

# A Web-based Analysis and Design System for Automated Material Handling Equipment Applications

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## 웹 기반의 자동물류설비 운영을 위한 분석 및 설계 시스템에 관한 연구

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This paper describes a web-based system called DESIGNER for the analysis and design for automated material handling equipment(MHE) applications in manufacturing. DESIGNER models the processes for system integration, economic analysis, performance analysis, and automated storage/retrieval system(AS/RS) design. Based on the information specified by users, the various analysis modules are invoked to meet the needs of the material handling applications. The results of the analyses provide system users with useful data for material handling system design and decision on investment in automated MHE. Example problems are also presented to demonstrate the use of the system.

**Keywords:** automated MHE, system integration, cost-estimation functions, hybrid AI approach

### 1. Introduction

Designing a material handling system usually involves selection of material handling equipment(MHE) and assignment of the MHE to material flow links. This is a complex task because there are many factors that need to be considered and there are no unique rules to be followed for achieving a successful material handling system. Therefore, material handling system design is one of the manufacturing functions that have been the focus of attention for many researchers(e.g. Chan, 2002; Park, 1996; Welgama and Gibson, 1995 and 1996; Chu *et al.*, 1995; Kim and Eom, 1997; Gabbert and Brown, 1989; Fisher and

Farber, 1988; Heragu, 1997; Mohsen, 1985; Lashkari *et al.*, 2004). Chan(2002) integrated an expert system with an analytic hierarchy approach(AHP) for the selection of MHE for material transport and storage in a facility. Park(1996) introduced an intelligent consultant system called ICMESSE for MHE selection and evaluation. Welgama and Gibson(1995 & 1996) combined expert system and optimization algorithm to solve the MHE selection problem. A knowledge- based system and with an AHP were used in choosing the MHE. Chu, Egbelu, and Wu(1995) developed a computer-aided MHE selection system to automate the equipment selection process. An economic analysis was included in the decision making process. Kim and Eom(1997)

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developed a MHE selection expert system for electronic assembly. Gabbert and Brown(1989) introduced a knowledge-based design approach to combine expert system and decision methodology. Fisher and Farber(1988) presented a knowledge-based approach for the selection of MHE to be used in transporting unit loads between facilities. Heragu(1997) introduced a deterministic optimization model to help material-handling designers select the required MHE. Mohsen(1985) formulated the selection problem as a mix integer program with the objective of minimizing the total operating and purchasing costs of the selected MHE. Lashkari (2004) proposed an integrated approach to operation allocation and material handling systems selection in cellular manufacturing systems.

However very little attention has been paid for the selection and evaluation of automated MHE-centered in the set of work reported above. There are no reports of the deployment of such automated MHE analysis systems or platforms on the Internet to make it widely accessible to potential users as well. The use of automated MHE such as automated guided vehicle(AGV), monorail system, and automated storage/retrieval system(AS/RS) in factory environments is on the increase and is projected to increase dramatically in the next decade. Accordingly, for the automated MHE applications, the analysis and design stages can be important steps and have to be performed to get more practical material handling system designs.

With more manufacturing industries switching to computer-based manufacturing, the focus is on the integration of material handling systems with computer control and high levels of automation (Chan, 2002). The basic functions of automated material handling in manufacturing are movement, storage, and positioning. In each of those areas, the uses of computer technology and information systems have become common. Especially, the design of system integration for data transfer between automated MHE control system, sub-devices, and host systems is an essential and important task.

This paper presents a web-based system called DESIGNER for the analyses for automated MHE applications in manufacturing. The system provides analysis and design modules including system integration & specification, economic analysis, performance analysis, and automated

storage/retrieval system(AS/RS) design. Benefits from the system include savings in total time required to accomplish the analysis processes for automated MHE and reduction in equipment analysis error. The system also provides a useful guide for the non-experienced users by automating the analysis processes on the web. The following section illustrates the system architecture and the attributes to be specified by users. This is followed by descriptions of analysis and design modules.

## 2. System Architecture and Attributes

### 2.1 System Architecture

The consultation system provided in this paper for automated MHE analyses for a production shop is termed DESIGNER. DESIGNER is composed of GUI & consultation driver, database, and five analysis and design modules. The overall system structure is as depicted in <Figure 1>. DESIGNER is written using ASP, Java Script, and MS SQL. A database is constructed to store the lists of commercial models of automated MHE types with specifications and possible system configurations. The GUI and consultation driver includes sub modules for user input and system output. The module for user input provides the interface between system and user. The system output includes economic analysis, performance analysis, commercial model and specification, system integration guides, and AS/RS design if an AS/RS is requested.

System integration module searches a most suitable automated MHE model and provides information on the system configuration for each automated MHE application. The system configuration contains information on system integration of automated MHE, MHE control computer, host computer, and other equipment such as conveyors. The module for specification suggests commercial models of automated MHE types with their specifications. The economic analysis module provides economic information that allows users to estimate the approximate cost of the MHE. The module for performance analysis calculates several performance indicators or values such as the utilization of the MHE. The AS/RS design module provides design data associated with the

design of an AS/RS-such output data include the number of S/R machines needed and all three dimensions of the physical storage space.

### 2.2 Automated MHE Types and Attributes

The population and makes of automated MHE are ever changing. While some are standard equipment and are widely known, others are simply customized for specific applications and discarded after use. Therefore constructing a database that includes all types of automated MHE is not feasible. The system considers a total of 15 types of automated MHE and a total of 151 commercial models of the types of automated MHE are surveyed(Kulweic, 1980 and 1985; Plant Engineering Reprint Series; MHE catalogs; <http://www.mhia.org/>). The 15 equipment types and the commercial models of the MHE types together constitute the basic database of the MHE used by DESIGNER. Based on the needs of a specific design situation, the expansion capability allows a user to include other types of equipment not presently represented in the system, if such additional equipment is deemed necessary for the particular design scenario under consideration. <Table 1> shows the list of automated MHE types identified from a survey.

In the design of the system, key attributes of the automated MHE types were identified and included. The same primary group of automated MHE is distinguished from one another by their key attributes. The main functions of the automated MHE considered in this research are movement and storage. The attributes and their values are summarized in <Table 2> and <Table 3>.

Table 1. Automated MHE types used

AGV	low-lift AGV, high-lift AGV, roller deck AGV, stationary deck AGV, lift deck AGV, tugged AGV, fork AGV (Groups: magnetic paint guidance laser beam guidance electric wire guidance )
Monorail	EMS(electrically powered monorail system), PMS(pneumatically powered monorail system)
AS/RS	unitload AS/RS, miniload AS/RS, longload AS/RS, man-on-board AS/RS, deep-lane AS/RS, carousel

Table 2. Attributes of the transport equipment

Attributes		
Material	Move	Operation
<i>Unit load type</i>	<i>Move type</i>	<i>Path-following method</i>
in-container	on floor	magnetic paint
on-pallet	overhead	laser beam
individual		electric wire
toto box	<i>Space</i>	
bulk	linear	<i>Positional accuracy</i>
barstock	two dimensional	low
	three dimensional	medium
		high
<i>Unit weight</i>	<i>Driving speed</i>	<i>Preceding MHE</i>
light	slow	AS/RS
medium	medium	conveyor
heavy	fast	storage rack
		crane
<i>Unit load volume</i>	<i>Path</i>	<i>Subsequent MHE</i>
small	fixed	AS/RS
medium	variable	conveyor
large		storage rack
		crane
<i>Total quantity</i>	<i>Frequency</i>	
low	continuous	
medium	intermittent	
high		
	<i>Distant</i>	<i>Turning radius</i>
	short	small
	medium	medium
	long	large
		<i>Aisle width</i>
		narrow
		medium
		wide

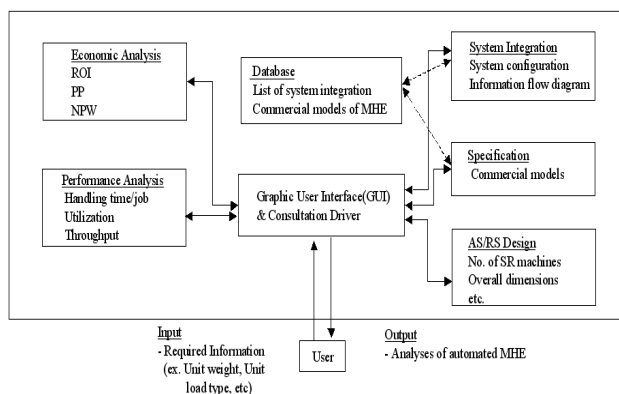


Figure 1. System configuration.

Table 3. Attributes of the storage equipment

Attributes		
Material	Storage & Retrieval	Operation
<i>Unit load type</i> on-pallet bins cylinder barstock package	<i>Retrieval rule</i> LIFO FIFO random access	<i>Level of automation</i> low medium high
	<i>Equipment</i> S/R machine fork lift cassette	<i>Preceding MHE</i> AGV monorail lift truck crane
<i>Unit weight</i> light medium heavy	<i>Density</i> low medium high	<i>Subsequent MHE</i> AGV monorail lift truck crane
		<i>Truss height</i> short medium high
<i>Unit load volume</i> small medium large		<i>Aisle width</i> narrow medium wide

### 3. Analyse and design modules

#### 3.1 System Integration & Specification

In this paper, a hybrid AI problem-solving (object-oriented and knowledge-based) approach is used for the selection of a suitable automated MHE model and the design of system integration between the automated MHE and other systems.

##### 3.1.1 Object-oriented knowledge representation and database

The object-oriented paradigm is used for representation of the hierarchy of automated MHE which is integral parts of the domain knowledge base. A hierarchical representation of objects has been developed in three levels: abstract, classification, and instance. <Figure 2> shows object classes as an example and illustrates small parts of the specialization hierarchy and compositional hierarchy of automated MHE. The top level of the objects represents an ‘automated material handling entity’ object class. This object class has function and move type methods as shown in <Figure 2>. For example, if a user specifies

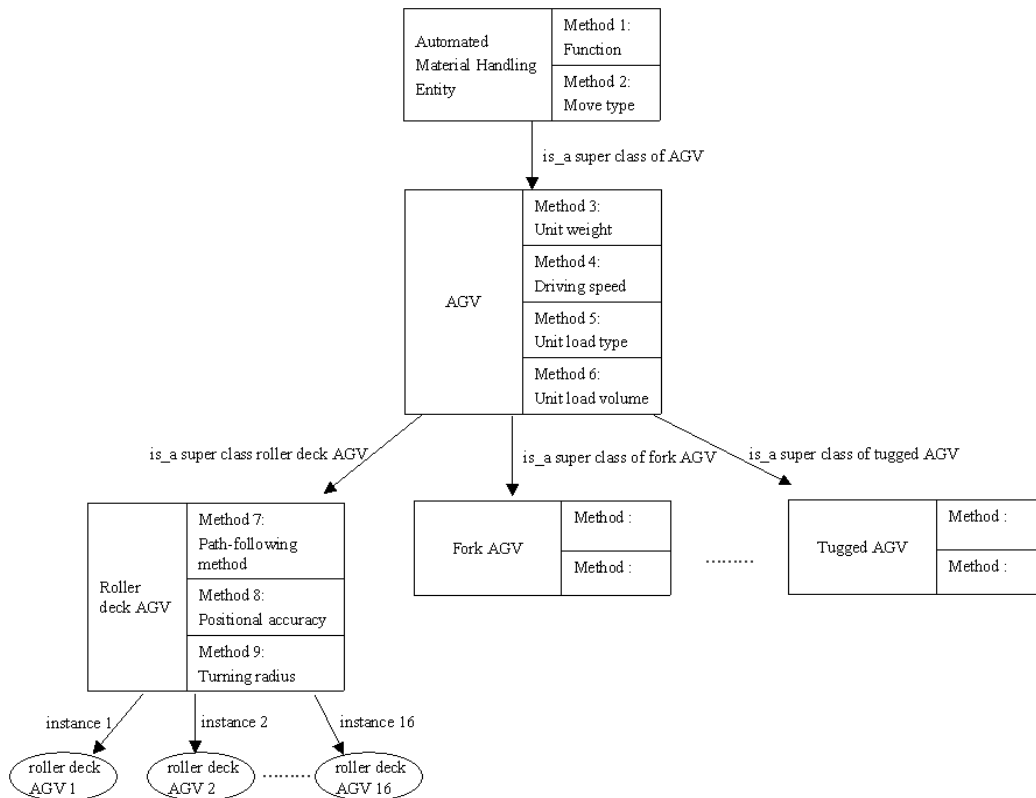


Figure 2. Specialization and compositional hierarchy of automated MHE.

automated MHE for 'movement' and 'on floor', AGV will be selected as next level object. This type of the decision chain or search tree method is described in the previous works (Park, 1996; Matson and Mellichamp, 1992; Chu *et al.*, 1995; Gabbert and Brown, 1989; Fisher and Farber, 1988). The second level represents an 'AGV' object class with additional methods such as unit weight, driving speed, unit load type, and unit load volume. The third level of the objects represents the object class for a specialized type of 'AGV' object, e.g., 'roller deck AGV' object. Since the 'roller deck AGV' instance is created as specialization of the object class 'AGV', it inherits all the attributes that apply to both 'automated material handling entity' and 'AGV'. Finally, the instances (commercial models) of 'roller deck AGV' such as 'roller deck AGV1', 'roller deck AGV2', and 'roller deck AGV16' can also be created in the same way as 'roller deck AGV'.

All information belonging to an object for design of system integration and generation of specifications is stored in the database. The information is largely divided into two categories such as for system integration and for equipment specification.

The major sources from which the database was compiled are MHE catalogs (<http://www.mhia.org/>) and the magazines related to material handling (Modern Material Handling, Plant Engineering Reprint Series). Many automated MHE applications and references in action are also surveyed (e.g. Hyundai heavy industries Co., Samsung electro-mechanics Co., etc), especially for the design of system integration. For example, a total of 16 commercial models were considered as instances of 'roller deck AGV' and a total of 13 system integration cases using the AGV are referred in the database.

### 3.1.2 Sample consultation

A user can apply DESIGNER for an application of automated MHE for movement by providing a response to the following questions. It then matches its knowledge to the specific values of the methods and informs the user of the specialized type of automated MHE.

- function of the MHE : movement
- move type : on floor
- unit weight : heavy

- driving speed : medium
- unit load type : on-pallet
- unit load volume : medium

Let's assume the suggested third level of the object in the specialization hierarchy is 'roller deck AGV'. The following is a part of the questions posed to the user for the design of system configuration and the generation of equipment specification with a commercial model. DESIGNER allows the user to specify a confidence value between 0% and 100% depending on the user's judgement that accounts for a varying level of certainty for the response. The closer the confidence value is to 100%, the higher is the indicating that the response to the question is more certain, whereas a confidence value of 50% represents a crossover point. The confidence value for the final recommendation is calculated as the total confidence values for responses divided by the total number of responses.

- SFC (shop floor control) system : MES (100%)
- any automated MHE #1 to be integrated & no. of the MHE: AS/RS (100%), 1
- type of preceding MHE : roller conveyor (100%)
- type of subsequent MHE : roller conveyor (100%)
- communication with SFC system : ethernet (100%)
- .....
- path : variable (50%)
- path-following method : laser beam guided (50%)
- positional accuracy :  $\pm 0.39'$  (90%)
- turning radius : 6-8' (100%)
- load transferring equipment : roller conveyor (100%)
- weight control necessity : yes (100%)

DESIGNER retrieves all possible commercial models of 'roller deck AGV' from the database and choose the most favorable model (e.g., Murata RAV1-X with certainty of 90%) along with specifications by using the user's response data about the critical features and comparisons. According to the above information, this application consists of an MES as the shop floor control system, an AS/RS control system, an AGV control system, and sub controllers for auxiliary MHE such as roller conveyors. Generally, the MES computer generates the job

schedules, material movement routes, order picking lists, and material retrieval & storage orders. <Figure 3> illustrates a possible system configuration when AS/RS and AGV are interconnected for material flow links. The recommended configuration of DESIGNER is dependent on cases and user's requirements and responses to the queries. A total of 153 rules for system configuration are stored in the knowledge base. An example of the corresponding rule is represented as follows:

IF : suggested automated MHE is roller deck AGV and  
 SFC system is available and  
 any automated MHE #1 to be integrated is AS/RS and  
 numbers of the MHE is 1 and  
 any other automated MHE to be integrated is not available and  
 communication with SFC system is ethernet and  
 weight control necessity is yes

THEN : {recommended\_system-integration-no = '35'}

In this case, the MES computer is connected to the AS/RS control computer and this computer, in turn, is connected to the AGV control computer. The AS/RS control computer manages the S/R(storage and retrieval) machine and input/output conveyors. This computer also downloads the orders of the AGV operation to the AGV control computer. The AS/RS control computer uploads the inventory data files to the MES computer and this host computer downloads the job schedule files, material order files, and material route files to the AS/RS control computer. The management program of AS/RS control computer usually consists of sub-modules, namely, order management, job status, data management, data status, and others. Radio frequency or optical data can be used for communication between the AS/RS control computer and the AGV, and between the AS/RS control computer and the S/R machine. Examples of system integration guide and equipment specification provided on DESIGNER are shown in <Figure 4> and <Figure 5>, respectively.

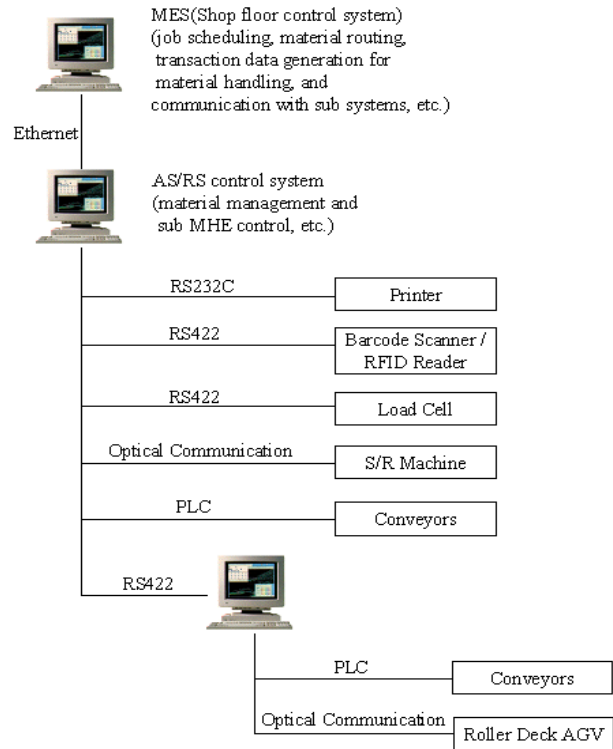


Figure 3. System integration of a material handling system.

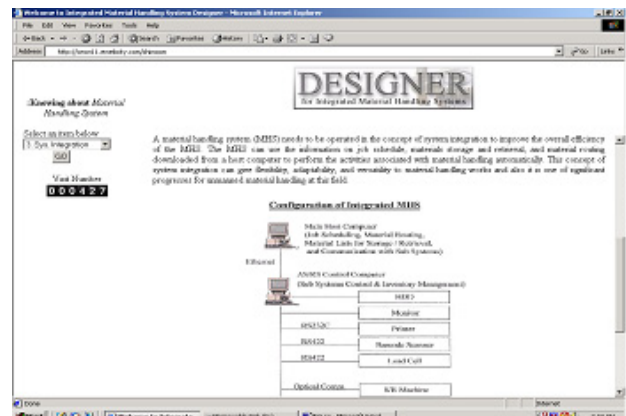


Figure 4. Example of system integration guide on DESIGNER.



Figure 5. Example of equipment specification on DESIGNER.

### 3.2 Economic Analysis

#### 3.2.1 Cost-estimation functions

One of the important objectives of any automated MHE application is to minimize the equipment costs such as purchase cost, operating cost, and depreciation cost. To satisfy the objective of the task, accurate cost-estimation functions are needed. However, these cost elements are situation specific, thus, it is not easy to develop a general cost model for MHE applications. For example, most of MHE have options that might decrease potential accidents and its impact on the total cost model should be considered to be more practical. Therefore, the proposed cost-estimation functions in this paper do not consider the cost of borrowing funds, discount, depreciation cost, equipment unavailability, name brands, and special options which are situation specific. The major sources investigated to develop the cost-estimation functions were the MHE vendor's guides(<http://www.mhia.org/>) and magazines(Modern Material Handling, Plant Engineering Reprint Series). Several automated MHE applications and references in action were also surveyed(e.g., Hyundai heavy industries Co., Samsung electro-mechanics Co., etc.).

#### Purchase cost

The purchase cost of automated MHE is dependent on several factors. Such factors include the rated load carrying capacity, move distance, rated maximum travel speed, name brands, and built-in technology. Also installation cost and maintenance cost are needed to be considered in a real world. In this model, name brands are not considered. For automated estimation of purchase costs, the models assumed that the cost components that make up the total cost vary linearly according to the levels of the factors that contribute to the total cost. Based on this assumption, then the purchase cost  $PC_{ij}$  of automated MHE  $j$  for move  $i$  can be summarized as shown in <Table 4>.

For AGV, the purchase cost can vary based on AGV type, guidance way, and load-carrying capacity. The purchase cost is assumed to be linearly proportionate to the carrying capacity. The costs related to the guidance way such as path installation cost and guiding instrument cost need to be considered. The path installation cost

is also assumed to be linearly proportionate to the travelling distance of AGV. The guiding instrument is not necessary for monorail application so the cost of the guiding instrument for monorail,  $C_j^p$ , is not required for monorail. In addition, the costs of pallets, racks, S/R machines, control system, and interface with host computer systems for data communication, have to be considered for determining the purchase cost of an AS/RS. The purchase cost is assumed to be linearly proportionate to the carrying capacity, number of pallets, and number of pallet positions.

Key to <Table 4>:

- $C_j^b$  = basic fixed cost associated with MHE  $j$ .  
It includes initial installation charge and test cost
- $C_j^u$  = cost per unit load capacity of MHE  $j$
- $l_j$  = load carrying capacity of MHE  $j$
- $C_j^p$  = cost of the instrument for guiding MHE  $j$
- $C_j^d$  = guide path cost per unit distance for MHE  $j$
- $d_i$  = distance associated with move  $i$
- $C_j^{pt}$  = cost per pallet for MHE  $j$
- $p$  = total number of pallets
- $C_j^r$  = cost per pallet position(PP) for MHE  $j$
- $r$  = total number of pallet positions(PP)
- $C_j^{cs}$  = cost of control system including computer system and interface for MHE  $j$

Table 4. Purchase cost function

Equipment type	Purchase cost( $PC_{ij}$ ) expression
AGV	$C_j^b + C_j^p + C_j^d d_i + C_j^u l_j$
Monorail	$C_j^b + C_j^d d_i + C_j^u l_j$
AS/RS	$C_j^b + C_j^{pt} p + C_j^r r + C_j^u l_j + C_j^{cs}$

#### Operating cost

Usually energy, operators, maintenance, and spare parts contribute to the operation cost of MHE. Although, estimating these costs separately and precisely is difficult, in general, they tend to 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 and 1996). It is worth pointing out that they did not study the operation cost

for storage equipment such as AS/RS.

The estimate of the annual operating cost  $OC_{ij}$  of MHE j for move i is given by

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

where  $t_{ij}$  = annual operating time of MHE j for move i  
 $C_j$  = operating cost for MHE j per unit time

The expressions for annual operating costs of automated MHE j for move i,  $OC_{ij}$ , are summarized as shown in <Table 5>.

Table 5. Operating cost function

Equipment type	Annual operating cost( $OC_{ij}$ ) expression
AGV and Monorail	$\frac{2d_i V_i}{s_j} \times C_j$ The MHE is assumed to be returning empty to the home position.
AS/RS	$V_i (SC + 2PD) C_j$ : For single command cycle $\left(\frac{V_i}{2}\right)(DC + 4PD) C_j$ : For dual command cycle

Key to <Table 5>:

- $s_j$  = velocity of MHE j
- $V_i$  = flow-volume(jobs) per year associated with move i
- $d_i$  = distance associated with move i
- $SC$  = 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

For the annual operating time of MHE which belongs to the class of variable path equipment such as AGV and monorail, the loading/unloading time are not explicitly considered because the velocity of the MHE can be controlled to reflect the loading/unloading time. In addition, it assumes that a variable path MHE moving items from station i to j will return empty on its return trip from station j to i. The annual operating time of an AS/RS depends on its operation mode, namely, single versus dual command cycles and the transaction

volume. A single command cycle consists of either a storage or a retrieval task, but not both, whereas a dual command cycle involves a storage operation and a retrieval operation.

**Costs of space and interface**

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

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

where

- $R$  = annual rental cost per unit space
- $S_{ij}$  = space occupied by MHE j for move i

The expressions for  $SC_{ij}$  of various equipment are summarized as shown in <Table 6>.

Table 6. Space cost function

Equipment Type	Space cost( $SC_{ij}$ ) expression
AGV	$R^* K_j d_i^a$
Monorail	$R^{**} K_j d_i$
AS/RS	$R^{**} W_j L_j H_j$

- \* annual rental cost per two-dimensional unit space
- \*\* annual rental cost per three-dimensional unit space

Key to <Table 6>:

- $K_j$  = 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
- $W_j$  = overall width of AS/RS j including the width for S/R movement
- $L_j$  = overall length of AS/RS j
- $H_j$  = overall height of AS/RS j

Interface cost is incurred when additional devices are needed to transfer unit loads between MHE and 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 conveyor is required as interface equipment 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:

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

where

- $C_I^b$  = basic fixed cost of the interface equipment. It is assumed that this cost considers the effect of load, installation, operation, and maintenance.
- $C_I^u$  = cost per unit size 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

### 3.2.2 Economic criteria

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(refer to subsection 3.2.1).

For an example of costs and cash flow calculations, let's assume a miniload AS/RS is considered for material storage operations and the miniload AS/RS is expected to have a salvage value of 10% of the purchase cost at the end of the expected economic life of 7 years. Let's also say the expected annual saving is \$65,000 and applicable interest rate is 8%. In addition, let's assume <Table 7> shows the results of costs and savings calculated. Table 8 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),

Table 7. 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

payback period(PP), and present worth(PW). Equations 1 through 4 represent the computational expression for these measures.

Table 8. Cash flow results

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

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

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

$$\text{Alternative, ROI} = r = \frac{\sum_{t=0}^n f_t^*}{\sum_{t=0}^n f_t^{**}} \quad (2)$$

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

$$PP = \frac{\text{Investment cost}}{\text{Average annual cash flow}} \quad (3)$$

$$PW = \sum_{t=0}^n f_t (1+i^*)^{-t} \quad (4)$$

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 9>.

Table 9. Indexes of economic analysis

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

### 3.3 Performance Analysis

A number of different performance measures have been used in analyzing automated MHE operations. A performance measure may be defined as a value quantifying effectiveness of an MHE. In this research, three performance

measures that include MHE utilization, handling time per unit load, and throughput are employed.

For an example of the performance measures, let's assume a miniload AS/RS is considered for material storage operations. Let us say  $O_t$  (operation time of the MHE per day) = 8hr,  $N_w$  (number of working days per year) = 260days,  $N_{sr}$  (number of SR machines) = 1,  $V$  (flow-volume per year associated with the operations) = 26000,  $DC$  (the average dual command cycle time) = 2.7min, and  $PD$  (the required time to pick-up or deposit the unit load) = 0.5min. In general, the utilization  $U_{ij}$  of MHE  $j$  by the move or operation  $i$  can be expressed as:

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

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

Accordingly, the utilization of the miniload AS/RS is obtained as below:

Utilization

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

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:

$$\begin{aligned} &\text{Handling time per job} \\ &= \frac{\text{dual command cycle time}}{2} \\ &= \frac{DC + 4 \times PD}{2} = 2.35 \text{min} \end{aligned}$$

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:

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

### 3.4 AS/RS Design Analysis

To design an AS/RS system means determining all three dimensions of the physical storage space and total number of S/R 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 total storage requirement is 5,000 unit loads. Based on the above conditions, the number of S/R machines can be determined as follows:

For single cycle S/R machines:

$$\begin{aligned} \text{Number of S/R machines} &= \\ &= \frac{\text{throughput}}{(60 \text{min}/\text{single command cycle time}) \times \text{efficiency}} \end{aligned}$$

For dual cycle S/R machines:

$$\begin{aligned} \text{Number of S/R machines} &= \\ &= \frac{\text{throughput}}{(60 \text{min}/\text{dual command cycle time}) \times \text{efficiency}} \end{aligned}$$

The single command cycle time and dual command cycle time depend on the dimensions of the rack, the length of the aisle and the length-to-height ratio (Sule, 1994). For the initial design, a major manufacturer and system installer of AS/RS, Hyundai Elevator co., suggests using 1.7 min and 2.5 min for single command cycle time and dual command cycle time, respectively. Therefore, it is required to check more accurate estimates with the AS/RS manufacturer after the initial planning. Let's say the expected efficiency of AS/RS is 0.85. The numbers of single cycle S/R machines and dual cycle S/R machines

required to handle a throughput of 50 transactions per hour can be obtained respectively as follows:

For single cycle S/R machines:

$$\begin{aligned} \text{Number of SR machines} &= \frac{100}{\left(\frac{60}{1.7}\right) \times 0.85} \\ &= 3.33 \text{ or } 4(\text{round up}) \\ \text{Number of rows} &= 4 \times 2 = 8 \end{aligned}$$

For dual cycle S/R machines:

$$\begin{aligned} \text{Number of SR machines} &= \frac{50}{\left(\frac{60}{2.5}\right) \times 0.85} \\ &= 2.45 \text{ or } 3(\text{round up}) \\ \text{Number of rows} &= 3 \times 2 = 6 \end{aligned}$$

The numbers of stacks that can be accommodated with a 44-inch(3.67-foot) height unit load is(assuming for 6-inch clearance between stacks)  $\frac{60}{(3.67 + 0.5)} - 1 = 13.4$  or 13 unit loads(round down). Thus the number of bays required can be calculated as follows:

For single cycle S/R machines:

$$\begin{aligned} \text{Number of bays} &= \frac{500 \text{ unit loads}}{2 \times 4 \text{ machines} \times 13 \text{ unit load high}} \\ &= 48.1 \text{ or } 49(\text{round up}) \end{aligned}$$

For dual cycle S/R machines:

$$\begin{aligned} \text{Number of bays} &= \frac{500 \text{ unit loads}}{2 \times 3 \text{ machines} \times 13 \text{ unit load high}} \\ &= 64.1 \text{ or } 65(\text{round up}) \end{aligned}$$

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 S/R machines:

$$\begin{aligned} \text{Length of AS/RS} &= 3.7\text{feet} \times 49\text{bays} \\ &+ 25\text{feet}(\text{for S/R machine clearance}) \\ &= 206\text{feet} \end{aligned}$$

For dual cycle S/R machines:

$$\begin{aligned} \text{Length of AS/RS} &= 3.7\text{feet} \times 65\text{bays} \\ &+ 25\text{feet}(\text{for S/R machine clearance}) \\ &= 266\text{feet} \end{aligned}$$

Multiplying the aisle unit by the number of S/R machines gives the width of the AS/RS system. 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 S/R machines:

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

For dual cycle S/R machines:

$$\begin{aligned} \text{Width of AS/RS} &= 13\text{feet} \times 3 \text{ machines} \\ &= 39\text{feet} \end{aligned}$$

Accordingly, the physical storage space needed for the AS/RS operations is approximately as follows:

For single cycle S/R machines :  $52 \times 206 \times 60\text{feet}$   
For dual cycle S/R machines :  $39 \times 266 \times 60\text{feet}$

It is possible to obtain different dimensions for the storage facility by adjusting the height of the facility.

#### 4. Discussion & Conclusion

At present, relatively few expert systems for MHE evaluation and selection have been developed (Chan, 2002; Park, 1996; Chu *et al.*, 1995; Welgama, 1995; Fisher, 1988; Gabbert, 1989; Matson *et al.*, 1992). Some suppliers and industry associations provide online sites(www. mhia.org, www.mmh.com, www.grainger.com, etc.) that feature expert systems that assist material handling engineers in the evaluation and selection of MHE. At this point, a natural question to ask is how similar or different is DESIGNER from these other known automated material handling systems design platforms that have been developed in the past? <Table 10> shows examples of results provided by the systems.

As shown in <Table 10>, DESIGNER has a more, wider scope and capabilities than most publicly reported material handling equipment selection platforms. Besides, its deployment on the Internet makes it accessible to users worldwide.

There are deterministic and stochastic models

Table 10. Output examples of the systems

	DESIGNER	MHESA <sup>1</sup>	ADVISOR <sup>2</sup>	Online tools <sup>3</sup>
Output Examples	MHE commercial model with specification, economic analysis, performance analysis, AS/RS design and numbers of MHE required, system integration and configuration, etc.	MHE : Roller Deck AGV - Speed : 60m/min - Capacity : 1000kg - Accuracy : ±5mm - Turning radius : 0.6m - Acceleration : 0.5m/s <sup>2</sup>	MHE :Industrial robot - PW : \$32960 - EUAC : \$16885 - ROI : 0.44years - PP : 1.82years	MHE : Slat Conveyor - Steel slat - 6" pitch steel bushed roller - Capacity :200lbs - App. Price : \$600/ft

1: MHESA(Material Handling Equipment Selection Advisor, Chan, 2002)

2: ADVISOR(A computer-aided material handling equipment selection system, Chu *et al.* 1995)

3: www.mhia.org, www.mmh.com, www.grainger.com, etc.

for determining the required number of automated MHE for movement like AGV and EMS to perform all necessary material moves. The problem with deterministic models assumes that all the information is known with certainty. However the material handling environment is highly stochastic so that the problem with stochastic models often overestimate or underestimate the required number of MHE because it is difficult to estimate the MHE congestion and empty travel times. In this research, a performance(work-volume) analysis with a deterministic model(i.e. the required information is known) is used to estimate the required number of MHE and performance measures including MHE utilization, handling time per unit load, and throughput.

In this article, a web-based intelligent system called DESIGNER to support problem solving in analysis and design for automated MHE applications is presented. The system consists of four analysis and design modules including system integration & specification, economic analysis, performance analysis, and AS/RS design. DESIGNER will be a useful design tool for material handling system designer, especially for those who are not familiar with automated MHE, and enrich existing design process with more intelligent abilities.

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