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Material handling is defined by the Material Handling Industry of America\footnote{The Material Handling Industry of America (MHIA) is the trade association for material handling companies that do business in North America. The definition is published in their Annual Report each year.} as "the movement, storage, protection and control of materials throughout the manufacturing and distribution process including their consumption and disposal" \cite{5}. The handling of materials must be performed safely, efficiently, at low cost, in a timely manner, accurately (the right materials in the right quantities to the right locations), and without damage to the materials. Material handling is an important yet often overlooked issue in production. The cost of material handling is a significant portion of total production cost, estimates averaging around 20–25\% of total manufacturing labor cost in the United States \cite{1}. The proportion varies, depending on the type of production and degree of automation in the material handling function.

In this part of the book, we discuss the types of material handling equipment used in production systems. The position of material handling in the larger production system is
shown in Figure 9.1. Material transport equipment is surveyed in Chapter 10. Storage systems are discussed in Chapter 11. And material identification and tracking are described in Chapter 12. In addition, several kinds of material handling devices are discussed in other chapters of the text, including: industrial robots used for material handling (Section 7.5.1), pallet shuttles in NC machining centers (Section 14.2.2), conveyors in manual assembly lines (Section 17.1.2), transfer mechanisms in automated transfer lines (Section 18.1.2), and parts feeding devices in automated assembly (Section 19.1.2).

This opening chapter serves as an introduction to the subject of material handling. Here we discuss some of the general considerations and principles that are useful in designing and managing material handling systems. Let us begin by defining the various types of material handling equipment.

9.1 Overview of Material Handling Equipment

A great variety of material handling equipment is available commercially. Material handling equipment includes: (1) transport equipment, (2) storage systems, (3) unitizing equipment, and (4) identification and tracking systems.

Material Transport Equipment. Material transport includes equipment that is used to move materials inside a factory, warehouse, or other facility. This equipment can be divided into the following five categories, illustrated in Figure 9.2:

(a) Industrial trucks. Industrial trucks divide into two types: non-powered and powered. Nonpowered trucks are platforms or containers with wheels that are pushed or pulled by human workers to move materials. Powered industrial trucks are steered by human workers. They provide mechanized movement of materials.

(b) Automated guided vehicles (AGVs). AGVs are battery-powered, automatically steered vehicles that follow defined pathways in the floor. The pathways are unobtrusive. AGVs are used to move unit loads between load and unload stations in the facility. Routing variations are possible, meaning that different loads move between differ-
Sec. 9.1 / Overview of Material Handling Equipment

Figure 9.2 Examples of the five basic types of material handling equipment: (a) fork lift truck, industrial truck, (b) unit load automated guided vehicle, (c) monorail, (d) roller conveyor, and (e) jib crane with hoist.

cent stations. They are usually interfaced with other systems to achieve the full benefits of integrated automation.

(c) Monorails and other rail guided vehicles. These are self-propelled vehicles that ride on a fixed rail system that is either on the floor or suspended from the ceiling. The vehicles operate independently and are usually driven by electric motors that pick up power from an electrified rail. Like AGVs, routing variations are possible in rail-guided vehicle systems.

(d) Conveyors. Conveyors constitute a large family of material transport equipment that are designed to move materials over fixed paths, generally in large quantities or volumes. Examples include roller, belt, and tow-line conveyors. Conveyors can be either powered or nonpowered. Powered conveyors are distinguished from other types of powered material transport equipment in that the mechanical drive system is built into the fixed path. Nonpowered conveyors are activated either by human workers or by gravity.

(e) Cranes and hoists. These are handling devices for lifting, lowering, and transporting materials, often as very heavy loads. Hoists accomplish vertical lifting; both manually operated and powered types are available. Cranes provide horizontal travel and generally include one or more hoists.
In addition to the equipment types listed here, which are discussed in greater detail in Chapter 10, there are many kinds of transport equipment that move materials outside the factory or warehouse, including highway tractor-trailer trucks, railway trains, cargo aircraft, ships, and barges.

**Storage Systems.** Although it is generally desirable to reduce the storage of materials in manufacturing, it seems unavoidable that raw materials and work-in-process will spend some time being stored, even if only temporarily. And finished products are likely to spend some time in a warehouse or distribution center before being delivered to the final customer. Accordingly, companies must give consideration to the most appropriate methods for storing materials and products prior to, during, and after manufacture. Storage methods and equipment can be classified as follows:

(a) **Bulk storage.** This consists of simply storing materials in an open floor area, generally in pallet loads or other containers. It requires little or no storage equipment.

(b) **Rack systems.** Rack systems are structural frames designed to stack unit loads vertically, thus increasing the vertical storage efficiency compared to bulk storage.

(c) **Shelving and bins.** Steel shelving comes in standard widths, depths, and heights to serve a variety of storage requirements. Shelves can include bins, which are containers for loose items.

(d) **Drawer storage.** This storage medium is more costly than shelves, but it is more convenient. Finding items stored in shelves can be difficult if the shelf level is too high or too low or too deep. Drawers compensate for this by pulling out to reveal their entire contents. Drawer storage is generally used for tools, hardware, and other small items.

(e) **Automated storage systems.** Automated and semiautomated systems are available to deposit and withdraw items into and from the storage compartments. There are two basic types: (1) automated storage/retrieval systems, consisting of rack and shelf systems that are accessed by an automated or mechanized crane, and (2) carousel systems that rotate storage bins past a stationary load/unload station.

These storage methods are described in greater detail in Chapter 11. Mathematical models are developed to predict throughput and other performance measures of the automated systems.

**Unitizing Equipment.** The term unitizing equipment refers to (1) containers used to hold individual items during handling and (2) equipment used to load and package the containers. Containers include pallets, boxes, baskets, barrels, pails, and drums, some of which are shown in Figure 9.3. Although seemingly mundane, this type of equipment is very important for moving materials efficiently as a unit load, rather than as individual items. A given facility must often standardize on a specific type and size of container if it utilizes automatic transport and/or storage equipment to handle the loads.

The second category of unitizing equipment, loading and packaging equipment, includes palletizers, designed to automatically load cartons onto pallets and shrink-wrap plastic film around them for shipping. Other wrapping and packaging machines are also included in this equipment category, as are depalletizers, designed to unload cartons from pallets.

**Identification and Tracking Systems.** Material handling must include a means of keeping track of the materials being moved or stored. This is usually done by affixing
some kind of label to the item, carton, or unit load that uniquely identifies it. The most common label used today consists of bar codes that can be read quickly and automatically by bar code readers. This is the same basic technology used by grocery stores and retail merchandisers. Other types of labels include magnetic stripes and radio frequency tags that are generally capable of encoding more data than bar codes. These and other automatic identification techniques are discussed in Chapter 12.

9.2 CONSIDERATIONS IN MATERIAL HANDLING SYSTEM DESIGN

Material handling equipment is usually assembled into a system. The system must be specified and configured to satisfy the requirements of a particular application. Design of the system depends on the materials to be handled, quantities and distances to be moved, type of production facility served by the handling system, and other factors, including available budget. In this section, we consider these factors that influence the design of the material handling system.

9.2.1 Material Characteristics

For handling purposes, materials can be classified by the physical characteristics presented in Table 9.1, suggested by a classification scheme of Muther and Haganas [7]. Design of the material handling system must take these factors into account. For example, if the material is a liquid and is to be moved in this state over long distances in great volumes, then a pipeline is probably the appropriate transport means. But this handling method would be quite inappropriate for moving a liquid contained in barrels or other containers. Materials in a factory usually consist of solid items: raw materials, parts, and finished or semi-finished products.
TABLE 9.1 Characteristics of Materials in Material Handling

<table>
<thead>
<tr>
<th>Category</th>
<th>Measures or Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical state</td>
<td>Solid, liquid, or gas</td>
</tr>
<tr>
<td>Size</td>
<td>Volume; length, width, height</td>
</tr>
<tr>
<td>Weight</td>
<td>Weight per piece, weight per unit volume</td>
</tr>
<tr>
<td>Shape</td>
<td>Long and flat, round, square, etc.</td>
</tr>
<tr>
<td>Condition</td>
<td>Hot, cold, wet, dirty, sticky</td>
</tr>
<tr>
<td>Risk of damage</td>
<td>Fragile, brittle, sturdy</td>
</tr>
<tr>
<td>Safety risk</td>
<td>Explosive, flammable, toxic, corrosive, etc.</td>
</tr>
</tbody>
</table>

9.2.2 Flow Rate, Routing, and Scheduling

In addition to material characteristics, other factors must be considered in analyzing system requirements and determining which type of equipment is most appropriate for the application. These other factors include: (1) quantities and flow rates of materials to be moved, (2) routing factors, and (3) scheduling of the moves.

The amount or quantity of material to be moved affects the type of handling system that should be installed. If large quantities of material must be handled, then a dedicated handling system is appropriate. If the quantity of a particular material type is small but there are many different material types to be moved, then the handling system must be designed to be shared by the various materials moved. The amount of material moved must be considered in the context of time, that is, how much material is moved within a given time period. We refer to the amount of material moved per unit time as the flow rate. Depending on the form of the material, flow rate is measured in pieces/hr, pallet loads/hr, tons/hr, ft³/day, or similar units. Whether the material must be moved as individual units, in batches, or continuously has an effect on the selection of handling method.

Routing factors include pickup and drop-off locations, move distances, routing variations, and conditions that exist along the routes. Given that other factors remain constant, handling cost is directly related to the distance of the move: The longer the move distance, the greater the cost. Routing variations occur because different materials follow different flow patterns in the factory or warehouse. If these differences exist, the material handling system must be flexible enough to deal with them. Conditions along the route include floor surface condition, traffic congestion, whether a portion of the move is outdoors, whether the path is straight line or involves turns and changes in elevation, and the presence or absence of people along the path. All of these routing factors affect the design of the material transport system. Figure 9.4 is presented as a rough guide to the selection of material transport equipment as a function of material quantity and distance moved.
handling equipment for some of the application characteristics we have discussed here, specifically flow rate and distance moved.

Scheduling relates to the timing of each individual delivery. In production as well as in many other material handling applications, the material must be picked up and delivered promptly to its proper destination to maintain peak performance and efficiency of the overall system. To the extent required by the application, the handling system must be responsive to this need for timely pickup and delivery of the items. Rush jobs increase material handling cost. Scheduling urgency is often mitigated by providing space for buffer stocks of materials at pickup and drop-off points. This allows a “float” of materials to exist in the system, thus reducing the pressure on the handling system for immediate response to a delivery request.

9.2.3 Plant Layout

Plant layout is an important factor in the design of a material handling system. In the case of a new facility, the design of the handling system should be considered part of the layout design. In this way, there is greater opportunity to create a layout that optimizes material flow in the building and utilizes the most appropriate type of handling system. In the case of an existing facility, there is less flexibility in the design of the handling system. The present arrangement of departments and equipment in the building usually limits the attainment of optimum flow patterns.

The plant layout design should provide the following data for use in the design of the handling system: total area of the facility and areas within specific departments in the plant, arrangement of equipment in the layout, locations where materials must be picked up (load stations) and delivered (unload stations), possible routes between these locations, and distances traveled. Opportunities to combine deliveries and potential locations in the layout where congestion might occur must be considered. Each of these factors affects flow patterns and selection of material handling equipment.

In Section 1.1, we described the conventional types of plant layout used in manufacturing: fixed-position layout, process layout, and product layout. Different material handling systems are generally required for the three layout types. In a fixed-position layout, the product is large and heavy and therefore remains in a single location during most of its fabrication. Heavy components and subassemblies must be moved to the product. Handling systems used for these moves in fixed-position layouts are large and often mobile. Cranes, hoists, and trucks are common in this situation.

In process layouts, a variety of different products are manufactured in small or medium batch sizes. The handling system must be flexible to deal with the variations. Considerable work-in-process is usually one of the characteristics of batch production, and the material handling system must be capable of accommodating this inventory. Hand trucks and forklift trucks (for moving pallet loads of parts) are commonly used in process type layouts. Factory applications of automated guided vehicle systems are growing because they represent a versatile means of handling the different load configurations in medium and low volume production. Work-in-progress is often stored on the factory floor near the next scheduled machines. More systematic ways of managing in-process inventory include automated storage systems (Section 1.4).

Finally, a product layout involves production of a standard or nearly identical type of product in relatively high quantities. Final assembly plants for cars, trucks, and appliances are usually designed as product layouts. The transport system that moves the product is typically characterized as fixed route, mechanized, and capable of large flow rates. It
### Chap. 9 / Introduction to Material Handling

**TABLE 9.2** Types of Material Handling Equipment Associated with Three Layout Types

<table>
<thead>
<tr>
<th>Layout Type</th>
<th>Characteristics</th>
<th>Typical Material Handling Equipment</th>
</tr>
</thead>
</table>
| Fixed-position Process | Large product size, low production rate  
Variations in product and processing, 
low and medium production rates | Cranes, hoists, industrial trucks  
Hand trucks, forklift trucks, automated guided vehicle systems |
| Product       | Limited product variety, high production rate         | Conveyors for product flow, trucks to deliver components to stations |

sometimes serves as a storage area for work-in-process to reduce effects of downtime between production areas along the line of product flow. Conveyor systems are common in product layouts. Delivery of component parts to the various assembly workstations along the flow path is accomplished by trucks and similar unit load vehicles.

Table 9.2 summarizes the characteristics of the three conventional layout types and the kinds of material handling equipment usually associated with each layout type.

### 9.3 The 10 Principles of Material Handling

Over time certain principles have been found to be applicable in the analysis, design, and operation of material handling systems. The 10 principles of material handling are listed and explained in Table 9.3. Implementing these principles will result in safer operating conditions, lower costs, and better utilization and performance of material handling systems.

The unit load principle stands as one of the most important and widely applied principles in material handling. In material handling, a unit load is simply the mass that is to be moved or otherwise handled at one time. The unit load may consist of only one part, it may consist of a container loaded with multiple parts, or it may consist of a pallet loaded with multiple containers of parts. In general, the unit load should be designed to be as large as is practical for the material handling system that will move or store it, subject to considerations of safety, convenience, and access to the materials making up the unit load. This principle is widely applied in the truck, rail, and ship industries. Palletized unit loads are collected into truck loads, which then become unit loads themselves, but larger. Then these truck loads are aggregated once again on freight trains or ships, in effect becoming even larger unit loads.

There are good reasons for using unit loads in material handling: (1) Multiple items can be handled simultaneously; (2) the required number of trips is reduced; (3) loading and unloading times are reduced, and (4) product damage is decreased. These reasons result in lower cost and higher operating efficiency.

Included in the definition of unit load is the container that holds or supports the materials to be moved. To the extent possible, these containers are standardized in size and configuration to be compatible with the material handling system. Examples of containers used to form unit loads in material handling are illustrated in Figure 9.3. Of the available

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1. The 10 principles were developed by the College Industry Council on Material Handling Education (CICMHE), a Council of the Material Handling Institute (MHI), which is the educational division of the Material Handling Industry of America. MHI first published the 10 principles in 1997. They are based on two earlier versions of material handling principles published in 1968 and 1923 by CICMHE.
TABLE 9.3 The 10 Principles of Material Handling

Principle 1. PLANNING PRINCIPLE: All material handling should be the result of a deliberate plan where the needs, performance objectives, and functional specification of the proposed methods are completely defined at the outset.

- The plan should be developed in consultation between the planner(s) and all who will use and benefit from the equipment to be employed.
- 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.
- The plan should promote concurrent engineering of product, process design, process layout, and material handling methods as opposed to independent and sequential design practices.
- The plan should reflect the strategic objectives of the organization as well as the more immediate needs.

Principle 2. STANDARDIZATION PRINCIPLE: 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.
- Standardization applies to sizes of containers and other load forming components as well as operating procedures and equipment.
- 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.
- Standardization, flexibility, and modularity must not be incompatible.

Principle 3. WORK PRINCIPLE: Material handling work should be minimized without sacrificing productivity or the level of service required of the operation.

- The measure of material handling work is flow rate (volume, weight, or count per unit of time) multiplied by distance moved.
- Consider each pickup and set-down, or placing material in and out of storage, as distinct moves and components of the distance moved.
- Simplifying processes by reducing, combining, shortening, or eliminating unnecessary moves will reduce work.
- 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.
- The Work Principle applies universally, from mechanized material handling in a factory to over-the-road trucking.
- The Work Principle is implemented best by appropriate layout planning: locating the production equipment into a physical arrangement corresponding to the flow of work. This arrangement tends to minimize the distances that must be traveled by the materials being processed.

Principle 4. ERGONOMIC PRINCIPLE: Human capabilities and limitations must be recognized and respected in the design of material handling tasks and equipment to ensure safe and effective operations.

- Ergonomics is the science that seeks to adapt work or working conditions to suit the abilities of the worker.
- The material handling workplace and the equipment must be designed so they are safe for people.
- The ergonomic principle embraces both physical and mental tasks.
- Equipment should be selected that eliminates repetitive and strenuous manual labor and that effectively interacts with human operators and users.

Principle 5. UNIT LOAD PRINCIPLE: Unit loads shall be appropriately sized and configured in a way which achieves the material flow and inventory objectives at each stage in the supply chain.

- 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.
- 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.
- Large unit loads are common both pre- and postmanufacturing in the form of raw materials and finished goods.
- Smaller unit loads are consistent with manufacturing strategies that embrace operating objectives such as flexibility, continuous flow and just-in-time delivery. Smaller unit loads (as few as one item) yield less in-process inventory and shorter item throughput times.

CONTINUED ON NEXT PAGE
TABLE 9.3  Continued

Principle 6. **Space Utilization Principle**: Effective and efficient use must be made of all available space.
- Space in material handling is three-dimensional and therefore is counted as cubic space.
- In storage areas, the objective of maximizing storage density must be balanced against accessibility and selectivity.
- When transporting loads within a facility, the use of overhead space should be considered as an option. Use of overhead material handling systems saves valuable floor space for productive purposes.

Principle 7. **System Principle**: 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.
- Systems integration should encompass the entire supply chain, including reverse logistics. It should include suppliers, manufacturers, distributors, and customers.
- Inventory levels should be minimized at all stages of production and distribution while respecting considerations of process variability and customer service.
- Information flow and physical material flow should be integrated and treated as concurrent activities.
- 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.

Principle 8. **Automation Principle**: 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.
- In any project in which automation is being considered, pre-existing processes and methods should be simplified and/or re-engineered before any efforts to install mechanized or automated systems. Such analysis may lead to elimination of unnecessary steps in the method. If the method can be sufficiently simplified, it may not be necessary to automate the process.
- Items that are expected to be handled automatically must have standard shapes and/or features that permit mechanized and/or automated handling.
- Interface issues are critical to successful automation, including equipment-to-equipment, equipment-to-load, equipment-to-operator, and in-control communications.
- Computerized material handling systems should be considered where appropriate for effective integration of material flow and information management.

Principle 9. **Environmental Principle**: Environmental impact and energy consumption should be considered as criteria when designing or selecting alternative equipment and material handling systems.
- 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.
- Containers, pallets, and other products used to form and protect unit loads should be designed for reusability when possible and/or biodegradability after disposal.
- Materials specified as hazardous have special needs with regard to spill protection, combustibility, and other risks.

Principle 10. **Life Cycle Cost Principle**: A thorough economic analysis should account for the entire life cycle of all material handling equipment and resulting systems.
- Life cycle costs include all cash flows that occur between the time the first dollar is spent to plan a new material handling method or piece of equipment until that method and/or equipment is totally replaced.
- 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.
- 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.
- A long-range plan for replacement of the equipment when it becomes obsolete should be prepared.
- 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 and that form the basis for competition in the market place should be considered and quantified whenever possible.
TABLE 9.4  Standard Pallet Sizes Commonly Used  
in Factories and Warehouses

<table>
<thead>
<tr>
<th>Depth = x Dimension</th>
<th>Width = y Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 mm (32 in)</td>
<td>1000 mm (40 in)</td>
</tr>
<tr>
<td>900 mm (36 in)</td>
<td>1200 mm (48 in)</td>
</tr>
<tr>
<td>1000 mm (40 in)</td>
<td>1200 mm (48 in)</td>
</tr>
<tr>
<td>1060 mm (42 in)</td>
<td>1060 mm (42 in)</td>
</tr>
<tr>
<td>1200 mm (48 in)</td>
<td>1200 mm (48 in)</td>
</tr>
</tbody>
</table>

Sources: MHI/IT&W.

containers, pallets are probably the most widely used, owing to their versatility, low cost, and compatibility with various types of material handling equipment. Most factories and warehouses use forklift trucks to move materials on pallets. Table 9.4 lists some of the most popular standard pallet sizes in use today. We make use of these standard pallet sizes in some of our analysis of automated storage/retrieval systems in Chapter 11.

REFERENCES


In this chapter we examine the five categories of material transport equipment commonly used to move parts and other materials in manufacturing and warehouse facilities: (1) industrial trucks, (2) automated guided vehicles, (3) monorails and other rail guided vehicles, (4) conveyors, and (5) cranes and hoists. Table 10.1 summarizes the principal features and kinds of applications for each equipment category. In Section 10.6, we consider quantitative techniques by which material transport systems consisting of this equipment can be analyzed.
TABLE 10.1 Summary of Features and Applications of Five Categories of Material Handling Equipment

<table>
<thead>
<tr>
<th>Material Handling Equipment</th>
<th>Features</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial trucks, manual</td>
<td>Low cost</td>
<td>Moving light loads in a factory</td>
</tr>
<tr>
<td></td>
<td>Low rate of deliveries/hr</td>
<td></td>
</tr>
<tr>
<td>Industrial trucks, powered</td>
<td>Medium cost</td>
<td>Movement of pallet loads and palletized containers in a factory or warehouse</td>
</tr>
<tr>
<td>Automated guided vehicle systems</td>
<td>High cost</td>
<td>Moving pallet loads in factory or warehouse</td>
</tr>
<tr>
<td></td>
<td>Battery-powered vehicles</td>
<td>Moving work-in-process along variable routes in low and medium production</td>
</tr>
<tr>
<td></td>
<td>Flexible routing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nonobstructive pathways</td>
<td></td>
</tr>
<tr>
<td>Monorails and other rail guided vehicles</td>
<td>High cost</td>
<td>Moving single assemblies, products, or pallet loads along variable routes in factory or warehouse</td>
</tr>
<tr>
<td></td>
<td>Flexible routing</td>
<td>Moving large quantities of items over fixed routes in a factory or warehouse</td>
</tr>
<tr>
<td></td>
<td>On-the-floor or overhead types</td>
<td></td>
</tr>
<tr>
<td>Conveyors, powered</td>
<td>Great variety of equipment</td>
<td>Moving products along a manual assembly line</td>
</tr>
<tr>
<td></td>
<td>In-floor, on-the-floor, or overhead</td>
<td>Sortation of items in a distribution center</td>
</tr>
<tr>
<td></td>
<td>Mechanical power to move loads resides in pathway</td>
<td></td>
</tr>
<tr>
<td>Cranes and hoists</td>
<td>Lift capacities ranging up to more than 100 tons</td>
<td>Moving large, heavy items in factories, mills, warehouses, etc.</td>
</tr>
</tbody>
</table>

1.1 INDUSTRIAL TRUCKS

Industrial trucks are divided into two categories: nonpowered and powered. The nonpowered types are often referred to as hand trucks because they are pushed or pulled by human workers. Quantities of material moved and distances are relatively low when this type of equipment is used to transport materials. Hand trucks are classified as either two-wheel or multiple-wheel. Two-wheel hand trucks, Figure 10.1(a), are generally easier to manipulate.

Figure 10.1 Examples of non-powered industrial trucks (hand trucks): (a) two-wheel hand truck, (b) four-wheel dolly, and (c) hand-operated low-lift pallet truck.
by the worker but are limited to lighter loads. Multiple-wheeled hand trucks are available in several types and sizes. Two common types are dollies and pallet trucks. Dollies are simple frames or platforms as shown in Figure 10.1(b). Various wheel configurations are possible, including fixed wheels and caster-type wheels. Pallet trucks, Figure 10.1(c), have two forks that can be inserted through the openings in a pallet. A lift mechanism is actuated by the worker to lift and lower the pallet off the ground using small diameter wheels near the end of the forks. In operation, the worker inserts the forks into the pallet, elevates the load, pulls the truck to its destination, then lowers the pallet, and removes the forks.

Powered trucks are self-propelled to relieve the worker of manually having to move the truck. Three common types are used in factories and warehouses: (a) walkie trucks, (b) forklift rider trucks, and (c) towing tractors. Walkie trucks, Figure 10.2(a), are battery-powered vehicles equipped with wheeled forks for insertion into pallet openings but with no provision for a worker to ride on the vehicle. The truck is steered by a worker using a control handle at the front of the vehicle. The forward speed of a walkie truck is limited to around 3 mi/hr (5 km/hr), which is about equal to the normal walking speed of a human.

Forklift rider trucks, Figure 10.2(b), are distinguished from walkie trucks by the presence of a modest cab for the worker to sit in and drive the vehicle. Forklift trucks range in load carrying capacity from about 450 kg (1,000 lb) up to more than 4,500 kg (10,000 lb). The various applications for which forklift trucks are used have resulted in a variety of vehicle features and configurations. These include trucks with high reach capacities for accessing pallet loads on high rack systems and trucks capable of operating in the narrow

![Figure 10.2](image_url)
An automated guided vehicle system (AGVS) is a material handling system that uses independently operated, self-propelled vehicles guided along defined pathways. The vehicles are powered by on-board batteries that allow many hours of operation (8-16 hr is typical) between recharging. A distinguishing feature of an AGVS, compared to rail guided vehicle systems and most conveyor systems, is that the pathways are unobtrusive. An AGVS is appropriate where different materials are moved from various load points to various unload points. An AGVS is therefore suitable for automating material handling in batch production and mixed model production. The first AGV was operated in 1954 (Historical Note 10.1).

10.2 AUTOMATED GUIDED VEHICLE SYSTEMS

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Historical Note 10.1  Automated guided vehicles [2, 6]

The first automated guided vehicle was developed in 1954 by A. M. Barrett, Jr., who used an overhead wire to guide a modified towing truck pulling a trailer in a grocery warehouse. Commercial AGVs were subsequently introduced by Barrett.

Around 1973, Volvo, the Swedish carmaker, developed automated guided vehicles to serve as assembly platforms for moving car bodies through its final assembly plants. The primary purpose of Volvo's development project was not to market the AGV commercially, but rather to advance a new method of assembly as an alternative to the traditional assembly line. The new assembly system emphasized teamwork, job enlargement, and asynchronous movement of products through the plant. However, by developing the guided moving platforms in assembly, the company had introduced a new type of AGV, the unit load vehicle. Volvo later entered the AGV business and marketed their unit load AGVs to other car companies.

Advances in AGVS technology have been motivated largely by rapid developments in electronics and computer technologies. By exploiting these technologies, the AGVS industry has made improvements and refinements in vehicle guidance and navigation, on-board vehicle intelligence and control, overall system management, and safety.

10.2.1 Types of Vehicles and AGVS Applications

Automated guided vehicles can be divided into the following three categories: (1) driverless trains, (2) pallet trucks, and (3) unit load carriers, illustrated in Figure 10.3. A driverless train consists of a towing vehicle (which is the AGV) that pulls one or more trailers to form a train, as in Figure 10.3(a). It was the first type of AGVS to be introduced and is still widely used today. A common application is moving heavy payloads over large distances.
Figure 10.3 Three types of automated guided vehicles: (a) driverless automated guided train, (b) AGV pallet truck, and (c) unit load carrier.

in warehouses or factories with or without intermediate pickup and drop-off points along the route. For trains consisting of five to ten trailers, this is an efficient transport system.

Automated guided pallet trucks. Figure 10.3(b), are used to move palletized loads along predetermined routes. In the typical application the vehicle is backed into the loaded pallet by a human worker who steers the truck and uses its forks to elevate the load slightly. Then the worker drives the pallet truck to the guidepath, programs its destination, and the vehicle proceeds automatically to the destination for unloading. The capacity of an AGVS pallet truck ranges up to several thousand kilograms, and some trucks are capable of handling two pallets rather than one. A more recent introduction related to the pallet truck is the fork lift AGV. This vehicle can achieve significant vertical movement of its forks to reach loads on racks and shelves.

AGV unit load carriers are used to move unit loads from one station to another. They are often equipped for automatic loading and unloading of pallets or tote pans by means of powered rollers, moving belts, mechanized lift platforms, or other devices built into the vehicle deck. A typical unit load AGV is illustrated in Figure 10.3(c). Variations of unit load carriers include light load AGVs and assembly line AGVs. The light load AGV is a relatively small vehicle with corresponding load capacity (typically 250 kg or less). It does not require the same large aisle width as a conventional AGV. Light load guided vehicles are designed to move small loads (single parts, small baskets or tote pans of parts, etc.) through plants of limited size engaged in light manufacturing. An assembly line AGV
Automated guided vehicle systems are used in a growing number and variety of applications. The applications tend to parallel the vehicle types previously described. We have already described driverless train operations, which involve the movement of large quantities of material over relatively large distances.

A second application area is in storage and distribution. Unit load carriers and pallet trucks are typically used in these applications, which involve movement of material in unit loads. The applications often interface the AGVS with some other automated handling or storage system, such as an automated storage/retrieval system (AS/RS, Section 11.4.1) in a distribution center. The AGVS delivers incoming unit loads contained on pallets from the receiving dock to the AS/RS, which places the items into storage, and the AS/RS retrieves individual pallet loads from storage and transfers them to vehicles for delivery to the shipping dock. Storage/distribution operations also include light manufacturing and assembly plants in which work-in-process is stored in a central storage area and distributed to individual workstations for processing. Electronics assembly is an example of these kinds of applications. Components are “kitted” at the storage area and delivered in tote pans or trays by the guided vehicles to the assembly workstations in the plant. Light load AGVs are the appropriate vehicles in these applications.

AGV systems are used in assembly line applications, based on a trend that began in Europe. Unit load carriers and light load guided vehicles are used in these lines. In the usual application, the production rate is relatively low (the product spends perhaps 4-10 min per station), and there are several different product models made on the line, each requiring a different processing time. Workstations are generally arranged in parallel to allow the line to deal with differences in assembly cycle time for different products. Between stations, components are kitted and placed on the vehicle for the assembly operations to be performed at the next station. The assembly tasks are usually performed with the work unit on-board the vehicle, thus avoiding the extra time required for unloading and reloading.

Another application area for AGVS technology is flexible manufacturing systems (FMSs, Chapter 16). In the typical operation, starting workparts are placed onto pallet fixtures by human workers in a staging area, and the AGVs deliver the parts to the individual workstations in the system. When the AGV arrives at the assigned station, the pallet is transferred from the vehicle platform to the station (such as the worktable of a machine tool) for processing. At the completion of processing a vehicle returns to pick up the work and transport it to the next assigned station. An AGVS provides a versatile material handling system to complement the flexibility of the FMS.

Other applications of automated guided vehicle systems include office mail delivery and hospital material transport. Hospital guided vehicles transport meal trays, linen, medical and laboratory supplies, and other materials between various departments in the building. These transports typically require movement of vehicles between different floors in the hospital, and hospital AGV systems have the capability to summon and use elevators for this purpose.

AGVS technology is still developing, and the industry is continually working to design new systems to respond to new application requirements. An interesting example that combines two technologies involves the use of a robotic manipulator mounted on an automated guided vehicle to provide a mobile robot for performing complex handling tasks.
at various locations in a plant. These robot-vehicles have potential applications in clean rooms in the semiconductor industry.

10.2.2 Vehicle Guidance Technology

The guidance system is the method by which AGVS pathways are defined and vehicles are controlled to follow the pathways. In this section, we discuss three technologies that are used in commercial systems for vehicle guidance: (1) imbedded guide wires, (2) paint strips, and (3) self-guided vehicles.

Imbedded Guide Wires and Paint Strips. In the imbedded guide wire method, electrical wires are placed in a small channel cut into the surface of the floor. The channel is typically 3-12 mm (1/8-1/2 in) wide and 13-26 mm (1/2-1.0 in) deep. After the guide wire is installed, the channel is filled with cement to eliminate the discontinuity in the floor surface. The guide wire is connected to a frequency generator, which emits a low-voltage, low-current signal with a frequency in the range 1-15 kHz. This induces a magnetic field along the pathway that can be followed by sensors on-board each vehicle. The operation of a typical system is illustrated in Figure 10.4. Two sensors (coils) are mounted on the vehicle on either side of the guide wire. When the vehicle is located such that the guide wire is directly between the two coils, the intensity of the magnetic field measured by each coil will be equal. If the vehicle strays to one side or the other, or if the guide wire path changes direction, the magnetic field intensity at the two sensors will be different. This difference is used to control the steering motor, which makes the required changes in vehicle direction to equalize the two sensor signals, thereby tracking the guide wire.

A typical AGVS layout contains multiple loops, branches, side tracks, and spurs, as well as pickup and drop-off stations. The most appropriate route must be selected from the alternative pathways available to a vehicle in its movement to a specified destination in the system. When a vehicle approaches a branching point where the guide path forks into two (or more) pathways, a means of deciding which path to take must be provided. The two principal methods of making this decision in commercial wire guided systems are: (1) the frequency select method and (2) the path switch select method. In the frequency select method, the guide wires leading into the two separate paths at the switch have different frequencies.
cies. As the vehicle enters the switch, it reads an identification code on the floor to determine its location. Depending on its programmed destination, the vehicle selects the correct guidepath by following only one of the frequencies. This method requires a separate frequency generator for each different frequency used in the guidepath layout. The path switch select method operates with a single frequency throughout the guidepath layout. To control the path of a vehicle at a switch, the power is turned off in all other branches except the one that the vehicle is to travel on. To accomplish routing by the path switch select method, the guidepath layout is divided into blocks that are electrically insulated from each other. The blocks can be turned on and off either by the vehicles themselves or by a central control computer.

When paint strips are used to define the pathway, the vehicle uses an optical sensor system capable of tracking the paint. The strips can be taped, sprayed, or painted on the floor. One system uses a 1-in-wide paint strip containing fluorescent particles that reflect an ultraviolet (UV) light source from the vehicle. An on-board sensor detects the reflected light in the strip and controls the steering mechanism to follow it. Paint strip guidance is useful in environments where electrical noise renders the guide wire system unreliable or when the installation of guide wires in the floor surface is not practical. One problem with this guidance method is that the paint strip deteriorates with time. It must be kept clean and periodically repainted.

Self-Guided Vehicles. Self-guided vehicles (SGVs) represent the latest AGVS guidance technology. Unlike the previous two guidance methods, SGVs operate without continuously defined pathways. Instead, they use a combination of dead reckoning and beacons located throughout the plant, which can be identified by on-board sensors. Dead reckoning refers to the capability of a vehicle to follow a given route in the absence of a defined pathway in the floor. Movement of the vehicle along the route is accomplished by computing the required number of wheel rotations in a sequence of specified steering angles. The computations are performed by the vehicle's on-board computer. As one would expect, positioning accuracy of dead reckoning decreases with increasing distance. Accordingly, the location of the self-guided vehicle must be periodically verified by comparing the calculated position with one or more known positions. These known positions are established using beacons located strategically throughout the plant. There are various types of beacons used in commercial SGV systems. One system uses bar-coded beacons mounted along the aisles. These beacons can be sensed by a rotating laser scanner on the vehicle. Based on the positions of the beacons, the on-board navigation computer uses triangulation to update the positions calculated by dead reckoning. Another guidance system uses magnetic beacons imbedded in the plant floor along the pathway. Dead reckoning is used to move the vehicle between beacons, and the actual locations of the beacons provide data to update the computer's dead reckoning map.

It should be noted that dead reckoning can be used by AGV systems that are normally guided by in-floor guide wires or paint strips. This capability allows the vehicle to cross steel plates in the factory floor where guide wires cannot be installed or to depart from the guidepath for positioning at a load/unload station. At the completion of the dead reckoning maneuver, the vehicle is programmed to return to the guidepath to resume normal guidance control.

The advantage of self-guided vehicle technology over fixed pathways (guide wires and paint strips) is its flexibility. The SGV pathways are defined in software. The path network can be changed by entering the required data into the navigation computer. New docking
points can be defined. The pathway network can be expanded by installing new beacons. These changes can be made quickly and without major alterations to the plant facility.

10.2.3 Vehicle Management and Safety

For the AGVS to operate efficiently, the vehicles must be well managed. Delivery tasks must be allocated to vehicles to minimize waiting times at load/unload stations. Traffic congestion in the guidepath network must be minimized. And the AGVS must be operated safely. In this section we consider these issues.

Traffic Control. The purpose of traffic control in an automated guided vehicle system is to minimize interference between vehicles and to prevent collisions. Two methods of traffic control used in commercial AGV systems are: (1) on-board vehicle sensing and (2) zone control. The two techniques are often used in combination. On-board vehicle sensing, also called forward sensing, involves the use of one or more sensors on each vehicle to detect the presence of other vehicles and obstacles ahead on the guide path. Sensor technologies include optical and ultrasonic devices. When the on-board sensor detects an obstacle in front of it, the vehicle stops. When the obstacle is removed, the vehicle proceeds. If the sensor system is 100% effective, collisions between vehicles are avoided. The effectiveness of forward sensing is limited by the capability of the sensor to detect obstacles that are in front of it on the guide path. These systems are most effective on straight pathways. They are less effective at turns and convergence points where forward vehicles may not be directly in front of the sensor.

In zone control, the AGVS layout is divided into separate zones, and the operating rule is that no vehicle is permitted to enter a zone if that zone is already occupied by another vehicle. The length of a zone is at least sufficient to hold one vehicle plus allowances for safety and other considerations. Other considerations include number of vehicles in the system, size and complexity of the layout, and the objective of minimizing the number of separate zone controls. For these reasons, the zones are normally much longer than a vehicle length. Zone control is illustrated in Figure 10.5 in its simplest form. When one vehicle occupies a given zone, any trailing vehicle is not allowed to enter that zone. The leading vehicle must proceed into the next zone before the trailing vehicle can occupy the current zone. By controlling the forward movement of vehicles in the separate zones, collisions are prevented, and traffic in the overall system is controlled.

One means of implementing zone control is to use separate control units mounted along the guide path. When a vehicle enters a given zone, it activates the block in that zone to prevent any trailing vehicle from moving forward and colliding with the present vehicle. As the present vehicle moves into the next (downstream) zone, it activates the block

Figure 10.5 Zone control to implement blocking system. Zones A, B, and D are blocked. Zone C is free. Vehicle 2 is blocked from entering Zone A by Vehicle 1. Vehicle 3 is free to enter Zone C.
in that zone and deactivates the block in the previous zone. In effect, zones are turned on
and off to control vehicle movement by the blocking system. Another method to implement
zone control is to use a central computer, which monitors the location of each vehicle and
attempts to optimize the movement of all vehicles in the system.

Vehicle Dispatching. For an AGVS to serve its function, vehicles must be dis-
patched in a timely and efficient manner to the points in the system where they are need-
ed. Several methods are used in AGV systems to dispatch vehicles: (1) on-board control
panel, (2) remote call stations, and (3) central computer control. These dispatching meth-
ods are generally used in combination to maximize responsiveness and efficiency.

Each guided vehicle is equipped with some form of on-board control panel for the pur-
pose of manual vehicle control, vehicle programming, and other functions. Most commer-
cial vehicles can be dispatched by means of this control panel to a given station in the
AGVS layout. Dispatching with an on-board control panel represents the lowest level of
sophistication among the possible methods. It provides the AGVS with flexibility and time-
liness in coping with changes and variations in delivery requirements.

Remote call stations represent another method for an AGVS to satisfy delivery re-
quirements. The simplest call station is a press button mounted at the load/unload station.
This transmits a hailing signal for any available vehicle in the neighborhood to dock at the
station and either pick up or drop off a load. The on-board control panel might then be used
to dispatch the vehicle to the desired destination point. More sophisticated remote call sta-
tions permit the vehicle’s destination to be programmed at the same time the vehicle is
called. This is a more-automated dispatching method that is useful in AGV systems capa-
bile of automatic loading and unloading operations.

In a large factory or warehouse involving a high degree of automation, the AGVS ser-
vicing the facility must also be highly automated to achieve efficient operation of the en-
tire production-storage-handling system. Central computer control is used to accomplish
automatic dispatching of vehicles according to a preplanned schedule of pickups and de-
liveries in the layout and/or in response to calls from the various load/unload stations.
In this dispatching method, the central computer issues commands to the vehicles in the sys-
tem concerning their destinations and the operations they must perform. To accomplish the
dispatching function, the central computer must possess current information on the loca-
tion of each vehicle in the system so that it can make appropriate decisions about which
vehicles to dispatch to what locations. Hence, the vehicles must continually communicate
their whereabouts to the central controller. Radio frequency (RF) is commonly used to
achieve the required communication links.

A useful tool in systems management is a performance report for each shift (or other
appropriate time period) of AGVS operation. Periodic reporting of system performance
provides summary information about uptime and downtime, number of deliveries made
during a shift, and other data about each station and each vehicle in the system. Reports
containing this type of information permit managers to compare operations from shift to
shift and month to month to identify differences and trends and to maintain a high level
of system performance.

Safety. The safety of humans located along the pathway is an important objective
in AGVS design. An inherent safety feature of an AGV is that its traveling speed is slow-
er than the normal walking pace of a human. This minimizes the danger of overtaking a
human walking along the guide path in front of the vehicle.
In addition, AGVs are usually provided with several other features specifically for safety reasons. A safety feature included in most guidance systems is automatic stopping of the vehicle if it strays more than a short distance, typically 50–150 mm (2–6 in), from the guide path. The distance is referred to as the vehicle's acquisition distance. This automatic stopping feature prevents a vehicle from running wild in the building. Alternatively, in the event that the vehicle is off the guideway (e.g., for loading), its sensor system is capable of locking onto the guide path when the vehicle is moved within the acquisition distance.

Another safety device is an obstacle detection sensor located on each vehicle. This is the same on-board sensor used for traffic control. The sensor can detect obstacles along the forward path, including humans. The vehicles are programmed either to stop when an obstacle is sensed ahead or to slow down. The reason for slowing down is that the sensed object may be located off to the side of the vehicle path or directly ahead but beyond a turn in the guide path, or the obstacle may be a person who will move out of the way as the AGV approaches. In any of these cases, the vehicle is permitted to proceed at a slower (safer) speed until it has passed the obstacle. The disadvantage of programming a vehicle to stop when it encounters an obstacle is that this delays the delivery and degrades system performance.

A safety device included on virtually all commercial AGVs is an emergency bumper. This bumper is prominent in several of our figures. The bumper surrounds the front of the vehicle and protrudes ahead of it by a distance of 300 mm (12 in) or more. When the bumper makes contact with an object, the vehicle is programmed to brake immediately. Depending on the speed of the vehicle, its load, and other conditions, the braking distance will vary from several inches to several feet. Most vehicles are programmed to require manual restarting after an obstacle has been encountered by the emergency bumper. Other safety devices on a typical vehicle include warning lights (blinking or rotating lights) and/or warning bells, which alert humans that the vehicle is present.

10.3 MONORAILS AND OTHER RAIL GUIDED VEHICLES

The third category of material transport equipment consists of motorized vehicles that are guided by a fixed rail system. The rail system consists of either one rail (called a monorail) or two parallel rails. Monorail systems in factories and warehouses are typically suspended overhead from the ceiling. In rail guided vehicle systems using parallel fixed rails, the tracks generally protrude up from the floor. In either case, the presence of a fixed rail pathway distinguishes these systems from automated guided vehicle systems. As with AGVs, the vehicles operate asynchronously and are driven by an on-board electric motor. But unlike AGVs, which are powered by their own on-board batteries, rail guided vehicles pick up electrical power from an electrified rail (similar to an urban rapid transit rail system). This relieves the vehicle from periodic recharging of its battery; however, the electrified rail system introduces a safety hazard not present in an AGVS.

Routing variations are possible in rail guided vehicle systems through the use of switches, turntables, and other specialized track sections. This permits different loads to travel different routes, similar to an AGVS. Rail guided systems are generally considered to be more versatile than conveyor systems but less versatile than automated guided vehicle systems. One of the original applications of nonpowered monorails was in the meat processing industry before 1900. For dressing and cleaning, the slaughtered animals were hung from meat hooks attached to overhead monorail trolleys. The trolleys were moved
through the different departments of the plant manually by the workers. It is likely that Henry Ford got the idea for the assembly line from observing these meat packing operations. Today, the automotive industry makes considerable use of electrified overhead monorails to move large components and subassemblies in its manufacturing operations.

10.4 CONVEYOR SYSTEMS

Conveyors are used when material must be moved in relatively large quantities between specific locations over a fixed path. The fixed path is implemented by a track system, which may be in-the-floor, above-the-floor, or overhead. Conveyors divide into two basic categories: (1) powered and (2) non-powered. In powered conveyors, the power mechanism is contained in the fixed path, using chains, belts, rotating rolls, or other devices to propel loads along the path. Powered conveyors are commonly used in automated material transport systems in manufacturing plants, warehouses, and distribution centers. In non-powered conveyors, materials are moved either manually by human workers who push the loads along the fixed path or by gravity from one elevation to a lower elevation.

10.4.1 Types of Conveyors

A variety of conveyor equipment is commercially available. In the following paragraphs, we describe the major types of powered conveyors, organized according to the type of mechanical power provided in the fixed path.

Roller and Skate Wheel Conveyors. These conveyors have rolls or wheels on which the loads ride. Loads must possess a flat bottom surface of sufficient area to span several adjacent rollers. Pallets, tote pans, or cartons serve this purpose well. The two main entries in this category are roller conveyors and skate wheel conveyors, pictured in Figure 10.6.

In roller conveyors, the pathway consists of a series of tubes (rollers) that are perpendicular to the direction of travel, as in Figure 10.6(a). The rollers are contained in a fixed frame that elevates the pathway above floor level from several inches to several feet. Flat pallets or tote pans carrying unit loads are moved forward as the rollers rotate. Roller conveyors can either be powered or non-powered. Powered roller conveyors are driven

![Figure 10.6](image-url)
by belts or chains. Non-powered roller conveyors are often driven by gravity so that the pathway has a downward slope sufficient to overcome rolling friction. Roller conveyors are used in a wide variety of applications, including manufacturing, assembly, packaging, sortation, and distribution.

Skate-wheel conveyors are similar in operation to roller conveyors. Instead of rollers, they use skate wheels rotating on shafts connected to a frame to roll pallets or tote pans or other containers along the pathway, as in Figure 10.6(b). This provides the skate wheel conveyor with a lighter weight construction than the roller conveyor. Applications of skate-wheel conveyors are similar to those of roller conveyors, except that the loads must generally be lighter since the contacts between the loads and the conveyor are much more concentrated. Because of their lighter construction, skate wheel conveyors are sometimes built as portable equipment that can be used for loading and unloading truck trailers at shipping and receiving docks at factories and warehouses.

Belt Conveyors. Belt conveyors consist of a continuous loop: Half its length is used for delivering materials, and the other half is the return run, as in Figure 10.7. The belt is made of reinforced elastomer (rubber), so that it possesses high flexibility but low extensibility. At one end of the conveyor is a drive roll that powers the belt. The flexible belt is supported by a frame that has rollers or support sliders along its forward loop. Belt conveyors are available in two common forms: (1) flat belts for pallets, individual parts, or even certain types of bulk materials; and (2) troughed belts for bulk materials. Materials placed on the belt surface travel along the moving pathway. In the case of troughed belt conveyors, the rollers and supports give the flexible belt a V-shape on the forward (delivery) loop to contain bulk materials such as coal, gravel, grain, or similar particulate materials.

Conveyors Driven by Chains and Cables. The conveyors in this group are driven by a powered chain or cable that forms an endless loop. In some cases, the loop forms a straight line, with a pulley at each end. This is usually in an over-and-under configuration. In other conveyors, the loop has a more-complex path, with more than two pulleys needed to define the shape of the path. We discuss the following conveyors in this category: (1) chain, (2) slat, (3) in-floor towline, (4) overhead trolley, and (5) power-and-free overhead trolley.

Chain conveyors consist of chain loops in an over-and-under configuration around powered sprockets at the ends of the pathway. One or more chains operating in parallel may
be used to form the conveyor. The chains travel along channels in the floor that provide support for the flexible chain sections. Either the chains slide along the channel or they ride on rollers in the channel. The loads are generally dragged along the pathway using bars that project up from the moving chain.

The slat conveyor uses individual platforms, called slats, connected to a continuously moving chain. Although the drive mechanism is a powered chain, it operates much like a belt conveyor. Loads are placed on the slats and are transported along with them. Straight line flows are common in slat conveyor systems. However, because of the chain drive and the capability to alter the chain direction using sprockets, the conveyor pathway can have turns in its continuous loop.

Another variation of the chain conveyor is the in-floor towline conveyor. These conveyors make use of four-wheel carts powered by moving chains or cables located in trenches in the floor, as in Figure 10.8. The chain or cable is called a towline; hence, the name of the conveyor. Pathways for the conveyor system are defined by the trench and cable, and the cable is driven as a powered pulley system. Switching between powered pathways is possible in a towline system to achieve flexibility in routing. The carts use steel pins that project below floor level into the trench to engage the chain for towing. (Gripper devices are substituted for pins when cable is used as the pulley system, similar to the San Francisco trolley.) The pin can be pulled out of the chain (or the gripper releases the cable) to disengage the cart for loading, unloading, switching, accumulation of parts, and manually pushing a cart off the main pathway. Towline conveyor systems are used in manufacturing plants and warehouses.

All of the preceding chain and cable drive conveyors operate at floor level or slightly above. Chain-driven conveyors can also be designed to operate overhead, suspended from the ceiling of the facility so as not to consume floorspace. The most common types are overhead trolley conveyors. These are available either as constant speed (synchronous) or as power-and-free (asynchronous) systems.

![Diagram of in-floor towline conveyor.](image-url)
A trolley in material handling is a wheeled carriage running on an overhead rail from which loads can be suspended. An overhead trolley conveyor, Figure 10.9, consists of multiple trolleys, usually equally spaced along a fixed track. The trolleys are connected together and moved along the track by means of a chain or cable that forms a complete loop. Suspended from the trolleys are hooks, baskets, or other receptacles to carry loads. The chain (or cable) is attached to a drive wheel that supplies power to move the chain at a constant velocity. The conveyor path is determined by the configuration of the track system, which has turns and possible changes in elevation. Overhead trolley conveyors are often used in factories to move parts and assemblies between major production departments. They can be used for both delivery and storage.

A power-and-free overhead trolley conveyor is similar to the overhead trolley conveyor, except that the trolleys are capable of being disconnected from the drive chain, providing this conveyor with an asynchronous capability. This is usually accomplished by using two tracks, one just above the other. The upper track contains the continuously moving endless chain, and the trolleys that carry loads ride on the lower track. Each trolley includes a mechanism by which it can be connected to the drive chain and disconnected from it. When connected, the trolley is pulled along its track by the moving chain in the upper track. When disconnected, the trolley is idle.

Other Conveyor Types. Other powered conveyors include cart-on-track, screw, vibration-based systems, and vertical lift conveyors. Cart-on-track conveyors consist of individual carts riding on a track a few feet above floor level. The carts are driven by means of a rotating shaft, as illustrated in Figure 10.10. A drive wheel, attached to the bottom of the cart and set at an angle to the rotating tube, rests against it and drives the cart forward. The cart speed is controlled by regulating the angle of contact between the drive wheel and the spinning tube. When the axis of the drive wheel is 45°, the cart is propelled forward. When the axis of the drive wheel is parallel to the tube, the cart does not move. Thus, control of the drive wheel angle on the cart allows power-and-free operation of the conveyor. One of the advantages of cart-on-track systems relative to many other conveyors is that the carts can be positioned with high accuracy. This permits their use for positioning work during production. Applications of cart-on-track systems include robotic spot welding lines in automobile body plants and mechanical assembly systems.
Screw conveyors are based on the Archimedes screw, the water-raising device devised in ancient times (circa 236 B.C.), consisting of a large screw inside a cylinder, turned by hand to pump water up-hill for irrigation purposes. Vibration-based conveyors use a flat track connected to an electromagnet that imparts an angular vibratory motion to the track to propel items in the desired direction. This same principle is used in vibratory bowl feeders to deliver components in automated assembly systems (Section 19.1.2). Vertical lift conveyors include a variety of mechanical elevators designed to provide vertical motion, such as between ﬂoors or to link ﬂoor-based conveyors with overhead conveyors. Other conveyor types include nonpowered chutes, ramps, and tubes, which are driven by gravity.

10.4.2 Conveyor Operations and Features

As indicated by our preceding discussion, conveyor equipment covers a wide variety of operations and features. Let us restrict our discussion here to powered conveyors, excluding nonpowered types. Conveyor systems divide into two basic types in terms of the characteristic motion of the materials moved by the system: (1) continuous and (2) asynchronous. Continuous motion conveyors move at a constant velocity \( v_c \) along the path. They include belt, roller, skate-wheel, overhead trolley, and slat conveyors.

Asynchronous conveyors operate with a stop-and-go motion in which loads, usually contained in carriers (e.g., hooks, baskets, carts), move between stations and then stop and remain at the station until released. Asynchronous handling allows independent movement of each carrier in the system. Examples of this type include overhead power-and-free trolley, in-floor towline, and cart-on-track conveyors. Some roller and skate-wheel
Conveyors can also be operated asynchronously. Reasons for using asynchronous conveyors include: (1) to accumulate loads, (2) temporary storage, (3) to allow for differences in production rates between adjacent processing areas, (4) to smooth production when cycle times vary at stations along the conveyor, and (5) to accommodate different conveyor speeds along the pathway.

Conveyors can also be classified as: (1) single direction, (2) continuous loop, and (3) recirculating. In the following paragraphs, we describe the operating features of these categories. In Section 10.6.3, we present equations and techniques with which to analyze these conveyor systems. Single direction conveyors are used to transport loads one way from origination point to destination point, as depicted in Figure 10.11(a). These systems are appropriate when there is no need to move loads in both directions or to return containers or carriers from the unloading stations back to the loading stations. Single direction powered conveyors include roller, skate wheel, belt, and chain-in-floor types. In addition, all gravity conveyors operate in one direction.

Continuous loop conveyors form a complete circuit, as in Figure 10.11(b). An overhead trolley conveyor is an example of this conveyor type. However, any conveyor type can be configured as a loop, even those previously defined as single direction conveyors, simply by connecting several single direction conveyor sections into a closed loop. A continuous loop system allows materials to be moved between any two stations along the pathway. Continuous loop conveyors are used when loads are moved in carriers (e.g., hooks, baskets) between load and unload stations and the carriers are affixed to the conveyor loop. In this design, the empty carriers are automatically returned from the unload station back to the load station.

The preceding description of a continuous loop conveyor assumes that items loaded at the load station are unloaded at the unload station. There are no loads in the return loop; the purpose of the return loop is simply to send the empty carriers back for reloading. This method of operation overlooks an important opportunity offered by a closed-loop conveyor: to store as well as deliver parts. Conveyor systems that allow parts to remain on the return loop for one or more revolutions are called recirculating conveyors. In providing a storage function, the conveyor system can be used to accumulate parts to smooth out effects of loading and unloading variations at stations in the conveyor. There are two

![Figure 10.11](a) Single direction conveyor and (b) continuous loop conveyor.)
problems that can plague the operation of a recirculating conveyor system. One is that there may be times during the operation of the conveyor that no empty carriers are immediately available at the loading station when needed. The other problem is that no loaded carriers are immediately available at the unloading station when needed.

It is possible to construct branching and merging points into a conveyor track to permit different routings for different loads moving in the system. In nearly all conveyor systems, it is possible to build switches, shuttles, or other mechanisms to achieve these alternate routings. In some systems, a push-pull mechanism or lift-and-carry device is required to actively move the load from the current pathway onto the new pathway.

10.5 CRANES AND HOISTS

The fifth category of transport equipment in material handling consists of cranes and hoists. Cranes are used for horizontal movement of materials in a facility, and hoists are used for vertical lifting. A crane invariably includes a hoist; thus, the hoist component of the crane lifts the load, and the crane transports the load horizontally to the desired destination. This class of material handling equipment includes cranes capable of lifting and moving very heavy loads, in some cases over 100 tons.

A hoist is a mechanical device that can be used to raise and lower loads. As seen in Figure 10.12, a hoist consists of one or more fixed pulleys, one or more moving pulleys, and a rope, cable, or chain strung between the pulleys. A hook or other means for attaching the load is connected to the moving pulley(s). The number of pulleys in the hoist determines its mechanical advantage, which is the ratio of the load weight to the driving force required to lift the weight. The mechanical advantage of the hoist in our illustration is 4.0. The driving force to operate the hoist is applied either manually or by electric or pneumatic motor.

Figure 10.12 A hoist with a mechanical advantage of 4.0: (a) sketch of the hoist and (b) diagram to illustrate mechanical advantage.
Crane include a variety of material handling equipment designed for lifting and moving heavy loads using one or more overhead beams for support. Principal types of cranes found in factories include: (a) bridge cranes, (b) gantry cranes, and (c) jib cranes. In all three types, at least one hoist is mounted to a trolley that rides on the overhead beam of the crane. A bridge crane consists of one or two horizontal girders or beams suspended between fixed rails on either end which are connected to the structure of the building, as shown in Figure 10.13(a). The hoist trolley can be moved along the length of the bridge, and the bridge can be moved the length of the rails in the building. These two drive capabilities provide motion in the x- and y-axes of the building, and the hoist provides motion in the z-axis direction. Thus the bridge crane achieves vertical lifting due to its hoist and achieves horizontal movement of the material due to its orthogonal rail system. Large bridge cranes have girders that span up to 36.5 m (120 ft) and are capable of carrying loads up to 90,000 kg (100 tons). Large bridge cranes are controlled by operators riding in cabs on the bridge. Applications include heavy machinery fabrication, steel and other metal mills, and power-generating stations.

A gantry crane is distinguished from a bridge crane by the presence of one or two vertical legs that support the horizontal bridge. As with the bridge crane, a gantry crane includes one or more hoists that accomplish vertical lifting. Gantry cranes are available in a variety of sizes and capacities, the largest possessing spans of about 46 m (150 ft) and load capacities of 136,000 kg (150 tons). A double gantry crane has two legs. Other types include half gantries and cantilever gantries. A half gantry crane, Figure 10.13(b), has a single leg on one end of the bridge, and the other end is supported by a rail mounted on the wall or other structural member of a building. A cantilever gantry crane is identified by the fact that its bridge extends beyond the span created by the support legs.

A jib crane consists of a hoist supported on a horizontal beam that is cantilevered from a vertical column or wall support, as illustrated in Figure 9.2(e). The horizontal beam is pivoted about the vertical axis formed by the column or wall to provide a horizontal sweep.
for the crane. The beam also serves as the track for the hoist trolley to provide radial travel along the length of the beam. Thus, the horizontal area included by a jib crane is circular or semicircular. As with other cranes, the hoist provides vertical lift and lower motions. Standard capacities of jib cranes range up to about 5000 kg. Wall-mounted jib cranes can achieve a swing of about 180°, while floor-mounted jib cranes using a column or post as its vertical support can sweep a full 360°.

10.6 ANALYSIS OF MATERIAL TRANSPORT SYSTEMS

Charting techniques are helpful for visualizing the movement of materials, and quantitative models are useful for analyzing material flow rates, delivery cycle times, and other aspects of performance. Research on these analysis methods is encouraged and supported by the College Industry Council on Material Handling Education (CICMHE) and the Material Handling Institute (MHI), which hold a semiannual Research Colloquium whose Proceedings [11] are available through MHI. In this section, we discuss the following: (1) charting techniques in material handling, (2) analysis of vehicle-based systems, and (3) conveyor analysis.

10.6.1 Charting Techniques in Material Handling

A useful charting technique for displaying information about material flow is the From-To Chart, illustrated in Table 10.2. In this table, the left-hand vertical column lists origination points (loading stations) from which trips are made, and the horizontal row at the top of the chart lists destination points (unload stations). The chart is organized for possible material flows in both directions between the load/unload stations in the layout. From-To Charts can be used to represent various parameters of the material flow problem, including number of deliveries or flow rates between locations in the layout and travel distances between from-to locations. Table 10.2 represents one possible format to display both flow rates and corresponding distances for a given material handling problem.

<table>
<thead>
<tr>
<th>TABLE 10.2</th>
<th>From-To Chart Showing Flow Rates, loads/hr (Value Before the Slash Mark) and Travel Distances, m (Value After the Slash Mark) Between Stations in a Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>To</td>
<td>1</td>
</tr>
<tr>
<td>From 1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

1 The Material Handling Institute, based in Charlotte, North Carolina, is the research and education agency of the Material Handling Industry of America, the trade association representing companies that sell material handling products and services in the United States. The College Industry Council on Material Handling Education consists of academic and industry representatives and reports to the Material Handling Institute.
Muther and Haganas [19] suggest several graphical techniques for visualizing transports, including mathematical plots and flow diagrams of different types. The flow diagram in Figure 10.14 indicates movement of materials and corresponding origination and destination points of the moves. In this diagram, origination and destination points are represented by nodes, and material flows are depicted by arrows between the points. The nodes might represent production departments between which parts are moved or load and unload stations in a facility. Our flow diagram portrays the same information as in the From-To Chart of Table 10.2.

### 10.6.2 Analysis of Vehicle-Based Systems

Mathematical equations can be developed to describe the operation of vehicle-based material transport systems. Equipment used in such systems include industrial trucks (both hand trucks and powered trucks), automated guided vehicles, monorails and other rail guided vehicles, certain types of conveyor systems (e.g., in-floor towline conveyors), and certain crane operations. We assume that the vehicle operates at a constant velocity throughout its operation and ignore effects of acceleration, deceleration, and other speed differences that might depend on whether the vehicle is traveling loaded or empty or other reasons. The time for a typical delivery cycle in the operation of a vehicle-based transport system consists of: (1) loading at the pickup station, (2) travel time to the drop-off station, (3) unloading at the drop-off station, and (4) empty travel time of the vehicle between deliveries. The total cycle time per delivery per vehicle is given by

\[
T_c = T_L + \frac{L_d}{v_c} + T_u + \frac{L_e}{v_c}
\]  

(10.1)

where \(T_c\) = delivery cycle time (min/del), \(T_L\) = time to load at load station (min), \(L_d\) = distance the vehicle travels between load and unload station (m, ft), \(v_c\) = carrier velocity (m/min, ft/min), \(T_u\) = time to unload at unload station (min), and \(L_e\) = distance the vehicle travels empty until the start of the next delivery cycle (m, ft).

\(T_c\) calculated by Eq. (10.1) must be considered an ideal value, because it ignores any time losses due to reliability problems, traffic congestion, and other factors that may slow
down a delivery. In addition, not all delivery cycles are the same. Originations and destinations may be different from one delivery to the next, which will affect the $L_d$ and $L_e$ terms in the preceding equation. Accordingly, these terms are considered to be average values for the population of loaded and empty distances traveled by the vehicle during the course of a shift or other period of analysis.

The delivery cycle time can be used to determine certain parameters of interest in the vehicle-based transport system. Let us make use of $T_c$ to determine two parameters: (1) rate of deliveries per vehicle and (2) number of vehicles required to satisfy a specified total delivery requirement. We will base our analysis on hourly rates and requirements; however, the equations can readily be adapted for other periods.

The hourly rate of deliveries per vehicle is 60 min divided by the delivery cycle time $T_c$, adjusting for any time losses during the hour. The possible time losses include: (1) availability, (2) traffic congestion, and (3) efficiency of manual drivers in the case of manually operated trucks. *Availability* (symbolized $A$) is a reliability factor (Section 2.4.3) defined as the proportion of total shift time that the vehicle is operational and not broken down or being repaired.

To deal with the time losses due to *traffic congestion*, let us define the *traffic factor* $T_f$ as a parameter for estimating the effect of these losses on system performance. Sources of inefficiency accounted for by the traffic factor include waiting at intersections, blocking of vehicles (as in an AGVS), and waiting in a queue at load/unload stations. If there is no blocking of vehicles, then $F_t = 1.0$. As blocking increases, the value of $F_t$ decreases. Blocking, waiting at intersections, and vehicles waiting in line at load/unload stations are affected by the number of vehicles in the system relative to the size of the layout. If there is only one vehicle in the system, little or no blocking should occur, and the traffic factor will be very close to 1.0. For systems with many vehicles, there will be more instances of blocking and congestion, and the traffic factor will take a lower value. Typical values of traffic factor for an AGVS range between 0.85 and 1.0 [4].

For systems based on industrial trucks, including both hand trucks and powered trucks that are operated by human workers, traffic congestion is probably not the main cause of the low operating performance sometimes observed in these systems. Their performance is very dependent on the work efficiency of the operators who drive the trucks. Let us define *efficiency* here as the actual work rate of the human operator relative to work rate expected under standard or normal performance. Let $E$ symbolize the worker efficiency.

With these factors defined, we can now express the available time per hour per vehicle as 60 min adjusted by $A$, $T_f$, and $E$. That is:

$$AT = 60A T_f E$$  \hspace{1cm} (10.2)

where $AT = \text{available time (min/hr per vehicle)}$, $A = \text{availability}$, $T_f = \text{traffic factor}$, and $E = \text{worker efficiency}$. The parameters $A$, $T_f$, and $E$ do not take into account poor vehicle routing, poor guidepath layout, or poor management of the vehicles in the system. These factors should be minimized, but if present they are accounted for in the values of $L_d$ and $L_e$.

We can now write equations for the two performance parameters of interest. The rate of deliveries per vehicle is given by:

$$R_{dv} = \frac{AT}{T_c}$$  \hspace{1cm} (10.3)
where \( R_{dv} \) = hourly delivery rate per vehicle (del/hr per vehicle), \( T_c \) = delivery cycle time computed by Eq. (10.1) (min/del), and \( AT \) = the available time in 1 hr with adjustments for time losses (min/hr).

The total number of vehicles (trucks, AGVs, trolleys, carts, etc.) needed to satisfy a specified total delivery schedule \( R_f \) in the system can be estimated by first calculating the total workload required and then dividing by the available time per vehicle. Workload is defined as the total amount of work, expressed in terms of time, that must be accomplished by the material transport system in 1 hr. This can be expressed as follows:

\[
WL = R_f T_c
\]

(10.4)

where \( WL \) = workload (min/hr), \( R_f \) = specified flow rate of total deliveries per hour for the system (del/hr), and \( T_c \) = delivery cycle time (min/del). Now the number of vehicles required to accomplish this workload can be written as

\[
n_c = \frac{WL}{AT}
\]

(10.5)

where \( n_c \) = number of carriers required, \( WL \) = workload (min/hr), and \( AT \) = available time per vehicle (min/hr per vehicle). It can be shown that Eq. (10.5) reduces to the following:

\[
n_c = \frac{R_f}{R_{dv}}
\]

(10.6)

where \( n_c \) = number of carriers required, \( R_f \) = total delivery requirements in the system (del/hr), and \( R_{dv} \) = delivery rate per vehicle (del/hr per vehicle). Although the traffic factor accounts for delays experienced by the vehicles, it does not include delays encountered by a load/unload station that must wait for the arrival of a vehicle. Because of the random nature of the load/unload demands, workstations are likely to experience waiting time while vehicles are busy with other deliveries. The preceding equations do not consider this idle time or its impact on operating cost. If station idle time is to be minimized, then more vehicles may be needed than the number indicated by Eqs. (10.5) or (10.6). Mathematical models based on queueing theory are appropriate to analyze this more-complex stochastic situation.

**EXAMPLE 10.1 Determining Number of Vehicles in an AGVS**

Given the AGVS layout shown in Figure 10.15. Vehicles travel counterclockwise around the loop to deliver loads from the load station to the unload station. Loading time at the load station = 0.75 min, and unloading time at the unload station = 0.50 min. It is desired to determine how many vehicles are required to satisfy demand for this layout if a total of 40 del/hr must be completed by the AGVS. The following performance parameters are given: vehicle velocity = 50 m/min, availability = 0.95, traffic factor = 0.90, and operator efficiency does not apply, so \( E = 1.0 \). Determine: (a) travel distances loaded and empty, (b) ideal delivery cycle time, and (c) number of vehicles required to satisfy the delivery demand.
Solution: (a) Ignoring effects of slightly shorter distances around the curves at corners of the loop, the values of $L_d$ and $L_r$ are readily determined from the layout to be 110 m and 80 m, respectively.

(b) Ideal cycle time per delivery per vehicle is given by Eq. (10.1).

$$T_c = 0.75 + \frac{110}{50} + 0.50 + \frac{80}{50} = 5.05 \text{ min}$$

(c) To determine the number of vehicles required to make 40 del/hr, we compute the workload of the AGVS and the available time per hour per vehicle.

$$WL = 40(5.05) = 202 \text{ min/hr}$$

$$AT = 60(0.95)(0.90)(1.0) = 51.3 \text{ min/hr per vehicle}$$

Therefore, the number of vehicles required is

$$n_r = \frac{202}{51.3} = 3.94 \text{ vehicles}$$

This value should be rounded up to $n_r = 4$ vehicles, since the number of vehicles must be an integer.

Determining the average travel distances, $L_d$ and $L_r$, requires analysis of the particular AGVS layout. For a simple loop layout such as in Figure 10.15, determining these values is straightforward. For a complex AGVS layout, the problem is more difficult. The following example illustrates this issue.

EXAMPLE 10.2 Determining $L_d$ for a More-Complex AGVS Layout

The layout for this example is shown in Figure 10.16, and the From-To Chart is presented in Table 10.2. The AGVS includes load station 1 where raw parts
Figure 10.16 AGVS layout for production system of Example 10.2.

Key: Proc = processing operation, Aut = automated, Unld = unload, Man = manual operation, dimensions in meters (m).

Enter the system for delivery to any of three production stations 2, 3, and 4. Unload station 5 receives finished parts from the production stations. Load and unload times at stations 1 and 5 are each 0.5 min. Production rates for each workstation are indicated by the delivery requirements in Table 10.2. A complicating factor is that some parts must be transshipped between stations 2 and 3. Vehicles move in the direction indicated by the arrows in the figure. Determine the average delivery distance, $L_d$.

Solution. Table 10.2 shows the number of deliveries and corresponding distances between the stations. The distance values are taken from the layout drawing in Figure 10.16. To determine the value of $L_d$, a weighted average must be calculated based on the number of trips and corresponding distances shown in the From-To Chart for the problem.

$$L_d = \frac{9(50) + 5(120) + 6(205) + 9(80) + 2(85) + 3(170) + 8(85)}{9 + 5 + 6 + 9 + 2 + 3 + 8} = \frac{4360}{42} = 103.8 \text{ m}$$

Determining $L_e$, the average distance a vehicle travels empty during a delivery cycle, is more complicated. It depends on the dispatching and scheduling methods used.
to decide how a vehicle should proceed from its last drop-off to its next pickup. In Figure 10.16, if each vehicle must travel back to station 1 after each drop-off at stations 2, 3, and 4, then the empty distance between pick-ups would be very large indeed. $L_e$ would be greater than $L_d$. On the other hand, if a vehicle could exchange a raw workpart for a finished part while stopped at a given workstation, then empty travel time for the vehicle would be minimized. However, this would require a two-position platform at each station to enable the exchange. So this issue must be considered in the initial design of the AGVS. Ideally, $L_e$ should be reduced to zero. It is highly desirable to minimize the average distance a vehicle travels empty through good AGVS design and good scheduling of the vehicles. Our mathematical model of AGVS operation indicates that the delivery cycle time will be reduced if $L_e$ is minimized, and this will have a beneficial effect on the vehicle delivery rate and the number of vehicles required to operate the AGVS. Two of our exercise problems at the end of the chapter ask the reader to determine $L_e$ under different operating scenarios.

### 10.6.3 Conveyor Analysis

Conveyor operations have been analyzed in the research literature, some of which is identified in our list of references [8], [9], [14]–[17]. In our discussion here, we consider the three basic types of conveyor operations discussed in Section 10.4.2: (1) single direction conveyors, (2) continuous loop conveyors, and (3) recirculating conveyors.

**Single Direction Conveyors.** Consider the case of a single direction powered conveyor with one load station at the upstream end and one unload station at the downstream end, as in Figure 10.11(a). Materials are loaded at one end and unloaded at the other. The materials may be parts, cartons, pallet loads, or other unit loads. Assuming the conveyor operates at a constant speed, the time required to move materials from load station to unload station is given by:

$$T_d = \frac{L_d}{v_c} \tag{10.7}$$

where $T_d$ = delivery time (min), $L_d$ = length of conveyor between load and unload stations (m, ft), and $v_c$ = conveyor velocity (m/min, ft/min).

The flow rate of materials on the conveyor is determined by the rate of loading at the load station. The loading rate is limited by the reciprocal of the time required to load the materials. Given the conveyor speed, the loading rate establishes the spacing of materials on the conveyor. Summarizing these relationships,

$$R_f = R_L = \frac{v_c}{s_c} \leq \frac{1}{T_L} \tag{10.8}$$

where $R_f$ = material flow rate (parts/min), $R_L$ = loading rate (parts/min), $s_c$ = center-to-center spacing of materials on the conveyor (m/part, ft/part), and $T_L$ = loading time (min/part). One might be tempted to think that the loading rate $R_L$ is the reciprocal of the loading time $T_L$. However, $R_L$ is set by the flow rate requirement $R_f$, while $T_L$ is determined by ergonomic factors. The worker who loads the conveyor may be capable of performing the loading task at a rate that is faster than the required flow rate. On the other
hand, the flow rate requirement cannot be set faster than it is humanly possible to perform the loading task.

An additional requirement for loading and unloading is that the time required to unload the conveyor must be equal to or less than the loading time. That is,

$$T_U \leq T_L$$

(10.9)

where $T_U = $ unloading time (min/part). If unloading requires more time than loading, then unremoved loads may accumulate or be dumped onto the floor at the downstream end of the conveyor.

We are using parts as the material in Eqs. (10.8) and (10.9), but the relationships apply to other unit loads as well. The advantage of the unit load principle (Table 9.3, Principle 5) can be demonstrated by transporting $n_p$ parts in a carrier rather than a single part. Recasting Eq. (10.8) to reflect this advantage, we have

$$R_f = \frac{n_p v_c}{s_c} \leq \frac{1}{T_L}$$

(10.10)

where $R_f = $ flow rate (parts/min), $n_p = $ number of parts per carrier, $s_c = $ center-to-center spacing of carriers on the conveyor (m/carrier, ft/carrier), and $T_L = $ loading time per carrier (min/carrier). The flow rate of parts transported by the conveyor is potentially much greater in this case. However, loading time is still a limitation, and $T_L$ may consist of not only the time to load the carrier onto the conveyor but also the time to load parts into the carrier. The preceding equations must be interpreted and perhaps adjusted for the given application.

**EXAMPLE 10.3 Single Direction Conveyor**

A roller conveyor follows a pathway 35 m long between a parts production department and an assembly department. Velocity of the conveyor is 40 m/min. Parts are loaded into large tote pans, which are placed onto the conveyor at the load station in the production department. Two operators work the loading station. The first worker loads parts into tote pans, which takes 25 sec. Each tote pan holds 20 parts. Parts enter the loading station from production at a rate that is in balance with this 25-sec cycle. The second worker loads tote pans onto the conveyor, which takes only 10 sec. Determine: (a) spacing between tote pans along the conveyor, (b) maximum possible flow rate in parts/min, and (c) the minimum time required to unload the tote pan in the assembly department.

**Solution:**

(a) Spacing between tote pans on the conveyor is determined by the loading time. It takes only 10 sec to load a tote pan onto the conveyor, but 25 sec are required to load parts into the tote pan. Therefore, the loading cycle is limited by this 25 sec. At a conveyor speed of 40 m/min, the spacing will be

$$s_c = \frac{25}{60} \text{ min}(40 \text{ m/min}) = 16.67 \text{ m}$$

(b) Flow rate is given by Eq. (10.10):

$$R_f = \frac{20(40)}{16.67} = 48 \text{ parts/min}$$
This is consistent with the parts loading rate of 20 parts in 25 sec, which is 0.8 parts/sec or 48 parts/min.

(c) The minimum allowable time to unload a tote pan must be consistent with the flow rate of tote pans on the conveyor. This flow rate is one tote pan every 25 sec, so

\[ T_U \leq 25 \text{ sec} \]

**Continuous Loop Conveyors.** Consider a continuous loop conveyor such as an overhead trolley in which the pathway is formed by an endless chain moving in a track loop, and carriers are suspended from the track and pulled by the chain. The conveyor moves parts in the carriers between a load station and an unload station. The complete loop is divided into two sections: a delivery (forward) loop in which the carriers are loaded and a return loop in which the carriers travel empty, as shown in Figure 10.11(b). The length of the delivery loop is \( L_d \), and the length of the return loop is \( L_e \). Total length of the conveyor is therefore \( L = L_d - L_e \). The total time required to travel the complete loop is

\[ T_c = \frac{L}{v_c} \quad (10.11) \]

where \( T_c \) = total cycle time (min), and \( v_c \) = speed of the conveyor chain (m/min, ft/min).

The time a load spends in the forward loop is

\[ T_d = \frac{L_d}{v_c} \quad (10.12) \]

where \( T_d \) = delivery time on the forward loop (min).

Carriers are equally spaced along the chain at a distance \( s_c \) apart. Thus, the total number of carriers in the loop is given by:

\[ n_c = \frac{L}{s_c} \quad (10.13) \]

where \( n_c \) = number of carriers, \( L \) = total length of the conveyor loop (m, ft), and \( s_c \) = center-to-center distance between carriers (m/crrier, ft/crrier). The value of \( n_c \) must be an integer, and so \( L \) and \( s_c \) must be consistent with that requirement.

Each carrier is capable of holding \( n_p \) parts on the delivery loop, and it holds no parts on the return trip. Since only those carriers on the forward loop contain parts, the maximum number of parts in the system at any one time is given by:

\[ \text{Total parts in system} = \frac{n_p n_c L_d}{L} \quad (10.14) \]

As in the single direction conveyor, the maximum flow rate between load and unload stations is

\[ R_f = \frac{n_c v_c}{s_c} \]
where $R_f$ = parts per minute. Again, this rate must be consistent with limitations on the time it takes to load and unload the conveyor, as defined in Eqs (10.8)-(10.10).

**Recirculating Conveyors: Kwo Analysis.** Recall (Section 10.4.2) and the two problems complicating the operation of a recirculating conveyor system: (1) the possibility that no empty carriers are immediately available at the loading station when needed and (2) the possibility that no loaded carriers are immediately available at the unloading station when needed. In the Kwo analysis [8],[9], the case of a recirculating conveyor with one load station and one unload station is considered. According to Kwo, there are three basic principles that must be obeyed in designing such a conveyor system:

1. **Speed Rule.** This principle states that the operating speed of the conveyor must be within a certain range. The lower limit of the range is determined by the required loading and unloading rates at the respective stations. These rates are dictated by the external systems served by the conveyor. Let $R_L$ and $R_U$ represent the required loading and unloading rates at the two stations, respectively. Then the conveyor speed must satisfy the following relationship:

$$\frac{n_c v_c}{s_c} \geq \frac{\text{Max}\{R_L, R_U\}}{s_c} \quad (10.15)$$

where $R_L$ = required loading rate (parts/min), and $R_U$ = the corresponding unloading rate. The upper speed limit is determined by the physical capabilities of the material handlers to perform the loading and unloading tasks. Their capabilities are defined by the time required to load and unload the carriers, so that

$$\frac{n_c v_c}{s_c} \leq \frac{\text{Min}\{\frac{1}{T_L}, \frac{1}{T_U}\}}{s_c} \quad (10.16)$$

where $T_L$ = time required to load a carrier (min/carrier), and $T_U$ = time required to unload a carrier. In addition to Eqs (10.15) and (10.16), another limitation is of course that the speed must not exceed the technological limits of the mechanical conveyor itself.

2. **Capacity Constraint.** The flow rate capacity of the conveyor system must be at least equal to the flow rate requirement to accommodate reserve stock and allow for the time elapsed between loading and unloading due to delivery distance. This can be expressed as follows:

$$\frac{n_p v_c}{s_c} \geq R_f \quad (10.17)$$

In this case, $R_f$ must be interpreted as a system specification required of the recirculating conveyor.

3. **Uniformity Principle.** This principle states that parts (loads) should be uniformly distributed throughout the length of the conveyor, so that there will be no sections of the conveyor in which every carrier is full while other sections are virtually empty. The
reason for the uniformity principle is to avoid unusually long waiting times at the load or unload stations for empty or full carriers (respectively) to arrive.

**EXAMPLE 10.4 Recirculating Conveyor Analysis: Kwo**

A recirculating conveyor has a total length of 300 m. Its speed is 60 m/min, and the spacing of part carriers along its length is 12 m. Each carrier can hold two parts. The task time required to load two parts into each carrier is 0.20 min and the unload time is the same. The required loading and unloading rates are both defined by the specified flow rate, which is 4 parts/min. Evaluate the conveyor system design with respect to Kwo's three principles.

**Solution:** *Speed Rule:* The lower limit on speed is set by the required loading and unloading rates, which is 4 parts/min. Checking this against Eq. (10.15),

\[
\frac{n_u n_c}{\delta_c} \geq \text{Max} \left\{ R_L, R_U \right\}
\]

\[
\frac{(2 \text{ parts/carrier})(60 \text{ m/min})}{12 \text{ m/carrier}} = 10 \text{ parts/min} > 4 \text{ parts/min}
\]

Checking the lower limit:

\[
\frac{60 \text{ m/min}}{12 \text{ m/carrier}} = 5 \text{ carriers/min} \leq \text{Min} \left\{ \frac{1}{0.2}, \frac{1}{0.2} \right\} = \text{Min} \{5, 5\} = 5
\]

The Speed Rule is satisfied.

*Capacity Constraint:* The conveyor flow rate capacity = 10 parts/min as computed above. Since this is substantially greater than the required delivery rate of 4 part/min, the capacity constraint is satisfied. Kwo provides guidelines for determining the flow rate requirement that should be compared to the conveyor capacity [8], [9].

*Uniformity Principle:* The conveyor is assumed to be uniformly loaded throughout its length, since the loading and unloading rates are equal and the flow rate capacity is substantially greater than the load/unload rate. Conditions for checking the uniformity principle are available, and the reader is referred to the original papers by Kwo [8], [9].

**REFERENCES**

PROBLEMS

Charting Techniques

10.1 A flexible manufacturing system is being planned. It has a ladder layout as pictured in Figure 10.1 and uses a rail guided vehicle system to move parts between stations in the layout. All workparts are loaded into the system at station 1, moved to one of three processing stations (2, 3, or 4), and then brought back to station 1 for unloading. Once loaded onto its RGV, each workpart stays onboard the vehicle throughout its time in the FMS. Load and unload times at station 1 are each 1.0 min. Processing times at other stations are: 5.0 min at station 2, 7.0 min at station 3, and 9.0 min at station 4. Hourly production of parts through the system is: 7 parts through station 2, 6 parts through station 3, and 5 parts through station 4. (a) Develop the From-To Chart for trips and distances using the same format as Table 10.2. (b) Develop the flow diagram for this data similar to Figure 10.14. The From-To Chart developed here is used in Problem 10.4.

10.2 In Example 10.2 in the text, suppose that the vehicles operate according to the following scheduling rules: (1) vehicles delivering raw workparts from station 1 to stations 2, 3, and 4 must return empty to station 5; and (2) vehicles picking up finished parts at stations 2, 3, and
Problems

10.3 In Example 10.2 in the text, suppose that the vehicles operate according to the following scheduling rule to minimize the distances the vehicles travel empty: Vehicles delivering raw workpieces from station 1 to stations 2, 3, and 4 must pick up finished parts at these respective stations for delivery to station 5. Determine the empty travel distances associated with each delivery and develop a From-To Chart in the format of Table 10.2 in the text. The From-To Chart developed here is used in Problem 10.6.

Analysis of Vehicle-Based Systems

10.4 This is a continuation of Problem 10.1. Determine the number of rail guided vehicles that are needed to meet the requirements of the flexible manufacturing system, if vehicle speed = 60 m/min and the anticipated traffic factor = 0.85. Assume availability $A = 100\%$ and efficiency $E = 1.0$.

10.5 This problem is a continuation of Problem 10.2, which extends Example 10.2 in the text. Suppose the AGVs travel at a speed of 40 m/min and the traffic factor = 0.90. As determined in Example 10.2, the delivery distance = 103.8 m. (a) Determine the value of $T_c$ for the layout based on your table. (b) How many automated guided vehicles will be required to operate the system? Assume availability $A = 100\%$ and efficiency $E = 1.0$.

10.6 This problem is a continuation of Problem 10.3, which extends Example 10.2 in the text. Suppose the AGVs travel at a speed of 40 m/min, and the traffic factor = 0.90. As determined in Example 10.2, the delivery distance = 103.8 m. (a) Determine the value of $T_c$ for the layout based on your table. (b) How many automated guided vehicles will be required to operate the system? Assume availability $A = 100\%$ and efficiency $E = 1.0$.

10.7 A planned fleet of forklift trucks has an average travel distance per delivery = 500 ft and an average empty travel distance = 350 ft. The fleet must make a total of 60 del/hr. Load and unload times are each 0.5 min and the speed of the vehicles = 300 ft/min. The traffic factor for the system = 0.85. Availability is expected to be 0.95 and worker efficiency is assumed to be 0.90. Determine: (a) ideal cycle time per delivery, (b) the resulting average number of deliveries per hour that a forklift truck can make, and (c) how many trucks are required to accomplish the 60 del/hr.

10.8 An automated guided vehicle system has an average travel distance per delivery = 200 m and an average empty travel distance = 150 m. Load and unload times are each 24 s and the speed of the AGV = 1 m/s. Traffic factor = 0.9. How many vehicles are needed to satisfy a delivery requirement of 30 del/hr? Assume $A = 0.95$. 

Figure P10.1 FMS layout for Problem 10.1.

4 for delivery to station 5 must travel empty from station 1. Determine the empty travel distances associated with each delivery and develop a From-To Chart in the format of Table 10.2 in the text. The From-To Chart developed here is used in Problem 10.5.
10.9 Four forklift trucks are used to deliver pallet loads of parts between work cells in a factory. Average travel distance loaded is 350 ft, and the travel distance empty is estimated to be the same. The trucks are driven at an average speed of 3 mi/hr when loaded and 4 mi/hr when empty. Terminal time per delivery averages 1.0 min (load = 0.5 min and unload = 0.5 min). If the traffic factor is assumed to be 0.90, availability = 1.0 and work efficiency = 0.95, what is the maximum hourly delivery rate of the four trucks?

10.10 An AGVS has an average loaded travel distance per delivery = 400 ft. The average empty travel distance is not known. Required number of deliveries per hour = 60. Load and unload times are each 0.6 min and the AGV speed = 125 ft/min. Anticipated traffic factor = 0.80. Availability = 0.95. Develop an equation that relates the number of vehicles required to operate the system as a function of the average empty travel distance 

10.11 A rail guided vehicle system is being planned as part of an assembly cell. The system consists of two parallel lines, as in Figure P10.11. In operation, a base part is loaded at station 1 and delivered to either station 2 or 4, where components are added to the base part. The RGV then goes to either station 3 or 5, respectively, where further assembly of components is accomplished. From stations 3 or 5, the product moves to station 6 for removal from the system. Vehicles remain with the products as they move through the station sequence, thus, there is no loading and unloading of parts at stations 2, 3, 4, and 5. After unloading parts at station 6, the vehicles then travel empty back to station 1 for reloading. The hourly moves (parts/hr) and distances (ft) are listed in the table below. RGV speed = 100 ft/min. Assembly cycle times at stations 2 and 3 = 4.0 min each and at stations 4 and 5 = 6.0 min each. Load and unload times at stations 1 and 6, respectively, are each 0.75 min. Traffic factor = 1.0. How many vehicles are required to operate the system? Assume A = 1.0.

<table>
<thead>
<tr>
<th>To:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>From:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>0/0</td>
<td>14L/200</td>
<td>0/NA</td>
<td>8L/150</td>
<td>0/NA</td>
<td>0/NA</td>
</tr>
<tr>
<td>2</td>
<td>0/NA</td>
<td>0/0</td>
<td>14L/50</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/NA</td>
</tr>
<tr>
<td>3</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/0</td>
<td>0/NA</td>
<td>0/NA</td>
<td>14L/50</td>
</tr>
<tr>
<td>4</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/0</td>
<td>9L/50</td>
<td>0/NA</td>
</tr>
<tr>
<td>5</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/0</td>
<td>9L/100</td>
</tr>
<tr>
<td>6</td>
<td>23E/400</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/0</td>
</tr>
</tbody>
</table>

Figure P10.11 Layout for Problem 10.11.

10.12 An AGVS will be used to satisfy material flows indicated in the From-To Chart in the following table, which shows deliveries per hour between stations (above the slash) and distances in meters between stations (below the slash). Moves indicated by “L” are trips in which the vehicle is loaded, while “E” indicates moves in which the vehicle is empty. A traffic factor = 0.85 is assumed. Assume availability A = 0.90. Speed of an AGV = 0.9 m/s. If
load handling time per delivery = 1.0 min, determine the number of vehicles needed to satisfy the indicated deliveries per hour.

<table>
<thead>
<tr>
<th>To:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>From:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0/0</td>
<td>9L/90</td>
<td>7L/120</td>
<td>5L/75</td>
</tr>
<tr>
<td>2</td>
<td>5L/90</td>
<td>0/0</td>
<td>0/NA</td>
<td>4L/80</td>
</tr>
<tr>
<td>3</td>
<td>7L/120</td>
<td>0/NA</td>
<td>0/0</td>
<td>0/NA</td>
</tr>
<tr>
<td>4</td>
<td>9L/75</td>
<td>0/NA</td>
<td>0/NA</td>
<td>0/0</td>
</tr>
</tbody>
</table>

10.13 An automated guided vehicle system is being proposed to deliver parts between 40 workstations in a factory. Loads must be moved from each station about once every hour; thus, the delivery rate = 40 loads/hr. Average travel distance loaded is estimated to be 250 ft and travel distance empty is estimated to be 300 ft. Vehicles move at a speed = 200 ft/min. Total handling time per delivery = 1.5 min (load = 0.75 min and unload = 0.75 min). Traffic factor \( F_t \) becomes increasingly significant as the number of vehicles \( n_c \) increases; this can be modeled as:

\[ F_t = 1.0 - 0.05(n_c - 1) \quad \text{for } n_c = \text{Integer} > 0 \]

Determine the minimum number of vehicles needed in the factory to meet the flow rate requirement. Assume \( A = 1.0 \).

10.14 An automated guided vehicle system is being planned for a warehouse complex. The AGVS will be a driverless train system, and each train will consist of the towing vehicle plus four pulled carts. The speed of the trains will be 160 ft/min. Only the pulled carts carry loads. The average loaded travel distance per delivery cycle is 2000 ft and empty travel distance is the same. Anticipated travel factor = 0.95. The load handling time per train per delivery is expected to be 10 min. If the requirements on the AGVS are 25 cart loads/hr, determine the number of trains required. Assume \( A = 1.0 \).

10.15 The From-To Chart in the table below indicates the number of loads moved per 8-hr day (above the slash) and the distances in feet (below the slash) between departments in a particular factory. Fork lift trucks are used to transport materials between departments. They move at an average speed = 275 ft/min (loaded) and 350 ft/min (empty). Load handling time per delivery is 1.5 min, and anticipated traffic factor = 0.9. Assume \( A = 0.95 \) and worker efficiency = 110%. Determine the number of trucks required under each of the following assumptions: (a) The trucks never travel empty, and (b) the trucks travel empty a distance equal to their loaded distance.

<table>
<thead>
<tr>
<th>To Dept.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Dept.</td>
<td>A</td>
<td>62/500</td>
<td>51/450</td>
<td>45/350</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>—</td>
<td>0</td>
<td>22/400</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>—</td>
<td>0</td>
<td>76/200</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>—</td>
<td>65/150</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

10.16 Major appliances are assembled on a production line at the rate of 55 per hour. The products are moved along the line on work pallets (one product per pallet). At the final workstation the finished products are removed from the pallets. The pallets are then removed from the line and delivered back to the front of the line for reuse. Automated guided vehicles are used to transport the pallets to the front of the line, a distance of 600 ft. Return trip distance (empty) to the end of the line is also 600 ft. Each AGV carries four pallets and travels at a
speed of 150 ft/min (either loaded or empty). The pallets form queues at each end of the line, so that neither the production line nor the AGVs are ever starved for pallets. Time required to load each pallet onto an AGV = 15 sec; time to release a loaded AGV and move an empty AGV into position for loading at the end of the line = 12 sec. The same times apply for pallet handling and release/positioning at the unload station located at the front of the production line. Assume the traffic factor is 1.0 since the route is a simple loop. Also, assume $A = 1.0$. How many vehicles are needed to operate the AGV system?

10.17 For the production line in Problem 10.16, assume that a single AGV train consisting of a tractor and multiple trailers is used to make deliveries rather than separate vehicles. Time required to load a pallet onto a trailer = 15 sec, and the time to release a loaded train and move an empty train into position for loading at the end of the production line = 30 sec. The same times apply for pallet handling and release/positioning at the unload station located at the front of the production line. If each trailer is capable of carrying four pallets, how many trailers should be included in the train?

**Analysis of Conveyor Systems**

10.18 An overhead trolley conveyor is configured as a continuous closed loop. The delivery loop has a length of 120 m and the return loop = 80 m. All parts loaded at the load station are unloaded at the unload station. Each hook on the conveyor can hold one part, and the hooks are separated by 4 m. Conveyor speed = 1.25 m/s. Determine: (a) maximum number of parts in the conveyor system, (b) parts flow rate, and (c) maximum loading and unloading times that are compatible with the operation of the conveyor system.

10.19 A 300-ft long roller conveyor, which operates at a velocity = 80 ft/min, is used to move pallets between load and unload stations. Each pallet carries 12 parts. Cycle time to load a pallet is 15 sec, and one worker at the load station is able to load pallets at the rate of 4 per minute. It takes 12 sec to unload at the unload station. Determine: (a) center-to-center distance between pallets, (b) the number of pallets on the conveyor at one time, and (c) hourly flow rate of parts. (d) By how much must conveyor speed be increased to increase flow rate to 3000 parts/hr?

10.20 A roller conveyor moves tote pans in one direction at 150 ft/min between a load station and an unload station, a distance of 200 ft. The time to load parts into a tote pan at the load station is 3 sec per part. Each tote pan holds 8 parts. In addition, it takes 9 sec to load a tote pan onto the conveyor. Determine: (a) spacing between tote pan centers flowing in the conveyor system and (b) flow rate of parts on the conveyor system. (c) Consider the effect of the unit load principle. Suppose the tote pans were smaller and could hold only one part rather than eight. Determine the flow rate in this case if it takes 7 sec to load a tote pan onto the conveyor (instead of 9 sec for the larger tote pan), and it takes the same 3 sec to load the part into the tote pan.

10.21 A closed loop overhead conveyor must be designed to deliver parts from one load station to one unload station. The specified flow rate of parts that must be delivered between the two stations is 300 parts/hr. The conveyor has carriers spaced at a center-to-center distance that is to be determined. Each carrier holds one part. Forward and return loops will each be 90 m long. Conveyor speed = 0.5 m/s. Times to load and unload parts at the respective stations are each = 12 s. Is the system feasible, and if so, what is the appropriate number of carriers and spacing between carriers that will achieve the specified flow rate?

10.22 Consider Problem 10.21, only that the carriers are larger and capable of holding up to four parts ($n_p = 1, 2, 3, \text{ or } 4$). The loading time $T_L = 9 + 3n_p$, where $T_L$ is in seconds. With other parameters defined as in the previous problem, determine which of the four values of $n_p$ are feasible. For those values that are feasible, specify the appropriate design parameters for (a) spacing between carriers and (b) number of carriers that will achieve this flow rate.
10.23 A recirculating conveyor has a total length of 700 ft and a speed of 90 ft/min. Spacing of part carriers = 14 ft. Each carrier can hold one part. Automatic machines load and unload the conveyor at the load and unload stations. Time to load a part is 0.10 min, and unload time is the same. To satisfy production requirements, the loading and unloading rates are each 2.0 parts/min. Evaluate the conveyor system design with respect to the three Kwa principles.

10.24 A recirculating conveyor has a total length of 200 m and a speed of 50 m/min. Spacing of part carriers = 5 m. Each carrier holds two parts. Time needed to load a part carrier = 0.15 min. Unloading time is the same. The required loading and unloading rates are 6 parts/min. Evaluate the conveyor system design with respect to the three Kwa principles.

10.25 There is a plan to install a continuous loop conveyor system with a total length of 1000 ft and a speed of 50 ft/min. The conveyor will have carriers that are separated by 25 ft. Each carrier will be capable of holding one part. A load station and an unload station are to be located 500 ft apart along the conveyor loop. Each day, the conveyor system is planned to operate as follows, starting empty at the beginning of the day. The load station will load parts at the rate of one part every 30 sec, continuing this loading operation for 10 min, then resting for 10 min, during which no loading occurs. It will repeat this 20-min cycle throughout the 8-hr shift. The unload station will wait until loaded carriers begin to arrive, then will unload parts at the rate of 1 part/min during the 8 hr, continuing until all carriers are empty.

(a) If the length of each station is 10 ft, and so loading and unloading must be accomplished on a moving conveyor within that space, what is the maximum time available to perform the loading and unloading operations? (b) Will the planned conveyor system work? Present calculations and arguments to justify your answer.
The function of a material storage system is to store materials for a period of time and to permit access to those materials when required. Materials stored by manufacturing firms include a variety of types, as indicated in Table 11.1. Categories (1)–(5) relate directly to the product, (6)–(8) relate to the process, and (9) and (10) relate to overall support of factory operations. The different categories of materials require different storage methods and controls. Many production plants use manual methods for storing and retrieving items. The storage function is often accomplished inefficiently, in terms of human resources, factory floor space, and material control. Automated methods are available to improve the efficiency of the storage function.

In this chapter, we begin by defining the most important measures of storage system performance. We also discuss the different strategies that can be used to decide appropriate locations for items in the storage system. We then describe the types of storage equipment and methods, dividing these into conventional and automated types. The final section
TABLE 11.1 Types of Materials Typically Stored in a Factory

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Raw materials</td>
<td>Raw stock to be processed (e.g., bar stock, sheet metal, plastic molding compound)</td>
</tr>
<tr>
<td>2. Purchased parts</td>
<td>Parts from vendors to be processed or assembled (e.g., castings, purchased components)</td>
</tr>
<tr>
<td>3. Work-in-process</td>
<td>Partially completed parts between processing operations or parts awaiting assembly</td>
</tr>
<tr>
<td>4. Finished product</td>
<td>Completed product ready for shipment</td>
</tr>
<tr>
<td>5. Rework and scrap</td>
<td>Parts that are out of specification, either to be reworked or scrapped</td>
</tr>
<tr>
<td>6. Refuse</td>
<td>Chips, swarf, nips, other waste products left over after processing; these materials must be disposed of, sometimes using special precautions</td>
</tr>
<tr>
<td>7. Tooling</td>
<td>Cutting tools, jigs, fixtures, molds, dies, welding wire, and other tooling used in manufacturing and assembly; supplies such as helmets, gloves, etc., are usually included</td>
</tr>
<tr>
<td>8. Spare parts</td>
<td>Parts needed for maintenance and repair of factory equipment</td>
</tr>
<tr>
<td>9. Office supplies</td>
<td>Paper, paper forms, writing instruments, and other items used in support of plant office</td>
</tr>
<tr>
<td>10. Plant records</td>
<td>Records on product, equipment, and personnel</td>
</tr>
</tbody>
</table>

presents a quantitative analysis of automated storage systems, whose performance is generally measured in terms of capacity and throughput.

11.1 STORAGE SYSTEM PERFORMANCE

The performance of a storage system in accomplishing its function must be sufficient to justify its investment and operating expense. Various measures used to assess the performance of a storage system include: (1) storage capacity, (2) density, (3) accessibility, and (4) throughput. In addition, standard measures used for mechanized and automated systems include (5) utilization and (6) reliability.

Storage capacity can be measured in two ways: (1) as the total volumetric space available or (2) as the total number of storage compartments in the system available for items or loads. In many storage systems, materials are stored in unit loads that are held in standard size containers (pallets, tote pans, or other containers). The standard container can readily be handled, transported, and stored by the storage system and by the material handling system that may be connected to it. Hence, storage capacity is conveniently measured as the number of unit loads that can be stored in the system. The physical capacity of the storage system should be greater than the maximum number of loads anticipated to be stored, to provide available empty spaces for materials being entered into the system and to allow for variations in maximum storage requirements.

Storage density is defined as the volumetric space available for actual storage relative to the total volumetric space in the storage facility. In many warehouses, aisle space and wasted overhead space account for more volume than the volume available for actual storage of materials. Floor area is sometimes used to assess storage density, because it is convenient to measure this on a floor plan of the facility. However, volumetric density is usually a more-appropriate measure than area density.

For efficient use of space, the storage system should be designed to achieve a high density. However, as storage density is increased, accessibility, another important measure of
Storage performance, is adversely affected. *Accessibility* refers to the capability to access any desired item or load stored in the system. In the design of a given storage system, trade-offs must be made between storage density and accessibility.

*System throughput* is defined as the hourly rate at which the storage system (1) receives and puts loads into storage and/or (2) retrieves and delivers loads to the output station. In many factory and warehouse operations, there are certain periods of the day when the required rate of storage and/or retrieval transactions is greater than at other times. The storage system must be designed for the maximum throughput that will be required during the day.

System throughput is limited by the time to perform a storage or retrieval (S/R) transaction. A typical storage transaction consists of the following elements: (1) pick up load at input station, (2) travel to storage location, (3) place load into storage location, and (4) travel back to input station. A retrieval transaction consists of: (1) travel to storage location, (2) pick item from storage, (3) travel to output station, and (4) unload at output station. Each element takes time. The sum of the element times is the transaction time that determines throughput of the storage system. Throughput can sometimes be increased by combining storage and retrieval transactions in one cycle, thus reducing travel time; this is called a *dual command cycle*. When either a storage or a retrieval transaction alone is performed in the cycle, it is called a *single command cycle*.

There are variations in the way a storage/retrieval cycle is performed, depending on the type of storage system. In manually operated systems, time is often lost looking up the storage location of the item being stored or retrieved. Also, element times are subject to the variations and motivations of human workers, and there is a lack of control over the operations. The ability to perform dual command cycles rather than single command cycles depends on demand and scheduling issues. If, during a certain portion of the day, there is demand for only storage transactions and no retrievals, then it is not possible to include both types of transactions in the same cycle. If both transaction types are required, then greater throughput will be achieved by scheduling dual command cycles. This scheduling is more readily done by a computerized (automated) storage system.

Throughput is also limited by the capability of the material handling system that is interfaced to the storage system. If the maximum rate at which loads can be delivered to the storage system or removed from it by the handling system is less than the S/R cycle rate of the storage system, then throughput will be adversely affected.

Two additional performance measures applicable to mechanized and automated storage systems are utilization and availability. *Utilization* is defined as the proportion of time that the system is actually being used for performing storage and retrieval operations compared with the time it is available. Utilization varies throughout the day, as requirements change from hour to hour. It is desirable to design an automated storage system for relatively high utilization, in the range 80–90%. If utilization is too low, then the system is probably overdesigned. If utilization is too high, then there is no allowance for rush periods or system breakdowns.

*Availability* is a measure of system reliability, defined as the proportion of time that the system is capable of operating (not broken down) compared with the normally scheduled shift hours. Malfunctions and failures of the equipment cause downtime. Reasons for downtime include computer failures, mechanical breakdowns, load jams, improper maintenance, and incorrect procedures by personnel using the system. The reliability of an existing system can be improved by good preventive maintenance procedures and by having repair parts on hand for critical components. Backup procedures should be devised to mitigate the effects of system downtime.
11.2 STORAGE LOCATION STRATEGIES

There are several strategies that can be used to organize stock in a storage system. These storage location strategies affect several of the performance measures discussed above. The two basic strategies are (1) randomized storage and (2) dedicated storage. Let us explain these strategies as they are commonly applied in warehousing operations. Each item type stored in a warehouse is known as a stock-keeping-unit (SKU). The SKU uniquely identifies that item type. The inventory records of the storage facility maintain a count of the quantities of each SKU that are in storage. In randomized storage, items are stored in any available location in the storage system. In the usual implementation of randomized storage, incoming items are placed into storage in the nearest available open location. When an order is received for a given SKU, the stock is retrieved from storage according to a first-in-first-out policy so that the items held in storage the longest are used to make up the order.

In dedicated storage, SKUs are assigned to specific locations in the storage facility. This means that locations are reserved for all SKUs stored in the system, and so the number of storage locations for each SKU must be sufficient to accommodate its maximum inventory level. The basis for specifying the storage locations is usually one of the following: (1) items are stored in part number or product number sequence; (2) items are stored according to activity level, the more active SKUs being located closer to the input/output station; or (3) items are stored according to their activity-to-space ratios, the higher ratios being located closer to the input/output station.

When comparing the benefits of the two strategies, it is generally found that less total space is required in a storage system that uses randomized storage, but higher throughput rates can usually be achieved when a dedicated storage strategy is implemented based on activity level. Example 11.1 illustrates the advantage of randomized storage in terms of its better storage density.

EXAMPLE 11.1 Comparison of Storage Strategies

Suppose that a total of 50 SKUs must be stored in a storage system. For each SKU, average order quantity = 100 cartons, average depletion rate = 2 cartons/day, and safety stock level = 10 cartons. Each carton requires one storage location in the system. Based on this data, each SKU has an inventory cycle that lasts 50 days. Since there are 50 SKUs in all, management has scheduled incoming orders so that a different SKU arrives each day. Determine the number of storage locations required in the system under two alternative strategies: (a) randomized storage and (b) dedicated storage.

Solution: Our estimates of space requirements are based on average order quantities and other values in the problem statement. Let us first calculate the maximum inventory level and average inventory level for each SKU. The inventory for each SKU varies over time as shown in Figure 11.1. The maximum inventory level, which occurs just after an order has been received, is the sum of the order quantity and safety stock level.

Maximum inventory level = 100 + 10 = 110 cartons

The average inventory is the average of the maximum and minimum inventory levels under the assumption of uniform depletion rate. The minimum value
occurs just before an order is received when the inventory is depleted to the safety stock level.

Minimum inventory level = 10 cartons

Average inventory level = \((110 + 10)/2 = 60\) cartons

(a) Under a randomized storage strategy, the number of locations required for each SKU is equal to the average inventory level of the item since incoming orders are scheduled each day throughout the 50-day cycle. This means that when the inventory level of one SKU near the beginning of its cycle is high, the level for another SKU near the end of its cycle is low. Thus, the number of storage locations required in the system is:

Number of storage locations = \((50 \text{ SKUs})(60 \text{ cartons}) = 3000\) locations

(b) Under a dedicated storage strategy, the number of locations required for each SKU must equal its maximum inventory level. Thus, the number of storage locations required in the system is:

Number of storage locations = \((50 \text{ SKUs})(110 \text{ cartons}) = 5500\) locations

Some of the advantages of both storage strategies can be obtained in a class-based dedicated storage allocation, in which the storage system is divided into several classes according to activity level, and a randomized storage strategy is used within each class. The classes containing more-active SKUs are located closer to the input/output point of the storage system for increased throughput, and the randomized locations within the classes reduce the total number of storage compartments required. We examine the effect of class-based dedicated storage on throughput in Example 11.4 and several of our end-of-chapter problems.

11.3 CONVENTIONAL STORAGE METHODS AND EQUIPMENT

A variety of storage methods and equipment are available to store the various materials listed in Table 11.1. The choice of method and equipment depends largely on the material to be stored, the operating philosophy of the personnel managing the storage facility, and
TABLE 11.2 Application Characteristics of the Types of Storage Equipment and Methods

<table>
<thead>
<tr>
<th>Storage Equipment</th>
<th>Advantages and Disadvantages</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk storage</td>
<td>Highest density is possible</td>
<td>Storage of low turnover, large stock or large unit loads</td>
</tr>
<tr>
<td></td>
<td>Low accessibility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lowest possible cost per sq ft</td>
<td></td>
</tr>
<tr>
<td>Rack systems</td>
<td>Low cost</td>
<td>Palletized loads in warehouses</td>
</tr>
<tr>
<td></td>
<td>Good storage density</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good accessibility</td>
<td></td>
</tr>
<tr>
<td>Shelves and bins</td>
<td>Some stock items not clearly visible</td>
<td>Storage of individual items on shelves</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Storage of commodity items in bins</td>
</tr>
<tr>
<td>Drawer storage</td>
<td>Contents of drawer easily visible</td>
<td>Small tools</td>
</tr>
<tr>
<td></td>
<td>Good accessibility</td>
<td>Small stock items</td>
</tr>
<tr>
<td></td>
<td>Relatively high cost</td>
<td>Repair parts</td>
</tr>
<tr>
<td>Automated storage systems</td>
<td>High throughput rates</td>
<td>Work-in-process storage</td>
</tr>
<tr>
<td></td>
<td>Facilitates use of computerized inventory control system</td>
<td>Final product warehousing and distribution center</td>
</tr>
<tr>
<td></td>
<td>Highest cost equipment</td>
<td>Order picking</td>
</tr>
<tr>
<td></td>
<td>Facilitates interface to automated material handling systems</td>
<td>Kitting of parts for electronic assembly</td>
</tr>
</tbody>
</table>

Budgetary limitations. In this section, we discuss the traditional (nonautomated) methods and equipment types. Automated storage systems are discussed in the following section. Application characteristics for the different equipment types are summarized in Table 11.2.

**Bulk Storage.** Bulk storage refers to the storage of stock in an open floor area. The stock is generally contained in unit loads on pallets or similar containers, and unit loads are stacked on top of each other to increase storage density. The highest density is achieved when unit loads are placed next to each other in both floor directions, as in Figure 11.2(a). However, this provides very poor access to internal loads. To increase

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**Figure 11.2** Various bulk storage arrangements: (a) high-density bulk storage provides low accessibility; (b) bulk storage with loads arranged to form rows and blocks for improved accessibility.
accessibility, bulk storage loads can be organized into rows and blocks, so that natural aisles are created between pallet loads, as in Figure 11.2(b). The block widths can be designed to provide an appropriate balance between density and accessibility. Depending on the shape and physical support provided by the items stored, there may be a restriction on how high the unit loads can be stacked. In some cases, loads cannot be stacked on top of each other, either because of the physical shape or limited compressive strength of the individual loads. The inability to stack loads in bulk storage reduces storage density, removing one of its principal benefits.

Although bulk storage is characterized by the absence of specific storage equipment, material handling equipment must be used to put materials into storage and to retrieve them. Industrial trucks such as pallet trucks and powered forklifts (Section 10.1) are typically used for this purpose.

**Rack Systems.** Rack systems provide a method of stacking unit loads vertically without the need for the loads themselves to provide support. One of the most common rack systems is the pallet rack, consisting of a frame that includes horizontal load-supporting beams, as illustrated in Figure 11.3. Pallet loads are stored on these horizontal beams. Alternative storage rack systems include:

- **Cantilever racks,** which serve a similar function as pallet racks except the supporting horizontal beams are cantilevered from the vertical central frame. Elimination of the vertical beams at the front of the frame provides unobstructed spans, which facilitates storage of long materials such as rods, bars, and pipes.
- **Portable racks,** which consist of portable box-frames that hold a single pallet load and can be stacked on top of each other, thus preventing load crushing that might occur in bulk vertical storage.
- **Drive-through racks.** These consist of aisles, open at each end, having two vertical columns with supporting rails for pallet loads on either side but no obstructing beams spanning the aisle. The rails are designed to support pallets of specific widths (Table 9.4). Forklift trucks are driven into the aisle to place the pallets onto the supporting rails. A related rack system is the drive-in rack, which is open at one end, permitting forklifts to access loads from one direction only.
- **Flow-through racks.** In place of the horizontal load-supporting beams in a conventional rack system, the flow-through rack uses long conveyor tracks capable of supporting a row of unit loads. The unit loads are loaded from one side of the rack and unloaded from the other side, thus providing first-in-first-out stock rotation. The conveyor tracks are often inclined at a slight angle to allow gravity to move the loads toward the output side of the rack system.

**Shelving and Bins.** Shelves represent one of the most common storage equipment types. A shelf is a horizontal platform, supported by a wall or frame, on which materials are stored. Steel shelving sections are manufactured in standard sizes, typically ranging from about 0.9 to 1.2 m (3 to 4 ft) long (in the aisle direction), from 0.3 to 0.6 m (12 to 24 in) wide, and up to 3.0 m (10 ft) tall. Shelving often includes bins, which are containers or boxes that hold loose items.

**Drawer Storage.** Finding items in shelving can sometimes be difficult, especially if the shelf is either far above or below eye level for the storage attendant. Storage draw-
Figure 11.3 Pallet rack system for storage of unit loads on pallets.

ers, Figure 11.4, can alleviate this problem because each drawer pulls out to allow its entire contents to be readily seen. Modular drawer storage cabinets are available with a variety of drawer depths for different item sizes and are widely used for storage of tools and maintenance items.

11.4 AUTOMATED STORAGE SYSTEMS

The storage equipment described in the preceding section requires a human worker to access the items in storage. The storage system itself is static. Mechanized and automated storage systems are available that reduce or eliminate the amount of human intervention
required to operate the system. The level of automation varies. In less-automated systems, a human operator is required in each storage/retrieval transaction. In highly automated systems, loads are entered or retrieved under computer control, with no human participation except to input data to the computer. Table 11.2 lists the advantages and disadvantages as well as typical applications of automated storage systems.

An automated storage system represents a significant investment, and it often requires a new and different way of doing business. Companies have different reasons for automating the storage function. Table 11.3 provides a list of possible objectives that a company may want to achieve by automating its storage operations. Automated storage systems divide into two general types: (1) automated storage/retrieval systems and (2) carousel storage systems. These two types are discussed in the following sections.

### 11.4.1 Automated Storage/Retrieval Systems

An automated storage/retrieval system (AS/RS) can be defined as a storage system that performs storage and retrieval operations with speed and accuracy under a defined degree of automation. A wide range of automation is found in commercially available AS/R

<table>
<thead>
<tr>
<th>TABLE 11.3 Possible Objectives for Automating a Company's Storage Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>• To increase storage capacity</td>
</tr>
<tr>
<td>• To increase storage density</td>
</tr>
<tr>
<td>• To recover factory floor space presently used for storing work-in-process</td>
</tr>
<tr>
<td>• To improve security and reduce pilferage</td>
</tr>
<tr>
<td>• To reduce labor cost and/or increase labor productivity in storage operations</td>
</tr>
<tr>
<td>• To improve safety in the storage function</td>
</tr>
<tr>
<td>• To improve control over inventories</td>
</tr>
<tr>
<td>• To improve stock rotation</td>
</tr>
<tr>
<td>• To improve customer service</td>
</tr>
<tr>
<td>• To increase throughput</td>
</tr>
</tbody>
</table>
Automated Storage Systems

At the most sophisticated level, the operations are totally automated, computer controlled, and fully integrated with factory and/or warehouse operations; at the other extreme, human workers control the equipment and perform the storage/retrieval transactions. Automated storage/retrieval systems are custom designed for each application, although the designs are based on standard modular components available from each respective AS/RS supplier.

Our definition can be interpreted to include carousel storage systems. However, in the material handling industry, the carousel-based systems are distinguished from AS/RSs. The biggest difference is in the construction of the equipment. The basic AS/RS consists of a rack structure for storing loads and a storage/retrieval mechanism whose motions are linear (x-y-z motions). By contrast, a basic carousel system uses storage baskets suspended from an overhead conveyor that revolves around an oval track loop to deliver the baskets to a load/unload station. The differences between an AS/RS and a carousel storage system are summarized in Table 11.4.

An AS/RS consists of one or more storage aisles that are each serviced by a storage/retrieval (S/R) machine. (The S/R machines are sometimes referred to as cranes.) The aisles have storage racks for holding the stored materials. The S/R machines are used to deliver materials to the storage racks and to retrieve materials from the racks. Each AS/RS aisle has one or more input/output stations where materials are delivered into the storage system or moved out of the system. The input/output stations are called pickup-and-deposit (P&D) stations in AS/RS terminology. P&D stations can be manually operated or interfaced to some form of automated handling system such as a conveyor or an AGVS.

**AS/RS Types and Applications.** Several important categories of automated storage/retrieval system can be distinguished. The following are the principal types:

- **Unit load AS/RS.** The unit load AS/RS is typically a large automated system designed to handle unit loads stored on pallets or in other standard containers. The system is computer controlled, and the S/R machines are automated and designed to handle the unit load containers. A unit load AS/RS is pictured in Figure 11.5. The unit load system is the generic AS/RS. Other systems described below represent variations of the unit load AS/RS.

### Table 11.4 Differences Between an AS/RS and a Carousel Storage System

<table>
<thead>
<tr>
<th>Feature</th>
<th>Basic AS/RS</th>
<th>Basic Carousel Storage System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage structure</td>
<td>Rack system to support pallets or shelf system to support tote bins</td>
<td>Baskets suspended from overhead conveyor trolleys</td>
</tr>
<tr>
<td>Motions</td>
<td>Linear motions of S/R machine</td>
<td>Revolution of overhead conveyor trolleys around oval track</td>
</tr>
<tr>
<td>Storage/retrieval operation</td>
<td>S/R machine travels to compartments in rack structure</td>
<td>Conveyor revolves to bring baskets to load/unload station</td>
</tr>
<tr>
<td>Replication of storage capacity</td>
<td>Multiple aisles, each consisting of rack structure and S/R machine</td>
<td>Multiple carousels, each consisting of oval track and suspended bins</td>
</tr>
</tbody>
</table>
• Deep-lane AS/RS. The deep-lane AS/RS is a high-density unit load storage system that is appropriate when large quantities of stock are stored, but the number of separate stock types (SKUs) is relatively small. Instead of storing each unit load so that it can be accessed directly from the aisle (as in a conventional unit load system), the deep-lane system stores ten or more loads in a single rack, one load behind the next. Each rack is designed for "flow-through," with input on one side and output on the other side. Loads are picked from one side of the rack by an S/R-type machine designed for retrieval, and another machine is used on the entry side of the rack for load input.

• Miniload AS/RS. This storage system is used to handle small loads (individual parts or supplies) that are contained in bins or drawers in the storage system. The S/R machine is designed to retrieve the bin and deliver it to a P&D station at the end of the aisle so that individual items can be withdrawn from the bins. The P&D station is usually operated by a human worker. The bin or drawer must then be returned to its location in the system. A miniload AS/RS system is generally smaller than a unit load AS/RS and is often enclosed for security of the items stored.

• Man-on-board AS/RS. A man-on-board (also called man-aboard) storage/retrieval system represents an alternative approach to the problem of retrieving individual items from storage. In this system, a human operator rides on the carriage of the S/R
machine. Whereas the mini load system delivers an entire bin to the end-of-aisle pick station and must return it subsequently to its proper storage compartment, the man-on-board system permits individual items to be picked directly at their storage locations. This offers an opportunity to increase system throughput.

- **Automated item retrieval system.** These storage systems are also designed for retrieval of individual items or small product cartons; however, the items are stored in lanes rather than bins or drawers. When an item is retrieved, it is pushed from its lane and drops onto a conveyor for delivery to the pickup station. The operation is somewhat similar to a candy vending machine, except that an item retrieval system has more storage lanes and a conveyor to transport items to a central location. The supply of items in each lane is periodically replenished, usually from the rear of the system so that there is flow-through of items, thus permitting first-in/first-out inventory rotation.

- **Vertical lift storage modules (VLSM) [10].** These are also called vertical lift automated storage/retrieval systems (VL-AS/RS) [7]. All of the preceding AS/RS types are designed around a horizontal aisle. The same principle of using a center aisle to access loads is used except that the aisle is vertical. Vertical lift storage modules, some with heights of 10 m (30 ft) or more, are capable of holding large inventories while saving valuable floor space in the factory.

Most applications of AS/RS technology have been associated with warehousing and distribution operations. An AS/RS can also be used to store raw materials and work-in-process in manufacturing. Three application areas can be distinguished for automated storage/retrieval systems: (1) unit load storage and handling, (2) order picking, and (3) work-in-process storage systems. Unit load storage and retrieval applications are represented by the unit load AS/RS and deep-lane storage systems. These kinds of applications are commonly found in warehousing for finished goods in a distribution center, rarely in manufacturing. Deep-lane systems are used in the food industry. As described above, order picking involves retrieving materials in less than full unit load quantities. Mini load, man-on-board, and item retrieval systems are used for this second application area.

Work-in-process (WIP) storage is a more recent application of automated storage technology. While it is desirable to minimize the amount of work-in-process, it is also important to effectively manage WIP that unavoidably does exist in a factory. Automated storage systems, either automated storage/retrieval systems or carousel systems, represent an efficient way of storing materials between processing steps, particularly in batch and job shop production. In high production, work-in-process is often carried between operations by conveyor systems, which thus serves both storage and transport functions.

The merits of an automated WIP storage system for batch and job shop production can best be seen by comparing it with the traditional way of dealing with work-in-process. The typical factory contains multiple work cells, each performing its own processing operations on different parts. At each cell, orders consisting of one or more parts are waiting on the plant floor to be processed, while other completed orders are waiting to be moved to the next cell in the sequence. It is not unusual for a plant engaged in batch production to have hundreds of orders in progress simultaneously, all of which represent work-in-process. The disadvantages of keeping all of this inventory in the plant include: (1) time spent searching for orders, (2) parts or even entire orders becoming temporarily or permanently lost, sometimes resulting in repeat orders to reproduce the lost parts, (3) orders not being processed according to their relative priorities at each cell, and (4) orders spending too much time in the factory, causing customer deliveries to be late. These problems indicate poor control of work-in-process.
Automated storage/retrieval systems are also used in high-production operations. Examples are found in the automobile industry, where some final assembly plants use large capacity AS/RS systems to temporarily store car and small truck bodies between major assembly steps. The AS/RS can be used for staging and sequencing the work units according to the most efficient production schedule [1].

Automated storage systems help to regain control over WIP. Reasons that justify the installation of automated storage systems for work-in-process include:

- **Buffer storage in production.** A storage system can be used as a buffer storage zone between two processes whose production rates are significantly different. A simple example is a two-process sequence in which the first processing operation feeds a second process, which operates at a slower production rate. The first operation requires only one shift to meet production requirements, while the second step requires two shifts to produce the same number of units. An in-process buffer is needed between these operations to temporarily store the output of the first process.

- **Support of just-in-time delivery.** Just-in-time (JIT) is a manufacturing strategy in which parts required in production and/or assembly are received immediately before they are needed in the plant (Section 26.7). This results in a significant dependency of the factory on its suppliers to deliver the parts on time for use in production. To reduce the chance of stock-outs due to late supplier deliveries, some plants have installed automated storage systems as storage buffers for incoming materials. Although this approach subverts the objectives of JIT, it also reduces some of its risks.

- **Kitting of parts for assembly.** The storage system is used to store components for assembly of products or subassemblies. When an order is received, the required components are retrieved, collected into kits (tote pans), and delivered to the production floor for assembly.

- **Compatible with automatic identification systems.** Automated storage systems can be readily interfaced with automatic identification devices such as bar code readers. This allows loads to be stored and retrieved without human operators to identify the loads.

- **Computer control and tracking of materials.** Combined with automatic identification, an automated WIP storage system permits the location and status of work-in-process to be known.

- **Support of factory-wide automation.** Given the need for some storage of work-in-process in batch production, an appropriately sized automated storage system becomes an important subsystem in a fully automated factory.

**Components and Operating Features of an AS/RS.** Virtually all of the automated storage/retrieval systems described above consist of the following components, shown in Figure 11.5: (1) storage structure, (2) S/R machine, (3) storage modules (e.g., pallets for unit loads), and (4) one or more pickup-and-deposit stations. In addition, a control system is required to operate the AS/RS.

The storage structure is the rack framework, made of fabricated steel, which supports the loads contained in the AS/RS. The rack structure must possess sufficient strength and rigidity that it does not deflect significantly due to the loads in storage or other forces on the framework. The individual storage compartments in the structure must be designed to accept and hold the storage modules used to contain the stored materials. The rack structure may also be used to support the roof and siding of the building in which the AS/RS resides. Another function of the storage structure is to support the aisle hardware required
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10 the S/R machines with respect to the storage compartments of the AS/RS. This
hardware includes guide rails at the top and bottom of the structure as well as end stops
and other features required to provide safe operation.

The S/R machine is used to accomplish storage transactions, delivering loads from
the input station into storage, and retrieving loads from storage and delivering them to the
output station. To perform these transactions, the storage/retrieval machine must be capa-
ble of horizontal and vertical travel to align its carriage (which carries the load) with the
storage compartment in the rack structure. The S/R machine consists of a rigid mast on
which is mounted a rail system for vertical motion of the carriage. Wheels are attached at
the base of the mast to permit horizontal travel along a rail system that runs the length of
the aisle. A parallel rail at the top of the storage structure is used to maintain alignment of
the mast and carriage with respect to the rack structure.

The carriage includes a shuttle mechanism to move loads into and from their stor-
age compartments. The design of the shuttle system must also permit loads to be trans-
ferred from the S/R machine to the P&D station or other material-handling interface
with the AS/RS. The carriage and shuttle are positioned and actuated automatically in
the usual AS/RS. Man-on-board S/R machines are equipped for a human operator to ride
on the carriage.

To accomplish the desired motions of the S/R machine, three drive systems are re-
quired: horizontal movement of the mast, vertical movement of the carriage, and shuttle
transfer between the carriage and a storage compartment. Modern S/R machines are avail-
able with horizontal speeds up to 200 m/min (600 ft/min) along the aisle and vertical or
lift speeds up to around 50 m/min (150 ft/min). These speeds determine the time required
for the carriage to travel from the P&D station to a particular location in the storage aisle.
Acceleration and deceleration have a more-significant effect on travel time over short dis-
rances. The shuttle transfer is accomplished by any of several mechanisms, including forks
(for pallet loads) and friction devices for flat bottom tote pans.

The storage modules are the unit load containers of the stored material. These in-
clude pallets, steel wire baskets and containers, plastic tote pans, and special drawers (used
in miniload systems). These modules are generally made to a standard base size that can
be handled automatically by the carriage shuttle of the S/R machine. The standard size is
also designed to fit in the storage compartments of the rack structure.

The pick-and-deposit station is where loads are transferred into and out of the AS/RS.
They are generally located at the end of the aisles for access by the external handling sys-

The principal AS/RS controls problem is positioning the S/R machine within an ac-
ceptable tolerance at a storage compartment in the rack structure to deposit or retrieve a
load. The locations of materials stored in the system must be determined to direct the S/R
machine to a particular storage compartment. Within a given aisle in the AS/RS, each com-
partment is identified by its horizontal and vertical positions and whether it is on the right
side or left side of the aisle. A scheme based on alphanumeric codes can be used for this
purpose. Using this location identification scheme, each unit of material stored in the sys-
tem can be referenced to a particular location in the aisle. The record of these locations is
called the "item location file." Each time a storage transaction is completed, the transaction must be recorded into the item location file.

Given a specified storage compartment to go to, the S/R machine must be controlled to move to that location and position the shuttle for load transfer. One positioning method uses a counting procedure in which the number of bays and levels are counted in the direction of travel (horizontally and vertically) to determine position. An alternative method is a numerical identification procedure in which each compartment is provided with a reflective target with binary-coded location identifications on its face. Optical scanners are used to read the target and position the shuttle for depositing or retrieving a load.

Computer controls and programmable logic controllers are used to determine the required location and guide the S/R machine to its destination. Computer control permits the physical operation of the AS/RS to be integrated with the supporting information and record-keeping system. Storage transactions can be entered in real-time, inventory records can be accurately maintained, system performance can be monitored, and communications can be facilitated with other factory computer systems. These automatic controls can be superseded or supplemented by manual controls when required under emergency conditions or for man-on-board operation of the machine.

11.4.2 Carousel Storage Systems

A carousel storage system consists of a series of bins or baskets suspended from an overhead chain conveyor that revolves around a long oval rail system, as depicted in Figure 11.6. The purpose of the chain conveyor is to position bins at a load/unload station at the end of the oval. The operation is similar to the powered overhead rack system used by dry cleaners to deliver finished garments to the front of the store. Most carousels are operated by a human worker located at the load/unload station. The worker activates the powered carousel to deliver a desired bin to the station. One or more parts are removed from or added to the bin, and then the cycle is repeated. Some carousels are automated by using transfer mechanisms at the load/unload station to move loads into and from the carousel.

Carousel Technology. Carousels can be classified as horizontal or vertical. The more common horizontal configuration, as in Figure 11.6, comes in a variety of sizes, ranging between 3 m (10 ft) and 30 m (100 ft) in length. Carousels at the upper end of the range have higher storage density, but the average access cycle time is greater. Accordingly, most carousels are 10-16 m (30-50 ft) long to achieve a proper balance between these competing factors.

The structure of a horizontal carousel storage system consists of welded steel framework that supports the oval rail system. The carousel can be either an overhead system (called a top-driven unit) or a floor-mounted system (called a bottom-driven unit). In the top-driven unit, a motorized pulley system is mounted at the top of the framework and drives an overhead trolley system. The bins are suspended from the trolleys. In the bottom-driven unit, the pulley drive system is mounted at the base of the frame, and the trolley system rides on a rail in the base. This provides more load-carrying capacity for the carousel storage system. It also eliminates the problem of dirt and oil dripping from the overhead trolley system in top-driven systems.

The design of the individual bins and baskets of the carousel must be consistent with the loads to be stored. Bin widths range from about 50 to 75 cm (20 to 30 in), and depths
are up to about 55 cm (22 in). Heights of horizontal carousels are typically 1.8–2.4 m (6–8 ft). Standard bins are made of steel wire to increase operator visibility.

Vertical carousels are constructed to operate around a vertical conveyor loop. They occupy much less floor space than the horizontal configuration, but require sufficient overhead space. The ceiling of the building limits the height of vertical carousels, and therefore their storage capacity is typically lower than for the average horizontal carousel.

Controls for carousel storage systems range from manual call controls to computer control. Manual controls include foot pedals, hand switches, and specialized keyboards. Foot pedal control allows the operator at the pick station to rotate the carousel in either direction to the desired bin position. Hand control involves use of a hand-operated switch that is mounted on an arm projecting from the carousel frame within easy reach of the operator. Again, bidirectional control is the usual mode of operation. Keyboard control permits a greater variety of control features than the previous control types. The operator can enter the desired bin position, and the carousel is programmed to determine the shortest route to deliver the bin to the pick station.

Computer control increases opportunities for automation of the mechanical carousel and for management of the inventory records. On the mechanical side, automatic loading and unloading is available on modern carousel storage systems. This allows the carousel to be interfaced with automated handling systems without the need for human participation in the load/unload operations. Data management features provided by computer control
include the capability to maintain data on bin locations, items in each bin, and other inventory control records.

Carousel Applications. Carousel storage systems provide a relatively high throughput and are often an attractive alternative to a miniload AS/RS in manufacturing operations where its relatively low cost, versatility, and high reliability are recognized. Typical applications of carousel storage systems include: (1) storage and retrieval operations, (2) transport and accumulation, (3) work-in-process, and (4) unique applications.

Storage and retrieval operations can be efficiently accomplished using carousels when individual items must be selected from groups of items in storage. Sometimes called "pick and load" operations, this kind of procedure is common in order-picking of tools in a toolroom, raw materials in a stockroom, service parts or other items in a wholesale firm, and work-in-process in a factory. In small electronics assembly, carousels are used for kitting of parts to be transported to assembly workstations.

In transport and accumulation applications, the carousel is used to transport and/or sort materials as they are stored. One example of this is in progressive assembly operations where the workstations are located around the periphery of a continuously moving carousel, and the workers have access to the individual storage bins of the carousel. They remove work from the bins to complete their own respective assembly tasks, then place their work into another bin for the next operation at some other workstation. Another example of transport and accumulation applications is sorting and consolidation of items. Each bin is defined for collecting the items of a particular type or customer. When the bin is full, the collected load is removed for shipment or other disposition.

Carousel storage systems often compete with automated storage and retrieval systems for applications where work-in-process is to be temporarily stored. Applications of carousel systems in the electronics industry are common. Unique applications involve specialized uses of carousel systems. Examples include: electrical testing of components, where the carousel is used to store the item during testing for a specified period of time; and drawer or cabinet storage, in which standard drawer-type cabinets are mounted on the carousel.

11.5 ENGINEERING ANALYSIS OF STORAGE SYSTEMS

Several aspects of the design and operation of a storage system are susceptible to quantitative engineering analysis. In this section, we examine capacity sizing and throughput performance for the two types of automated storage systems.

11.5.1 Automated Storage/Retrieval Systems

While the methods developed here are specifically for an automated storage/retrieval system, similar approaches can be used for analyzing traditional storage facilities, such as warehouses consisting of pallet racks and bulk storage.

Sizing the AS/RS Rack Structure. The total storage capacity of one storage aisle depends on how many storage compartments are arranged horizontally and vertically in the aisle, as indicated in our diagram in Figure 11.7. This can be expressed as follows:

\[
\text{Capacity per aisle} = 2n_1n_2
\]  

(11.1)
Figure 11.7 Top and side views of a unit load AS/RS, with nine storage compartments horizontally \((n_x = 9)\) and six compartments vertically \((n_z = 6)\).

where \(n_x\) = number of load compartments along the length of the aisle, and \(n_z\) = number of load compartments that make up the height of the aisle. The constant, 2, accounts for the fact that loads are contained on both sides of the aisle.

If we assume a standard size compartment (to accept a standard size unit load), then the compartment dimensions facing the aisle must be larger than the unit load dimensions. Let \(x\) and \(y\) = the depth and width dimensions of a unit load (e.g., a standard pallet size as given in Table 9.4), and \(z\) = the height of the unit load. The width, length, and height of the rack structure of the AS/RS aisle are related to the unit load dimensions and number of compartments as follows \([6]\):

\[
W = 3(x + a) \tag{11.2a}
\]
\[
L = n_x(y + b) \tag{11.2b}
\]
\[
H = n_z(z + c) \tag{11.2c}
\]

where \(W\), \(L\), and \(H\) are the width, length, and height of one aisle of the AS/RS rack structure (mm, in); \(x\), \(y\), and \(z\) are the dimensions of the unit load (mm, in); and \(a\), \(b\), and \(c\) are allowances designed into each storage compartment to provide clearance for the unit load and to account for the size of the supporting beams in the rack structure (mm, in). For the case of unit loads contained on standard pallets, recommended values for the allowances \([6]\) are: \(a = 150\) mm (6 in), \(b = 200\) mm (8 in), and \(c = 250\) mm (10 in). For an AS/RS with
multiple aisles. \( W \) is simply multiplied by the number of aisles to obtain the overall width of the storage system. The rack structure is built above floor level by 300–600 mm (12–24 in), and the length of the AS/RS extends beyond the rack structure to provide space for the P&D station.

**EXAMPLE 11.2  Sizing an AS/RS System**

Each aisle of a four-aisle AS/RS is to contain 60 storage compartments in the length direction and 12 compartments vertically. All storage compartments will be the same size to accommodate standard size pallets of dimensions: \( x = 42 \) in and \( y = 48 \) in. The height of a unit load \( z = 36 \) in. Using the allowances, \( a = 6 \) in, \( b = 8 \) in, and \( c = 10 \) in, determine: (a) how many unit loads can be stored in the AS/RS, and (b) the width, length, and height of the AS/RS.

**Solution:**

(a) The storage capacity is given by Eq. (11.1):

\[
\text{Capacity per aisle} = 2(60)(12) = 1440 \text{ unit loads.}
\]

With four aisles, the total capacity is:

\[
\text{AS/RS capacity} = 4(1440) = 5760 \text{ unit loads}
\]

(b) From Eqs. (11.2), we can compute the dimensions of the storage rack structure:

\[
W = 3(42 + 6) = 144 \text{ in} = 12 \text{ ft/aisle}
\]

Overall width of the AS/RS = 4(12) = 48 ft

\[
L = 60(48 + 8) = 3360 \text{ in} = 280 \text{ ft}
\]

\[
H = 12(36 + 10) = 552 \text{ in} = 46 \text{ ft}
\]

**AS/RS Throughput.** System throughput is defined as the hourly rate of S/R transactions that the automated storage system can perform (Section 11.1). A transaction involves depositing a load into storage or retrieving a load from storage. Either one of these transactions alone is accomplished in a single command cycle. A dual command cycle accomplishes both transaction types in one cycle; since this reduces travel time per transaction, throughput is increased by using dual command cycles.

Several methods are available to compute AS/RS cycle times to estimate throughput performance. The method we present is recommended by the Material Handling Institute [2]. It assumes: (1) randomized storage of loads in the AS/RS (i.e., any compartment in the storage aisle is equally likely to be selected for a transaction). (2) storage compartments are of equal size, (3) the P&D station is located at the base and end of the aisle, (4) constant horizontal and vertical speeds of the S/R machine, and (5) simultaneous horizontal and vertical travel. For a single command cycle, the load to be entered or retrieved is assumed to be located at the center of the rack structure, as in Figure 11.8(a). Thus, the S/R machine must travel half the length and half the height of the AS/RS, and it must return the same distance. The single command cycle time can therefore be expressed by:

\[
T_{sc} = 2 \text{Max} \left\{ \frac{0.5L}{v_y}, \frac{0.5H}{v_z} \right\} + 2T_{pd} = \text{Max} \left\{ \frac{L}{v_y}, \frac{H}{v_z} \right\} + 2T_{pd}
\]  
(11.3a)
Figure 11.8  Assumed travel trajectory of the S/R machine for (a) single command cycle and (b) dual command cycle.

where $T_{cs}$ = cycle time of a single command cycle (min/cycle), $L$ = length of the AS/RS rack structure (m, ft), $v_y$ = velocity of the S/R machine along the length of the AS/RS (m/min, ft/min), $H$ = height of the rack structure (m, ft), $v_z$ = velocity of the S/R machine in the vertical direction of the AS/RS (m/min, ft/min), and $T_{pd}$ = pickup-and-deposit time (min). Two P&D times are required per cycle, representing load transfers to and from the S/R machine.

For a dual command cycle, the S/R machine is assumed to travel to the center of the rack structure to deposit a load, and then it travels to 3/4 the length and height of the AS/RS to retrieve a load, as in Figure 11.8(b). Thus, the total distance traveled by the S/R machine is 3/4 the length and 3/4 the height of the rack structure, and back. In this case, cycle time is given by:

$$T_{cd} = 2 \max \left( \frac{0.75L}{v_y}, \frac{0.75H}{v_z} \right) + 4T_{pd} = \max \left( \frac{1.5L}{v_y}, \frac{1.5H}{v_z} \right) + 4T_{pd} \quad (11.3b)$$

where $T_{cd}$ = cycle time for a dual command cycle (min/cycle), and the other terms are defined above.

System throughput depends on the relative numbers of single and dual command cycles performed by the system. Let $R_s = \text{number of single command cycles performed per hour}$ and $R_{sd} = \text{number of dual command cycles per hour at a specified or assumed utilization level}$. We can formulate an equation for the amounts of time spent in performing single command and dual command cycles each hour:

$$R_s T_{cs} + R_{sd} T_{cd} = 60 U \quad (11.4)$$

where $U = \text{system utilization during the hour}$. The right-hand side of the equation gives the total number of minutes of operation per hour. To solve Eq. (11.4), the relative proportions of $R_s$ and $R_{sd}$ must be determined, or assumptions about these proportions must be made. Then the total hourly cycle rate is given by

$$R_c = R_s + R_{sd} \quad (11.5)$$

where $R_c = \text{total S/R cycle rate (cycles/hr)}$. Note that the total number of storage and retrieval transactions per hour will be greater than this value unless $R_{sd} = 0$, since there are
two transactions accomplished in each dual command cycle. Let \( R_t \) = the total number of transactions performed per hour; then

\[
R_t = R_c + 2R_{cd}
\]

**EXAMPLE 11.3 AS/RS Throughput Analysis**

Consider the AS/RS from previous Example 11.2, in which an S/R machine is used for each aisle. The length of the storage aisle = 280 ft and its height = 46 ft. Suppose horizontal and vertical speeds of the S/R machine are 200 ft/min and 75 ft/min, respectively. The S/R machine requires 20 sec to accomplish a P&D operation. Find: (a) the single command and dual command cycle times per aisle, and (b) throughput per aisle under the assumptions that storage system utilization = 90% and the number of single command and dual command cycles are equal.

**Solution:** (a) We first compute the single and dual command cycle times by Eqs. (11.3):

\[
T_c = \text{Max}\{280/200, 46/75\} + 2(20/60) = 2.066 \text{ min/cycle}
\]

\[
T_{cd} = \text{Max}\{1.5 \times 280/200, 1.5 \times 46/75\} + 4(20/60) = 3.432 \text{ min/cycle}
\]

(b) From Eq. (11.4), we can establish the single command and dual command activity levels each hour as follows:

\[
2.066 R_c + 3.432 R_{cd} = 60(0.90) = 54.0 \text{ min}
\]

According to the problem statement, the number of single command cycles is equal to the number of dual command cycles. Thus, \( R_c = R_{cd} \).

Substituting this relation into the above equation, we have

\[
2.066 R_c + 3.432 R_c = 54
\]

\[
5.498 R_c = 54
\]

\[
R_c = 9.822 \text{ single command cycles/hr}
\]

\[
R_{cd} = R_c = 9.822 \text{ dual command cycles/hr}
\]

System throughput = the total number of S/R transactions per hour from Eq. (11.6):

\[
R_t = R_c + 2R_{cd} = 29.46 \text{ transactions/hr}
\]

With four aisle, \( R_t \) for the AS/RS = 117.84 transactions/hr

**EXAMPLE 11.4 AS/RS Throughput Using a Class-Based Dedicated Storage Strategy**

The aisles in the AS/RS of the previous example will be organized following a class-based dedicated storage strategy. There will be two classes, according to activity level. The more-active stock is stored in the half of the rack system that is located closest to the input/output station, and the less-active stock is stored in the other half of the rack system farther away from the input/output station. Within each half of the rack system, random storage is used. The more-active stock accounts for 75% of the transactions, and the less-active stock accounts for the remaining 25%. As before, assume that system utilization = 90%, and the
number of single command cycles = the number of dual command cycles. Determine the throughput of the AS/RS, basing the computation of cycle times on the same kinds of assumptions used in the MHI method.

**Solution:** With a total length of 280 ft, each half of the rack system will be 140 ft long and 46 ft high. Let us identify the stock nearest the input/output station (accounting for 75% of the transactions) as Class A, and the other half of the stock (accounting for 25% of the transactions) as Class B. The cycle times are computed as follows:

For Class A stock:

\[ T_{\text{cycle A}} = \max \left\{ \frac{140}{200}, \frac{46}{75} \right\} + 2(0.333) = 1.366 \text{ min} \]

\[ T_{\text{dual A}} = \max \left\{ \frac{1.5 \times 140}{200}, \frac{1.5 \times 46}{75} \right\} + 4(0.333) = 2.382 \text{ min} \]

For Class B stock:

\[ T_{\text{cycle B}} = 2 \max \left\{ \frac{140 + 0.5(140)}{200}, \frac{0.5(46)}{75} \right\} + 2(0.333) = 2.766 \text{ min} \]

\[ T_{\text{dual B}} = 2 \max \left\{ \frac{140 + 0.75(140)}{200}, \frac{0.75(46)}{75} \right\} + 4(0.333) = 3.782 \text{ min} \]

Consistent with the previous problem, let us conclude that

\[ R_{\text{c1A}} = R_{\text{cdA}} \quad \text{and} \quad R_{\text{c1B}} = R_{\text{cdB}} \quad \text{(a)} \]

We are also given that 75% of the transactions are Class 1 and 25% are Class 2. Accordingly,

\[ R_{\text{c1A}} = 3R_{\text{c1B}} \quad \text{and} \quad R_{\text{cdA}} = 3R_{\text{cdB}} \quad \text{(b)} \]

We can establish the following equation for how each aisle spends its time during 1 hr:

\[ R_{\text{c1A}} T_{\text{cycle A}} + R_{\text{cdA}} T_{\text{dual A}} + R_{\text{c1B}} T_{\text{cycle B}} + R_{\text{cdB}} T_{\text{dual B}} = 60(0.90) \]

Based on Eqs. (a),

\[ R_{\text{c1A}} T_{\text{cycle A}} + R_{\text{cdA}} T_{\text{dual A}} + R_{\text{c1B}} T_{\text{cycle B}} + R_{\text{cdB}} T_{\text{dual B}} = 60(0.90) \]

Based on Eqs. (b),

\[ 3R_{\text{c1B}} T_{\text{cycle A}} + 3R_{\text{c1B}} T_{\text{dual A}} + R_{\text{c1B}} T_{\text{cycle B}} + R_{\text{cdB}} T_{\text{dual B}} = 60(0.90) \]

\[ 3(1.366) R_{\text{c1B}} + 3(2.382) R_{\text{c1B}} + 2.766 R_{\text{c1B}} + 3.782 R_{\text{c1B}} = 54 \]

\[ 17.792 R_{\text{c1B}} = 54 \]

\[ R_{\text{c1B}} = 3.035 \]

\[ R_{\text{c1A}} = 3 R_{\text{c1B}} = 9.105 \]

\[ R_{\text{c1B}} = R_{\text{d1B}} = 3.035 \]

\[ R_{\text{d1A}} = 3 R_{\text{d1B}} = 9.105 \]
For one aisle,
\[ R_t = R_\text{clA} + R_\text{cB} + 2(R_\text{rdA} + R_\text{rDB}) \]
\[ = 9.105 + 3.035 + 2(9.105 + 3.035) = 36.42 \text{ transactions/hr} \]

For four aisles, \( R_t = 145.68 \text{ transactions/hr} \)
This represents almost a 24% improvement over the randomized storage strategy in Example 11.3.

11.5.2 Carousel Storage Systems

Let us develop the corresponding capacity and throughput relationships for a carousel storage system. Because of its construction, carousel systems do not possess nearly the volumetric capacity of an AS/RS. However, according to our calculations, a typical carousel system is likely to have higher throughput rates than an AS/RS.

**Storage Capacity.** The size and capacity of a carousel can be determined with reference to Figure 11.9. Individual bins or baskets are suspended from carriers that revolve around the carousel oval rail. The circumference of the rail is given by

\[ C = 2(L - W) + \pi W \]  \hspace{1cm} (11.7)

where \( C \) = circumference of oval conveyor track (m, ft), and \( L \) and \( W \) are the length and width of the track oval (m, ft).

The capacity of the carousel system depends on the number and size of the bins (or baskets) in the system. Assuming standard size bins each of a certain volumetric capacity, then the number of bins can be used as our measure of capacity. As illustrated in Figure 11.9, the number of bins hanging vertically from each carrier is \( n_b \), and \( n_c \) = the number of carriers around the periphery of the rail. Thus,

\[ \text{Total number of bins} = n_c n_b \]  \hspace{1cm} (11.8)

**Figure 11.9** Top and side views of horizontal storage carousel with 18 carriers \((n_c = 18)\) and 4 bins/carrier \((n_b = 4)\).
The carriers are separated by a certain distance to maximize storage density yet avoid the suspended bins interfering with each other while traveling around the ends of the carousel. Let \( s_c \) = the center-to-center spacing of carriers along the oval track. Then the following relationship must be satisfied by the values of \( s_c \) and \( n_c \):

\[
s_c n_c = C
\]  

(11.9)

where \( C \) = circumference (m, ft), \( s_c \) = carrier spacing (m/carrier, ft/carrier), and \( n_c \) = number of carriers, which must be an integer value.

**Throughput Analysis.** The storage/retrieval cycle time can be derived based on the following assumptions. First, only single command cycles are performed; a bin is accessed in the carousel either to put items into storage or to retrieve one or more items from storage. Second, the carousel operates with a constant speed \( v_c \); acceleration and deceleration effects are ignored. Third, random storage is assumed; that is, any location around the carousel is equally likely to be selected for an S/R transaction. And fourth, the carousel can move in either direction. Under this last assumption of bidirectional travel, it can be shown that the mean travel distance between the load/unload station and a bin randomly located in the carousel is \( C/4 \). Thus, the S/R cycle time is given by

\[
T_c = \frac{C}{4v_c} + T_{pd}
\]

(11.10)

where \( T_c \) = S/R cycle time (min), \( C \) = carousel circumference as given by Eq. (11.7) (m, ft), \( v_c \) = carousel velocity (m/min, ft/min), and \( T_{pd} \) = average time required to pick or deposit items each cycle by the operator at the load/unload station (min). The number of transactions accomplished per hour is the same as the number of cycles and is given by the following:

\[
R_t = R_c = \frac{60}{T_c}
\]

(11.11)

**EXAMPLE 11.5 Carousel Operation**

The oval rail of a carousel storage system has length = 12 m and width = 1 m. There are 75 carriers equally spaced around the oval. Suspended from each carrier are six bins. Each bin has volumetric capacity = 0.026 m³. Carousel speed = 20 m/min. Average P&D time for a retrieval = 20 sec. Determine:

(a) volumetric capacity of the storage system and (b) hourly retrieval rate of the storage system.

**Solution:** (a) Total number of bins in the carousel is

\[
n_c n_b = 75 \times 6 = 450 \text{ bins}
\]

Total volumetric capacity = \( 450(0.026) \) = 11.7 m³

(b) The circumference of the carousel rail is determined by Eq. (11.7):

\[
C = 2(12 - 1) + \pi = 25.14 \text{ m}
\]
Cycle time per retrieval is given by Eq. (11.10):

\[ T_r = \frac{25.14}{4(20)} + \frac{20}{60} = 0.647 \text{ min} \]

Expressing throughput as an hourly rate, we have

\[ R_c = \frac{60}{0.647} = 92.7 \text{ retrieval transactions/hr} \]

REFERENCES


PROBLEMS

SIZING THE AS/RS RACK STRUCTURE

Sizing the AS/RS Rack Structure

11.1 Each aisle of a six-aisle Automated Storage/Retrieval System is to contain 50 storage compartments in the length direction and eight compartments in the vertical direction. All storage compartments will be the same size to accommodate standard size pallets of dimensions: \( x = 36 \) in and \( y = 48 \) in. The height of a unit load \( z = 30 \) in. Using the allowances \( a = 6 \) in, \( b = 8 \) in, and \( c = 10 \) in, determine: (a) how many unit loads can be stored in the AS/RS and (b) the width, length, and height of the AS/RS. The rack structure will be built 18 in above floor level.

11.2 A unit load AS/RS is being designed to store 1000 pallet loads in a distribution center located next to the factory. Pallet dimensions are: \( x = 1000 \) mm, \( y = 1200 \) mm, and the maximum...
Problems

height of a unit load = 1300 mm. The following is specified: (1) The AS/RS will consist of two aisles with one S/R machine per aisle, (2) length of the structure should be approximately five times its height, and (3) the rack structure will be built 500 mm above floor level. Using the allowances $a = 150$ mm, $b = 200$ mm, and $c = 250$ mm, determine the width, length, and height of the AS/RS rack structure.

11.3 You are given the rack structure dimensions computed in Problem 11.2. Assuming that only 80% of the storage compartments are occupied on average, and that the average volume of a unit load per pallet in storage = 0.75 $m^3$, compute the ratio of the total volume of unit loads in storage relative to the total volume occupied by the storage rack structure.

11.4 A unit load AS/RS for work-in-process storage in a factory must be designed to store 2000 pallet loads, with an allowance of no less than 20% additional storage compartments for peak periods and flexibility. The unit load pallet dimensions are: depth $(x) = 36$ in and width $(y) = 48$ in. Maximum height of a unit load = 42 in. It has been determined that the AS/RS will consist of four aisles with one S/R machine per aisle. The maximum ceiling height (interior) of the building permitted by local ordinance is 60 ft, so the AS/RS must fit within this height limitation. The rack structure will be built 2 ft above floor level, and the clearance between the rack structure and the ceiling of the building must be at least 18 in. Determine the dimensions (height, length, and width) of the rack structure.

AS/RS Throughput Analysis

11.5 The length of the storage aisle in an AS/RS = 240 ft and its height = 60 ft. Suppose horizontal and vertical speeds of the S/R machine are 300 ft/min and 60 ft/min, respectively. The S/R machine requires 18 sec to accomplish a pick-and-deposit operation. Find: (a) the single command and dual command cycle times per aisle and (b) throughput for the aisle under the assumptions that storage system utilization = 85% and the numbers of single command and dual command cycles are equal.

11.6 Solve Problem 11.5 except that the ratio of single command to dual command cycles is 3:1 instead of 1:1.

11.7 An AS/RS is used for work-in-process storage in a manufacturing facility. The AS/RS has five aisles, each aisle being 120 ft long and 40 ft high. The horizontal and vertical speeds of the S/R machine are 400 ft/min and 50 ft/min, respectively. The S/R machine requires 21 sec to accomplish a pick-and-deposit operation. The number of single command cycles equals the number of dual command cycles. If the requirement is that the AS/RS must have a throughput rate of 200 S/R transactions/hr during periods of peak activity, will the AS/RS satisfy this requirement? If so, what is the utilization of the AS/RS during peak hours?

11.8 An automated storage/retrieval system installed in a warehouse has five aisles. The storage racks in each aisle are 30 ft high and 150 ft long. The S/R machine for each aisle travels at a horizontal speed of 350 ft/min and a vertical speed of 60 ft/min. The pick-and-deposit time = 0.35 min. Assume that the number of single command cycles per hour is equal to the number of dual command cycles per hour and that the system operates at 75% utilization. Determine the throughput rate (loads moved per hour) of the AS/RS.

11.9 A 10-aisle automated storage/retrieval system is located in an integrated factory-warehouse facility. The storage racks in each aisle are 18 m high and 95 m long. The S/R machine for each aisle travels at a horizontal speed of 1.5 m/sec and a vertical speed of 0.5 m/sec. Pick-and-deposit time = 20 sec. Assume that the number of single command cycles per hour is one-half the number of dual command cycles per hour and that the system operates at 80% utilization. Determine the throughput rate (loads moved per hour) of the AS/RS.

11.10 An automated storage/retrieval system for work-in-process has five aisles. The storage racks in each aisle are 10 m high and 50 m long. The S/R machine for each aisle travels at a horizontal speed of 2.0 m/sec and a vertical speed of 0.4 m/sec. Pick-and-deposit time = 15 sec.
Assume that the number of single command cycles per hour is equal to three times the number of dual command cycles per hour and that the system operates at 90% utilization. Determine the throughput rate (loads moved per hour) of the AS/RS.

11.11 The length of one aisle in an AS/RS is 100 m and its height is 20 m. Horizontal travel speed is 2.0 m/sec. The vertical speed is specified so that the storage system is “square in time,” which means that \( L/w_h = H/v_v \). The pick-and-deposit time is 15 sec. Determine the expected throughput rate (transactions per hour) for the aisle if the expected ratio of the number of transactions performed under single command cycles to the number of transactions performed under dual command cycles is 2:1. The system operates continuously during the hour.

11.12 An automated storage/retrieval system has four aisles. The storage racks in each aisle are 40 ft high and 200 ft long. The S/R machine for each aisle travels at a horizontal speed of 400 ft/min and a vertical speed of 60 ft/min. If the pick-and-deposit time = 0.3 min, determine the throughput rate (loads moved per hour) of the AS/RS, under the assumption that time spent each hour performing single command cycles is twice the time spent performing dual command cycles and that the AS/RS operates at 90% utilization.

11.13 An AS/RS with one aisle is 300 ft long and 60 ft high. The S/R machine has a maximum speed of 300 ft/min in the horizontal direction. It accelerates from 0 to 300 ft/min in a distance of 15 ft. On approaching its target position (where the S/R machine will transfer a load onto or off of its platform), it decelerates from 300 ft/min to a full stop in 15 ft. The maximum vertical speed is 60 ft/min, and the acceleration and deceleration distances are each 3 ft. Assume simultaneous horizontal and vertical movement and that the rates of acceleration and deceleration are constant in both directions. The pick-and-deposit time = 0.3 min. Using the general approach of the MHI method for computing cycle time but adding considerations of acceleration and deceleration, determine the single command and dual command cycle times.

11.14 An AS/RS with four aisles is 80 m long and 18 m high. The S/R machine has a maximum speed of 1.6 m/sec in the horizontal direction. It accelerates from 0 to 1.6 m/sec in a distance of 2.0 m. On approaching its target position (where the S/R machine will transfer a load onto or off of its platform), it decelerates from 1.6 m/sec to a full stop in 2.0 m. The maximum vertical speed is 0.5 m/sec, and the acceleration and deceleration distances are each 0.3 m. Rates of acceleration and deceleration are constant in both directions. Pick-and-deposit time = 12 sec. Utilization of the AS/RS is assumed to be 90%, and the number of dual command cycles equals the number of single command cycles. (a) Calculate the single command and dual command cycle times, including considerations for acceleration and deceleration. (b) Determine the throughput rate for the system.

11.15 Your company is seeking proposals for an automated storage/retrieval system that will have a throughput rate of 300 storage/retrieval transactions/hr during the one 8-hr shift/day. The request for proposals indicates that the number of single command cycles is expected to be four times the number of dual command cycles. The first proposal received is from a vendor who specifies the following: ten aisles, each aisle 150 ft long and 50 ft high; horizontal and vertical speeds of the S/R machine = 200 ft/min and 66.67 ft/min, respectively; and pick-and-deposit time = 0.5 min. As the responsible engineer for the project, you must analyze the proposal and make recommendations accordingly. One of the difficulties you see in the proposed AS/RS is the large number of S/R machines that would be required—one for each of the ten aisles. This makes the proposed system very expensive. Your recommendation is to reduce the number of aisles from ten to six and to select an S/R machine with horizontal and vertical speeds of 300 ft/min and 100 ft/min, respectively. Although each high-speed S/R machine is slightly more expensive than the slower model, reducing the number of machines from ten to six will significantly reduce total cost. Also, fewer aisles will reduce the cost of the rack structure, even though each aisle will be somewhat larger, since total storage capacity must remain the same. The problem is that throughput rate will be adversely affected. (a) De-
Problems

11.16 A unit load automated storage/retrieval system has five aisles. The storage racks are 60 ft high and 280 ft long. The S/R machine travels at a horizontal speed of 200 ft/min and a vertical speed of 80 ft/min. The pick-and-deposit time is 0.30 min. Assume that the number of single command cycles per hour is four times the number of dual command cycles per hour and that the system operates at 80% utilization. A dedicated storage scheme is used for organizing the stock, in which unit loads are separated into two classes, according to activity level. The more-active stock is stored in the half of the rack system located closest to the input/output station, and the less-active stock is stored in the other half of the rack system (farther away from the input/output station). Within each half of the rack system, random storage is used. The more-active stock accounts for 75% of the transactions, and the less-active stock accounts for the remaining 25%. Determine the throughput rate (loads moved per hour into and out of storage) of the AS/RS, basing your computation of cycle times on the same types of assumptions used in the MHI method. Assume that when dual command cycles are performed, the 2 transactions/cycle are both in the same class.

11.17 The AS/RS aisle of Problem 11.16 will be organized following a class-based dedicated storage strategy. There will be two classes, according to activity level. The more-active stock is stored in the half of the rack system that is located closest to the input/output station, and the less-active stock is stored in the other half of the rack system, farther away from the input/output station. Within each half of the rack system, random storage is used. The more-active stock accounts for 80% of the transactions, and the less-active stock accounts for the remaining 20%. Assume that system utilization is 85% and the number of single command cycles equals the number of dual command cycles in each half of the AS/RS. (a) Determine the throughput rate (loads moved per hour into and out of storage) of the AS/RS, basing the computation of cycle times on the same kinds of assumptions used in the MHI method. (b) A class-based dedicated storage strategy is supposed to increase throughput. Why is throughput less here than in Problem 11.16?

Carousel Storage Systems

11.18 A single carousel storage system is located in a factory making small assemblies. It is 20 m long and 1.0 m wide. The pick-and-deposit time is 0.25 min. The speed at which the carousel operates is 0.5 m/sec. The storage system has a 90% utilization. Determine the hourly throughput rate.

11.19 A storage system serving an electronics assembly plant has three storage carousels, each with its own manually operated pick-and-deposit station. The pick-and-deposit time is 0.30 min. Each carousel is 60 ft long and 2.5 ft wide. The speed at which the system revolves is 85 ft/min. Determine the throughput rate of the storage system.

11.20 A single carousel storage system has an oval rail loop that is 30 ft long and 3 ft wide. Sixty carriers are equally spaced around the oval. Suspended from each carrier are five bins. Each bin has a volumetric capacity = 0.75 ft³. Carousel speed = 100 ft/min. Average pick-and-deposit time for a retrieval = 20 sec. Determine: (a) volumetric capacity of the storage system and (b) hourly retrieval rate of the storage system.

11.21 A carousel storage system is to be designed to serve a mechanical assembly plant. The specifications on the system are that it must have a total of 400 storage bins and a throughput of at least 125 S/R transactions/hr. Two alternative configurations are being considered: (1) a one-carousel system and (2) a two-carousel system. In both cases, the width of the carousel

determine the throughput rate of the proposed ten-aisle AS/RS and calculate its utilization relative to the specified 300 transactions/hr. (b) Determine the length and height of a six-aisle AS/RS whose storage capacity would be the same as the proposed ten-aisle system. (c) Determine the throughput rate of the six-aisle AS/RS and calculate its utilization relative to the specified 300 transactions/hr. (d) Given the dilemma now confronting you, what other alternatives would you analyze, and what recommendations would you make to improve the design of the system?
is to be 4.0 ft and the spacing between carriers = 2.5 ft. One picker-operator will be required for the one-carousel system and two picker-operators will be required for the two-carousel system. In either system $v_c = 75 \text{ ft/min}$. For the convenience of the picker-operator, the height of the carousel will be limited to five bins. The standard time for a pick-and-deposit operation at the load/unload station $= 0.4 \text{ min}$ if one part is picked or stored per bin and $0.6 \text{ min}$ if more than one part is picked or stored. Assume that 50\% of the transactions will involve more than one component. Determine: (a) the required length and (b) corresponding throughput rate of the one-carousel system and (c) the required length and (d) corresponding throughput rate of the two-carousel system. (e) Which system better satisfies the design specifications?

11.22 Given your answers to Problem 11.21, the costs of both carousel systems are to be compared. The one-carousel system has an installed cost of $50,000, and the comparable cost of the two-carousel system is $75,000. Labor cost for a picker-operator is $20/hr, including fringe benefits and applicable overhead. The storage systems will be operated 250 day/yr for 7 hrs/day, although the operators will be paid for 8 hr. Using a 3-yr period in your analysis and a 25\% rate of return, determine: (a) the equivalent annual cost for the two design alternatives, assuming no salvage value at the end of 3 yr; and (b) the average cost per storage/retrieval transaction.
CHAPTER CONTENTS

12.1 Overview of Automatic Identification Methods
12.2 Bar Code Technology
   12.2.1 Linear (One-Dimensional) Bar Codes
   12.2.2 Two-Dimensional Bar Codes
12.3 Other ADC Technologies
   12.3.1 Radio Frequency Identification
   12.3.2 Magnetic Stripes
   12.3.3 Optical Character Recognition
   12.3.4 Machine Vision

The term automatic data capture (ADC), also known as automatic identification and data capture (AIDC), refers to the technologies that provide direct entry of data into a computer or other microprocessor controlled system without using a keyboard. Many of these technologies require no human involvement in the data capture and entry process. Automatic identification systems are being used increasingly to collect data in material handling and manufacturing applications. In material handling, the applications include shipping and receiving, storage, sortation, order picking, and kitting of parts for assembly. In manufacturing, the applications include monitoring the status of order processing, work-in-process, machine utilization, worker attendance, and other measures of factory operations and performance. Of course, ADC has many important applications outside the factory, including retail sales and inventory control, warehousing and distribution center operations, mail and parcel handling, patient identification in hospitals, check processing in banks, and
security systems. Our interest in this chapter emphasizes material handling and manufacturing applications.

The alternative to automatic data capture is manual collection and entry of data. This typically involves recording the data on paper and later entering them into the computer by means of a keyboard. There are several drawbacks to this method:

1. **Errors** occur in both data collection and keyboard entry of the data when accomplished manually. The average error rate of manual keyboard entry is one error per 300 characters.

2. **Time factor.** When manual methods are used, there is a time delay between when the activities and events occur and when the data on status are entered into the computer. In addition, manual methods are themselves inherently more time consuming than automated methods.

3. **Labor cost.** The full-time attention of human workers is required in manual data collection and entry, with the associated labor cost.

These drawbacks are virtually eliminated when automatic identification and data capture are used. With ADC, the data on activities, events, and conditions are acquired at the location and time of their occurrence and entered into the computer immediately or shortly thereafter.

Automatic data capture is often associated with the material handling industry. The ADC industry trade association, the Automatic Identification Manufacturers Association (AIM), started as an affiliate of the Material Handling Institute, Inc. Many of the applications of this technology relate to material handling. But automatic identification and data capture has also become a technology of growing importance in shop floor control in manufacturing plants (Chapter 26). In the present chapter, we examine the important ADC technologies as related to manufacturing.

### 12.1 Overview of Automatic Identification Methods

Nearly all of the automatic identification technologies consist of three principal components, which also comprise the sequential steps in ADC [7]:

1. **Encoded data.** A code is a set of symbols or signals (usually) representing alphanumeric characters. When data are encoded, the characters are translated into a machine-readable code. (For most ADC techniques, the encoded data are not readable by humans.) A label or tag containing the encoded data is attached to the item that is to be later identified.

2. **Machine reader or scanner.** This device reads the encoded data, converting them to alternative form, usually an electrical analog signal.

3. **Decoder.** This component transforms the electrical signal into digital data and finally back into the original alphanumeric characters.

Many different technologies are used to implement automated identification and data collection. Within the category of bar codes alone (bar codes are the leading ADC tech-
Optical. Most of these technologies use high-contrast graphical symbols that can be interpreted by an optical scanner. They include linear (one-dimensional) and two-dimensional bar codes, optical character recognition, and machine vision.

2. Magnetic. Which encode data magnetically, similar to recording tape. The two important techniques in this category are (a) magnetic stripe, widely used in plastic credit cards and bank access cards, and (b) magnetic ink character recognition, widely used in the banking industry for check processing.

3. Electromagnetic. The important ADC technology in this group is radio frequency identification (RFID).

4. Smart card. This term refers to small plastic cards (the size of a credit card) imbedded with microchips capable of containing large amounts of information. Other terms used for this technology include chip card and integrated circuit card.

5. Touch techniques, such as touch screens and button memory.

6. Biometric. These technologies are utilized to identify humans or to interpret vocal commands of humans. They include voice recognition, fingerprint analysis, and retinal eye scans.

Not all of these techniques are used in factory operations. According to a survey of industry users conducted by Modern Material Handling magazine and the industry trade association AIM USA, the most widely used ADC methods in the factory (in approximate descending order of application frequency at time of writing) are [2]: (1) bar codes, by far the most widely used, (2) radio frequency methods, (3) magnetic stripe, (4) optical character recognition, and (5) machine vision. Bar codes include two basic forms: one-dimensional or linear bar codes and two-dimensional. At time of writing, the linear codes are much more widely used, although two-dimensional codes are being adopted by certain industries that require high data density in a relatively small area. We discuss both types of bar code technologies in Section 12.2 and the other methods in Section 12.3. The features of these techniques are compared in Table 12.1.

According to the same industry survey [2], the most common applications of ADC technologies (in approximate descending order of application frequency) are: (1) receiving, (2) shipping, (3) order picking, (4) finished goods storage, (5) manufacturing processing, (6) work-in-process storage, (7) assembly, and (8) sortation.

Some of the automated identification applications require workers to be involved in the data collection procedure, usually to operate the identification equipment in the application. These techniques are therefore semiautomated rather than automated methods. Other applications accomplish the identification with no human participation. The same basic sensor technologies may be used in both cases. For example, certain types of bar code readers are operated by humans, whereas other types operate automatically.

As indicated in our chapter introduction, there are good reasons for using automatic identification and data collection techniques: (1) data accuracy, (2) timeliness, and (3) labor reduction. First and foremost, the accuracy of the data collected is improved with ADC, in many cases by a significant margin. The error rate in bar code technology is approximately 10,000 times lower than in manual keyboard data entry. The error rates of most of the other technologies are not as good as for bar codes but are still better than manual-based methods. The second reason for using automatic identification techniques
TABLE 12.1 Comparison of ADC Techniques and Manual Keyboard Data Entry

<table>
<thead>
<tr>
<th>Technique</th>
<th>Time to Enter</th>
<th>Error Rate**</th>
<th>Equipment Cost</th>
<th>Advantages/Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual entry</td>
<td>Slow</td>
<td>High</td>
<td>Low</td>
<td>Low initial cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Requires human operator</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Slow speed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(High error rate)</td>
</tr>
<tr>
<td>Bar codes: 1-D</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>High speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Good flexibility</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Low data density)</td>
</tr>
<tr>
<td>Bar codes: 2-D</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High data density</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(High equipment cost)</td>
</tr>
<tr>
<td>Radio frequency</td>
<td>Fast</td>
<td>Low</td>
<td>High</td>
<td>Label need not be visible</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Expensive labeling)</td>
</tr>
<tr>
<td>Magnetic stripe</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Much data can be encoded</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Data can be changed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Vulnerable to magnetic fields)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Contact required for reading)</td>
</tr>
<tr>
<td>OCR</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Can be read by humans</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Low data density)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(High error rate)</td>
</tr>
<tr>
<td>Machine vision</td>
<td>Fast</td>
<td>***</td>
<td>Very high</td>
<td>Equipment expensive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(Not suited to general) ADC</td>
</tr>
</tbody>
</table>

Source: Based on data from [13].

* Time to enter data is based on a 20-character field. All techniques except machine vision use a human to either enter the data (manual entry) or to operate the ADC equipment (bar codes, RFID, magnetic stripe, OCR). Key: Slow = 5–10 sec, Medium = 2–5 sec, Fast = < 2 sec.

** Substitution error rate (SER); see definition (Section 12.1).

*** Application dependent.

is to reduce the time required by human workers to make the data entry. The speed of data entry for handwritten documents is approximately 5–7 characters/sec and is 10–15 characters/sec (at best) for keyboard entry [15]. Automatic identification methods are capable of reading hundreds of characters per second. This comparison is certainly not the whole story in a data collection transaction, but the time savings in using automatic identification techniques can mean substantial labor cost benefits for large plants with many workers.

Although the error rate in automatic identification and data collection technologies is much lower than for manual data collection and entry, errors do occur in ADC. The industry has adopted two parameters to measure the errors:

1. **First Read Rate** (FRR). This is the probability of a successful (correct) reading by the scanner in its initial attempt.

2. **Substitution Error Rate** (SER). This is the probability or frequency with which the scanner incorrectly reads the encoded character as some other character. In a given set of encoded data containing \( n \) characters, the expected number of errors = SER multiplied by \( n \).

Obviously, it is desirable for the ADC system to possess a high first read rate and a low substitution error rate. A subjective comparison of substitution error rates for several ADC technologies is presented in Table 12.1.
12.2 BAR CODE TECHNOLOGY

As indicated earlier, bar codes divide into two basic types: (1) linear, in which the encoded data are read using a linear sweep of the scanner, and (2) two-dimensional, in which the encoded data must be read in both directions. These two important optical technologies are discussed in this section.

12.2.1 Linear (One-Dimensional) Bar Codes

As mentioned previously, linear bar codes are currently the most widely used automatic identification and data collection technique. There are actually two forms of linear bar code symbologies, illustrated in Figure 12.1: (a) width-modulated, in which the symbol consists of bars and spaces of varying width; and (b) height-modulated, in which the symbol consists of evenly spaced bars of varying height. The only significant application of the height-modulated bar code symbologies is in the U.S. Postal Service for ZIP Code identification, so our discussion will focus on the width-modulated bar codes, which are used widely in retailing and manufacturing.

In linear width-modulated bar code technology, the symbol consists of a sequence of wide and narrow colored bars separated by wide and narrow spaces (the colored bars are usually black and the spaces are white for high contrast). The pattern or bars and spaces is coded to represent numeric or alphanumeric characters. Palmer [13] uses the interesting analogy that bar codes might be thought of as a printed version of the Morse code, where narrow bands represent dots and wide bands represent dashes. Using this scheme, the bar code for the familiar SOS distress signal would be as shown in Figure 12.2. The difficulties with a “Morse” bar code symbology are that: (1) only the dark bars are used, thus increasing the length of the symbol, and (2) the number of bars making up the alphanumeric characters differs, thus making decoding more difficult [13].

Bar code readers interpret the code by scanning and decoding the sequence of bars. The reader consists of the scanner and decoder. The scanner emits a beam of light that is swept past the bar code (either manually or automatically) and senses light reflections to

Figure 12.1 Two forms of linear bar codes: (a) width-modulated, exemplified here by the Universal Product Code; and (b) height-modulated, exemplified here by Postnet, used by the U.S. Postal Service.

Figure 12.2 The SOS distress signal in “Morse” bar codes.
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Figure 12.3 Conversion of bar code into a pulse train of electrical signals: (a) bar code and (b) corresponding electrical signal.

distinguish between the bars and spaces. The light reflections are sensed by a photodetector, which converts the spaces into an electrical signal and the bars into absence of an electrical signal. The width of the bars and spaces is indicated by the duration of the corresponding signals. The procedure is depicted in Figure 12.3. The decoder analyzes the pulse train to validate and interpret the corresponding data.

Certainly a major reason for the acceptance of bar codes is their widespread use in grocery markets and other retail stores. In 1973, the grocery industry adopted the Universal Product Code (UPC) as its standard for item identification (Historical Note 12.1). This is a 12-digit bar code that uses six digits to identify the manufacturer and five digits to identify the product. The final digit is a check character. The U.S. Department of Defense provided another major endorsement in 1982 by adopting a bar code standard (Code 39) that must be applied by vendors on product cartons supplied to the various agencies of DOD. The UPC is a numerical code (0-9), while Code 39 provides the full set of alphanumeric characters plus other symbols (44 characters in all). These two linear bar codes and several others are compared in Table 12.2.

TABLE 12.2 Some Widely Used Linear Bar Codes

<table>
<thead>
<tr>
<th>Bar Code</th>
<th>Date</th>
<th>Description</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPC*</td>
<td>1973</td>
<td>Numeric only, length = 12 digits</td>
<td>Widely used in U.S. and Canada grocery and other retail stores</td>
</tr>
<tr>
<td>Codabar</td>
<td>1972</td>
<td>Only 16 characters: 0-9, $, :, /, , +, -</td>
<td>Used in libraries, blood banks, and some parcel freight applications</td>
</tr>
<tr>
<td>Code 39</td>
<td>1974</td>
<td>Alphanumeric. See text for description</td>
<td>Adopted by Dept. of Defense, automotive, and other manufacturing industries</td>
</tr>
<tr>
<td>Code 93</td>
<td>1982</td>
<td>Similar to Code 39 but higher density</td>
<td>Same applications as Code 39</td>
</tr>
<tr>
<td>Code 128</td>
<td>1981</td>
<td>Alphanumeric, but higher density</td>
<td>Substitutes in some Code 39 applications</td>
</tr>
<tr>
<td>Postnet</td>
<td>1980</td>
<td>Numeric only**</td>
<td>U.S. Postal Service code for ZIP code numbers</td>
</tr>
</tbody>
</table>

Sources: Nelson (12), Painters (13).

* UPC = Universal Product Code, adopted by the grocery industry in 1973 and based on a symbol developed by IBM Corp. in early grocery tests. A similar standard bar code system was developed for Europe, called the European Article Numbering system (EAN), in 1978.

** This is the only height-modulated bar code in the table. All others are width-modulated.
Historical Note 12.1  Bar codes [12], [13].

The first patent relating to a bar code was issued to J. T. Kermode in 1934 (U.S. Patent 1,985,035). It used four bars to sort billing areas for the Cleveland Gas & Electric Co. The bar code industry began in the 1960s as small working groups in large companies. Some of the early companies involved with the technology included IBM, Magnavox, RCA, Sylvania, Bendix, and General Electric. What we believe was the first bar code scanning system was at a Scott Paper Company plant in Wisconsin installed in 1960 by the General Atronics Division of Magnavox Corp. The system was used to identify and divert cartons moving along a conveyor. No laser scanners were available at that time, and the Atronics system used photocells responding to light reflected from two rows of bars on the cartons. Although the crude system worked well, top executives at Magnavox did not believe that bar code technology had much of a future, and so in 1971 they sold the division to Al Wurz, who changed the name to Accu-Sort.

By the early 1970s, the major companies in the bar code scanning business were Accu-Sort, Computer Identities, Identicon, and Bendix Recognition Systems. It is of interest to note how each of these companies developed. We have already mentioned that Accu-Sort was purchased from Magnavox. Computer Identities and Identicon were started by former employees of Sylvania, and Bendix later decided to exit the business, based on the same kinds of perceptions that influenced Magnavox to sell out. There was no profitable future in bar codes.

In 1972, the companies involved in bar code technology formed the Automatic Identification Manufacturers Association (AIM) as a product section in the Material Handling Institute (the trade association for material handling companies at that time). In 1983, AIM separated from MHI to become an independent trade association. The starting membership of AIM in 1972 consisted of ten companies: Accu-Sort, Bendix Recognition, Computer Identities, Control Logic, Electronics Corp. of America (Photoswitch Div.), General Electric, Gould (Data Systems Div.), Identicon, Mekontrol, and 3M Company. (At time of writing, there are more than 150 members of AIM.)

In 1973, the Uniform Product Code (UPC) was adopted by the grocery industry, which had been working for several years to implement bar code technology for product identification, inventory control, and automation of the check-out procedure. All producers of over-the-counter goods for the grocery industry were now required to bar code their products. Other significant events motivating the development of bar code technology included the Department of Defense requirement in 1982 that its 33,000 suppliers use bar codes. And about one year later, the Automotive Industry Action Group established the requirement that the industry's 16,000 suppliers must bar code all of their deliveries. By now, the importance of bar code technology had become clearer to business leaders.

In 1987, Code 49, the first two-dimensional code, was developed by D. Allais and introduced by Intermec to reduce the area of the conventional bar code label and to increase the density of the data contained in the symbol.

The Bar Code Symbol. The bar code standard adopted by the automotive industry, the Department of Defense, the General Services Administration, and many other manufacturing industries is Code 39, also known as AIM USD-2 (Automatic Identification Manufacturers Uniform Symbol Description-2), although this is actually a subset of Code 39. We describe this format as an example of linear bar code symbols [3], [4], [13]. Code 39 uses a series of wide and narrow elements (bars and spaces) to represent alphanumeric and other characters. The wide elements are equivalent to a binary value of one and the narrow elements are equal to zero. The width of the wide bars and spaces is between two and three times the width of the narrow bars and spaces. Whatever the wide-to-narrow ratio, the width must be uniform throughout the code for the reader to be able to consistently interpret the resulting pulse train. Figure 12.4 presents the character structure for USD-2, and Figure 12.5 illustrates how the character set might be developed in a typical bar code.
The reason for the name Code 39 is that nine elements (bars and spaces) are used in each character and three of the elements are wide. The placement of the wide spaces and bars in the code is what uniquely designates the character. Each code begins and ends with either a wide or narrow bar. The code is sometimes referred to as code three-of-nine. In addition to the character set in the bar code, there must also be a so-called “quiet zone” both preceding and following the bar code, in which there is no printing that might confuse the decoder. This quiet zone is shown in Figure 12.5.
Bar Code Readers. Bar code readers come in a variety of configurations; some require a human to operate them and others are stand-alone automatic units. They are usually classified as contact or noncontact readers. Contact bar code readers are hand-held wands or light pens operated by moving the tip of the wand quickly past the bar code on the object or document. The wand tip must be in contact with the bar code surface or in very close proximity during the reading procedure. In a factory data collection application, they are usually part of a keyboard entry terminal. The terminal is sometimes referred to as a stationary terminal in the sense that it is placed in a fixed location in the shop. When a transaction is entered in the factory, the data are usually communicated to the computer system immediately. In addition to their use in factory data collection systems, stationary contact bar code readers are widely used in retail stores to enter the item identification in a sales transaction.

Contact bar code readers are also available as portable units that can be carried around the factory or warehouse by a worker. They are battery-powered and include a solid-state memory device capable of storing data acquired during operation. The data can subsequently be transferred to the computer system. Portable bar code readers often include a keypad that can be used by the operator to input data that cannot be entered via bar code. These portable units are used for order picking in a warehouse and similar applications that require a worker to move large distances in a building.

Noncontact bar code readers focus a light beam on the bar code, and a photodetector reads the reflected signal to interpret the code. The reader probe is located a certain
distance from the bar code (several inches to several feet) during the read procedure. Non-contact readers are classified as fixed beam and moving beam scanners. Fixed beam readers are stationary units that use a fixed beam of light. They are usually mounted beside a conveyor and depend on the movement of the bar code past the light beam for their operation. Applications of fixed beam bar code readers are typically in warehousing and material handling operations where large quantities of materials must be identified as they flow past the scanner on conveyors. Fixed beam scanners in these kinds of operations represent some of the first applications of bar codes in industry.

Moving beam scanners use a highly focused beam of light, actuated by a rotating mirror to traverse an angular sweep in search of the bar code on the object. Lasers are often used to achieve the highly focused light beam. A scan is defined as a single sweep of the light beam through the angular path. The high rotational speed of the mirror allows for very high scan rates—up to 1440 scans/sec [1]. This means that many scans of a single bar code can be made during a typical reading procedure, thus permitting verification of the reading. Moving beam scanners can be either stationary or portable units. Stationary scanners are located in a fixed position to read bar codes on objects as they move past on a conveyor or other material handling equipment. They are used in warehouses and distribution centers to automate the product identification and sortation operations. A typical setup using a stationary scanner is illustrated in Figure 12.6. Portable scanners are hand-held devices that the user points at the bar code like a pistol. The vast majority of bar code scanners used in factories and warehouses are of this type [21].

Bar Code Printers. In many bar code applications, the labels are printed in medium-to-large quantities for product packages and the cartons used to ship the packaged products. These preprinted bar codes are usually produced off-site by companies specializing in these operations. The labels are printed in either identical or sequenced symbols. Printing technologies include traditional techniques such as letterpress, offset lithography, and flexographic printing.

Bar codes can also be printed on-site by methods in which the process is controlled by microprocessor to achieve individualized printing of the bar coded document or item label. These applications tend to require multiple printers distributed at locations where they are needed. The printing technologies used in these applications include [8], [13]:

- **Dot matrix.** In this technique, the bars are printed by overlapping dots to form wide or narrow bands. Dot matrix is a low-cost technique, but the quality of the printed bars

![Figure 12.6 Stationary moving beam bar code scanner located along a moving conveyor.](image)
depends on the degree of overlap: accordingly, there is a lower limit on the size of the bar code.

- **Ink-jet.** Like dot matrix, the ink-jet bars are formed by overlapping dots, but the dots are made by ink droplets. Recent advances in ink-jet technology, motivated by the personal computer market, have improved the resolution of ink-jet printing, and so bar codes of higher density than dot matrix bars are possible at relatively low cost.

- **Direct thermal.** In this technique, light-colored paper labels are coated with a heat-sensitive chemical that darkens when heated. The printing head of the thermal printer consists of a linear array of small heating elements that heat localized areas of the label as it moves past the head, causing the desired bar code image to be formed. Bar codes by direct thermal printing are of good quality, and the cost is low. Care must be taken with the printed label to avoid prolonged exposure to elevated temperatures and ultraviolet light.

- **Thermal transfer.** This technology is similar to direct thermal printing, except that the thermal printing head is in contact with a special ink ribbon that transfers its ink to the moving label in localized areas when heated. Unlike direct thermal printing, plain (uncoated) paper can be used, and so the concerns about ambient temperature and ultraviolet light do not apply. The disadvantage is that the thermally activated ink ribbon is consumed in the printing process and must be periodically replaced.

- **Laser printing.** Laser printing is the technology that is widely used in personal computers. In laser printing, the bar code image is written onto a photosensitive surface (usually a rotating drum) by a controllable light source (the laser), forming an electrostatic image on the surface. The surface is then brought into contact with toner particles that are attracted to selected regions of the image. The toner image is then transferred to plain paper (the label) and cured by heat and pressure. High-quality bar codes can be printed by this technique.

In addition, a laser etching process can be used to mark bar codes onto metal parts. The process provides a permanent identification mark on the item that is not susceptible to damage in the harsh environments that are encountered in many manufacturing processes. Other processes are also used to form permanent 3-D bar codes on parts, including molding, casting, engraving, and embossing [5]. Special 3-D scanners are required to read these codes.

Examples of applications of these individualized bar code printing methods include: keyboard entry of data for inclusion in the bar code for each item that is labeled, automated weighing scales and other inspection procedures in which unique grading and labeling of product is required, unique identification of production lots for pharmaceutical products, and preparation of route sheets and other documents included in a shop packet traveling with a production order, as in Figure 12.7. Production workers use bar code readers to indicate order number and completion of each step in the operation sequence.

### 12.2.2 Two-Dimensional Bar Codes

The first two-dimensional (2-D) bar code was introduced in 1987. Since then, more than a dozen 2-D symbol schemes have been developed, and the number is expected to increase. The advantage of 2-D codes is their capacity to store much greater amounts of data at higher area densities. Their disadvantage is that special scanning equipment is required to read the codes, and the equipment is more expensive than scanners used for conventional
bar codes. Two-dimensional symbologies divide into two basic types: (1) stacked bar codes and (2) matrix symbologies.

**Stacked Bar Codes.** The first 2-D bar code to be introduced was a stacked symbology. It was developed in an effort to reduce the area required for a conventional bar code. But its real advantage is that it can contain significantly greater amounts of data. A stacked bar code consists of multiple rows of conventional linear bar codes stacked on top of each other. Several stacking schemes have been devised over the years, nearly all of which allow for multiple rows and variations in the numbers of encoded characters possible. Several of the stacked bar code systems are listed and compared in Table 12.3. An example of a 2-D stacked bar code is illustrated in Figure 12.8.

The encoded data in a stacked bar code are decoded using laser-type scanners that read the lines sequentially. The technical problems encountered in reading a stacked bar code include: (1) keeping track of the different rows during scanning, (2) dealing with scanning swaths that cross between rows, and (3) detecting and correcting localized errors [13]. As in linear bar codes, printing defects in the 2-D bar codes are also a problem.
TABLE 12.3 2-D Bar Codes

<table>
<thead>
<tr>
<th>Symbology</th>
<th>Type</th>
<th>Date (Company or Inventor)</th>
<th>Relative Data Density*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code 49</td>
<td>Stacked</td>
<td>1987 (Intermecc)</td>
<td>5.8</td>
</tr>
<tr>
<td>Code 16K</td>
<td>Stacked</td>
<td>1988 (T. Williams)</td>
<td>5.8</td>
</tr>
<tr>
<td>PDF417</td>
<td>Stacked</td>
<td>1990 (Symbol Technology)</td>
<td>7.2</td>
</tr>
<tr>
<td>Code One</td>
<td>Matrix</td>
<td>1992 (T. Williams)</td>
<td>30</td>
</tr>
<tr>
<td>DataMatrix</td>
<td>Matrix</td>
<td>1999 (Priddy &amp; Cymbalski)</td>
<td>21</td>
</tr>
<tr>
<td>MaxiCode</td>
<td>Matrix</td>
<td>1992 (UPS)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Source: Palmer [19].

*Comparison is to Code 39 based on 20 alphanumeric characters. Relative data density of Code 39 is 1.0. Higher density means more data per unit square area.

Figure 12.8 A 2-D stacked bar code. Shown is an example of a PDF417 symbol.

Matrix Symbologies. A matrix symbology consists of 2-D patterns of data cells that are usually square and are colored dark (usually black) or white. The 2-D matrix symbologies were introduced around 1990, and several of the more common symbologies are listed in Table 12.3. Their advantage over stacked bar codes is their capability to contain more data. They also have the potential for higher data densities, although that potential is not always exploited, as shown in Table 12.3 for the case of MaxiCode. Their disadvantage compared to stacked bar codes is that they are more complicated, which requires more sophisticated printing and reading equipment. The symbols must be produced (during printing) and interpreted (during reading) both horizontally and vertically; therefore they are sometimes referred to as area symbologies. An example of a 2-D matrix code is illustrated in Figure 12.9.

Applications of the matrix symbologies are currently found in part and product identification during manufacturing and assembly. These kinds of applications are expected to grow as computer-integrated manufacturing becomes more pervasive throughout industry.

MaxiCode was developed by United Parcel Service for automated sortation applications. Small symbol size was not a major factor in its development.
The semiconductor industry has adopted Data Matrix ECC200 (a variation of the Data Matrix code listed in Table 12.3 and shown in Figure 12.9) as its standard for marking and identifying wafers and other electronic components [11].

12.3 OTHER ADC TECHNOLOGIES

The other automated identification and data collection techniques are either used in special applications in factory operations, or they are widely applied outside the factory. Brief descriptions of them are provided in the following.

12.3.1 Radio Frequency Identification

Of the alternative ADC technologies, radio frequency identification (RFID) represents the biggest challenge to the predominance of bar codes. In addition, radio frequency (RF) technology is widely used to augment bar code identification (and other ADC techniques) by providing the communication link between remote bar code readers and some central terminal. This latter application is called radio frequency data communication (RFDC), as distinguished from RFID. In radio frequency identification, an "identification tag" containing electronically coded data is attached to the subject item and communicates these data by RF to a reader as the item passes. The reader decodes and validates the RF signal prior to transmitting the associated data to a collection computer system.

Although the type of RF signal is similar to those used in wireless television transmission, there are differences in how RF technology is used in product identification. One difference is that the communication is in two directions rather than in one direction as in commercial radio and TV. The identification tag is a transponder, which is a device capable of emitting a signal of its own when it receives a signal from an external source. To be activated, the reader transmits a low-level RF magnetic field that serves as the power source for the transponder when in close-enough proximity. Another difference between RFID and commercial radio and TV is that the signal power is substantially lower in identification applications (from milliwatts to several watts), and the communication distances usually range between several millimeters and several meters. The communication distance can be
increased by the use of battery-powered tags, capable of transmitting the ID data over greater distances (typically 10 m and more). These battery-powered tags are called active tags, as opposed to the traditional passive tags, which have no battery.

One of the initial uses of RFID was for tracking railway cargo. In this application, the term “tag” may be misleading, because a brick-sized container was used to house the electronics for data storage and RF communications. Subsequent applications use tags available in a variety of different forms, such as credit-card-sized plastic labels for product identification and very small glass capsules injected into wild animals for tracking and research purposes.

Identification tags in RFID are usually read-only devices that contain up to 20 characters of data representing the item identification and other information that is to be communicated. Advances in the technology have provided much higher data storage capacity and the ability to change the data in the tag (read/write tags). This has opened many new opportunities for incorporating much more status and historical information into the automatic identification tag rather than using a central data base.

Advantages of RFID include: (1) Identification does not depend on physical contact or direct line of sight observation by the reader. (2) much more data can be contained in the identification tag than with most ADC technologies, and (3) data in the read/write tags can be altered for historical usage purposes or reuse of the tag. The disadvantage of RFID is that the hardware tends to be more expensive than for most other ADC technologies. For this reason, RFID systems are generally appropriate only for data collection situations in which environmental factors preclude the use of optical techniques such as bar codes. For example, RF systems are suited for identification of products with high unit values in manufacturing processes that would obscure any optically coded data (such as spray painting). They are also used for identifying railroad cars and in highway trucking applications where the environment and conditions make other methods of identification infeasible.

12.3.2 Magnetic Stripes

Magnetic stripes attached to the product or container are used for item identification in factory and warehouse applications. A magnetic stripe is a thin plastic film containing small magnetic particles whose pole orientations can be used to encode bits of data into the film. The film can be ensheathed in or attached to a plastic card or paper ticket for automatic identification. These are the same kinds of magnetic stripes used to encode data onto plastic credit cards and bank access cards. Although they are widely used in the financial community, their use seems to be declining in shop floor control applications for the following reasons: (1) the magnetic stripe must be in contact with the scanning equipment for reading to be accomplished, (2) unavailability of convenient shop floor encoding methods to write data into the stripe, and (3) the magnetic stripe labels are more expensive than bar code labels. Two advantages of magnetic stripes are their large data storage capacity and the ability to alter the data contained in them.

12.3.3 Optical Character Recognition

Optical character recognition (OCR) refers to the use of specially designed alphanumeric characters that are machine readable by an optical reading device. Optical character recognition is a 2-D symbology, and scanning involves interpretation of both the vertical and horizontal features of each character during decoding. Accordingly, when manually operated scanners are used, a certain level of skill is required by the human operator, and first read
rates are relatively low (often less than 50% [13]). The substantial benefit of OCR technology is that the characters and associated text can be read by humans as well as by machines.

As an interesting historical note, OCR was selected as the standard automatic identification technology by the National Retail Merchants Association (NRMA) shortly after the UPC bar code was adopted by the grocery industry. Many retail establishments made the investment in OCR equipment at that time. However, the problems with the technology became apparent by the mid-1990s [13]: (1) low first read rate and high substitution error rate when hand-held scanners were used, (2) lack of an omnidirectional scanner for automatic checkout, and (3) widespread and growing adoption of bar code technology. NRMA was subsequently forced to revise its recommended standard from OCR technology to bar codes.

For factory and warehouse applications, the list of disadvantages includes: (1) the requirement for near-contact scanning, (2) lower scanning rates, and (3) higher error rates compared to bar code scanning.

12.3.4 Machine Vision

The principal application of machine vision currently is for automated inspection tasks (Section 23.6). For ADC applications, machine vision systems are required to read 2-D matrix symbols, such as Data Matrix (Figure 12.9), and they can also be used for stacked bar codes, such as PDF-417 (Figure 12.8) [9]. Applications of machine vision also include other types of automatic identification problems, and these applications may grow in number as the technology advances. For example, machine vision systems are capable of distinguishing between a limited variety of products moving down a conveyor so that the products can be sorted. The recognition task is accomplished without requiring that a special identification code be placed on the product. The recognition by the machine vision system is based on the inherent geometric features of the object.

REFERENCES

References


