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Facilities Design and Planning

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1 Introduction

Facilities Design and Planning can be broadly defined as the art and science of building facilities—buildings where people use material, machines, and other resources to produce a product or deliver a service (Heragu 2016). An air-conditioner manufacturer must order the required amount of raw materials and sub-assemblies, provide the required fabrication and assembly equipment, as well as plan and organize the various manufacturing steps so that the desired number of air-conditioners can be manufactured to meet the customer demand. A warehouse, on the other hand, does not manufacture any product, but uses people and/or equipment to both store incoming pallets and retrieve them as needed, based on specific customer orders (see Figure 8.1). Proper design, planning, and operation of facilities allow companies to meet customer demand quickly using a minimum amount of resources and at minimum cost.

It is true that the location, design, layout, and planning of facilities has gained more attention as an area of study in the past seventy-five years, but surely “organizations” in ancient civilizations must have thought about proper planning based on sound principles. For example, the Harappa and Mohenjo-Daro civilizations were built in 2500 BCE near the Indus river, but on a ridge to avoid being flooded. They had granaries with air-ducts, public baths, and a covered waste-water drainage system. Similarly, siting decisions, transportation of material, as well as the actual planning and construction of the Pyramid of Giza surely involved sound principles of Facilities Design and Planning. The same can be said about the Colosseum and other public buildings built by Rome during the Roman Empire.

2 Motivating Case Study

When the first White Castle opened in Wichita, Kansas, in 1921, the idea of fast-food restaurants was launched. The fast-food industry (now almost a hundred years old) is a worldwide success and a huge industry—notable not only in the United States but also, in recent years, Asian countries. This industry is estimated to be worth $250 billion worldwide and employs more than 4 million people in the United States alone.

Jimmy Johns (shown in Figure 8.2) is a fast-food chain that specializes in limited menu options, but very fast service. The simple, open layout of a typical Jimmy Johns store allows
employees to keep the freaky-fast promise for walk-in, drive-through, and even delivery orders. Fast-food restaurants use process, material flow, layout, and technology to serve quickly, efficiently, and at low cost. For example, the 43,000 existing Subway stores have an assembly line layout with bread, meat, toppings, and dressing stations laid out in a sequence. The layout in McDonald’s

Figure 8.1 An Automated Warehouse Layout
Source: Courtesy of Savoye Logistics

Figure 8.2 Layout of a Jimmy Johns’ Fast-Food Restaurant
Source: Courtesy of Certified General Contractors, Inc.
restaurants permits unskilled workers to perform a single task repetitively. One worker is typically dedicated to entering the orders and receiving payments. The orders are displayed on monitors at the grilling, frying, and assembly stations where one worker at each station knows exactly how to prepare their component of each order.

3  Flow Patterns and Flow Process Charts

3.1  Flow Patterns

It is important to identify the general flow patterns when building a facility. The pattern shown in Figure 8.3 depicts the flow of material, sub-assemblies, and assembly at the Nissan plant in Smyrna, Tennessee, from the metal stamping operation at the beginning until the final car assembly at the end. The multiple flow patterns shown in Figure 8.4, allow organizations to make sub-assemblies and feed them to the main assembly line in the correct sequence. The spine flow pattern in Figure 8.4b, allows a Volkswagen plant in Brazil to have suppliers of sub-assemblies housed under one roof. In fact, each “vertebrae” shown in the layout is owned and operated by a supplier who produces sub-assemblies for the car manufactured at this plant.

3.2  Flow Process Chart

A flow process chart is a visual display of the various operations a product undergoes in a facility. It shows the various processing steps, but also shows the product’s travel and storage, as well as any delays it may encounter. Analyzing each step allows the analyst to determine the number of

![Flow Process Chart](image-url)

Figure 8.3  Flow Pattern of the Nissan Plant in Smyrna, TN (Adapted from Dilworth 1989)
value added and the number of non-value-added steps, thereby enabling them to devise more effective and efficient operations plans. The flow process chart shown in Figure 8.5 also shows the distance moved, operator and department identifiers, how a product is moved, and the transfer and operational batch size among other aspects of the processing steps.

Figure 8.4 Multiple Flow Patterns
Source: Heragu 2016
# FLOW PROCESS CHART

<table>
<thead>
<tr>
<th>Dist. (ft)</th>
<th>Time</th>
<th>Chart Symbol</th>
<th>Oper ID</th>
<th>Dept ID</th>
<th>M/C ID</th>
<th># of pieces</th>
<th>How moved</th>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td></td>
<td>1 ▼</td>
<td>A1</td>
<td>S&amp;R</td>
<td></td>
<td>100</td>
<td>Truck</td>
<td>Received material 0.022 wcs (51&quot; x 102&quot;)</td>
</tr>
<tr>
<td>220</td>
<td>0.02</td>
<td>1 ◆</td>
<td>H2</td>
<td>MF1</td>
<td></td>
<td>100</td>
<td>Forklift</td>
<td>To crane bay area</td>
</tr>
<tr>
<td>0.02</td>
<td></td>
<td>2 ▼</td>
<td>WIP1</td>
<td></td>
<td></td>
<td>100</td>
<td>Stored temporarily</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.02</td>
<td>2 ◆</td>
<td>H2</td>
<td>MF1</td>
<td></td>
<td>100</td>
<td>Conveyor</td>
<td>To hydra shear</td>
</tr>
<tr>
<td>0.01</td>
<td></td>
<td>1 ●</td>
<td>M1</td>
<td>MF1</td>
<td>HS1</td>
<td>100</td>
<td>Cut to length (front panel)</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.02</td>
<td>3 ◆</td>
<td>H3</td>
<td>MF2</td>
<td>13G</td>
<td>95</td>
<td>Forklift</td>
<td>To machine #13G (100 ton press) or Komatsu (machine 142) or to HYMAC 101 (7&quot; &amp; over neck)</td>
</tr>
<tr>
<td>0.01</td>
<td></td>
<td>2 ●</td>
<td>M2</td>
<td>MF2</td>
<td></td>
<td>101</td>
<td>95</td>
<td>Necking operation (punch hole)</td>
</tr>
<tr>
<td>160</td>
<td>0.03</td>
<td>4 ◆</td>
<td>H3</td>
<td>MF2</td>
<td>101</td>
<td>95</td>
<td>Forklift</td>
<td>To machine # 136</td>
</tr>
<tr>
<td>0.03</td>
<td></td>
<td>3 ●</td>
<td>M2</td>
<td>MF2</td>
<td>136</td>
<td>95</td>
<td>Punch holes</td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>0.01</td>
<td>5 ◆</td>
<td>H1</td>
<td>MF3</td>
<td></td>
<td>95</td>
<td>Forklift</td>
<td>To machine #155 or machine #104 or machine #111</td>
</tr>
<tr>
<td>0.05</td>
<td></td>
<td>4 ●</td>
<td>M2</td>
<td>MF3</td>
<td>155</td>
<td>95</td>
<td>Braking operation</td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>0.01</td>
<td>6 ◆</td>
<td>H1</td>
<td>WIP2</td>
<td></td>
<td>94</td>
<td>AGV</td>
<td>To marshalling area</td>
</tr>
<tr>
<td>150</td>
<td>0.01</td>
<td>7 ◆</td>
<td>H3</td>
<td>WIP3</td>
<td>94</td>
<td></td>
<td>AGV</td>
<td>To steel department</td>
</tr>
</tbody>
</table>

**Summary**

<table>
<thead>
<tr>
<th>Event</th>
<th>Total</th>
<th>Time</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Operations</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>■ Inspections</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>◆ Transportations</td>
<td>8</td>
<td></td>
<td>(min). 1100 ft.</td>
</tr>
<tr>
<td>▼ Storages</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>● Delays</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 8.5 Flow Process Chart
Source: Heragu 2016*
4 Facilities Layout

Facilities layout is a topic that has received much attention as a research topic since the mid-1950s. In this section, we discuss four important topics in facilities layout.

4.1 Types of Layout

In general, the types of layouts seen in manufacturing and service facilities can be classified as: product, process, group-technology, fixed position, and hybrid layouts. In a product layout, processing equipment is arranged according to the sequence of operations required on the product manufactured. In a process layout, the equipment is grouped based on the operations they can perform, with machines that can perform the same operation housed in their own separate department. For example, all the milling machines are located in one department or location. Thus, these two types of layouts are on the opposite ends of a spectrum, with the others falling somewhere in between. The group-technology layout organizes departments by placing a set of dissimilar equipment capable of producing a family of parts (e.g., rotational parts) in one “cell.” On the other hand, in a fixed-position layout, the product is fixed in one position and the equipment is brought to where the product is located, with aircraft assembly being one example. Hybrid layout, as the name indicates, has elements of one or more of the preceding layout types embedded in it. In the hybrid layout shown in Figure 8.6, a group-technology or cellular layout is located in the upper left corner. The process layout is on the upper right, and a product layout is at the bottom.

4.2 Systematic Layout Planning

Developed in the early 1960s, the Systematic Layout Planning (SLP) technique is a simple, yet effective way to develop rough layouts that can be refined further using modern software such as Sketchup and AutoCAD. Its simplicity is a prime factor that it has remained a popular layout development for more than fifty years. It offers a step-by-step guide on how to develop a layout, first by focusing on the layout of the major departments relative to one another and then by focusing on the layout of equipment within each department.

![Figure 8.6 Hybrid Layout with Group-Technology, Process, and Product Layouts](Source: Heragu 2016)
The SLP technique is explained in Figure 8.7. With manufacturing data on products, quantities, and routing (P-Q-R), a matrix representing the intensity of flow between machine pairs is constructed. Then, by considering the support services such as locker rooms, inspection stations, and other support services not directly used to manufacture a product, a relationship chart that captures qualitative, non-flow relationships is developed. Next, using the flow matrix and relationship chart, a relationship diagram is constructed. Machines are then connected by color coded lines that correspond to the desired closeness of the machine pairs—machine pairs that must be absolutely close to each other, essential, important, ordinary, and unimportant—A, E, I, O, U—representing the vowels of the English alphabet. Using color-coded lines, it is relatively easy to draw a relationship diagram that tells us which department pairs must be adjacent, which ones must not, and how the machines should be positioned relative to one another. Using the relationship diagram, machine dimensions, and spatial restrictions (if any) a space relationship diagram is constructed. This space relationship diagram is then used to develop three to five alternative layouts. The above-mentioned steps in SLP are illustrated in Figure 8.7.

### 4.3 Algorithms and Software for Layout Planning

In the past fifty years, several algorithms have been developed in order to solve the layout problem. Some of these have been developed specifically for the layout problem, while a majority have been to solve the quadratic assignment problem (QAP), which has been used to model the layout problem. As pointed out in Heragu (2016), due to the implicit assumption in formulating the layout problem as a QAP that all the departments are squares of equal size, the QAP and the algorithms developed to solve the QAP are not very useful in solving the layout problem.

#### 4.3.1 Layout Algorithms

Algorithms for the layout problem can be classified as being construction or improvement algorithms. Construction algorithms develop a layout from scratch, often by adding one department to the layout at a time until all the departments are included. Improvement algorithms, on the other hand, begin with an initial layout and modify it using a specific protocol until no further improvement is possible. Newer algorithms such as ant colony optimization (Baykasoglu et al. 2006), simulated annealing (Heragu and Alfa [1992]), genetic algorithm (Kochhar et al. 1998), tabu search (Chiang and Kouvelis 1996), and neural network (Tsuchiya et al. 1996), mimic natural phenomena such as how ants that find a food source leave pheromone trails from the source to their colony allowing other ants to follow the same path, principles in forming good quality crystals, survival of the fittest principle, and biological neural network.

#### 4.3.2 Software for Layout Design

Relative to layout software, software packages for layout have been developed since the 1960s. Some of these include ALDEP, CRAFT, BLOCPLAN, and PFAST. In the last two decades, some of the newer software programs that have been developed include Layout-iQ, VIP-PLANOPT, and FlowPath Calculator. Layout-iQ, and VIP-PLANOPT are capable of generating near-optimum layouts, whereas the others provide the user visual guidance on generating good layouts and for each layout that is generated by the user, they provide static performance measures. Heragu (2016) discusses many of the above state-of-the-art layout software packages.
II. General Overall Layout

Systematic layout planning in phases. The pattern of procedures followed to plan the general overall layout is essentially repeated to plan the detailed layout plan—once for each area of department involved. The pattern fits into the framework of four phases as phases II and III.

Figure 8.7 Systematic Layout Planning
Source: Redrawn with permission from Muther (1973)
5 Materials Handling

Materials handling involves the transfer of material between various stages of processing efficiently using manual or automated devices. According to Tompkins et al. (2010), materials handling is about using the right method to provide the right amount of the right material at the right place, at the right time, in the right sequence, in the right position, and at the right cost. This is often referred to as the “right” definition of materials handling.

5.1 Types of Material Handling Devices

Several types of material handling devices (MHDs) are available. Each must be chosen not only based on factors such as the cost of the device, but also the size, weight, and the volume of loads it can handle. Devices that minimize annualized leasing or purchases costs as well as annual operating costs without sacrificing throughput requirements are preferred. Examples of some MHDs are shown in Figure 8.9. The most commonly used types are conveyors (Figure 8.8a), trucks (Figure 8.8b), automated guided vehicles (Figure 8.8c), hoists (Figure 8.8d), jibs, and cranes.

![Different types of material handling devices](image-url)

Figure 8.8 Different types of material handling devices (Figure 8.8a Courtesy of Bastian Solutions; Figure 8.8b Courtesy of Crown Corporation; Figure 8.8c Courtesy of Savant Corporation, and Figure 8.8d Courtesy of Ingersoll-Rand)
5.2 Automated MHDs Used in a Shipping Port

The shipping port of Rotterdam in the Netherlands utilizes a variety of MHDs to load containers arriving via truck and rail on a ship using straddle carriers, gantry cranes mounted on rails, automated guided vehicles, and overhead cranes as shown in Figure 8.9. Containers are brought into the port via trucks and hauled to the shipyard via straddle carriers (Figure 8.9a). Mobile gantry cranes, which are mounted on rails similar to those shown in Figure 8.9b, then move the containers to waiting automated guided vehicles (AGVs) (see Figure 8.9c), which in turn transport

![Figure 8.9](image_url)

Figure 8.9  Automated Loading and Unloading of Containers from a Ship
Source: Europe Combined Terminals B.V.
the containers one at a time to the ship. Large gantry cranes shown in Figure 8.9d then load the containers on to the ship deck. Except for humans driving trucks into the shipyard and operating straddle carriers (see Figure 8.9a), the remainder of the loading and unloading of containers is entirely automated using mobile gantry cranes (Figure 8.9b), AGVs (Figure 8.9c), and overhead cranes (Figure 8.9d).

5.3 Ten Principles of Materials Handling

MHI, the nation’s largest association for materials handling, logistics, and supply chains, has identified ten principles of materials handling. These principles are planning, standardization, work, ergonomics, unit load, space utilization, system, automation, environmental, and life cycle cost. Using a multi-media educational module, Heragu et al. (2003), introduce the learner to the ten principles, explain the key aspects of each, provide a real-world example of an improper application of the principle, and contrast it with a proper application, and extend each principle to domains outside of materials handling. A screenshot of some of the images seen in the multi-media educational tool are shown in Figure 8.10. The tool allows a self-paced learner to understand the various types of MHDs, their applications, the ten principles, and their key aspects.

Figure 8.10  Ten Principles of Materials Handling Educational Module

Source: Developed by S.S. Heragu
6 Warehouse Design

Whereas some manufactured goods are made to order (e.g., Boeing planes), most are made to stock. This is because there is a lead time to make an item such as a television set or a mobile device and the length of this lead time may be so long that customers may not be willing to wait for the order to be placed and manufactured. Exceptions include high-demand items such as the Corvette or Tesla car. It is typically not possible to match demand with supply in most industries and therefore manufacturers generally make goods to stock. Thus, a warehouse, such as the one shown in Figure 8.1, is often used to store make-to-stock items so that a demand can be met when it occurs. Warehousing products is not a value-adding activity, but for the aforementioned reasons, is necessary. It is thus thought of as a necessary waste! A warehouse consists of an outer shell (the building), racks (for storage of products), and MHDs to store and retrieve items from the racks. Various types of warehouse MHDs exist, and these are illustrated in Figure 8.11. In Figure 8.11a, we have a pallet truck that maneuvers pallet loads into drive-through storage racks. Figure 8.11b illustrates an automated storage and retrieval system (AS/RS) capable of storing pallets on storage racks that are often a hundred feet deep and fifty feet tall. Figure 8.11c shows a set of robots used for automated order picking, and Figure 8.11d shows an AS/RS suitable for narrow aisles.

Designing a warehouse involves determining a footprint for the warehouse, its height, number of storage positions, types of storage, level of automation, desired throughput, and a myriad of other factors, some of which are inter-related. For example, the number of storage positions and the level of automation determine the warehouse dimensions. A warehouse with 50,000 storage spaces and one that requires high throughput (number of storage and retrieval transactions per hour) must often be automated. With an automated warehouse, it is possible to extend the warehouse dimensions vertically up to 75 feet. This means the horizontal dimensions or the footprint may be smaller than a manual warehouse with an equal number of storage spaces. In addition to designing a warehouse at minimum cost, designers must also be able to achieve the necessary throughput requirements at minimum operational costs. There are a number of operational problems that can be studied, and we examine a few in the next sub-section.

6.1 Warehouse Storage Policies

Products can be randomly stored in available storage locations in a warehouse or in designated locations. The two types of storage policies are referred to as random storage and dedicated storage policies, respectively. Random storage is widely used, especially in automated warehouses because it is simple to use, requires less space than dedicated storage, and allows faster replenishment. (Picking refers to the act of selecting or picking the required quantity and types of items in a pick list. Each pick list corresponds to a customer order. For example, a customer may have ordered three extra-large white T-shirts, four pairs of running socks of a certain brand, two wristbands of a particular kind, and two running shorts in large size of a particular type. The set of items in the order is called the pick list. Picking aisles for an order are the aisles that contain the items in the corresponding pick list and human or automated equipment enter and exit these aisles as needed in order to fulfill the order.) Dedicated policy allows operators to be more efficient in picking because they do not have to search for the SKU locations, but it requires more storage space. Other operational problems that arise in a warehouse include the sequence in which items in an order are to be picked, the routing policy to be used in picking items in an order, and whether items should be picked in batches. A variation of the dedicated policy, known as the cube-per order index storage policy stores products with a low cube-per order index (ratio of space occupied to ordering frequency) near the doors and those
with a high index to farther away locations (see Heskett 1963 and Malmborg and Bhaskaran 1990). The warehouse storage policies are explained in detail in Heragu (2016) and Tompkins et al. (2010), and the reader is referred to the two sources.

In warehouse management, it is important to understand the effect of the picking, storage, and routing process decisions on order picker travel. The order picker travel cost is a major component of order fulfillment costs. Numerous picking, storage, and routing policies must be evaluated to determine which process decision provides the greatest savings.
Order picking is the retrieval of stock keeping units (SKUs) in a warehouse and constitutes 50%–75% of the total operating costs for a typical warehouse (Coyle et al. 1996). Automation provides an opportunity to reduce labor costs, but many companies, especially in the United States, continue to use manual order picking due to a variety of factors including the variability in SKU shape, size, volume, the variability of demand, the seasonality of the products, and the large investment cost.

Order picking has been an important topic of research over the past several decades. Relative to the operational problems in a warehouse, the three that have received the most attention are identification of effective picking, storage, and routing policies. We discussed the storage policies briefly above. Picking policies determine how SKUs are assigned to a pick list and the sequence in which they are picked. Gibson and Sharp (1992) mention that combining several orders into batches (called batch-picking) can reduce total picking time, but it could be that the first order will have to wait until the last order arrives into the system, increasing the order wait times. Petersen and Aase (2003) described another policy called zone-picking which partitions the warehouse into zones. A set of pickers assigned to a zone only pick those SKUs in an order that are contained in their zone, one order at a time. Combining batch-picking and zone-picking results in wave-picking where each picker is responsible for SKUs in his or her zone for multiple orders.

7 Trends in Facilities Design

In this section, we discuss recent trends in facilities design and planning.

7.1 Material Handling and Logistics US Roadmap: Trends

Material handling and logistics is about moving goods from one location to another within the supply chain until it reaches the consumer’s hands. The challenge faced by this industry today is to deliver goods faster than ever before. As a result, materials handling and logistics is becoming one of the most important and innovative industries worldwide. This field represents a broad sector of the US economy thanks to the tools and the technologies used to increase the productivity and to satisfy the customer’s expectations.

In the summer of 2013, along with five association partners and eight publication partners, MHI organized four workshops in Atlanta, Chicago, Los Angeles, and Washington, D.C., that involved experts in the field of material handling and logistics from academia, industry, and government. The workshop participants were asked to predict what the industry would look like in 2025 and identify supporting trends, challenges, and capabilities faced by the industry. An outcome of the workshops was the development of the Material Handling and Logistics US Roadmap, which summarized the view of the participants relative to the charge they were given (Gue et al. 2014). This section and the succeeding sub-sections summarize the various trends, challenges, and capabilities contained in that publication.

7.1.1 E-Commerce

E-commerce continues to witness a rapid growth. By 2017, one in ten purchases will be made online. Not only are consumers spending more time online using handheld devices (and thereby making online purchases), but retailers also continue to make increasingly significant investments in e-commerce fulfillment. Order fulfillment times are expected to increase for picking, packing, and shipping as they are now measured in minutes rather than days. This increases the need for warehouse managers to optimize the type and quantity of inventory.
7.1.2 Competition among Third-Party Logistics Providers

The rise of third-party logistics (3PL) began several decades ago when companies wanted to outsource their transportation and logistics activities in order to focus more on their core competencies. Today, there is a significant amount of competition within the 3PL industry relative to price and services offered. 3PL companies must continually find ways to decrease costs while offering shorter delivery lead times, the ability to track and trace packages, accommodating minor changes to delivery times and locations, returns, and other factors that enhance the customer experience.

7.1.3 Mass Customization

Mass customization is defined in Gue et al. (2014) as the ability to produce and deliver a unique product that meets a customer’s specifications at mass production prices. Not only will the products see greater customization in the future, but the channels they use to place orders as well as the delivery modes manufacturer and distributors will use to make and deliver them will also need to become diverse ranging from web orders to kiosk orders and delivery modes ranging from fixed-time (e.g., two-day shipping) to same-day delivery.

7.1.4 Urbanization

As more and more of the world’s population continues to migrate to densely populated urban areas, congestion introduced because of the increased deliveries to urban areas, the increased complexity of the last-mile delivery, and the use of existing mass transit infrastructure for transport of goods will need to be addressed.

7.1.5 Mobile and Wearable Computing

Mobile computing allows us to get information, communicate, and make numerous decisions (including decisions to purchase goods or services) on the fly. Wearable computing devices such as a wristwatch, when coupled with a mobile device, not only allow customers to connect and know their locations, but they also allow companies to provide timely information about goods or services nearby.

7.1.6 Robotics and Automation

In addition to mobile and wearable computing devices, other emerging tools that will have a significant impact on logistics include robotics, autonomous control, and driverless vehicles. Robots are now available not only for manufacturing or warehousing operations, but for providing personal services at home as well. For example, consider the vacuum robot, which can clean an apartment when the occupant steps out. Not only are the capabilities of robots improving, but their costs are decreasing as well. Robots and autonomous vehicles can make and change decisions on their own depending upon the environment they are operating in. Driverless vehicles will significantly impact the way we travel and parcels are delivered in the future.

7.1.7 Sensors and the Internet of Things

According to Wikipedia, Kevin Ashton, a British technology pioneer invented the term “Internet of Things” or IoT, while he was with the Auto-ID center at the Massachusetts Institute of
Technology. The IoT is a network of physical devices that have sensors, software, and internet connectivity. These devices range from radio-frequency identification (RFID) tags, to appliances, automobiles, and even buildings. By exchanging information between themselves or a central server, each device can make local decisions for economic benefit without requiring human involvement. For example, a temperature sensor in a container mounted on a truck may be able to send directions to the truck’s air-conditioning unit based on the external and internal temperatures so that the contents (e.g., perishable food) arrive fresh at the destination by consuming the optimal amount of energy.

7.1.8 Big Data and Predictive Analytics

The pervasiveness of sensors coupled with advances in computing hardware and software technology, wireless connectivity, and cloud data storage has led to an explosion in the amount of data that is collected, stored, and processed for economic benefits. While on one hand, data mining and data visualization tools can give us basic and advanced information about the data, data analytics tools help predict the future. For example, using data mining techniques, a company knows that customers who purchased an outdoor, four-burner gas grill are likely to purchase a stainless steel barbecue grilling tool set. Therefore, it can make a suggestion for the customer to buy that product or provide an incentive to do so.

Data analytics techniques such as machine learning or neural networks can even predict when an event might occur. For example, using heart rate data that is collected by a wearable sleep apnea arm-band, a statistical tool can not only determine how many times and when sleep apnea episodes occurred during the past one hour but can also predict when the next one will occur. In fact, with this knowledge, a small electric stimulus can then be sent to the patient so they change position, preventing an apnea attack and providing that patient with a more restful night! For details on this, see Wongdhamma (2015).

7.1.9 The Changing Workforce

The material handling and logistics industry along with the other industries must find ways of recruiting, training, and maintaining a workforce that is not only skilled but also motivated to excel in that industry. Industries need to find a way to tap into the populations that are currently underrepresented. Examples include people with disabilities, women, veterans, and workers under the age of 35.

7.1.10 Sustainability

The material handling and logistics industry must focus on creating economic value for all its stakeholders in a way that preserves the environment and improves social development. Value creation for customers and the resulting profitability for shareholders are well understood. Preserving the environment refers to limiting the impact on wildlife as well as minimizing the amount of pollution and solid waste that is generated. Social development includes improving education, healthcare, and the livelihood of human populations.

7.2 Material Handling and Logistics US Roadmap: Capabilities by 2025

Relative to the capabilities that the material handling and logistics industry must have to meet the challenges faced in 2025, participants of the US Roadmap workshop felt as though customers will demand greater value at a higher speed. Value refers to the timeliness, ability to make
delivery changes made by the customer or necessitated by the environment, and the push to enhance the customer experience while being able to make deliveries quickly. The following sub-sections discuss the specific capabilities that will be required of the materials handling and logistics industry by 2025.

7.2.1 Total Supply Chain Visibility

Supply chain visibility will mean that it is not sufficient to know where a product was last tagged and traced. In the future, customers will want to also know that a hurricane problem in a hub located in a Gulf state has required the product to be re-routed through an airhub in Louisville, Kentucky. Details about the driver who will be delivering the product, their current location, as well as the precise delivery time also become important.

7.2.2 Standardization

Standardization is what has led the material handling and logistics industry to adopt containers for long-distance shipment of goods and pallets for unit-load handling. Similarly, the width of the Panama Canal (before its recent expansion) gave rise to the term Panamax ships, which have these maximum dimensions—950 feet length and 106 feet width. Post Panamax ships such as super tankers, container ships, and cruise ships have larger dimensions. In addition, the Panama Canal has undergone an expansion to increase the dimensions of the ships that can pass through the locks. Roadmap workshop participants felt that intermodal hubs in the future should be able to handle standardized pallets, cartons as well as containers, seamlessly. In addition, standardizing formats for exchanging and processing data emanating from sensors, open source access of data without company- or customer-specific information, cloud storage, software that can mine the data and process it for intelligent, and real-time decision making were all seen as important efforts towards standardizing how the product is handled and how the information is shared between multiple parties in a supply chain.

7.2.3 High-Speed Delivery

Nowadays, delivering in high speed has becoming obligatory in order to satisfy the needs of customers. In fact, the recent advances in delivery are all to provide items for consumers in the same day. This means that orders that have just been received will be delivered later the same day. However, such promises might be kept only within a very limited distance of the warehouse or retail outlet. Using strategically located warehouses, Amazon has offered same-day delivery in many cities.

7.2.4 Low-Cost, Low-Impact Materials Handling and Logistics

Material handling and logistics are a vital part of modern commerce. This is why they should operate at the lowest possible cost and should have the least possible negative impact on society. The financial burden is typically borne by the entities at the end of the supply chain. Therefore, cost reduction has always been the primary focus of the industry since its inception and will continue to be so into the indefinite future. This enables firms that execute logistics operations at a lower cost to enjoy a competitive advantage into perpetuity. Meanwhile, it’s very important to keep in mind that material handling and logistics has a huge impact on the environment.
The use of trucks for transportation add to the carbon emission and traffic congestion. The primary focus here is obviously to develop some capabilities that will enable us to reduce the cost and to eliminate the negative impact on society.

### 7.2.5 Planning and Optimization

The set of planning and optimization tools developed by researchers today are not being fully utilized by industry. Standardizing such tools for network design, warehouse design and planning, and inventory control, in turn making them real-time optimization tools for current decision making and predictive analytics, will increase their acceptance by the practitioner community.

### 7.2.6 Impact of E-Commerce

As previously mentioned, the explosion of e-commerce will mean that distribution centers and warehouses will have to slash order fulfillment times dramatically; be able to handle multiple channels of distribution (to retail stores in large quantities, to individual homes or businesses in much smaller quantities); be designed for high-density storage; and be able to support high-speed order processing using automated, high-throughput, capable storage and retrieval systems.

### 7.2.7 Collaboration

Competitors in the distribution, transportation, and logistics industries will need to learn to be collaborators as well. When these companies collaborate, they will be able to share transportation resources so that trucks are filled to capacity and do not return empty. They will also be able to share warehouse resources such as storage space, automated material handling systems, human resources, and so on. Just like we have food and fuel service plazas along interstate highways that have multiple competing facilities under the same roof, one can imagine a logistics park that accommodates the needs of multiple vendors in one area using a common set of resources.

### 7.3 Energy and Resource Efficient Manufacturing

Energy and physical resources such as raw materials are required for manufacturing. However, in order to protect and preserve the environment, the manufacturing and service industries must use these raw materials in an efficient manner and utilize the least possible amount of energy and natural resources. Duflou et al. (2012) mention that, on a global scale, the energy consumption among the four primary end users of energy, namely, commercial, residential, transportation, and industrial sectors, are 7%, 14%, 27%, and 51%, respectively. Of the 51% consumed by the industrial sector, 90% is for manufacturing activities (Schipper 2006). Therefore, manufacturing accounts for approximately 46% of the global energy consumption and therefore is a significant part of the CO₂ emissions. Note that the manufacturing sector includes semi-continuous processes such as petroleum refining, metal and non-metallic mineral processing, chemical and paper processing.

Duflou et al. (2012) define energy and resource efficiency as the amount of resources required to produce a given level of output and define effectiveness as making wise choices on how resources are used. They cite the following example to illustrate the difference between the two. Consider the following two improvements. The wheel type in a grinding operation and the cutting fluid were changed so that the same grinding operation could be performed using less energy and fewer resources. A second improvement was to change the pat design and associated process plan so the
grinding was entirely eliminated while still maintaining the functionality of the part manufactured. The first improvement relates to efficiency and the second to effectiveness. Duflou et al. (2012) survey 229 papers that focused on energy and resource efficiency in the manufacture of discrete parts.

7.4 Leadership in Energy and Environmental Design

Leadership in Energy and Environmental Design (LEED) is a rating system for evaluating the environmental performance of a building that was developed by the United States Green Building Council. Its use as a building certification tool has grown with more than 100,000 individuals who have been certified to have understood sustainable building practices (Gebken et al. 2009). LEED buildings use less water and energy while emitting much less greenhouse gases when compared to buildings that are not LEED compliant. They cover buildings that range from hospitals to homes, as well as the design, construction, operation, and maintenance of these buildings. For additional information on how buildings are being designed to not only be functional and aesthetic, but also to reduce the carbon footprint caused by its building and use, readers are encouraged to visit the US Green Building Council (USGBC) page on LEED compliance (2016).

7.5 Implications for Managers

The design and operations of facilities, whether they are manufacturing or service facilities, pose challenges to facilities designers. Here, we give a few examples of actual companies and how they design their facilities to give the reader an idea of the numerous decisions facility designers need to make.

Consider the “transparent factory” in Dresden, Germany. Located in the downtown area of an 800-year old city, the building shell and interiors are made of glass while the flooring is made of hardwood—Canadian maple! Although no stamping, welding, or painting operations take place in this facility, the Phaeton model is fully assembled here. Consider the myriad of design decisions that a facility designer has to make for this facility, which is intended to give a museum or a shopping-mall like experience for the customer who visits this plant to pick up their custom-ordered vehicle. These decisions range from having to make the factory blend in with the other downtown structures such as shopping malls, farmer’s markets, and churches in this 800-year old city; having to transport sub-assemblies using enclosed, cargo trams; a speaker system emulating bird language for the building exterior so the birds do not crash into the glass walls; and many other decisions which enrich the experience of visitors and customers who walk into this facility.

Similarly, construction companies building high-rise apartment complexes in Panama City, Panama, must build apartments in odd-shaped lots in a way that each room in each apartment has a view of the Pacific Ocean. Thus, the first five floors in a high-rise typically have a lobby and stores in the main floor and parking on levels two through five. Constructing apartments from the sixth floor and up allows the residents to have a better view as well as reduced noise or pollution from the traffic below.

Companies such as Google provide numerous facilities within their campus so employees do not have to leave work early to utilize these facilities outside. Examples include dry-cleaning, baby-sitting, tennis courts, soccer fields, multiple fitness centers, massage rooms, micro-kitchens, and Lego stations.

In addition to designing facilities that permit the efficient movement of goods and material, the buildings need to consider the support facilities and the aesthetic aspects mentioned above.
In addition, they must meet local and national building codes as well as Occupational Safety and Health Administration (OSHA) regulations and the requirements of the Americans with Disabilities Act (ADA). As mentioned in Heragu (2016), facilities design is part art and part science. In addition to minimizing the total distance traveled and optimizing other objective performance measures, numerous qualitative aspects must be incorporated in the design.

7.6 Directions for Future Research

Future research in facilities design will focus on how facilities can be designed to optimize static design criteria such as building codes that have a longer-term impact, as well as shorter-term, stochastic operational criteria such as minimizing production cycle time. The design of offices, malls, and apartment buildings will focus more on aesthetics and energy conservation and much less on quantitative criteria such as minimizing the total distance traveled. On the other hand, the design of manufacturing plants will continue to focus on making the flow of materials and sub-assemblies smooth and efficient, and the design of warehouses will focus on making the order picking process fast and efficient. The miniaturization of machines (for example, 3D printers that can be placed on a desk), the breakthroughs in non-contact manufacturing (Asari 1993), and the use of new composites (Fujine et al. 1993) and lightweight materials (Arimond and Ayles 1993) will mean the footprint of machines in a manufacturing plant will be small and lightweight. These factors coupled with the availability of software tools for facilities planning, will make the facilities design problem more of an art than a science. The topics of facilities design and layout as well as materials handling, as they pertain to research, appear to have matured with not many research topics remaining from an operations management perspective. However, the area of warehouse design and operations is fertile and provides abundant opportunity for researchers and we name a few areas and relevant papers in the remainder of this section.

In the remainder of this section, we discuss future research areas relative to warehouse design and operations. Following the models presented in Francis and White (1974), Gue and Meller (2009) propose fishbone-like, warehouse aisle designs that also have been implemented in warehouses with random storage policy and human order-pickers. Warehouse design is constantly evolving with the introduction of automation and new technologies. For example, with the introduction of the autonomous vehicle storage and retrieval systems (AVS/RSs) technology, see Roy et al. (2012), models for determining the location of dwell points and cross-aisle locations have been proposed in Roy et al. (2015).

Queuing or queuing network models have been extensively used to evaluate the performance of automated warehouses in the past ten years. For example, Jia and Heragu (2009) used semi-open queuing networks to model systems in which an entering job or customer must be paired with another resource. Then, the resource remains paired with the job until its service is completed. Following that, the resource is available to pick up another job that is already waiting or it waits for the next job. Examples include automated warehouses in which a pallet that must be stored or retrieved must wait to be paired with an available autonomous vehicle (or vice versa). Other examples include a CONWIP system (see Hopp and Spearman 2008) in which each job must be paired with a Kanban card until all its operations are completed in a CONWIP loop. Jia and Heragu (2009) have shown that such systems, which have been traditionally modeled as open- or closed-queuing network models, are not accurate in estimating critical performance measures because they do not account for the time that a job may have to wait for a resource or vice versa. Hence, they propose modeling such systems as semi-open queuing networks. A number of papers have adopted this model for modeling the operational problems in warehouses with
autonomous vehicles. Some examples include Heragu and Srinivasan (2008), Cai et al. (2014), Ekren and Heragu (2012), and Roy et al. (2015).

There has also been an increased interest in minimizing throughput time in manual order picking operations. De Koster (1994), De Koster et al. (2007), and Dekker et al. (2004) have developed analytical models that help minimize the throughput time. There is rich literature on warehouse operations and the reader is referred to Rouwenhorst et al. (2000), De Koster et al. (2007), and Roodbergen and Vis (2009), among other sources. To summarize, warehouse operations will continue to be an area of opportunity for researchers in the area of facilities design.

References and Bibliography


