CHAPTER 1

MATERIALS HANDLING SYSTEM DESIGN

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1 INTRODUCTION[1]

Material handling systems consist of discrete or continuous resources to move entities from one location to another. They are more common in manufacturing systems compared to service systems. Material movement occurs everywhere in a factory or warehouse—before, during, and after processing. Apple (1977) notes that material handling can account for up to 80 percent of production activity. Although material movement does not add value in the manufacturing process, half of the company's operation costs are material handling costs (Meyers 1993).

[1] Many of the sections in this chapter have been reproduced from Chapter 11 of Heragu (2008), with permission.

Therefore, keeping the material handling activity at a minimum is very important for companies.

Due to the increasing demand for a high variety of products and shorter response times in today's manufacturing industry, there is a need for highly flexible and efficient material handling systems. In the design of a material handling system, facility layout, product routings, and material flow control must be considered. In addition, various other factors must be considered in an integrated manner. The next section describes the ten principles of material handling as developed by the Material Handling Industry of America (MHIA). It presents a guideline for selecting equipment, designing a layout, standardizing, managing, and controlling the material movement as well as the handling system. Another section describes the common types of material handling systems. This chapter also discusses types of equipment, how to select material handling equipment, an operating model for material handling, and warehousing issues. It ends with a case study that implements some of these issues.

2 TEN PRINCIPLES OF MATERIAL HANDLING

If material handling is designed properly, it provides an important support to the production process. Following is a list of ten principles as developed by the MHIA, which can be used as a guide for designing material handling systems.

2.1 Planning

A *plan* is a prescribed course of action that is defined in advance of implementation. In its simplest form, a material handing plan defines the material (what) and the moves (when and where); together, they define the method (how and who). Five key aspects must be considered in developing a plan:

1. The plan should be developed in consultation between the planner(s) and all who will use and benefit from the equipment to be employed.
2. Success in planning large-scale material handling projects generally requires a team approach involving suppliers, consultants when appropriate, and end-user specialists from management, engineering, computer and information systems, finance, and operations.
3. The material handling plan should reflect the strategic objectives of the organization, as well as the more immediate needs.
4. The plan should document existing methods and problems, physical and economic constraints, and future requirements and goals.
5. The plan should promote concurrent engineering of product, process design, process layout, and material handling methods, as opposed to independent and sequential design practices.

2.2 Standardization

Material handling methods, equipment, controls, and software should be standardized within the limits of achieving overall performance objectives and without sacrificing needed flexibility, modularity, and throughput. Standardization means less variety and customization in the methods and equipment employed. There are three key aspects of achieving standardization:

1. The planner should select methods and equipment that can perform a variety of tasks under a variety of operating conditions and in anticipation of changing future requirements.
2. Standardization applies to sizes of containers and other load-forming components, as well as operating procedures and equipment.
3. Standardization, flexibility, and modularity must not be incompatible.

2.3 Work

The measure of work is material handling flow (volume, weight, or count per unit of time) multiplied by the distance moved. Material handling work should be minimized without sacrificing productivity or the level of service required of the operation. Five key points are important in optimizing the work:

1. Simplifying processes by reducing, combining, shortening, or eliminating unnecessary moves will reduce work.
2. Consider each pickup and set-down—that is, placing material in and out of storage—as distinct moves and components of the distance moved.
3. Process methods, operation sequences, and process/equipment layouts should be prepared that support the work minimization objective.
4. Where possible, gravity should be used to move materials or to assist in their movement while respecting consideration of safety and the potential for product damage (see Figure 1.1).
5. The shortest distance between two points is a straight line.

2.4 Ergonomics

Ergonomics is the science that seeks to adapt work or working conditions to suit the abilities of the worker. Human capabilities and limitations must be recognized and respected in the design of material handling tasks and equipment to ensure safe and effective operations. There are two key points in the ergonomic principles:

1. Equipment should be selected that eliminates repetitive and strenuous manual labor and that effectively interacts with human operators and users. The ergonomic principle embraces both physical and mental tasks.

Figure 1.1 Gravity Roller Conveyor (Source: Courtesy of Pentek)

2. The material handling workplace and the equipment employed to assist in that work must be designed so they are safe for people.

2.5 Unit Load

A unit load is one that can be stored or moved as a single entity at one time, such as a pallet, container, or tote, regardless of the number of individual items that make up the load. Unit loads shall be appropriately sized and configured in a way that achieves the material flow and inventory objectives at each stage in the supply chain. When unit load is used in material flow, six key aspects deserve attention:

1. Less effort and work are required to collect and move many individual items as a single load than to move many items one at a time.
2. Load size and composition may change as material and products move through stages of manufacturing and the resulting distribution channels.
3. Large unit loads are common both pre- and postmanufacturing in the form of raw materials and finished goods.
4. During manufacturing, smaller unit loads, including as few as one item, yield less in-process inventory and shorter item throughput times.
5. Smaller unit loads are consistent with manufacturing strategies that embrace operating objectives such as flexibility, continuous flow, and just-in-time delivery.

6. Unit loads composed of a mix of different items are consistent with just-in-time and/or customized supply strategies as long as item selectivity is not compromised.

2.6 Space Utilization

Space in material handling is three-dimensional and therefore is counted as cubic space. Effective and efficient use must be made of all available space. This is a three-step process:

1. Eliminate cluttered and unorganized spaces and blocked aisles in work areas (see Figure 1.2).
2. In storage areas, balance the objective of maximizing storage density against accessibility and selectivity. If items are going to be in the warehouse for a long time, storage density is an important consideration. Avoid honeycombing loss (Figure 1.3). If items enter and leave the warehouse frequently, their accessibility and selectivity are important. If the storage density is too high to access or select the stored product, high storage density may not be beneficial.
3. Consider the use of overhead space when transporting loads within a facility. Cube per order index (COI) storage policy is often used in a warehouse. COI is a storage policy in which each item is allocated warehouse space based on the ratio of its storage space requirements (its cube) to the number of storage/retrieval transactions for that item. Items are listed in a nondecreasing order of their COI ratios. The first item in the list is allocated to the required number of storage spaces that are closest to the input/output (I/O) point; the second item is allocated to the required

Figure 1.2 Retrieving material in blocked aisles

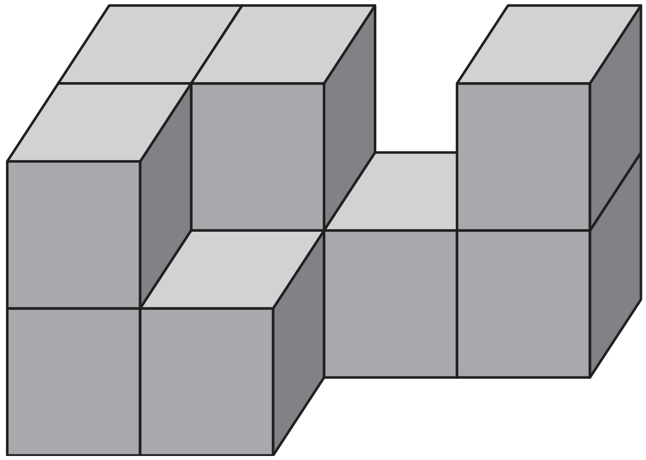

Figure 1.3 Honeycombing loss

number of storage spaces that are next closest to the I/O point, and so on. Figure 1.4 shows an interactive *playspace* in the "Ten principles of Materials Handling" CD that allows a learner to understand the fundamental concepts of the COI policy.

2.7 System

A *system* is a collection of interacting or interdependent entities that form a unified whole. Material movement and storage activities should be fully integrated to form a coordinated operational system that spans receiving, inspection, storage, production, assembly, packaging, unitizing, order selection, shipping, transportation, and the handling of returns. Here are five key aspects of the system principle:

1. Systems integration should encompass the entire supply chain, including reverse logistics. It should include suppliers, manufacturers, distributors, and customers.
2. Inventory levels should be minimized at all stages of production and distribution, while respecting considerations of process variability and customer service.
3. Information flow and physical material flow should be integrated and treated as concurrent activities.
4. Methods should be provided for easily identifying materials and products, for determining their location and status within facilities and within the supply chain, and for controlling their movement. For instance, bar coding is the traditional method used for product identification. Radio frequency identification (RFID) uses radio waves to automatically identify objects as

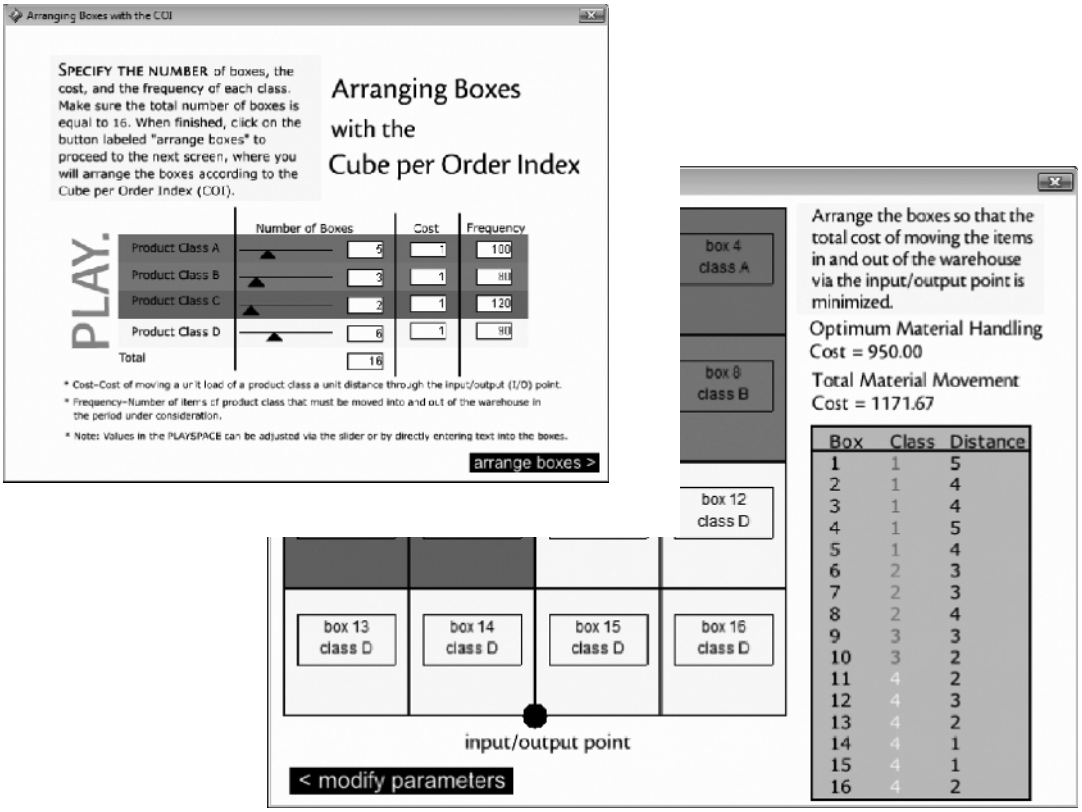

Figure 1.4 Example of COI policy

they move through the supply chain. The big difference between the two automatic data capture technologies is that bar coding is a line-of-sight technology. In other words, a scanner has to "see" the bar code to read it, which means people usually have to orient the bar code toward a scanner for it to be read. RFID tags can be read as long as they are within the range of a reader, even if there is no line of sight. Bar codes have other shortcomings, as well. If a label is ripped, soiled, or falls off, there is no way to scan the item. Also, standard bar codes identify only the manufacturer and product, not the unique item. The bar code on one gallon of 2 percent milk is the same as on every other gallon of the same brand, making it impossible to identify which one might pass its expiration date first. RFID can identify items individually.

5. Customer requirements and expectations regarding quantity, quality, and on-time delivery should be met without exception.

2.8 Automation

Automation is concerned with the application of electro-mechanical devices, electronics, and computer-based systems to operate and control production and service activities. It suggests the linking of multiple mechanical operations to create a system that can be controlled by programmed instructions. Material handling operations should be mechanized and/or automated where feasible to improve operational efficiency, increase responsiveness, improve consistency and predictability, decrease operating costs and eliminate repetitive or potentially unsafe manual labor. There are four key points in automation:

1. Preexisting processes and methods should be simplified and/or reengineered before any efforts at installing mechanized or automated systems.
2. Computerized material handling systems should be considered where appropriate for effective integration of material flow and information management.
3. All items expected to be handled automatically must have features that accommodate mechanized and automated handling.
4. All interface issues should be treated as critical to successful automation, including equipment to equipment, equipment to load, equipment to operator, and control communications.

2.9 Environment

Environmental consciousness stems from a desire not to waste natural resources and to predict and eliminate the possible negative effects of our daily actions on the environment. Environmental impact and energy consumption should be considered as criteria when designing or selecting alternative equipment and material handling systems. Here are the three key points:

1. Containers, pallets, and other products used to form and protect unit loads should be designed for reusability when possible and/or biodegradability as appropriate.
2. Systems design should accommodate the handling of spent dunnage, empty containers, and other byproducts of material handling.
3. Materials specified as hazardous have special needs with regard to spill protection, combustibility, and other risks.

2.10 Life Cycle

Life-cycle costs include all cash flows that will occur between the time the first dollar is spent to plan or procure a new piece of equipment, or to put in place a new method, until that method and/or equipment is totally replaced. A thorough economic analysis should account for the entire life cycle of all material handling equipment and resulting systems. There are four key aspects:

1. Life-cycle costs include capital investment, installation, setup and equipment programming, training, system testing and acceptance, operating (labor, utilities, etc.), maintenance and repair, reuse value, and ultimate disposal.
2. A plan for preventive and predictive maintenance should be prepared for the equipment, and the estimated cost of maintenance and spare parts should be included in the economic analysis.
3. A long-range plan for replacement of the equipment when it becomes obsolete should be prepared.
4. Although measurable cost is a primary factor, it is certainly not the only factor in selecting among alternatives. Other factors of a strategic nature to the organization that form the basis for competition in the marketplace should be considered and quantified whenever possible.

These ten principles are vital to material handling system design and operation. Most are qualitative in nature and require the industrial engineer to employ these principles when designing, analyzing, and operating material handling systems.

3 TYPES OF MATERIAL HANDLING EQUIPMENT

In this section, we list various equipments that actually transfer materials between the multiple stages of processing. There are a number of different types of material handling devices (MHDs), most of which move materials via material handling paths on the shop floor. However, there are some MHDs—such as cranes, hoists, and overhead conveyors—that utilize the space above the machines. The choice of a specific MHD depends on a number of factors, including cost, weight, size, and volume of the loads; space availability; and types of workstations. So, in some cases the MHS interacts with the other subsystems. If we isolate MHS from other subsystems, we might get an optimal solution relative to the MHDs but one that is suboptimal for the entire system.

There are seven basic types of MHDs (Heragu 2008): conveyors, palletizers, trucks, robots, automated guided vehicles, hoists cranes and jibs, and warehouse material handling devices. In this section, we will introduce the seven basic types of MHDs. In the following section, we will discuss how to choose the "right" equipment and how to operate equipment in the "right" way.

3.1 Conveyors

Conveyors are fixed-path MHDs. In other words, conveyors should be considered only when the volume of parts or material to be transported is large and when the transported material is relatively uniform in size and shape. Depending on the application, there are many types of conveyors—accumulation conveyor, belt conveyor, bucket conveyor, can conveyor, chain conveyor, chute conveyor, gravity conveyor, power and free conveyor, pneumatic or vacuum conveyor, roller conveyor, screw conveyor, slat conveyor, tow line conveyor, trolley conveyor, and wheel conveyor. Some are pictured in Figure 1.5. Our list is not meant to be complete, and other variations are possible. For example, belt conveyors may be classified as troughed belt conveyors (used for transporting bulky material such as coal) and magnetic belt conveyors (used for moving ferrous material against gravitational force). For the latest product information on conveyors and other types of material handling equipment, we strongly encourage the reader to refer to recent issues of *Material Handling Engineering* and *Modern*

(a)

Figure 1.5a Conveyors used in sortation applications (Source: Courtesy of Vanderlande Industries)

(b)

Figure 1.5b Accumulation conveyor (Source: Courtesy of Nike, Belgium)

(c)

Figure 1.5c Extendable dock conveyor (Source: Courtesy of DPD, Germany)

(d)

Figure 1.5d Belt conveyor (Source: Courtesy of FKI Logistex)

Materials Handling. These publications not only have articles illustrating use of the material handling equipment but also numerous product advertisements.

3.2 Palletizers

Palletizers are high-speed automated equipment used to palletize containers coming off production or assembly lines. With operator-friendly touch-screen controls, they palletize at the rate of a hundred cases per minute (see Figure 1.6), palletize two lines of cases simultaneously, or simultaneously handle multiple products.

(e)

Figure 1.5e Chute and tilt-tray conveyor (Source: Courtesy of Dematic Corp.)

(f)

Figure 1.5f Overhead conveyor used in automobile assembly plant (Source: Courtesy of Gould Communications)

3.3 Trucks

Trucks are particularly useful when the material moved varies frequently in size, shape, and weight, when the volume of the parts or material moved is low, and when the number of trips required for each part is relatively small. There are several trucks in the market with different weight, cost, functionality, and other features. Hand truck, fork lift truck, pallet truck, platform truck, counter-balanced truck, tractor-trailer truck, and automated guided vehicles (AGVs) are some examples of trucks (see Figure 1.7).

Figure 1.6 High-speed palletizer (Source: Courtesy of FKI Logistex)

3.4 Robots

Robots are programmable devices that resemble the human arm. They are also capable of moving like the human arm and can perform functions such as weld, pick and place, load and unload (see Figure 1.8). Some advantages of using a robot are that they can perform complex repetitive tasks automatically and they can work in hazardous and uncomfortable environments that a human operator cannot work. The disadvantage is that robots are relatively expensive.

3.5 Automated Guided Vehicles

AGVs have become very popular, especially in the past decade, and will continue to be the dominant type of MHD in the years to come. The first system was installed in 1953, and the technology continues to expand. AGVs can be regarded as a type of specially designed robots. Their paths can be controlled in a number of different ways. They can be fully automated or semiautomated. AGVs are becoming more flexible with a wider range of applications using more diverse vehicle types, load transfer techniques, guide path arrangements, controls, and control interfaces. They can also be embedded into other MHDs. A sample of AGVs and their applications are illustrated in Figure 1.9.

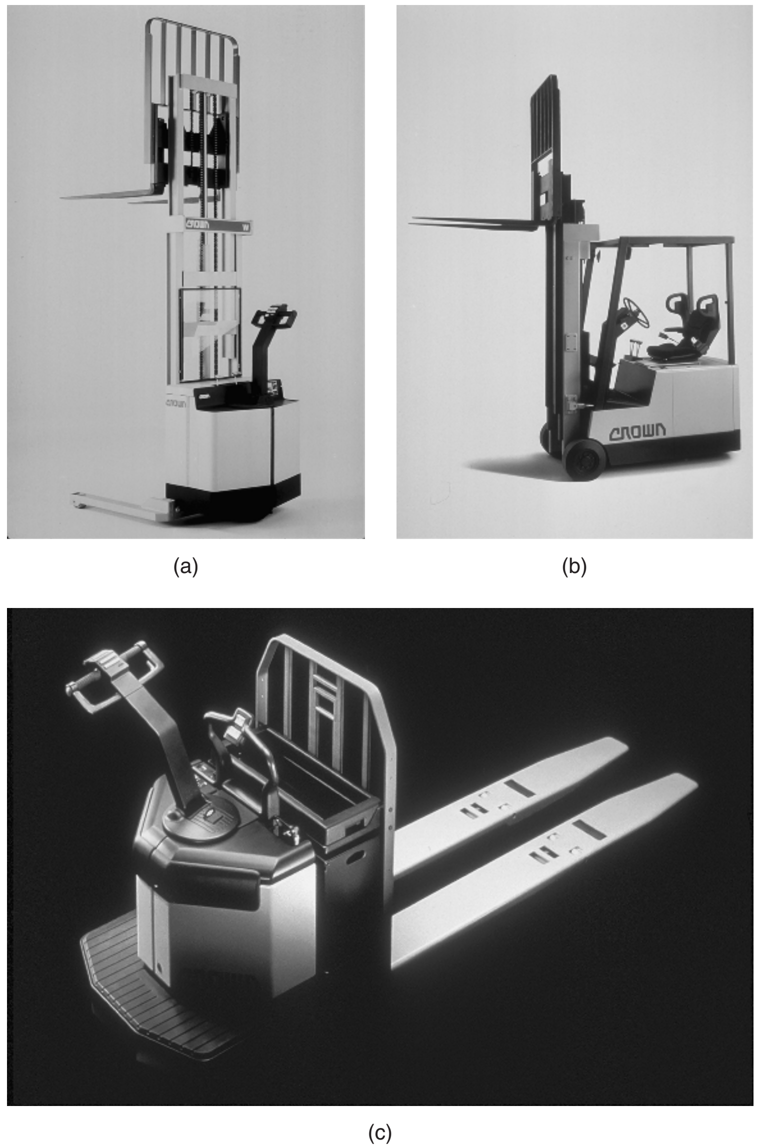

Figure 1.7a,b,c Examples of industrial trucks (Source: Courtesy of Crown Corporation)

3.6 Hoists, Cranes, and Jibs

These MHDs are preferred when the parts to be moved are bulky and require more space for transportation. Because the space above the machines is typically utilized only for carrying power and coolant lines, there is abundant room to transport bulky material. The movement of material in the overhead space does not affect production process and worker in a factory. The disadvantages

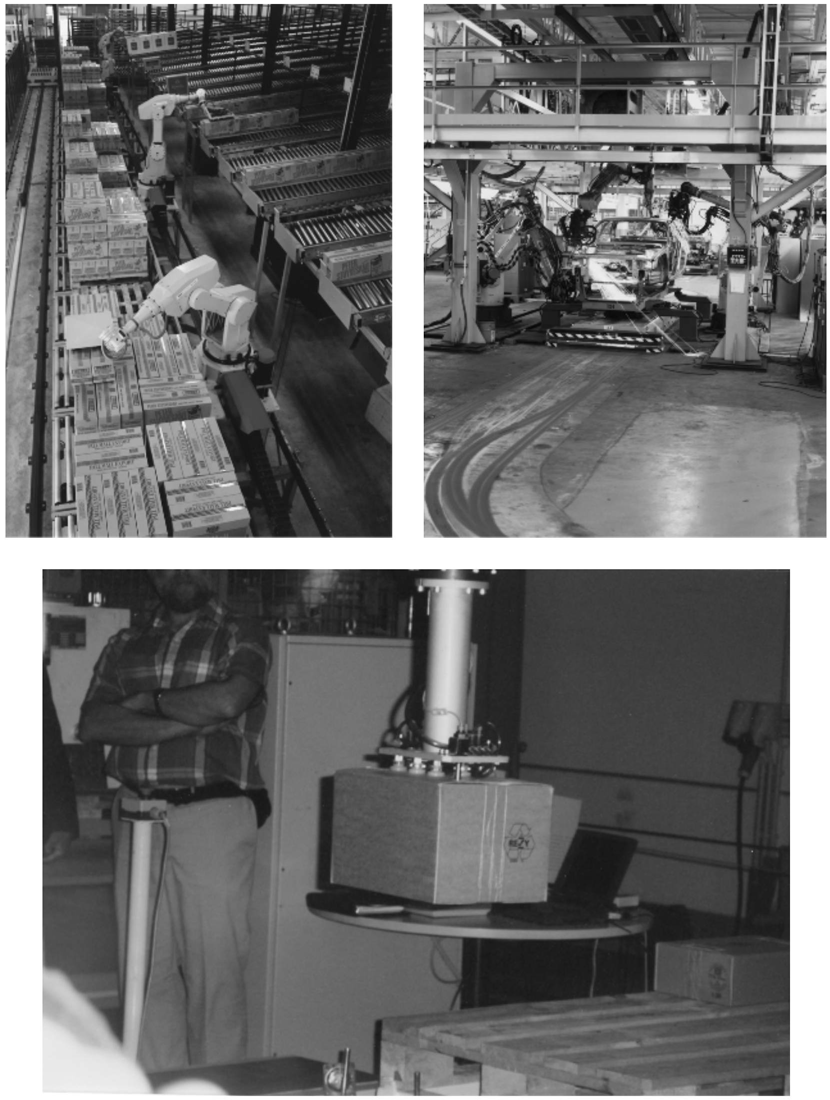

Figure 1.8 Use of robots in pick and place and welding operations (Source: Courtesy of Vanderlande Industries, Gould Communications, and Fraunhofer Institute, IML-Dortmund)

of these MHDs are that they are expensive and time-consuming to install (see Figures 1.10, 1.11, and 1.12).

3.7 Warehouse Material Handling Devices

These are typically referred to as storage and retrieval systems. If they are automated to a high degree, they are referred to as automated storage and retrieval systems (AS/RS). The primary functions of warehouse material handling

Figure 1.9 Use of AGVs in distribution and manufacturing activities (Source: Courtesy of Gould Communications)

devices are to store and retrieve materials as well as transport them between the pick/deposit (P/D) stations and the storage locations of the materials. An AS/RS is shown in Figure 1.13.

AS/RSs are capital-intensive systems. However, they offer a number of advantages, such as low labor and energy costs, high land or space utilization, high reliability and accuracy, and high throughput rates.

3.8 Autonomous Vehicle Storage and Retrieval System

Autonomous vehicle storage and retrieval systems (AVS/RS) represent a relatively new technology for automated unit load storage systems. In this system, the autonomous vehicles function as storage/retrieval (S/R) devices. Within the storage rack, the key distinction of AVS/R systems relative to traditional crane-based automated storage and retrieval systems (AS/RS) is the movement patterns of the S/R device. In AS/RS, aisle-captive storage cranes can move in the horizontal and vertical dimensions, simultaneously to store or retrieve unit loads. In an AVS/RS, vehicles use a fixed number of lifts for vertical movement and follow rectilinear

Figure 1.10 Manual, electric, and pneumatic hoists (Source: Courtesy of Harrington and Ingersoll-Rand)

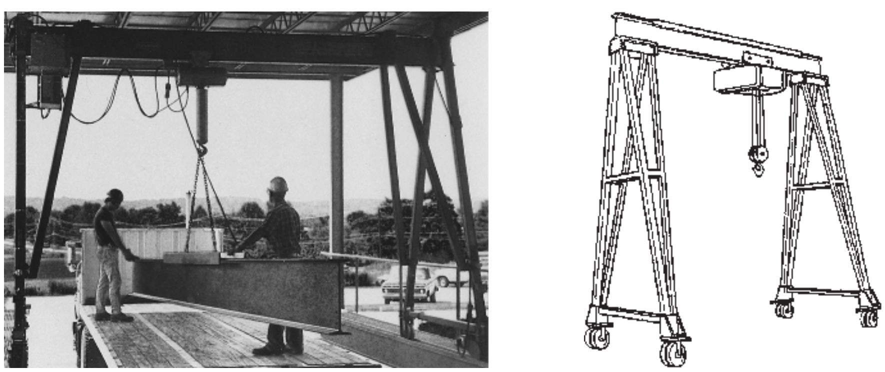

Figure 1.11 Gantry cranes (Source: Courtesy of B.E. Wallace Products Corp. and Mannesmann Dematic)

Figure 1.12 AGV and gantry crane used for loading containers on ships (Source: Courtesy of Europe Combined Terminals B.V., The Netherlands)

flow patterns for horizontal travel. Although the travel patterns in an AS/RS are generally more efficient within storage racks (see Figure 1.13), an AVS/RS has a significant potential advantage in the adaptability of system throughput capacity to transactions demand by changing the number of vehicles operating in a fixed storage configuration (see Figure 1.14). For example, decreasing the number of

Figure 1.13 AS/RS (Source: Courtesy of Vanderlande Industries)

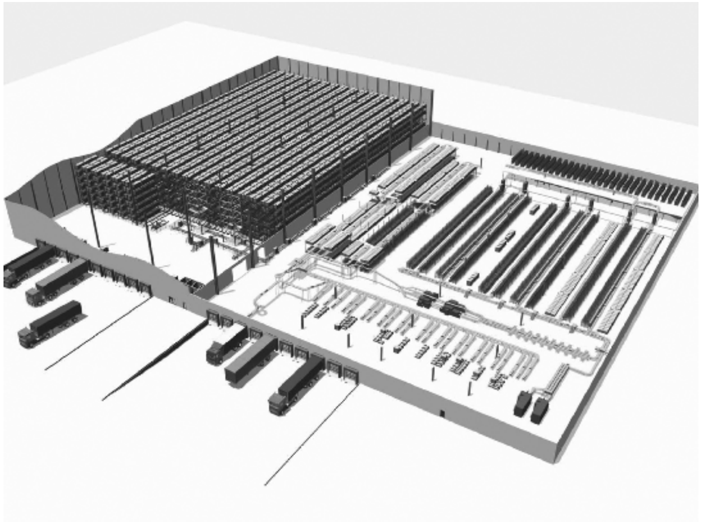

Figure 1.14 A typical AVS/RS (Source: Courtesy of Savoye Logistics)

vehicles increases the transaction cycle times and utilization, which are also key measures of system performance.

4 HOW TO CHOOSE THE "RIGHT" EQUIPMENT

Apple (1977) has suggested the use of the "material handling equation" in arriving at a material handling solution. The methodology illustrated in Figure 1.15 uses six major questions: why (select material handling equipment), what (is the material to be moved), where and when (is the move to be made), how (will the move be made), and who (will make the move). All these six questions are extremely important and should be answered satisfactorily.

The material handling equation can be specified as: *Material*+*Move*=*Method*, as shown in Figure 1.15. Very often, when the *material* and *move* aspects are analyzed thoroughly, it automatically uncovers the appropriate material handling *method*. For example, analysis of the type and characteristics of *material* may reveal that the material is a large unit load on wooden pallets. Further analysis of the logistics, characteristics and type of *move* may indicate that 6 meters load/unload lift is required, distance traveled is 50 meters, and some maneuvering is required while transporting the unit load. This suggests that a fork lift truck would be a suitable material handling device. Even further analysis of the method may tell us more about the specific features of the fork lift truck. For example, narrow aisle fork lift truck, with a floor load capacity of $^1/_2$ ton, and so on.

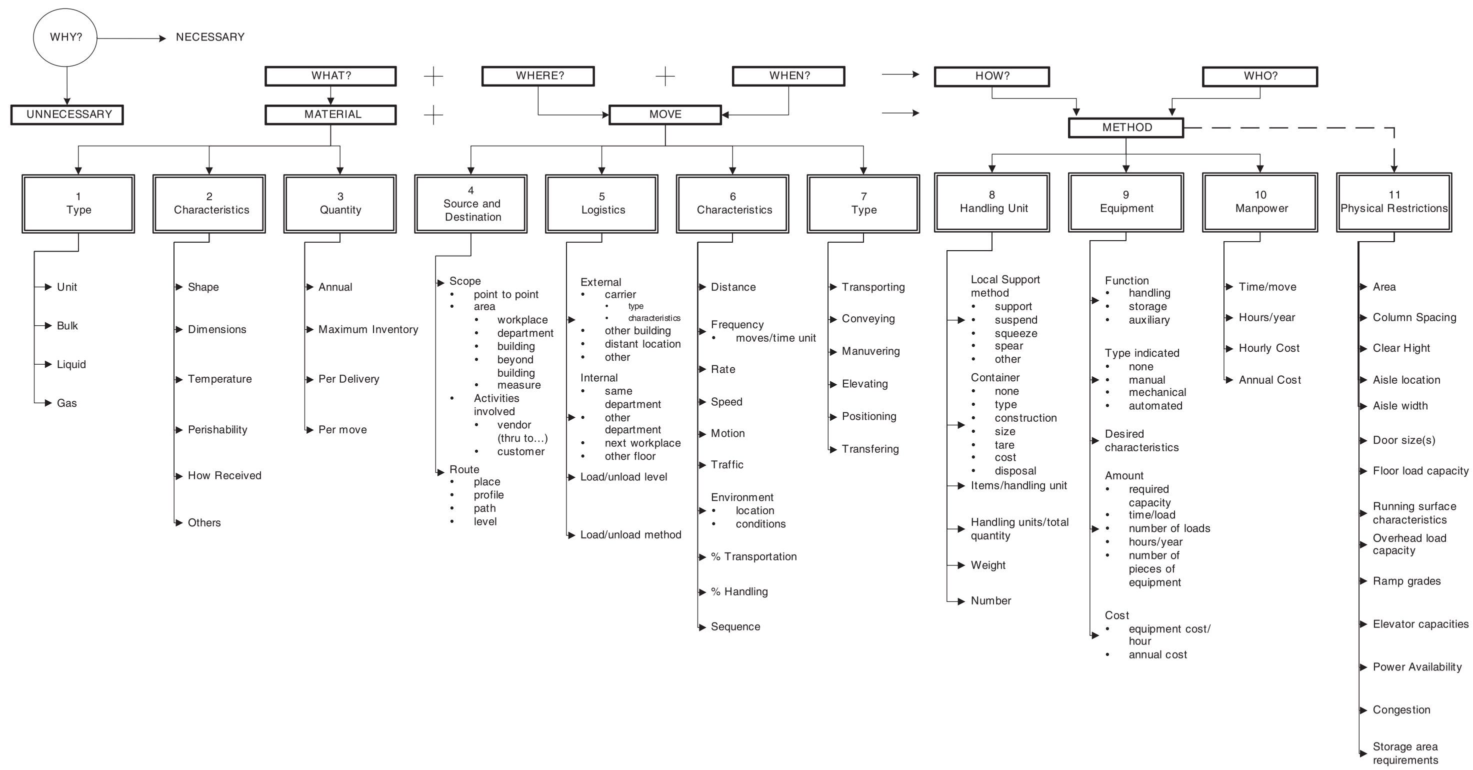

Figure 1.15 Material handling equation (Source: Courtesy of James M. Apple, Jr.)

5 A MULTIOBJECTIVE MODEL FOR OPERATION ALLOCATION AND MATERIAL HANDLING EQUIPMENT SELECTION IN FMS DESIGN

From both a conceptual as well as a computational point, only a few mathematical programming models have been proposed for the material handling system selection problem. Most of the studies have focused on material handling equipment optimization, rather than the entire material handling system. Sujono and Lashkari (2006) proposed a multiobjective model for selecting MHDs and allocating material handling transactions to them in flexible manufacturing system (FMS) design. They propose a model that integrates operation allocation (OA) and MHD selection problem. Their study is an extension of the Paulo et al. (2002) and Lashkari et al. (2004) studies. The main differences from the previous models are the new definition of the variables and the introduction of a new variable that links the selection of a machine to perform manufacturing operation with the material handling requirements of that operation. In addition, they include all the costs associated with material handling operations and suboperations, and the complete restructuring of the constraints that control the selection of the material handling equipment and their loading, in the objective function. Their model is presented as follows.

$h \in \{1, 2, \ldots, H\}$	: major MH operations
$\hat{h} \in \{1, 2, \ldots, \hat{H}\}$	: MH suboperations
$e \in E_{jh\hat{h}}\{1, 2, \ldots, E\}$	: set of MH equipment that can handle the combination of MH operation/suboperation at machine j
$j \in J_{ips}\{1, 2, \ldots, m\}$	: set of machines that can perform operation s of part type i under process plan p

Parameters

b_j	: time available on machine j
OC_{ipj}	: cost of performing operation s of part type i under process plan p on machine j (\$)
d_i	: demand for part type i (units)
SC_j	: setup cost of machine j (\$)
t_{ijp}	: time for performing operation s of part type i under process plan p on machine j
$T_{ijh\hat{h}e}$	: MH cost of performing the combination of MH operation/suboperation for part type i on machine j using MH equipment e (\$)
L_e	: time available on MH equipment e
$I_{h\hat{h}e}$	: time for MH equipment e to perform the combination of MH operation/suboperation
$\hat{W}_{it}$	: relative weight of the product variable t on part type i
W_{et}	: relative weight of the product variable t on MH equipment e

$W_{h\hat{h}e}$	: relative degree of capability of MH equipment e to perform the combination of MH operation/suboperation
C_{ei}	: compatibility between MH equipment e and part type i

Decision Variables

$Z(ip) \in \{1, 0\}$	: 1 if part type i uses process plan p; 0 otherwise
$Y_{sj}(ip) \in \{1, 0\}$	: 1 if machine j performs operation s of part type i under process plan p; 0 otherwise
$A_{ijph\hat{h}} \in \{1, 0\}$	: 1, if part type i under process plan p requires the combination of MH operation/suboperation at machine j; 0 otherwise
$X_{ijph\hat{h}e} \in \{1, 0\}$	: 1 if the combination of MH operation/suboperation requires MH equipment e at machine j where operation s of part type i under process plan p is performed; 0 otherwise
$M_j \in \{1, 0\}$	: 1 if machine j is selected; 0 otherwise
$D_e \in \{1, 0\}$	: 1 if MH equipment e is selected; 0 otherwise

The first part of the objective function is presented as equation (1):

$$F_1 = \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ips}} OC_{ipj} Y_{sj}(ip) + \sum_{j=1}^{m} SC_j M_j + \sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ips}} \sum_{h=1}^{H} \sum_{\hat{h}=1}^{\hat{H}} \sum_{e \in E_{jh\hat{h}}} T_{ijh\hat{h}e} X_{ijph\hat{h}e}. \tag{1}$$

The second part of the objective function is formulated as equation (2):

$$F_2 = \sum_{e=1}^{E} \sum_{h=1}^{H} \sum_{\hat{h}=1}^{\hat{H}} W_{h\hat{h}e} \sum_{i=1}^{n} C_{ei} \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{j \in J_{ips}} X_{ijph\hat{h}e}, \tag{2}$$

where

$$C_{ei} = 1 - \frac{\sum_{t=1}^{T} \left| W_{et} - \hat{W}_{it} \right|}{4T}.$$

Here, $T = 5$ and refers to the five major variables used to identify the dimensions of the characteristics mentioned by Ayres (1988). Integer numbers are used to assign values to the subjective factors, W parameters, W_{et}, $W_{h\hat{h}e}$ and $\hat{W}_{it}$. The rating scales range from 0 to 5 for W_{et} and $W_{h\hat{h}e}$ and 1 to 5 for $\hat{W}_{it}$ (Ayres 1988). A 5 for W_{et} means that the piece of equipment is best suited to handle parts with a very high rating of product variable t. A 0 means, do not allow this piece of equipment to handle parts with product variable t. A 5 for $W_{h\hat{h}e}$ means that it is excellent in performing the operation/suboperation combination. And a 0 means that it is incapable of performing the operation/suboperation combination. A 5 for $\hat{W}_{it}$ means that the part type exhibits a very high level of the key product variable t. And a 0 means that the part type exhibits a very low level of the key product variable t.

The first part of objective function's three terms indicates the manufacturing operation costs, the machine setup costs, and the MH operation costs, respectively. The second part of the objective function computes the overall compatibility of the MH equipment. As a result, the formulation of the problem is a multiobjective model seeking to strike a balance between the two objectives.

There are nine constraints in this model:

1. Each part type can use only one process plan:

$$\sum_{p=1}^{P(i)} Z(ip) = 1 \quad \forall i. \tag{3}$$

2. For a given part type i under process plan p, each operation of the selected process plan is assigned to only one of the available machines:

$$\sum_{j \in J_{ips}} Y_{sj}(ip) = Z(ip) \quad \forall i, p, s. \tag{4}$$

3. Once a machine is selected for operation s of part type i under process plan p, then all the $(h\hat{h})$ combinations corresponding to (sj) must be performed:

$$Y_{sj}(ip) = A_{sjh\hat{h}}(ip) \quad \forall i, p, s, j, h, \hat{h}. \tag{5}$$

4. Each $h\hat{h}$ combination can be assigned to only piece of available and capable MH equipment:

$$\sum_{e \in E_{jh\hat{h}}} X_{ijph\hat{h}e} = A_{ijph\hat{h}} \quad \forall i, p, s, j, h, \hat{h}. \tag{6}$$

5. At least one operation must be allocated to a selected machine:

$$\sum_{i=1}^{n} \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{h=1}^{H} \sum_{\hat{h}=1}^{\hat{H}} \sum_{e \in E_{jh\hat{h}}} X_{ijph\hat{h}e} \geq M_j \quad \forall j. \tag{7}$$

6. The allocated operations cannot exceed the corresponding machine's capacity:

$$\sum_{i=1}^{n} d_i \sum_{p=1}^{P(i)} \sum_{s=1}^{S(ip)} \sum_{h=1}^{H} \sum_{\hat{h}=1}^{\hat{H}} \sum_{e \in E_{jh\hat{h}}} t_{sj}(ip) X_{ijph\hat{h}e} \leq b_j M_j \quad \forall j. \tag{8}$$

7. A specific MH equipment can be selected only if the corresponding *type* of equipment is selected:

$$D_e \leq D_{\hat{e}} \quad \forall e, \hat{e}. \tag{9}$$

8. Each MH equipment selected must perform at least one operation:

$$\sum_{i=1}^{n}\sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}}\sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} X_{ijph\hat{h}e} \geq D_e \quad \forall e. \tag{10}$$

9. The MH equipment capacity cannot be exceeded:

$$\sum_{i=1}^{n} d_i \sum_{h=1}^{H}\sum_{\hat{h}=1}^{\hat{H}}\sum_{p=1}^{P(i)}\sum_{s=1}^{S(ip)}\sum_{j\in J_{ips}} X_{ijph\hat{h}e} \geq D_e \quad \forall e. \tag{11}$$

6 WAREHOUSING

Many manufacturing and distribution companies maintain large warehouses to store in-process inventories or components received from an external supplier. They are involved in various stages of the sourcing, production, and distribution of goods, from raw materials through the finished goods. The true value of warehousing lies in having the right product in the right place at the right time. Thus, warehousing provides the time-and-place utility necessary for a company and is often one of the most costly elements. Therefore, its successful management is critical.

6.1 Just-in-Time (JIT) Manufacturing

It has been argued that warehousing is a time-consuming and non–value-adding activity. Because additional paperwork and time are required to store items in storage spaces and retrieve them later when needed, the JIT manufacturing philosophy suggests that one should do away with any kind of temporary storage and maintain a pull strategy in which items are produced only as and when they are required. That is, they should be produced at a certain stage of manufacturing, only if they are required at the next stage.

JIT philosophy requires that the same approach be taken toward components received from suppliers. The supplier is considered as another (previous) stage in manufacturing. However, in practice, because the demand is continuous, that means that goods need to be always pulled through the supply chain to respond to demand quickly. The handling of returned goods is becoming increasingly important (e.g., Internet shopping may increase the handling of returned goods), and due to the uncertainty inherent in the supply chain, it is not possible to completely do away with temporary storage.

6.2 Warehouse Functions

Every warehouse should be designed to meet the specific requirements of the supply chain of which it is a part. In many cases, the need to provide better service to customers and be responsive to their needs appears to be the primary reason. Nevertheless, there are certain operations that are common to most warehouses:

- *Temporarily store goods*. To achieve economies of scale in production, transportation, and handling of goods, it is often necessary to store goods in warehouses and release them to customers as and when the demand occurs.
- *Put together customer orders*. Goods are received from order picking stock in the required quantities and at the required time to the warehouse to meet customer orders. For example, goods can be received from suppliers as whole pallet quantities, but are ordered by customers in less than pallet quantities.
- *Serve as a customer service facility*. In some cases, warehouses ship goods to customers and therefore are in direct contact with them. So, a warehouse can serve as a customer service facility and handle replacement of damaged or faulty goods, conduct market surveys, and even provide after sales service. For example, many Korean electronic goods manufacturers let warehouses handle repair and do after sales service in North America.
- *Protect goods*. Sometimes manufactured goods are stored in warehouses to protect them against theft, fire, floods, and weather elements because warehouses are generally secure and well equipped.
- *Segregate hazardous or contaminated materials*. Safety codes may not allow storage of hazardous materials near the manufacturing plant. Because no manufacturing takes place in a warehouse, this may be an ideal place to segregate and store hazardous and contaminated materials.
- *Perform value-added services*. In many warehouses after picking, goods are brought together and consolidated as completed orders ready to be dispatched to customers. This can involve packing into dispatch outer cases and cartons, and stretch- and shrink- wrapping for load protection and stability, inspecting, and testing. Here, inspection and testing do not add value to the product. However, we have included them because they may be a necessary function because of company policy or federal regulations.
- *Store seasonal inventory*. It is always difficult to forecast product demand accurately in many businesses. Therefore, it may be important to carry inventory and safety stocks to meet unexpected surges in demand. Some companies that produce seasonal products—for example, lawn mowers and snow throwers—may have excess inventory left over at the end of the season and have to store the unsold items in a warehouse.

A typical warehouse consists of two main elements:

1. Storage medium
2. Material handling system

In addition, there is a building that encloses the storage medium, goods, and the S/R system. Because the main purpose of the building is to protect its contents from theft and weather elements, it is made of strong, lightweight material. So, warehouses come in different shapes, sizes, and heights, depending on a number of factors, including the kind of goods stored inside, volume, type of S/R systems used. For example, the Nike warehouse in Laakdal, Belgium, covers a total area of 1 million square feet. Its high-bay storage is almost 100 feet in height, occupies roughly half of the total warehouse space, and is served by 26 man-aboard stacker cranes.

6.3 Inverse Storage

There is limited landfill space available for dumping wastes created throughout the supply chain. And the increasing cost of landfills, environmental laws and regulation, and the economic viability of environmental strategies are pushing manufacturers nowadays to consider reverse supply chain—also known as *reverse logistics*—management.

Manufacturers now must take full responsibility for their products through the product's life cycle, or they may be subject to legal action. For example, new laws regarding the disposal of motor or engine oil, vehicle batteries, and tires place the disposal responsibility on the manufacturer once these products have passed their useful life. Many manufacturers also realize that reverse logistics offers the opportunity to recycle and reuse product components and reduce the cost and the amount of waste. Therefore, manufacturers are developing disposition stocking areas and collecting used or expired original products from the customer and reshipping to their stocking places. For example, Kodak's single-use camera has a remarkable success story involving the inverse logistics philosophy. The products are collected in a stocking place to be remanufactured. In the United States, 63 percent return rate has been achieved for recycling. The details about the procedure can be obtained from Kodak's Web site at http://www.kodak.com/US/en/corp/environment/performance/recycling.html.

7 AVS/RS CASE STUDY

Savoye Logistics is a European logistics company that designs, manufactures, and integrates logistical systems. It provides solutions for order fulfillment and packing and storing/retrieval of unit loads.

Savoye has various teams to assist its customers with logistic expertise to provide them the best solution corresponding to their needs. Their aim is

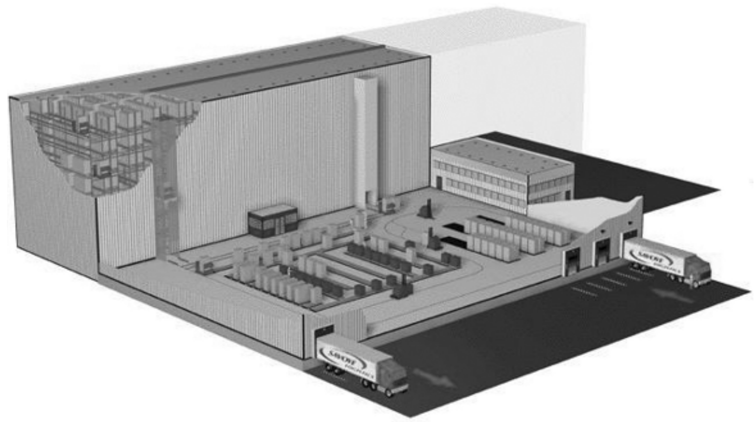

Figure 1.16 Three-dimensional view of a warehouse with an AVS/RS

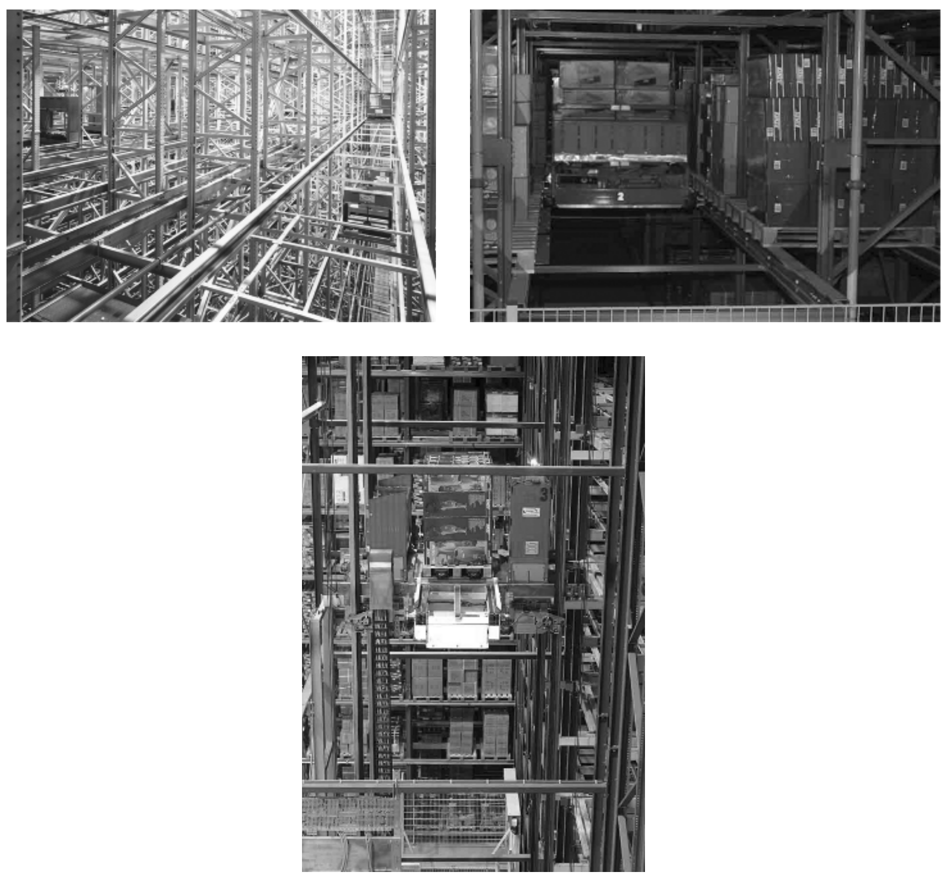

Figure 1.17 Main components of an AVS/RS (Source: Courtesy of Savoye Logistics)

to guarantee the performance to the customer by selecting the best equipment and a global management of the entire project.

Savoye Logistics has introduced the AVS/RS shown in Figure 1.16. The system has been successfully installed in 35 companies in Europe. Today, the installed systems' capacities are around 1,000,000 pallets and 100,000 movements per day, in eight countries.

Figures 1.17a to 1.17c illustrate the two components of the AVS/RS, one of which is autonomous vehicle and the other is the lift. Although the autonomous vehicle moves horizontally in the storage areas in a given tier, the lift moves the vehicle between tiers. In other words, autonomous vehicles move on rails in the aisles and interface with lifts for vertical movement of pallets between storage tiers. Here, lifts are like conveyors, but they can travel only vertically. Autonomous vehicles also transport pallets between lifts and shipping/receiving areas at the ground level. They can transform the loads from their stored areas to their respective storage addresses in the same tier because they can move within tiers. If the load movement is not on the same tier, then lifts are used for transferring the load to the related tier.

The different load movement patterns make AVS/RSs more flexible than AS/R systems, although at slightly lower efficiency. In AS/RSs, aisle-captive cranes are the main S/R devices to move unit loads simultaneously in the horizontal and vertical dimensions. Unlike storage cranes in AS/RS, AVS/RS vehicles can access any designated storage address but must move in a sequential, rectilinear pattern.

One of Savoye Logistics' AVS/RS applications completed in 1999 was for a telecommunication company that faced rapid growth in one of its warehouses. The logistical challenge in planning was to link the technological manufacturing levels of two buildings with a production supply chain to sustain the material flow from the assembly lines to dispatch. The AVS/RS designed by Savoye was able to satisfy these constructional requirements with a supply and unloading line offset at an angle of 90 degrees. The system has now been in operation and fulfils the short lead times and safety requirements and can achieve fill rate of 95 percent.

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