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Introduction

In this chapter, the background knowledge about manufacturing systems and concept of sustainable manufacturing are demonstrated. In Section 1.1, an overview of the current status of manufacturing industry development is given, followed by a discussion on existing challenges that need to be addressed in order to sustain the continuous growth in manufacturing sectors. More specifically, the significant obstacles that may impede the sustainable development of manufacturing industries are discussed, and the implications for sustainability and energy efficiency in manufacturing systems are depicted. In addition, the definition of sustainable manufacturing and associated essential factors are demonstrated in Section 1.1.2. To better illustrate the significance of the industrial transition to sustainable manufacturing, several industrial paradigms and representative case studies are presented to strengthen the connections between the concepts of sustainable manufacturing and real-world problems. In Section 1.2, the key components of manufacturing systems are discussed from the perspective of a product life cycle. A series of representative manufacturing systems are demonstrated, which are associated with the discussions on system configurations, component functionality, and respective system performances. Section 1.3 is the overview of the problem statement and scope, which are facilitated by the hierarchical categorization of research expertise under the context of sustainable manufacturing.

1.1 Definitions and Practices of Sustainable Manufacturing

1.1.1 Current Status of Manufacturing Industry

Ever since the conception of industrialization, manufacturing production, as an indispensable corner stone, has been of decisive significance to the development of the world economy. The concept of the manufacturing value added (MVA) is

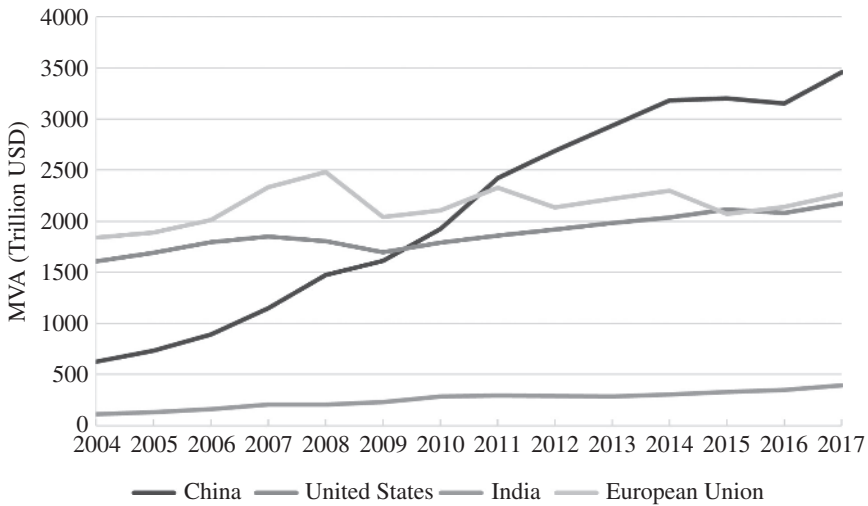


Figure 1.1 Changes in MVA among countries of different regions over the time from 2004 to 2017. *Source:* Adapted from [4].

proposed as one of the main indicators to measure the growth rate of manufacturing industry. By definition, it represents the total estimate of net output of all resident manufacturing activity units obtained by adding outputs and subtracting intermediate consumption [1]. According to the data released from the World Bank, in 2018, the total MVA has reached USD 13.976 trillion worldwide, which corresponds to approximately 16.82% of the global gross domestic product (GDP). Although the trend of declining manufacturing has been reported in developed regions due to the increased wage share of skilled worker and the competition from the service industry and other tertiary sectors [2, 3], manufacturing industries still maintain a good growth momentum and sustain their market value, especially in some developing countries and emerging economies. In reference to the World Bank report [4], Figure 1.1 illustrates the variations of MVA among countries of different regions over the period from 2004 to 2017. In particular, United States, European Union, China, and India are selected as the demonstrative regions.

As demonstrated in Figure 1.1, in the developed regions, such as United States and European Union, a steady increase in MVA can be observed. For example, the MVA in the United States was USD 1.61 trillion in 2004, and it increased by 34.8% to USD 2.17 trillion in 2017; a similar increment in MVA was also reported in the European Union. It is worth noting that fluctuations accompany the rise in MVA after 2008, which can be attributed to the relatively slower growth in manufacturing sectors after the nations survive during the post-economic-crisis period. Distinctively, in terms of the developing region, rapidly industrializing countries

such as China and India possessed a significant increase in MVA over the past decades. In particular, the value added of the China manufacturing sector was USD 0.63 trillion in 2004, which was approximately 2.5 times less than the counterpart in the United States during the same period. The MVA in China was continuously increasing during the study period and reached USD 3.46 trillion in 2017, which indicates a total increase of 449.2% since 2004. The continuous rise of MVA also suggests that the manufacturing sectors remain one of the main propellers of economic growth. It can be depicted that the manufacturing industry has a pivotal position in the world economy and should sustain its pace of change in the foreseeable future.

1.1.2 Sustainability in the Manufacturing Sector and Associated Impacts

Despite the rapid development in a manufacturing sector, the proliferation of manufacturing systems also brings about sustainability concerns. More specifically, manufacturing in the traditional sense refers to processing raw materials to make useful products. In such manufacturing systems, production activities are built upon the consumption of feedstock materials, energy, and other resources. Meanwhile, production processes are often coupled with manufacturing emissions, waste generation, and residual heat. With the increasing consensus on resource scarcity and environmental sustainability, nowadays, the manufacturing industries face more and more challenges, such as efficient energy management, greenhouse gas (GHG) emissions, waste material, and resource reclamation. In general, the main challenges in the manufacturing industry can be examined from the following three aspects: economy, environment, and society, as demonstrated in Figure 1.2.

In terms of economic challenges, considering the high dependence of manufacturing industries on energy resources, the cost fluctuations in the energy market can significantly affect the manufacturing output and overall production cost. For example, the price of crude oil reached about USD 166 per barrel in 2008, which dealt a severe blow to the manufacturing industry during the 2008 international financial crisis [5]. On the other hand, from the product life cycle perspective, due to the rapid technological advancements and the increased diversity and functionality in products, the life cycle of products is continuously shortening. The faster evolution of manufactured products also brings about additional capital investment in manufacturing facility upgrading and employment of well-trained personnel and skilled workers.

Apart from the economic challenges, the environmental burdens caused by manufacturing productions drew increasing attention around the world in the past decades. Energy consumption and emissions are regarded as two major environmental

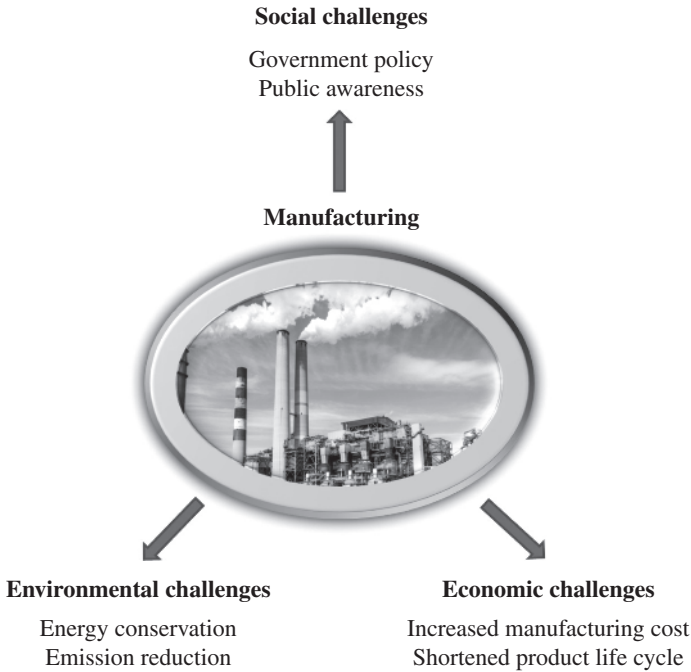


Figure 1.2 Challenges in the manufacturing sector. *Source:* cwizner/Pixabay.

concerns from production activities and other associated auxiliary processes. According to the Annual Energy Outlook 2020 published by the U.S. Energy Information Administration (EIA), the US energy consumption by sector in 2019 is illustrated in Figure 1.3. The overall energy consumption is subdivided into the following five primary sectors: industrial manufacturing, industrial non-manufacturing, residential, commercial, and transportation. As shown in Figure 1.3, industrial, electric power, and transportation sectors are the largest contributors to the total energy consumption in the United States, with the contributions of 23%, 37%, and 28%, respectively. The proportions of residential and commercial sectors are similar, which correspond to 7% and 5% of the total energy consumption, respectively.

In addition to the significance of energy consumption in the manufacturing sector, emission-related environmental issues may also hinder the development of the manufacturing industry. Considering the severity of global warming and resource scarcity, the environmental issues originated from manufacturing industries have gained increasing attention from the public, manufacturing enterprises, and government agencies. Based on the inventory report of US GHG emissions released by the U.S. Environmental Protection Agency (EPA) in 2018 [7], the sources of GHG emissions can be attributed to five major economic sectors, including transportation,

Figure 1.3 The US energy consumption by sector in 2019. *Source:* Adapted from [6].

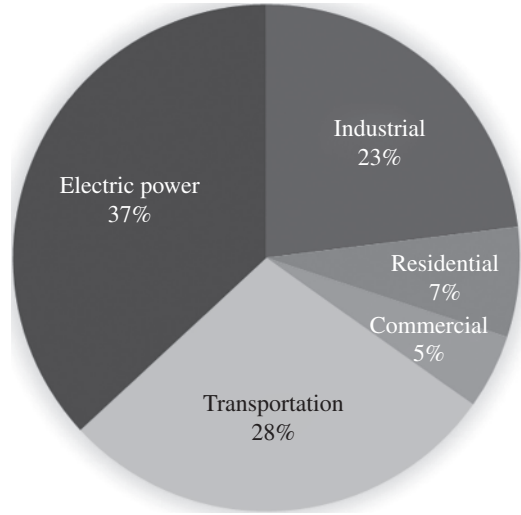
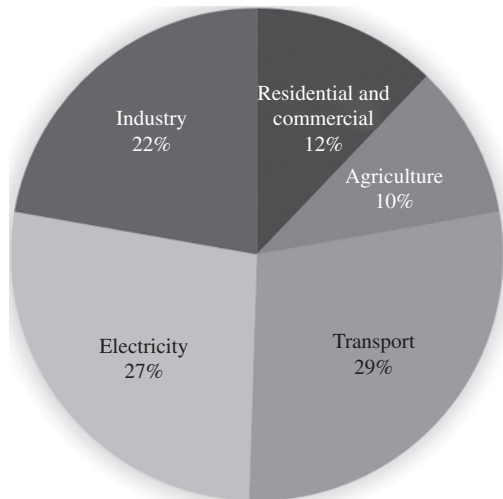


Figure 1.4 The total US GHG emissions by sector in 2018. *Source:* Adapted from [7].



electricity, industry, commercial and residential buildings, as well as agriculture. The total US GHG emissions by sector in 2018 are illustrated in Figure 1.4. More specifically, the total emissions in 2018 are approximately 6677 million metric tons of carbon dioxide (CO₂) equivalent. As shown in Figure 1.4, transportation, electricity, and industry sectors are the major contributors to the total GHG emissions. Among the five economic sectors, the industry sector possesses the third-largest

proportion (22%) of the total GHG emissions in the United States. The GHG emissions from the industrial sector can be further decomposed into two categories: direct emissions and indirect ones. The former are mainly contributed by the consumption of fossil fuels for power or heat at the manufacturing facilities, while the latter are primarily associated with the overall use of electricity.

From a societal perspective, the manufacturing industry is also facing challenges from the government and the public. On the government side, energy conservation, emission reduction, and environmental protection have increasingly become the guide for policy making. Internationally, the signing of the Kyoto Protocol and the Paris Agreement reflects the joint efforts of various governments on climate change and global warming. On the public side, the public consensus press is increasingly concerning energy conservation and emission reduction in the manufacturing sector. From the perspective of public awareness, consumers are more environmentally conscious as environmental degradation and pollution become more severe, and people are more eager for environmental-friendly products. At the same time, many organizations continue to call for restrictions on the development of high-polluting manufacturing industries. These factors have forced the manufacturing enterprises to branch new paths and adjust their development strategies.

Due to these existing challenges in the development of the manufacturing sector, traditional manufacturing strategies need to be urgently changed. The emergence of the sustainable development concept provides a direction for the sustainable transformation of the manufacturing industry. More specifically, the concept of sustainable development was first raised by the United Nations General Assembly in 1987 as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The concept has been widely applied to all walks of life, including manufacturing. In the United Nations Conference on Environment and Development (UNCED) in 1992, sustainable manufacturing was formally proposed and used to guide future manufacturing development.

Ever since the conception of sustainable manufacturing, many institutions and researchers have put forward new discussions and definitions of manufacturing sustainability. For example, the Lowell Center for Sustainable Production at the University of Massachusetts Lowell (UMASS) defines sustainable production as “the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable, safe and healthful for workers, communities, and consumers, socially and creatively rewarding for all working people” [8]. To date, the most widely accepted definition of sustainable manufacturing comes from the International Trade Administration (ITA) under the U.S. Department of Commerce (DOC). Sustainable manufacturing is defined as “the creation of manufactured products that use processes that are

non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers.” To reach the criteria mentioned above in manufacturing practices, a series of changes are required, such as eliminating the use of nonrenewable resources, switching to clean energy, and implementing energy-efficient production processes.

In general, sustainable manufacturing mainly consists of three pillars: economic, environmental, and social ones. The interconnections among them are demonstrated in Figure 1.5. More specifically, sustainable manufacturing can realize the protection of the environment and natural resources, which is conducive to mitigating the associated environmental impacts. On one hand, sustainable manufacturing responds to public concerns about environmental protection. For example, it can enhance environmental performances in terms of the consumption of raw materials and energy, which contributes positively to efficient resource utilization and emission reduction. On the other hand, sustainable manufacturing also contributes to business ethics and social responsibility, which ensures that companies do not disregard the common interests of the whole society for commercial interests. The implications of sustainability in the manufacturing enterprises are twofold. First, it facilitates the establishment of a sense of social responsibility in the manufacturing industry. Second, it reinforces the company’s image, which increases customer’s purchase intention and overall profits.

In addition, government agencies have paid more and more attention to the implementation of sustainable manufacturing. Companies that practice sustainable manufacturing have the opportunity to receive incentives such as government

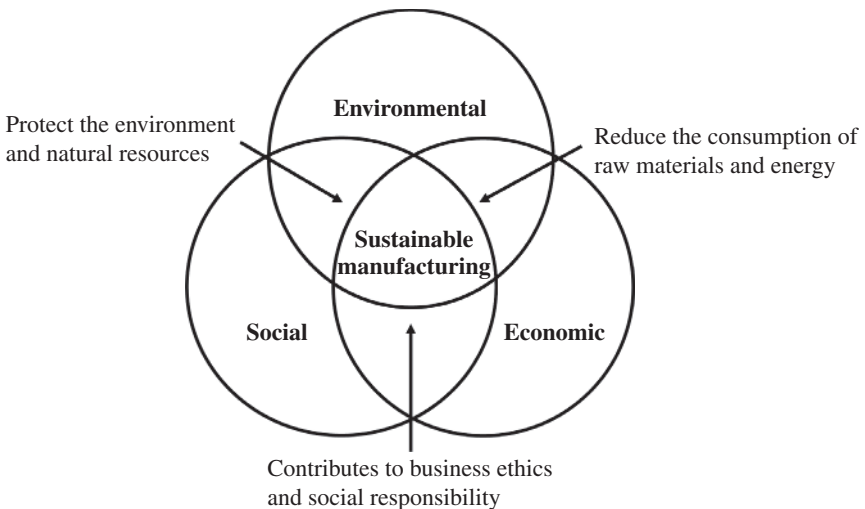


Figure 1.5 The three key pillars in sustainability. *Source:* Adapted from [9].

funding and tax relief. With the joint efforts from both government agencies and indigenous manufacturing enterprises, from 2005 to 2017, the United States' net GHG emissions were reduced by 13% [10]. The European Union also proposes the 2030 Climate Target Plan aiming at reducing the GHG emissions by at least 55% by 2030 [11]. In addition, the government works closely with universities and research institutions to provide additional technical support to local manufacturing business enterprises. For example, there are many Industrial Assessment Centers (IAC) located at universities across the United States, which are funded by the U.S. Department of Energy (DOE) to provide free industrial assessments for small- and medium-sized companies and facilitate the sustainable transitions of local manufacturing companies under the context of green manufacturing.

1.1.3 Sustainable Manufacturing Practices

To date, an increasing number of manufacturing enterprises have taken “sustainability” as an important goal of their development strategy and operation management to increase their market share and global competitiveness in the future. This trend has become more evident in recent years, and many well-known companies across different industry sectors have also begun taking actions. There are a number of reasons why manufacturing enterprises are pursuing sustainability [12]:

- 1) Increasing operational efficiency by reducing costs and wastes.
- 2) Responding to or reach new customers and increasing competitive advantages.
- 3) Protecting and strengthening brand and reputation and building public trust.
- 4) Building long-term business viability and success.
- 5) Responding to regulatory constraints and opportunities.

Sustainable manufacturing can be achieved from many perspectives, such as lean manufacturing, energy management, waste reduction, and re-/de-manufacturing. These efforts have led to remarkable results. In the following sections, a series of sustainable manufacturing practices are illustrated [13]:

- Lean manufacturing refers to the application of lean practices, principles, and tools to the development and manufacture of physical products to reduce waste. In terms of lean manufacturing, New Mexico Manufacturing Extension Partnership, a statewide assistance center, has been dedicated to increasing the competitiveness of the indigenous small- and medium-sized businesses by providing analysis and assessment services with respect to the production process arrangement and the production area layout planning. Through the implementation of lean manufacturing, companies can reduce the excessive transportation and excessive use of tools and materials. Through the practice of sustainable manufacturing, the company can reduce costs by 65%, increase production from

20 to 45 units per shift, reduce the scale of production facilities by 73%, and reduce the scrap rate from 24 to 1.8% according to [13].

- Energy management includes the planning and operation of energy production and energy consumption units. As an example of the implementation of energy management, Besam, a manufacturer of automatic doors, collaborated with the Carolina State University Industrial Evaluation Center and North Carolina State Industrial Extension Services' E3 (Economy, Energy and Environment) to improve energy efficiency in production processes. Several recommendations have been presented in the energy management survey, including replacing fluorescent lamp fixtures with metal halide lighting and installing high-efficiency lamps with occupancy sensors and electronic ballasts to reduce compressor air pressure and repair compressed air leakage. Through these efforts, a total reduction of 233,555 kWh in electricity consumption can be achieved per year, which corresponds to an annual saving of approximately USD 25,776.
- Waste reduction, also known as source reduction, is the practice of using less material and energy to minimize waste generation and preserve natural resources. In terms of manufacturing practice in waste reduction, Guardian Automobile's Ligonier plant takes measures to reduce waste generation by finding ways to recycle and reuse materials. The candidate recyclable materials include unused glass scrap, glass fiber, and waste polyvinyl chloride. In 2005, the Ligonier plant recycled more than 13,000 tons of waste, saving USD 360,000.

De-manufacturing and remanufacturing include a set of tools, knowledge-based methods, and technical solutions to systematically recover, reuse, and upgrade functions and materials from waste and end-of-life products [14–17]. Specifically, de-manufacturing liberates target materials and components [18, 19], while remanufacturing restores or upgrades their functions [20], as shown in Figure 1.6. The total 2022 US market size for automotive parts remanufacturing reaches USD 5.3 billion.

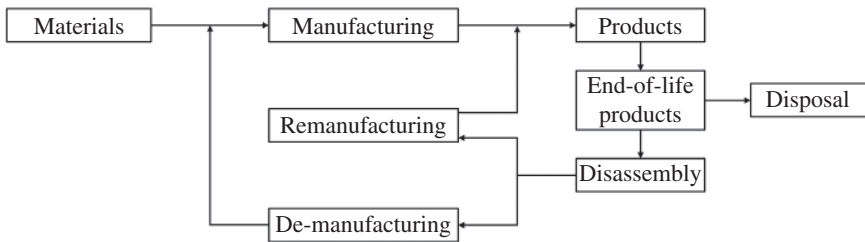


Figure 1.6 Illustration of the connections among manufacturing, remanufacturing, and de-manufacturing.

1.2 Fundamental of Manufacturing Systems

1.2.1 Stages of Product Manufacturing

In general, product manufacturing comprises four major stages: design, planning, control, and manufacturing. It has material and energy exchanges with the outside world, as demonstrated in Figure 1.7.

- Input, which represents the basic resources required in product development and manufacturing. The input resources can be categorized into the following types [22]:
 - 1) Raw materials: the primary feedstock materials required for a manufacturing system.
 - 2) Auxiliary and operating materials: the additional materials and supporting parts required by a manufacturing system.
 - 3) Energy: the energy and power required for system operation, such as electricity, gas, and fuel.
 - 4) Labor: the workforce required to maintain the operation of a system.
 - 5) Technical equipment: the equipment for supporting a main production process and various secondary processes, such as transport and storage.
 - 6) Information: the information obtained from the external of a system, such as market demand and price.
- Product design refers to the design of products with the joint consideration of market demand, availability of production resources, capability of machines and tools, and production cost.
- System planning, which aims to determine the optimal manufacturing system configuration, takes into account the capital investment, overall production cost, system reliability, and overall performance. In addition, the operation sequences of machines and resource allocations, as well as the processing parameters, are specified during this stage.
- Manufacturing system, which takes the feedstock materials as inputs, adds value, and eventually transforms the inputs into final products. Two major

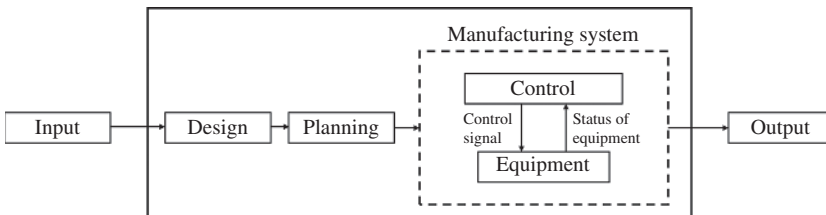


Figure 1.7 Illustrations of product manufacturing stages. *Source:* Adapted from [21].

factors that can affect the sustainable performance of a manufacturing system are equipment and control.

- Equipment is a fundamental component of a manufacturing system. The properties of the equipment can significantly affect the sustainable performance of the system. For example, the electric power of a machine determines the total energy consumed during a production period. The machine's processing accuracy, which indicates the percentage of non-defective items in all produced items, determines the amount of extra energy and materials need to be used to meet the production order quantity. The equipment properties provide a baseline of the system performance, and the control system determines whether the manufacturing system can perform its intended functions as expected.
- Control system analyzes the status of the equipment, develops the optimal operation strategies, and manages the equipment operations. The control system affects the system performance by adjusting the equipment behaviors, such as machine scheduling, resource assignment, and material handling route planning. An efficient control strategy can improve system sustainability without sacrificing product quality or system productivity [23].
- Output, which can be subdivided into final products and production wastes. In particular, the wastes generated during the manufacturing activities may include waste water, exhaust gas, solid and liquid wastes, excess heat, etc.

1.2.2 Classification of Manufacturing Systems

In general, manufacturing systems are classified into five categories based on the configuration of their material processing area, including job shop, project shop, cellular system, flow line, and continuous system [21].

1.2.2.1 Job Shop

In a job shop, machines are placed on the shop floor by functionality, and machines with the same or similar material processing capabilities are grouped together to form a work center. In this system, parts and materials need to move around different work centers to fulfill the processing requirements, as demonstrated in Figure 1.8.

This functionality-oriented job shop system layout has the following advantages: (i) when a specific machine breaks down or is under maintenance, its job can be easily taken over by other machines located in the same work center; and (ii) the system is capable of handling different types of parts with various process sequences, such as the Part 1 and Part 2 in Figure 1.8. However, in order to benefit from its internal flexibility, some challenges must be addressed. The first challenge

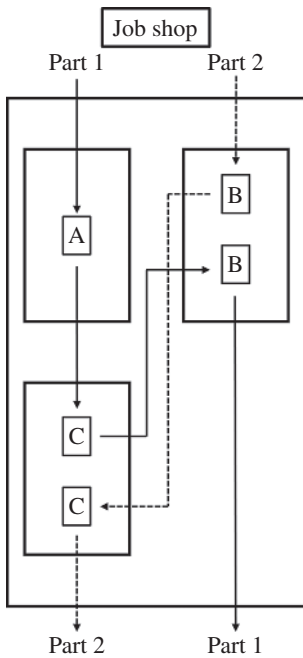


Figure 1.8 Schematic diagram of a job shop, where A, B, and C represent three types of machines.

is the material handling scheduling. Different types of parts have different process routings; hence, flexible material handling equipment, such as hand-carts, forklifts, and automated ground vehicles, are more suitable for this system. Precise, dynamic, and real-time material handling equipment assignment and delivery route planning strategies are also indispensable to this system. In addition, since each work center works individually, comprehensive machine scheduling is required by considering the workflows of different types of parts. A lack of decision-making coordination among different work centers can increase the semifinished product inventory levels and eventually affect overall production throughput [24].

1.2.2.2 Project Shop

In a project shop, the position of a product is fixed during its manufacturing process. Different machines and workers are transported in and out of this production zone during the operation, as shown in Figure 1.9. Project shops are often used to manufacture products of large size and high weight, such as airplanes and ships. This

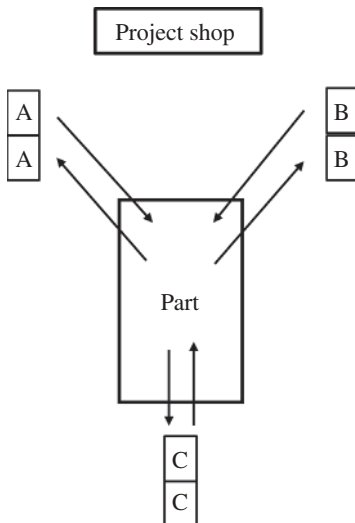


Figure 1.9 Schematic diagram of a project shop, where A, B, and C represent three types of machines.

configuration is also widely used in bridges or building constructions.

1.2.2.3 Cellular System

In a cellular system, the machines are arranged and divided into different cells according to the workflow of parts, as shown in Figure 1.10. In each cell, all the necessary devices are sequentially placed to process a single type of part. Unlike the job shop, where the material handling system needs to ship parts among different work centers, machines in one single cell can perform all the necessary work for a given type of part. This property eliminates the need for intercell material handling. The cellular system can significantly simplify the material handling system scheduling and reduce transportation time. Despite these advantages, this system is more fragile to machine failure. A failed machine can break down the entire cell, and it is hard to maintain productivity during the machine maintenance period [25].

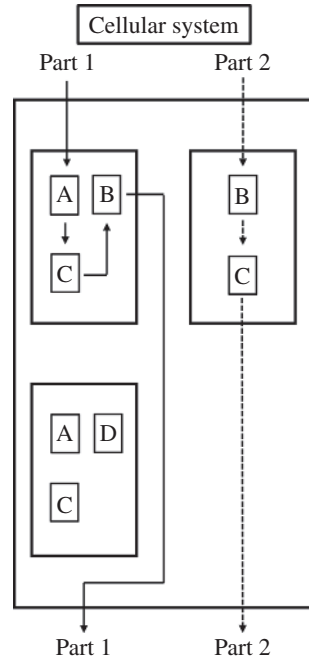


Figure 1.10 Schematic diagram of a cellular system, where A, B, C, and D represent four types of machines.

1.2.2.4 Flow Line

In a flow line, the machines are arranged and connected according to the part's process sequence, as illustrated in Figure 1.11. Generally, a flow line is designed for a specific type of part or several parts with the same workflow. Since the machine sequence is predefined and fixed, automated material handling methods, such as belt conveyors, powered roller conveyors, and overhead trolleys, are usually implemented to improve the system stability and production efficiency. The system configuration, machine processing rates, and inventories of semifinished products can be optimized in advance. Therefore, the flow line has a significant advantage in the mass production of a particular part. On the contrary, it may take hours or even days to reconfigure and optimize the flow line when the system is switched from the current part production to another type of parts.

1.2.2.5 Continuous System

Apart from the four aforementioned discrete manufacturing systems, a continuous system is designed to process materials without interruption. An example of a continuous system is shown in Figure 1.12. Different tanks or reactors are generally

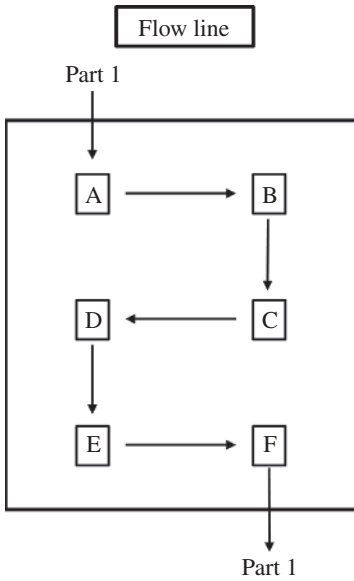


Figure 1.11 Schematic diagram of a flow line, where A–F represent six types of machines.

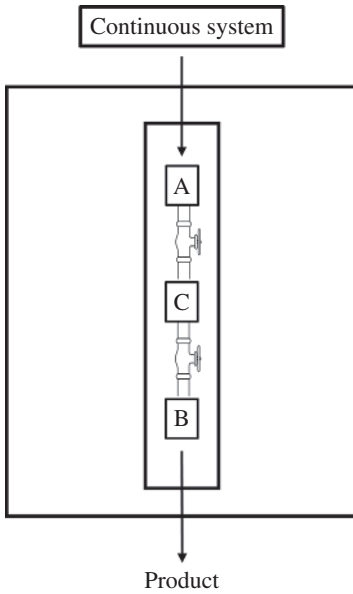


Figure 1.12 Schematic diagram of a continuous system, where A, B, and C represent three types of machines.

connected by pipelines. Unlike in a discrete system, where parts are processed from one machine to another until the manufacturing process of the product is finished, the materials pass through the continuous system as a whole and undergo chemical reactions and mechanical or thermal treatments without pauses. Continuous systems are commonly adopted in industries dealing with liquid or gas materials, such as oil, chemicals, and natural gas [26].

The selection of types of manufacturing systems depends on many factors, such as the lot size of products, the variety of processing workflows, the properties of the feedstock materials, and the responsiveness to market changes and customers' demands. For example, when the quantity of a product ordered by customers is relatively small, job shops and project shops are preferred over the other system configurations. A cellular system is more suitable for medium lot-size production since the different types of parts can be processed simultaneously in separate cells [28]. Besides, attributed to the implementation of the automatic material handling equipment, the flow line system provides the highest productivity and can meet the need for mass production. It should be noted that if the priority consideration is the system flexibility or ability to process various parts, the system selection could be different. More specifically, attributed to the flexible material handling systems and general-purpose machines, job shops are more suitable to manufacture various products from multiple product orders. In terms of a cellular system, each cell acts as an individual unit, which is designed for a specific workflow. The cellular system can handle different types of parts, but the total number of cells limits the part types. Additionally, compared to the other systems, the flow line is relatively more stable and harder to reconfigure; hence, it is only suitable for manufacturing of a single product family. The comparisons among different manufacturing systems are demonstrated in Figure 1.13. In the field applications, these

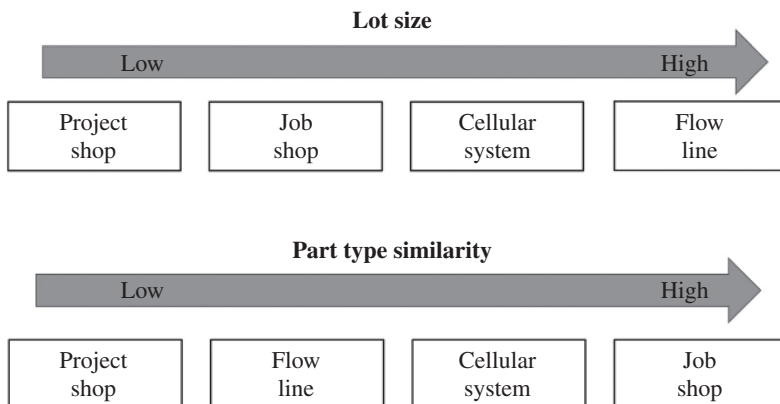


Figure 1.13 Selections of manufacturing systems.

standard systems may be combined together or adapted with necessary adjustments depending on the real production scenarios.

1.3 Problem Statement and Scope

To date, sustainable manufacturing has drawn wide attention and research interests. Current research on sustainable manufacturing can be mainly categorized into four layers, including manufacturing technologies, product life cycles, value creation networks, and global manufacturing impacts [27], as shown in Figure 1.14.

- Manufacturing technology and system performance. Research in this layer is mainly focused on “how to manufacture”, and the studies usually are system or process oriented. One research direction aims to systematically model or simulate the operational conditions of the major components in manufacturing systems and propose solutions to optimize the resource allocation and energy consumption without sacrificing the overall system performances. The other research direction is the advancement in manufacturing technologies and specialized apparatus toward low-cost and energy-efficient product manufacturing.
- Product life cycle. Research in this layer mainly addresses “what is to be produced,” and the research focuses on integrating sustainability criteria into product development processes. The main research directions include the life cycle management of products, the development of intelligent products, and the product sustainability assessment. This layer mainly integrates sustainability into several stages of a product life cycle, ranging from product design to manufacturing, and end-of-life management, considering the interactions among environmental, social, and economic

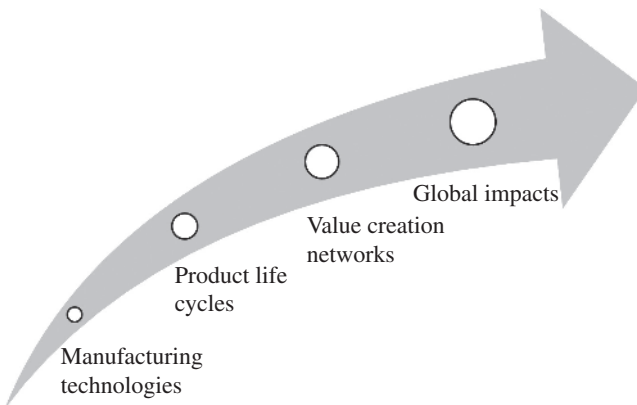


Figure 1.14 Four layers of sustainable manufacturing problems. *Source:* Adapted from [27].

factors. Due to the complex relationship among different life cycle stages, the research scope at this layer is broader in comparison with that of the first layer.

- Value creation network. Research in this layer is built upon the organizational context of manufacturing activities, and the main research objects are organizations such as companies and manufacturing networks. The main research directions involve resource-efficient supply chain planning and the development of industrial ecology. This layer is mainly focused on sustainability at the organizational level to make it meet the requirements of sustainable manufacturing. Compared with the first two layers, it has a broader research scope as the sustainable concerns grow beyond the products or production systems and involve the resource allocations and collaborations in different manufacturing networks.
- Global manufacturing impact. Research in this layer is mainly dedicated to the transition mechanism toward sustainable manufacturing. Different from the previous layer of manufacturing networks, the main research directions are the development of sustainability assessment methods, establishment of sustainability goals, and promotion of consensus for a sustainable future. Research in this layer mainly focuses on applying sustainable manufacturing on a global scale and the applicability of sustainable decision-making methods in the field. This layer of research sheds light on the standards in the implementation of sustainable manufacturing and potential directions for future development in manufacturing.

Problems

- 1.1 Why do we need to consider sustainability in the manufacturing industry? Presents some manufacturing challenges to the industry.
- 1.2 How to choose an appropriate manufacturing system?
- 1.3 State some commonly faced problems in the development of sustainable manufacturing.

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