubic ft to 35.28 cubic ft
  - c. Large: more than 35.28 cubic ft
14. Transaction rate per hour(dual-cycle based): The total number of storage and retrieval activities per hour
15. Bottom surface: The bottom surface of unit load. Options are
  - a. Rigid:
  - b. Not-Rigid:
16. Transaction data treatment: The type of data treatment for storage and retrieval. Options are
  - a. Manual : No use of computer
  - b. Semi-Automatic: Used computer to update the inventory data
  - c. Automatic: Used of automatic data treatment instruments like bar code reader
17. Weight control needed: If the weight of unit load needs to be managed?. Options are
  - a. Yes: Load cell is needed
  - b. No: Load Cell is not needed
18. MHE type transporting into storage: The type of MHE that transports the loads to this storage MHE. Options are
  - a. Not decided:
  - b. Manual:
  - c. Industrial Truck:
  - d. AGV:
  - e. Monorail:
  - f. Conveyor:
  - g. Crane:
19. MHE type transporting out of storage: The type of MHE that transports the loads from this storage MHE to next workstation. Options are



- a. Not decided:
- b. Manual:
- c. Industrial Truck:
- d. AGV:
- e. Monorail:
- f. Conveyor:
- g. Crane:

### **Questions associated with positioning MHE attributes**

1. Operation type: It is the level of automation of the MHE you want. Options are
  - a. Manual: The MHE is operated manually
  - b. Semi-Programmable: A powered system in which there is no computer control from the host computer
  - c. Programmable: A powered, computer-controlled system
2. Quantity to be handled per day:
3. Type of unit load: Options are
  - a. In-Container: Unit load is maintained in container
  - b. On-Pallet: Unit load is maintained on pallet
  - c. Tote Box: Unit load is maintained in tote box
  - d. Barstock: Unit load is long
  - e. Bulk: Unit load is bulk type
4. Weight of unit load (lbs):
5. Volume of unit load: Options are
  - a. Small: less than 1 cubic ft
  - b. Medium: 1 cubic ft to 35.28 cubic ft
  - c. Large: more than 35.28 cubic ft

6. **Bottom surface:** The bottom surface of unit load. Options are
  - a. Flat:
  - b. Not Flat:
7. **Type of motion:** The type of motion of the MHE. Options are
  - a. Transferring:
  - b. Rotation:
  - c. Gripping:
  - d. feeding:
8. **Accuracy required:** Options are
  - a. Low: more than  $\pm 2\text{mm}$
  - b. Medium:  $\pm 2\text{mm}$  to  $\pm 1\text{mm}$
  - c. High: less than  $\pm 1\text{mm}$
9. **Frequency:** The frequency of positioning activity required by the MHE. Options are
  - a. Continuous: MHE moves continuously
  - b. Intermittent: MHE does not move continuously
10. **Treatment number required per hour:** The total number of positioning activities required by the MHE per hour

**APPENDIX C : FUZZY EVALUATION MATRICES FOR  
ALTERNATIVES**

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Gravity ball-top conveyor	0.6	1	0.6*/0.8**	0.7	0.6
Gravity wheel conveyor	0.7	0.8	0.5/0.8	0.7	0.5
Hand truck/cart	0.9	0.6	0.4/0.6	0.7	0.4
Hoist crane	0.6	0.5	0.4/0.6	0.5	0.4

\* When expected production trend is increasing or highly increasing

\*\* When expected production trend is decreasing or highly decreasing

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Gravity wheel conveyor	0.6	1	0.7*/0.8**	0.7	0.6
Hand truck/cart	0.8	0.8	0.5/0.8	0.7	0.5
Hoist crane	0.5	0.6	0.4/0.6	0.6	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Gravity roller conveyor	0.6	1	0.6*/0.8**	0.7	0.6
Hand truck/cart	0.8	0.7	0.5/0.8	0.6	0.5
Pallet jack	0.7	0.8	0.4/0.7	0.6	0.5
Hoist crane	0.5	0.6	0.4/0.5	0.5	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Gravity chute conveyor	0.7	1	0.6*/0.8**	0.7	0.6
Hoist crane	0.6	0.8	0.4/0.6	0.4	0.5
Counterbalanced lift truck	0.4	0.8	0.4/0.7	0.5	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Belt conveyor1	0.6	1	0.7*/0.7**	0.6	0.7
Pallet jack	0.8	0.7	0.4/0.6	0.7	0.5
Pallet truck	0.5	0.8	0.5/0.7	0.7	0.5
Hoist crane	0.6	0.8	0.4/0.6	0.5	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Roller conveyor1	0.7	1	0.7*/0.7**	0.6	0.7
Pallet truck	0.7	0.7	0.5/0.7	0.7	0.5
Counterbalanced lift truck	0.5	0.8	0.4/0.7	0.6	0.4
Hoist crane	0.6	0.6	0.4/0.6	0.5	0.5

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Roller conveyor2	0.6	1	0.7*/0.8**	0.6	0.6
Wheel conveyor	0.7	1	0.7/0.8	0.5	0.5
Gantry crane	0.5	0.5	0.4/0.8	0.4	0.4
AGV	0.3	0.6	0.7/0.3	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Belt conveyor2	0.7	1	0.7*/0.8**	0.6	0.6
Counterbalanced lift truck	0.6	0.8	0.5/0.8	0.6	0.5
Gantry crane	0.5	0.8	0.4/0.7	0.4	0.4
AGV	0.3	0.8	0.7/0.4	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Roller conveyor3	0.8	1	0.7*/0.7**	0.6	0.6
Chain conveyor	0.7	1	0.7/0.7	0.6	0.6
Bridge crane	0.2	0.4	0.4/0.7	0.4	0.5
AGV	0.4	0.5	0.6/0.4	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Slate conveyor1	0.7	1	0.7*/0.7**	0.7	0.6
Cart-on-track conveyor	0.8	1	0.7/0.7	0.7	0.6
Bridge crane	0.2	0.4	0.4/0.7	0.4	0.5
Counterbalanced lift truck	0.6	0.4	0.5/0.7	0.7	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Tow-line conveyor	0.7	1	0.6*/0.8**	0.7	0.6
Platform truck	0.8	0.8	0.5/0.8	0.6	0.5
Bridge crane	0.3	0.4	0.4/0.7	0.4	0.5

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Belt conveyor3	0.8	1	0.6*/0.8**	0.6	0.6
EMS	0.5	0.6	0.8/0.5	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Power and free conveyor	0.6	1	0.6*/0.8**	0.6	0.6
Trolley conveyor	0.8	0.8	0.6/0.8	0.5	0.6
EMS	0.4	0.6	0.8/0.4	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Trolley conveyor	0.8	1	0.6*/0.8**	0.5	0.6
Power and free conveyor	0.6	0.8	0.6/0.8	0.6	0.6
EMS	0.4	0.6	0.8/0.4	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Gravity chute conveyor2	0.8	1	0.6*/0.8**	0.6	0.6
Hoist crane	0.6	0.7	0.4/0.7	0.5	0.5
Counterbalanced lift truck	0.4	0.8	0.5/0.7	0.6	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
<b>Roller conveyor4</b>	0.7	1	0.6*/0.8**	0.7	0.6
<b>Gantry crane</b>	0.4	0.7	0.5/0.7	0.6	0.5
<b>Counterbalanced lift truck</b>	0.6	0.8	0.6/0.7	0.6	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
<b>Belt conveyor4</b>	0.5	1	0.6*/0.8**	0.6	0.6
<b>Pallet jack</b>	0.8	0.8	0.5/0.8	0.7	0.5
<b>Hoist crane</b>	0.6	0.8	0.5/0.7	0.5	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
<b>Slat conveyor2</b>	0.7	1	0.6*/0.8**	0.7	0.6
<b>Counterbalanced lift truck</b>	0.6	0.8	0.6/0.8	0.6	0.4
<b>Gantry crane</b>	0.4	0.7	0.5/0.7	0.5	0.5

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
<b>Carousel</b>	0.6	1	0.6*/0.6**	0.7	0.6
<b>Mini load AS/RS</b>	0.4	0.7	0.8/0.4	0.8	0.8
<b>Mini rack</b>	0.8	0.7	0.4/0.8	0.6	0.4

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Mini load AS/RS	0.4	1	0.8*/0.4**	0.7	0.8
Carousel	0.6	0.8	0.6/0.5	0.6	0.7
Mini rack	0.8	0.5	0.4/0.7	0.4	0.4
Mobile rack	0.6	0.8	0.6/0.5	0.6	0.7

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Unit load AS/RS	0.4	1	0.8*/0.4**	0.7	0.8
Pallet rack	0.8	0.6	0.4/0.8	0.4	0.4
Mobile rack	0.6	0.8	0.6/0.6	0.5	0.6

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Pallet rack	0.8	1	0.4*/0.8**	0.4	0.4
Unit load AS/RS	0.4	0.5	0.8/0.4	0.7	0.8
Mobile rack	0.6	0.8	0.6/0.6	0.5	0.6

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Mini rack	0.8	1	0.4*/0.8**	0.4	0.5
Mini load AS/RS	0.4	0.4	0.8/0.4	0.7	0.8
Carousel	0.5	0.8	0.6/0.6	0.6	0.7
Mobile rack	0.6	0.8	0.6/0.6	0.5	0.6



	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Mobile rack	0.6	1	0.7*/0.6**	0.6	0.7
Mini rack	0.8	0.6	0.4/0.8	0.5	0.5
Carousel	0.6	0.8	0.7/0.6	0.6	0.7
Mini load AS/RS	0.4	0.7	0.8/0.4	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Magnetic paint guided AGV	0.4	1	0.8*/0.4**	0.7	0.8
Gantry crane	0.6	0.4	0.4/0.7	0.4	0.4
EMS	0.5	0.7	0.7/0.5	0.6	0.8
Roller conveyor	0.8	0.6	0.5/0.8	0.5	0.6

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Electric wire guided AGV	0.4	1	0.8*/0.4**	0.7	0.8
Gantry crane	0.6	0.6	0.4/0.7	0.4	0.4
EMS	0.5	0.8	0.7/0.5	0.6	0.8
Roller conveyor	0.8	0.7	0.5/0.8	0.5	0.6

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Laser guided AGV	0.4	1	0.8*/0.4**	0.7	0.8
Gantry crane	0.6	0.6	0.4/0.7	0.4	0.4
EMS	0.5	0.8	0.7/0.5	0.6	0.8
Roller conveyor	0.8	0.7	0.5/0.8	0.5	0.6

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Pallet jack	0.8	1	0.5*/0.7**	0.7	0.5
Hoist crane	0.6	0.7	0.5/0.7	0.5	0.4
Roller conveyor	0.5	0.8	0.7/0.5	0.6	0.7

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Hand truck/cart	0.8	1	0.5*/0.7**	0.7	0.5
Hoist crane	0.6	0.7	0.5/0.7	0.5	0.4
Roller conveyor	0.5	0.8	0.7/0.5	0.6	0.7

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Pallet truck	0.8	1	0.5*/0.7**	0.6	0.5
Counterbalanced lift truck	0.6	0.8	0.5/0.8	0.5	0.4
Slat conveyor	0.6	0.6	0.6/0.7	0.6	0.6
AGV	0.4	0.4	0.8/0.4	0.8	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Truck trailer	0.8	1	0.6*/0.7**	0.7	0.5
Gantry crane	0.7	0.7	0.5/0.6	0.5	0.4
Slat conveyor	0.5	0.8	0.7/0.5	0.6	0.6

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Platform truck	0.7	1	0.5*/0.7**	0.7	0.5
Slat conveyor	0.7	0.7	0.7/0.5	0.6	0.6
Bridge crane	0.3	0.7	0.4/0.7	0.4	0.5

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Bridge crane	0.3	1	0.5*/0.7**	0.4	0.6
Slat conveyor	0.6	0.7	0.6/0.6	0.6	0.7
Platform truck	0.7	0.6	0.6/0.7	0.6	0.5

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Gantry crane	0.6	1	0.6*/0.7**	0.5	0.5
Roller conveyor	0.7	0.7	0.6/0.7	0.6	0.6
Pallet truck	0.8	0.8	0.5/0.6	0.6	0.5
AGV	0.4	0.4	0.8/0.4	0.7	0.8

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
Hoist crane	0.6	1	0.5*/0.7**	0.6	0.4
Roller conveyor	0.5	0.7	0.7/0.6	0.7	0.6
Pallet jack	0.8	0.7	0.4/0.7	0.7	0.5

	$E_{ij}$	$A_{ij}$	$V_{ij}$	$M_{ij}$	$Q_{ij}$
EMS	0.6	1	0.8*/0.6**	0.7	0.7
AGV	0.4	0.8	0.7/0.5	0.7	0.8
Trolley conveyer	0.8	0.7	0.4/0.7	0.6	0.5
Gantry crane	0.6	0.6	0.4/0.7	0.5	0.4

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*“ The LORD is my shepherd, I shall not want. ... Surely goodness and lovingkindness will follow me all the days of my life, and I will dwell in the house of the LORD forever. ”*

*Psalm 23*