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Evolution of Automation and Development Strategy of Intelligent Manufacturing with Zero Defects

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1.1 Introduction

The evolution of automation from Industry 1.0 to 3.0 as well as e-Manufacturing, which is the predecessor of Industry 4.0 is described in this chapter. Then, the core technologies of Industry 4.0 and the concept of mass customization are presented. After that, the concept of Zero Defects (ZD), which is the vision of Industry 4.1, is introduced. Finally, the five-stage strategy of yield enhancement and ZD assurance is proposed in this chapter.

1.2 Evolution of Automation

While the first industrial revolution (Industry 1.0) introducing the steam engine, the second (Industry 2.0) carrying out the assembly line mass-production, and the third (Industry 3.0) framing the automated manufacturing with electronic controllers, industrial production requirements need further changes nowadays. There is an increasing demand for manufacturing to satisfy customer expectations precisely; at the same time, companies face growing pressure to manufacture at more competitive prices. To adapt to this evolution, the tools of systems engineering, information and communication technology (ICT), artificial intelligence, and business strategies will be applied to achieve a higher level than before for developing new scenarios of the automated production. Thus, the so-called Industry 4.0, which aims to increase productivity of the traditional manufacturing scenario, was proposed. In fact, e-Manufacturing presented by the semiconductor industry is the predecessor of Industry 4.0. Therefore, prior to introducing Industry 4.0, the concept and key components of e-Manufacturing are described as follows.

1.2.1 e-Manufacturing

Since market competition in the consumer electronics industry has intensified, short product lifecycle becomes essential. A company that generates innovative research and development can garner market share. The rapid development of the information and Internet technologies facilitates

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the computerization of the intra-company manufacturing execution system (MES) [1–3] and equipment engineering system (EES) [4–5], as well as expedites the networking of the inter-company supply chain (SC) [6–8] and engineering chain (EC) [9–11] to move toward a global business model of e-Manufacturing [12–13].

National Coalition for Advanced Manufacturing (NACFAM) [12] stated in 2001 that in the e-Manufacturing era, companies will be able to exchange information of all types with their suppliers at the speed of light. Also, design cycle times and intercompany costs of manufacturing complex products will implode. Information on design flows will be instantly transmitted from repair shops to manufacturers and their supply chains.

Figure 1.1 shows the e-Manufacturing hierarchy created by the international SEMATECH (ISMT) [4]. This hierarchy can be divided into the manufacturing portion and the engineering portion. In Figure 1.1, MES is a core system in the manufacturing portion that connects its upper factory-to-factory modules and lower equipment modules to dominate the overall manufacturing management. The highest (company-to-company) layer in the manufacturing portion is mainly for the purpose of SC. On the other hand, EES takes charge of the engineering portion that deals with equipment health monitoring, real-time quality control, and maintenance scheduling (e.g. e-diagnostics [15, 16]).

In the semiconductor manufacturing industry, Tag and Zhang [13] defined e-Manufacturing as the complete electronic integration of all factory components using industry standards. This e-Manufacturing model extends from equipment-to-equipment automation systems to the manufacturing execution system/yield management system/equipment engineering system (MES/YMS/EES) and to the enterprise resource planning (ERP).

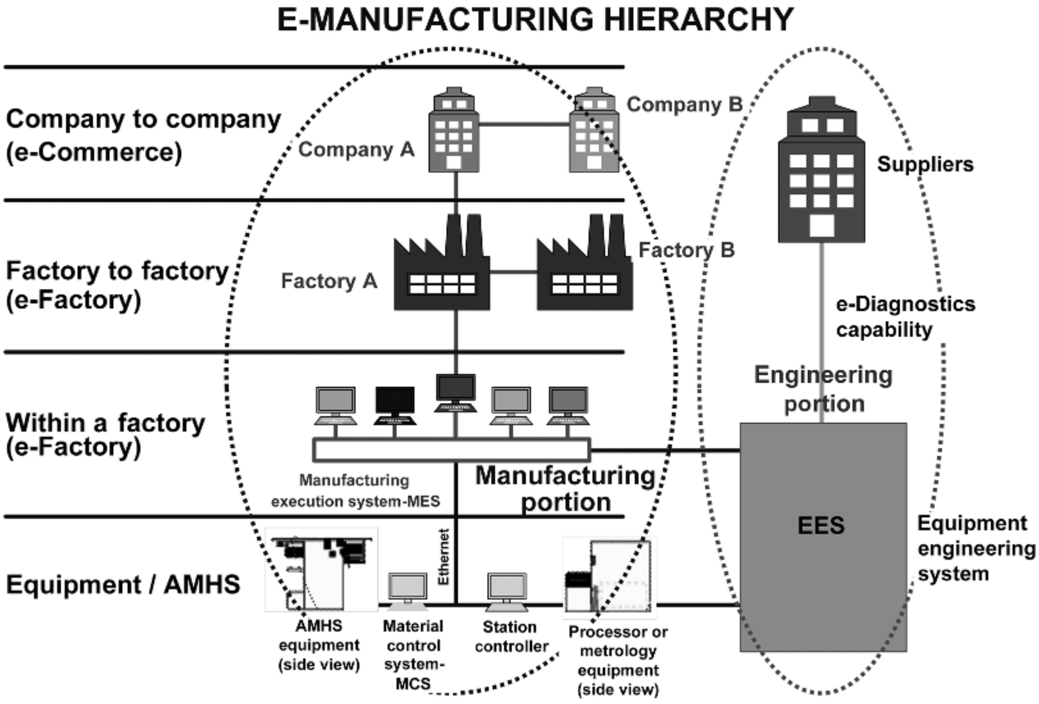

Figure 1.1 ISMT e-Manufacturing hierarchy. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

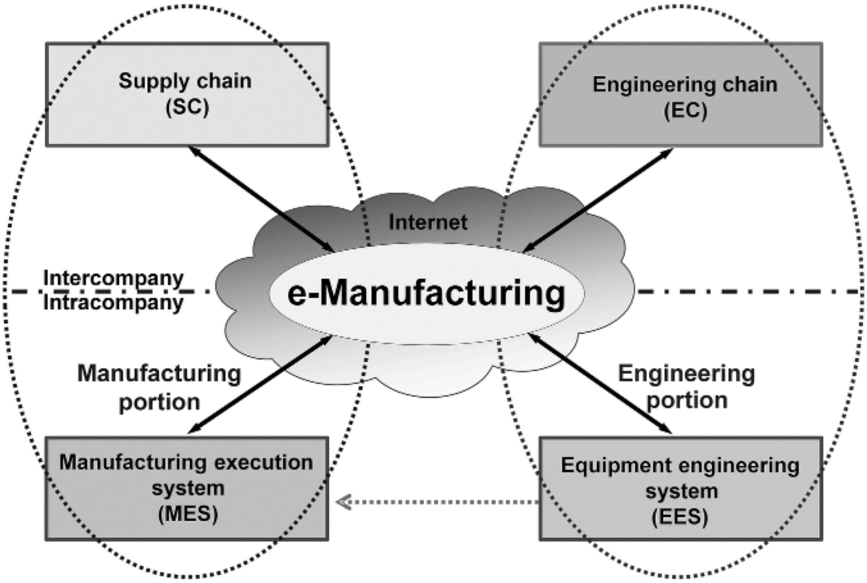

Figure 1.2 Four key components for the advanced e-Manufacturing model. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

The ISMT e-Manufacturing hierarchy shown in Figure 1.1 [4] merely takes care of the functions of MES, EES, and SC without EC. Another model defined in [13] also takes the related functions of MES, EES, and SC into consideration only.

To consider all of the functions and applications of MES, SC, EES, and EC simultaneously, and enhance the integrity of e-Manufacturing as shown in Figure 1.2, Cheng et al. [14] proposed an advanced e-Manufacturing model that takes advantage of the information and Internet technologies to efficiently integrate the MES and EES within a company (intra-company integration), and the SC and EC among member companies (inter-company integration). With this advanced e-Manufacturing model, the productivity and yield of a complete production platform can be improved (by MES), the overall equipment effectiveness (OEE) can be enhanced (by EES), the order-to-delivery (O2D) period can be reduced (by SC), and the time-to-market (T2M) can be shortened (by EC). Furthermore, the goal of improving agility, efficiency, and decision-making for the entire semiconductor manufacturing processes can be reached.

In the advanced e-Manufacturing model, both the MES and SC belong to the manufacturing portion, whereas the EES and EC are closely related to the engineering portion. The proposed e-Manufacturing model fully integrates the four key components (MES, EES, SC, and EC) to enhance the globalization and competitiveness of the semiconductor industry. The definitions, missions, primary issues, and feasible implementation frameworks of the four key components of e-Manufacturing are discussed in the following sections.

1.2.1.1 Manufacturing Execution System (MES)

The MES is a shop floor control system which includes either manual or automatic labor and production reporting as well as on-line inquiries and links to tasks that take place on the production floor. The MES provides links to work orders, receipt of goods, shipping, quality control, maintenance, scheduling, and other related tasks [17]. The mission of MES is to increase productivity and yield.

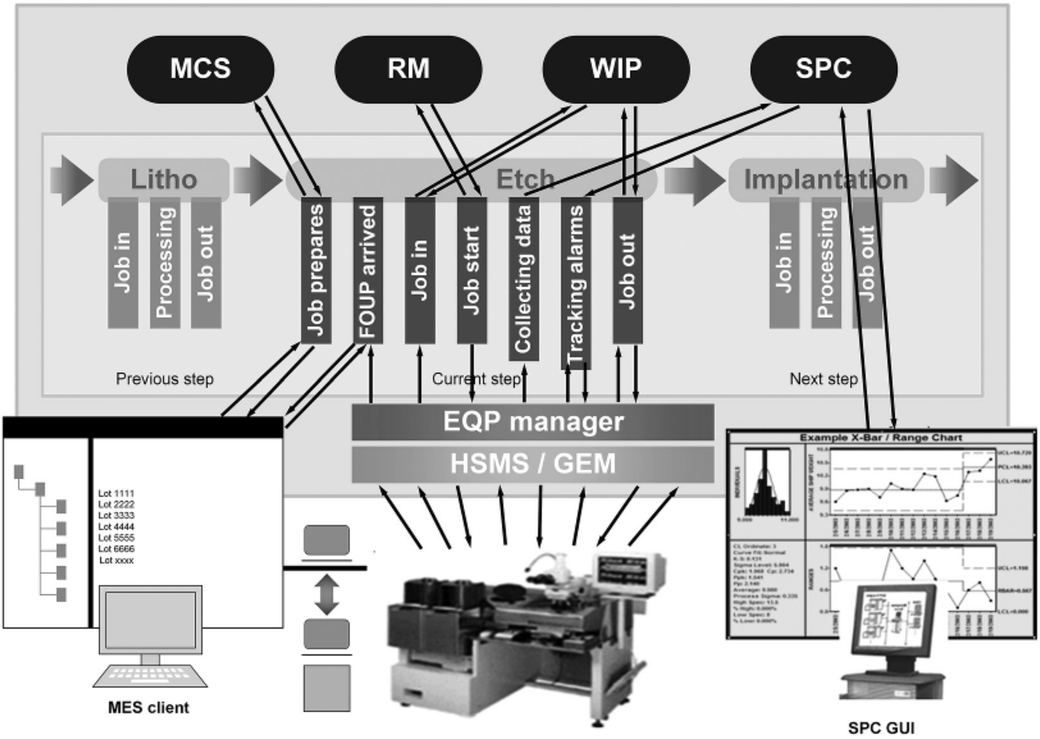

Figure 1.3 MES operation procedures. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

Figure 1.3 presents the MES operation procedures in semiconductor manufacturing. In Figure 1.3, a front opening unified pod (FOUP), containing 25 wafers, is processed via lithography, etching, and implantation. After finishing its procedures in the lithography process, the FOUP is prepared for the etching process by the MES. First, the MES client requires a material control system (MCS) to move the FOUP to the process equipment. When the FOUP arrives at the etching equipment, the equipment manager sends a message to notify the MES, reads the information of work in process (WIP), acquires a recipe for this FOUP from the recipe management (RM) system, and initiates fabrication. Next, the equipment manager sends the process data of each wafer under fabrication to the statistical process control (SPC) server for quality monitoring. Eventually, the equipment manager updates the WIP information when the etching process completes and asks the MCS to move the FOUP from the etching equipment to the implantation equipment.

Notably, ISMT developed a SEMATECH computer-integrated manufacturing (CIM) framework (Figure 1.4) [1] to specify the common MES infrastructure and the software functions of MES applications, and incorporate those MES applications into a coherent system. By specifying the standard interfaces and behaviors of the common MES components, manufacturers can collect system components from multiple suppliers. Thus, manufacturers can develop systems by extending the common components and substituting old components with improved ones of the same interfaces and behaviors.

The SEMATECH CIM framework is an abstract model for typical semiconductor manufacturing systems. This CIM framework is developed based on open-distributed system and object technologies. However, the fragility and security problems are not considered in this framework. For these reasons, Cheng et al. [3] adopted the concepts of holon and holarchy to propose a holonic

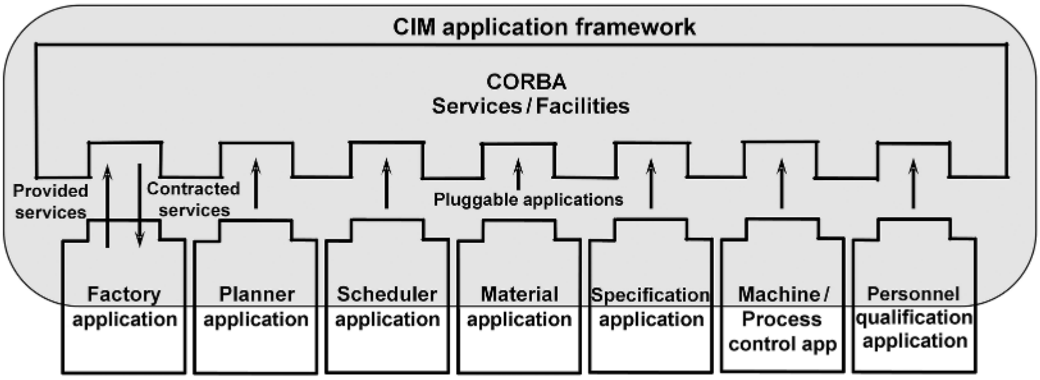

Figure 1.4 Functional architecture of the ISMT CIM framework. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

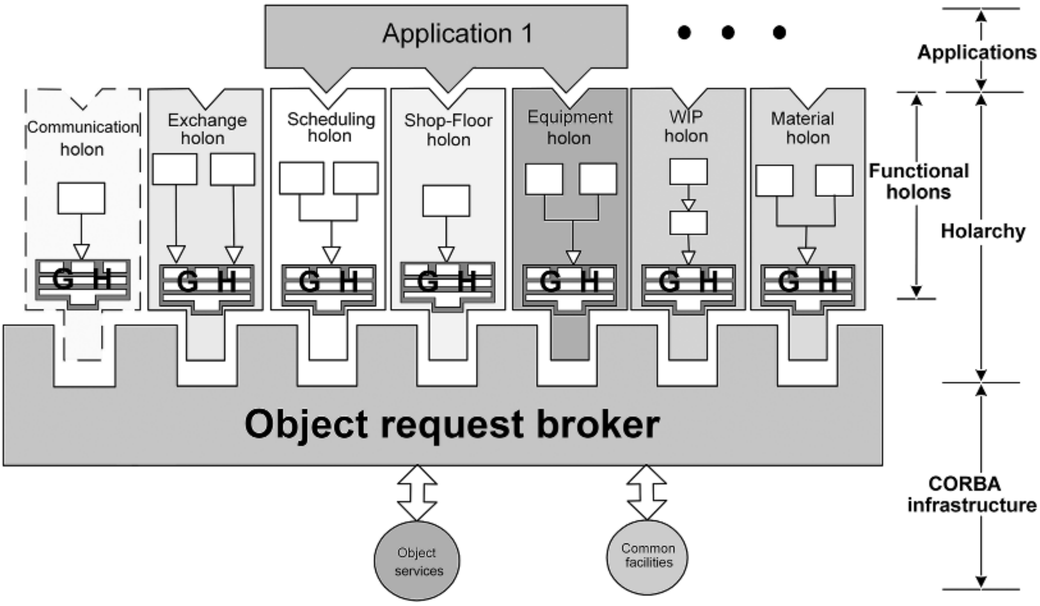

Figure 1.5 The HMES framework. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

manufacturing execution system (HMES) framework that is also suitable for industrial application (Figure 1.5). The HMES framework not only owns the characters of open-distributed system and object technologies but also has the properties of failure recovery and security certification.

A systematic approach was proposed for developing the HMES framework of the semiconductor industry (Figure 1.5) [3]. This systematic approach starts with a system analysis by collecting domain requirements and analyzing domain knowledge. The HMES holarchy is designed through the following processes: (i) constructing an abstract object model based on the domain knowledge; (ii) partitioning the application domain into functional holons; (iii) identifying the generic parts among functional holons; (iv) developing the generic holon (GH); (v) defining the holarchy messages and holarchy framework of HMES; and finally, (vi) designing the functional holons based on the GH. The HMES framework includes many functional holons, such as the material holon, WIP holon, equipment holon, scheduling holon, etc. and is open, modularized, distributed, configurable, interoperable, collaborative, and maintainable [3].

1.2.1.2 Supply Chain (SC)

The SC is defined as a network of facilities and distribution designed to perform tasks, such as procuring materials, transforming materials into intermediate and finished products, and distributing the finished products to customers [6]. The objective of the SC is to deliver the correct quantity of the right product at the right time at minimum cost. The SC is designed to achieve timely and economical delivery of products required by the O2D cycle [7], and to support the collaborative computing of distributed orders in the semiconductor industry to ensure coherent IC manufacturing operations.

Figure 1.6 presents the architecture of an electronic supply chain management (ESCM) and its key processes [18]. This ESCM has been deployed in Taiwan Semiconductor Manufacturing Company (tsmc) [19]. The ESCM architecture comprises demand-planning, allocation-planning, capacity-modeling, allocation-management, order-management, available-to-promise (ATP), and output-planning mechanisms. The demand-forecast process and purchase-order process of ESCM are presented in the following paragraphs.

- **Demand-Forecast Process**
  The demand-planning mechanism receives demand forecasts from a customer. The demand forecast specifies forecasted production of a process technology required by the customer in a predetermined period. Then, the demand forecast is adjusted by the demand-planning mechanism. The adjusted demand forecast is sent to an allocation-planning mechanism, which determines a capacity-allocated-support demand (CASD) based on the adjusted demand forecast and the capacity plan. Next, the CASD is forwarded to the allocation-management mechanism for support commitment is generated accordingly. Finally, the support commitment is sent to the customer.
- **Purchase-Order Process**
  When a purchase order (PO) is placed by a customer, the PO is received and forwarded to the ATP mechanism by the order-management mechanism. After receiving the information pertaining to

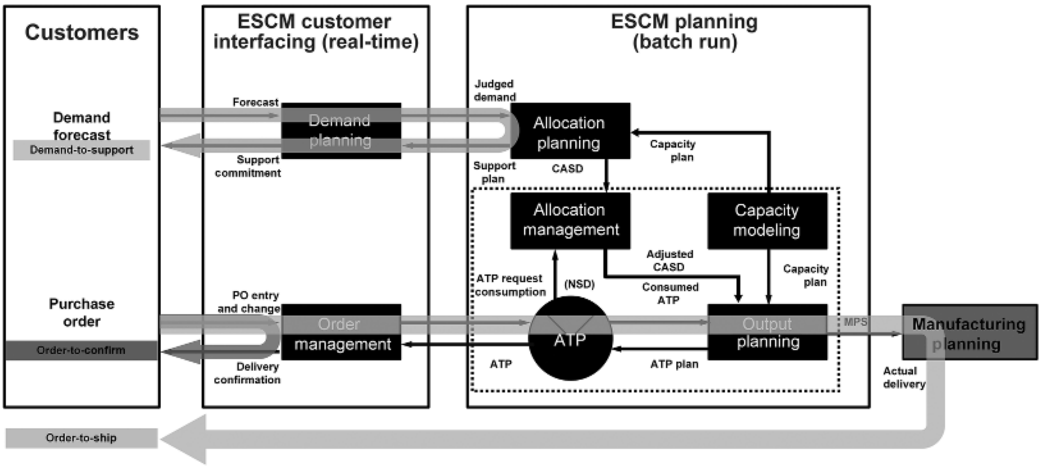

Figure 1.6 ESCM architecture and key processes. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

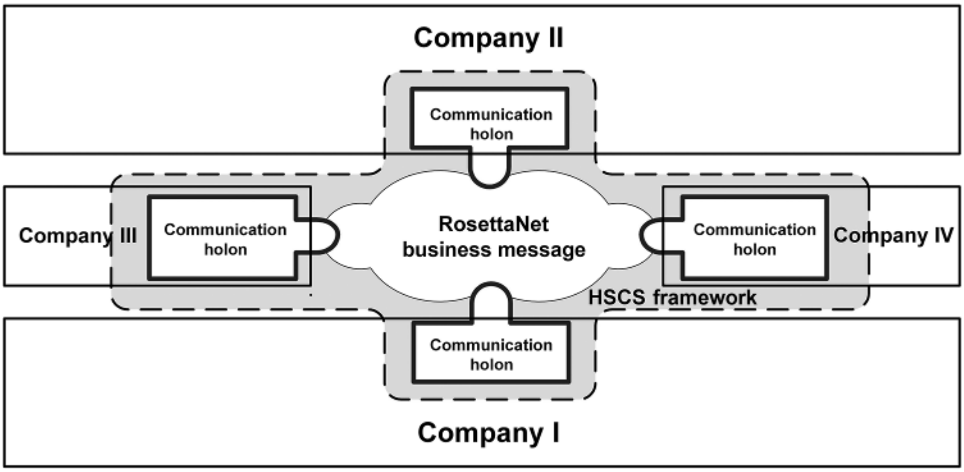

Figure 1.7 Functional-block diagram of the holonic supply-chain system. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

the PO, the ATP mechanism determines the amount of CASD to be booked and the ATP production to be consumed. Next, the ATP mechanism sends the information pertaining to the booked CASD to the allocation-management mechanism. Once the booked CASD is received, the allocation-management mechanism adjusts the initial CASD accordingly. Meanwhile, the ATP mechanism also sends information pertaining to the consumed ATP production to the output-planning mechanism. With the consumed ATP production received from the ATP mechanism and the capacity plan from the capacity-modeling mechanism, the output-planning mechanism can generate a master production schedule (MPS) accordingly, which is sent to the manufacturing planning subsystem for shipping the product to the customer.

Cheng et al. [8] have also developed a holonic supply-chain system (HSCS) as shown in Figure 1.7. The HSCS consists of several communication holons. Each company in the SC should possess a communication holon. The HSCS employs distributed object and mobile object technologies, RosettaNet implementation framework, and holon and holarchy concepts. The systematic approach applied to develop the HMES is also utilized in constructing the HSCS. The GH is first developed. Next, the communication holon is generated by inheriting the GH. As shown in Figure 1.7, each company in the SC, such as Company I, requires a communication holon as the communication component for correspondence with other companies in the SC. The communication holon exhibits basic holonic attributes, such as intelligence, autonomy, and cooperation. Furthermore, the communication holon can handle partner interface processes and data exchange of various data formats by following the standards of RosettaNet business messages. As a result, the HSCS can meet the future requirements of the SC information integration of virtual enterprises [8].

1.2.1.3 Equipment Engineering System (EES)

The EES is defined as the physical implementation of the equipment engineering capabilities (EECs), which are applications that address specific areas of equipment engineering (EE), such as fault detection and classification (FDC), predictive maintenance (PdM), virtual metrology (VM), run-to-run (R2R) control, etc. [4, 5].

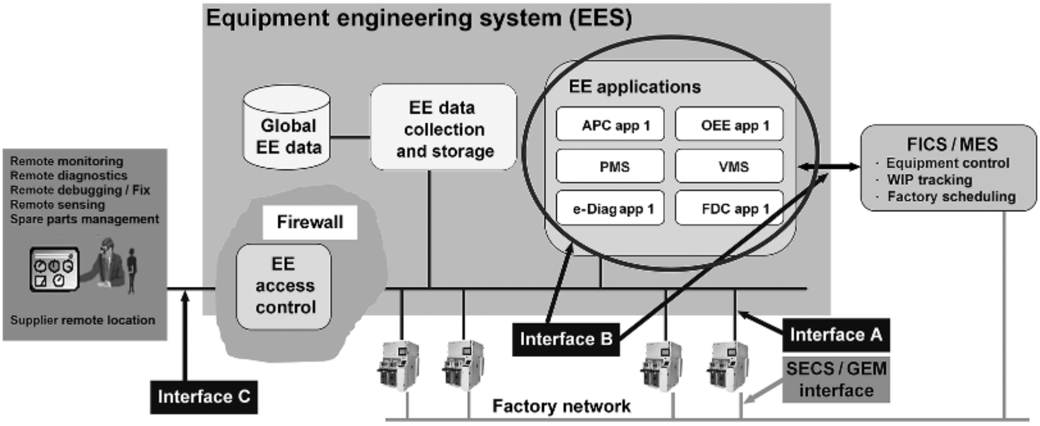

Figure 1.8 The ISMT EES framework. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

An EES framework is required to support the EECs [4]. Therefore, ISMT proposed an EES conceptual framework as shown in Figure 1.8 [4]. In the ISMT EES framework, three interfaces (Interface A, Interface B, and Interface C) are defined for different purposes. Interface A is an equipment data acquisition interface for getting more and better data from the equipment [20]. Interface B defines interfaces among EE applications and creates a connection between the MES and EES [24]. Interface C describes the external access to e-diagnostics [16, 25].

As displayed in Figure 1.8, the ISMT EES framework posits all the EE applications (such as advanced process control (APC), OEE, FDC, PdM, VM, and others) outside the equipment. Those architectures are suitable for the applications of R2R-type controls involving more than one piece of equipment. However, for self-related equipment applications (e.g. FDC, PdM, and VM), such architectures heavily consume factory network bandwidth. Another disadvantage of those architectures is that all the data are sent to the same remote client for processing and monitoring, which may result in data overloading to the remote client and further impact the real-time analysis efficiency. Additionally, if the remote client breaks down and lacks backup, the entire prognostics system is paralyzed [5].

To resolve the problems mentioned above, Su et al. [5] proposed another EES framework as shown in Figure 1.9. The proposed EES framework divides all the EE applications into three categories. The R2R-type applications (e.g. APC and RM) are installed in the remote-client side; the self-related-type applications (e.g. FDC, PdM, and VM) are plugged in the generic embedded devices (GEDs) [5] and distributed in each individual tools; the e-diagnostics-type applications are implemented in a remote client via Interface C for security considerations.

Among the abovementioned EES applications, VM is an emerging technology [26]. VM is a method to conjecture the manufacturing quality of a process tool based on the data sensed from the process tool and without physical metrology operation [27].

Fab-wide R2R control [28] is one of essential EES applications for semiconductor manufacturing. In general, a run can be a batch, lot, or an individual wafer. When lot-to-lot (L2L) control is applied, the promptness of each wafer's VM result for the feedback and feedforward purposes will not be necessary. However, when wafer-to-wafer (W2W) control is adopted, obtaining the real-time and on-line VM result of each wafer in the feedback loop is essential.

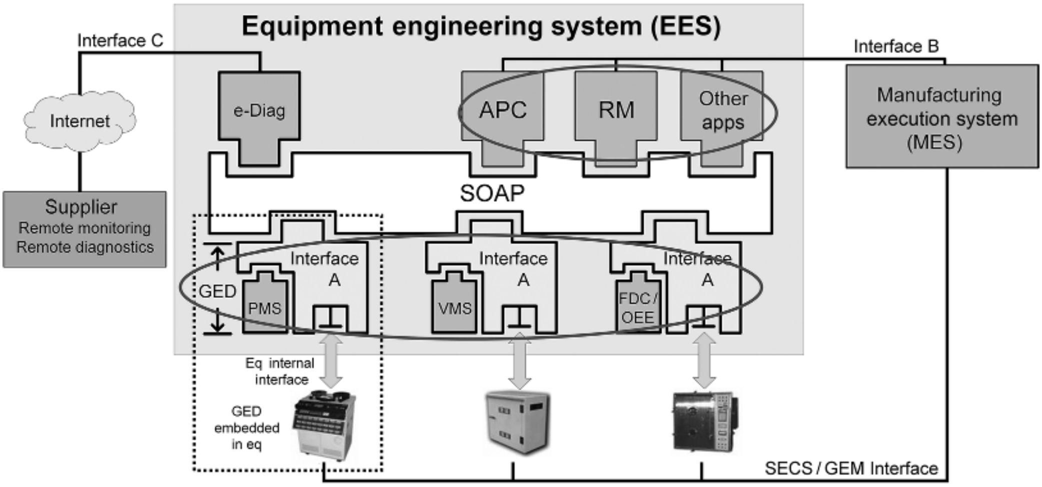

Figure 1.9 The proposed EES framework. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

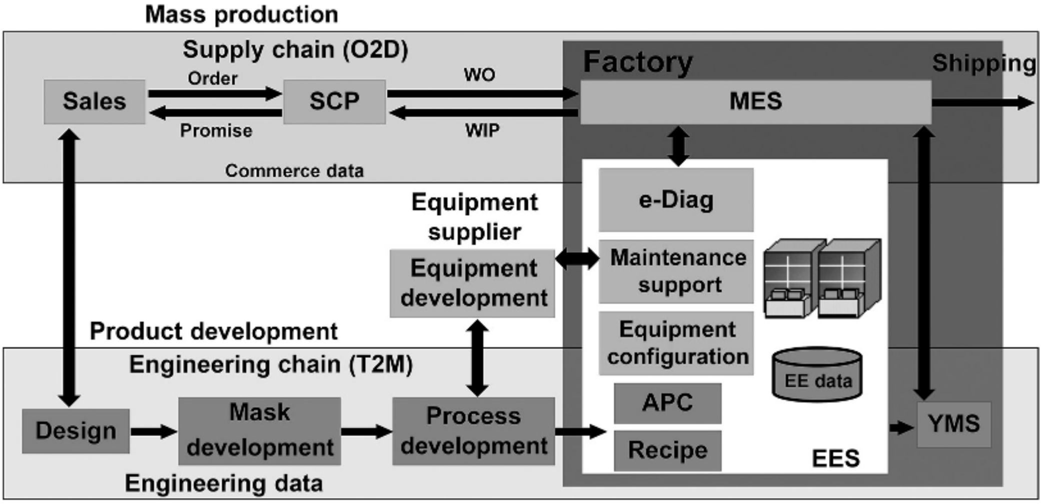

Figure 1.10 Comparison of SC and EC. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

1.2.1.4 Engineering Chain (EC)

International technology roadmap of semiconductor (ITRS) proposed the concept of EC to cope with the problems aroused from design collaboration in the semiconductor industry in 2003. In the semiconductor industry, the EC was defined as a network of facilities and distributed services that performs device design, verification of design, manufacturing pilot run, assembly and test operations, yield improvements, and final release for mass production [11]. Figure 1.10 compares the SC and the EC in the semiconductor industry [14].

In the mass-production phase after a successful IC design, the SC manages the entire operation from order input to wafer delivery. On the other hand, in the product-development phase, the EC plays the role of managing IC design operation from IC design to the release of mass production.

Both the SC and EC management systems should operate efficiently within the new collaborative operation model among all stakeholders to complete IC design and IC manufacturing. However, the EC supports product development, while the SC supports mass production.

The novel EC component and the traditional SC component for inter-company operation are combined with the intra-company MES component and EES component to create a new comprehensive e-Manufacturing scope in the semiconductor industry as illustrated in Figure 1.2. The proposed semiconductor e-Manufacturing concept focuses not only on the SC O2D for timely and economical delivery of desired products [6, 7] but also on the e-Manufacturing support to achieve a faster design cycle for reducing the EC T2M since some IC design cycles are longer than their corresponding mass-production cycles [29].

Cheng et al. [11] also proposed the concept of an engineering-chain-management system (ECMS) to supervise the collaborations with EC partners and EC capabilities for shortening the T2M in the IC production process. An EC environment consists of numerous design partners that are allocated among different locations but working together to produce advanced IC design. Therefore, considerable engineering data exchange is inevitable. Each professional partner of the EC focuses on its professional work. The ECMS can support the operating efficiency of the collaborative team, including first design success rate enhancement, design cycle time subtraction, and design cost reduction. The ECMS supports the EC operation and engineering data exchange by providing a new system framework and comprehensive operating scenarios.

Coherent IC design operations among many heterogeneous companies are the operating model of the EC. Enormous quantities of data, including design files, mask data, process specifications, and yield data, need to be exchanged among all the members of the EC. Therefore, transparent information sharing is essential for significant design efficiency improvement and to assure the first-pass tape out of an IC design.

To support the above EC operating scenarios in the ECMS architecture requires exchanging considerable engineering data. Although, there is no industrial standard for EC engineering-data exchange as that for logistics data in the semiconductor industry, an ECMS framework is required to implement and fulfill the key requirements of the EC [9].

The authors adopted the new generation distributed object-oriented technology with web services [15] as the enabling technology to propose the ECMS framework [11] that comprises many EC agents. As shown in Figure 1.11, five main companies, including the IC design house, IP/library house, masking house, foundry house, and assembly/test house, are consisted in the example ECMS framework. Notably, each company must possess an EC agent, which is in charge of the data exchange operations, to communicate with the other servers.

1.2.2 Industry 4.0

Germany proposed Industry 4.0 to takes first steps toward the next industrial revolution in 2012. The definition and core technologies of Industry 4.0 as well as the requirement of mass customization are introduced below.

1.2.2.1 Definition and Core Technologies of Industry 4.0

Industry 4.0 is a collective term for technologies and paves the way to and for visions of a smart factory and smart manufacturing [31], which can be achieved by the integration of both IoT [33, 35] and CPS [34]. A smart factory possesses smart-manufacturing scenarios; while smart manufacturing emphasizes man-machine cooperation and production logistics management by applying IoT, CPS, cloud-based approaches, big data, and communicating technologies [36, 37]. Briefly

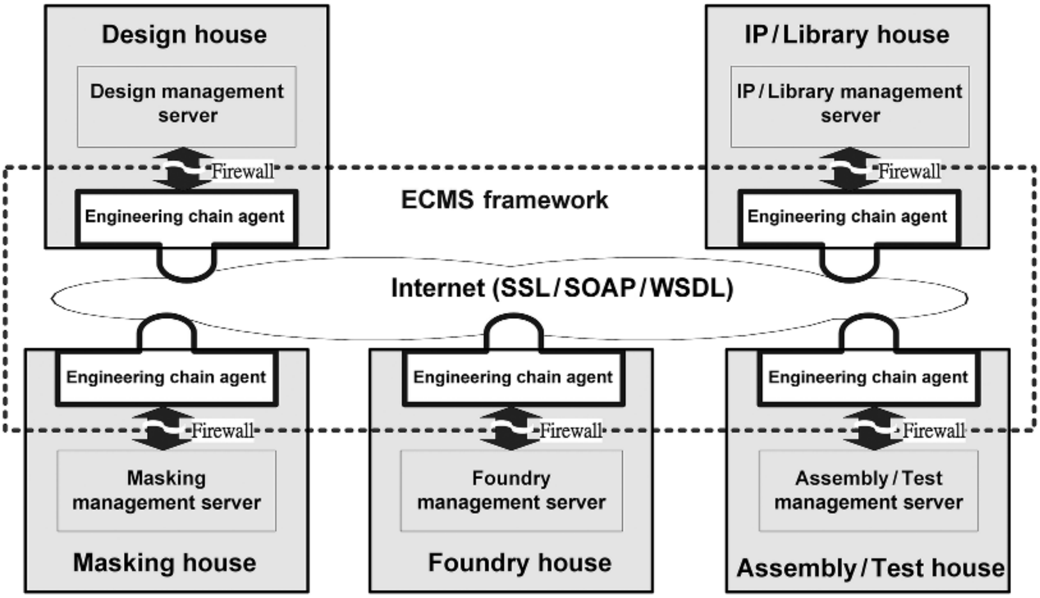

Figure 1.11 Engineering-chain-management system framework. *Source:* Reprinted with permission from Ref. [14]; © 2010 IEEE.

speaking, in order to step forward to the next advanced manufacturing level, Industry 4.0 focuses on enabling people, equipment, and products to communicate with each other independently; and allows venders and their customers to stay closer in the production processes and to react faster upon the changing market requirements.

IoT is a communication network for connecting every physical object (or “thing”) in the real world which has naming, sensing, and processing abilities [38]. As a production factor with ubiquitous connections, it has been considered the promising technology of IT infrastructure for seamlessly integrating classical networks and networked objects, for data acquisition and sharing great effects of the performance for many enterprise systems in modern manufacturing [33, 35]. On the other hand, CPS is a term to describe the interconnection between the physical and cyber world. By integrating analog/digital hardware, middleware, and highly flexible software behind cyberspace, CPS achieve the creation of a link between virtual elements and real entities [34, 36, 39]. In this way, physical entities can be controlled by the intelligence from cyber elements. Currently, embedded systems only focus on the stand-alone computation rather than interaction with physical elements. Thus, CPS are usually referred as advanced embedded systems because of being intrinsically connected with internet-connected objects [38] for performing desired functions that are frequently accompanied with real-time computing capability and are able to link each embedded system to digital networks for independently facilitating data processing. A large number of recent studies [37, 38, 40, 41] also emphasized that IoT and CPS are supposed to have intelligence because they are assumed capable of being identified, sensing events, interacting with others, and making decisions by themselves. In summary, IoT provides a basic platform for connecting all CPS, and CPS cooperate seamlessly with real and virtual spaces to make Industry 4.0 possible. Therefore, we can definitely say that there is no CPS without IoT; no Industry 4.0 without CPS and IoT.

Cloud computing has emerged as a new trend of internet application in recent years [42]. By leveraging and extending the characteristics of cloud computing to meet the global and distributed requirements of current manufacturing industry, cloud-based manufacturing, also referred as CMfg, has recently emerged as a next-generation manufacturing paradigm. As remarked in [42], CMfg is characterized by many factors (such as scalability, agility, resource pooling, virtualization, multi-tenancy, ubiquitous access, self-service, search engine, social media, crowdsourcing, etc.) and is different from traditional web- and agent-based manufacturing paradigms from several aspects, such as computing architecture, data storage, operational process, business model, etc. Hence, CMfg is surely a new paradigm which will revolutionize the manufacturing industry. In fact, CMfg is also regarded as one of the best solutions for implementing IoT/CPS [30, 32, 34, 36, 37, 42, 43, 44] because of its powerful computing capability.

To realize CPS, the technology of Big Data Analytics (BDA) are adopted widely. Therefore, BDA is also one of the core technologies of Industry 4.0.

1.2.2.2 Migration from e-Manufacturing to Industry 4.0

Both e-Manufacturing and Industry 4.0 adopt ICT as the enabling tool and emphasize the necessity of big data collection; while the former was proposed in 2000 and the later in 2012. The four key components of e-Manufacturing are MES, SC, EES, and EC; while the four core technologies of Industry 4.0 are IoT, CPS, CMfg, and BDA. Because the cloud-computing technology was not mature yet in 2000, e-Manufacturing did not adopt CMfg as one of the enabling technologies.

e-Manufacturing utilizes equipment managers in MES to collect all the process and metrology data; while Industry 4.0 applies IoT devices to collect all the data required. The technologies of IoT, CPS, and CMfg of Industry 4.0 can be applied to implement various EES functions (such as VM, PdM, and APC) of e-Manufacturing with a more systematic and efficient fashion. The functions of SC in e-Manufacturing can be accomplished by the CPS technology of Industry 4.0 as well. Also, BDA of Industry 4.0 can be applied to find the root causes of a yield loss for yield enhancement and yield management. Therefore, as mentioned previously, e-Manufacturing is the predecessor of Industry 4.0. However, the function of EC in e-Manufacturing is not considered in Industry 4.0 because EC is specific for the semiconductor industry but not the machinery industry.

1.2.2.3 Mass Customization

With the upcoming age of IoT [35, 43, 45] and CPS [46], Industry 4.0 redefines the industrial manufacturing system in a completely automated scenario. The characteristics of "digitization, intelligentization, and customization" of this industrial evolution advance the traditional manufacturing techniques from mass production towards a deep-rooted mass-customization (MC) [47].

Although MC is not a new concept, it is emphasized again in Industry 4.0 for the fact that customers are returning to the center of the core value [48, 49]. One of the core values of Industry 4.0 targets to integrate people's demand into manufacturing for enhanced products, systems, and services for a wider variety of increasingly personalized customization of products [49]. Thus, a further change will happen to the manufacturing industries with Industry 4.0 that the customers can benefit from [50].

Frankly, it is the birth of IoT/CPS that lifts data-collection and communication technologies to a new level so as to allow a faster response to customers' needs. Industrial manufacturers can efficiently build relationships with the end-customers by combining the flexibility and personalization of "custom-made" in real-time. MC is also known as the concept of "made to order" or "build to order" [51]. The production only happens after manufacturers know what customers' demands are. Customers or end-users can easily decide the certain functionalities or personal attributes of a unique product or service what they exactly want just via a web portal. In other words, customers, manufacturers, and equipment closely interact with one another through seamless connections via IoT/CPS – a win-win situation for all participants in modern manufacturing relationships.

MC aims to provide customers with varieties of increasing customized products and a near mass-production efficiency without the corresponding increase in cost and lead time. Since MC first coined by Davis [52], it has attracted a large number of researchers to take their great efforts to make MC possible for decades. So far there has been a significant progress, such as Gilmore and Pine [53] defined four approaches: collaborative, adaptive, cosmetic, and transparent customizations for targeting different mass consumer groups in MC markets depending on degrees of customization in the product itself, and representation of the product. Collaborative customization seeks to help clients who struggle to spot exactly what they want and helps to understand the needs of the customers and strives to make it clear to them. Adaptive customization allows customers to handle customized products themselves without manufacturer's assistance. Cosmetic customization presents a standard product with various representation to different customers. Transparent customization means that manufacturers provide unique products without needing to inform customers. Silveira et al. [54] surveyed the earlier studies on MC to point out the visionary and practical conceptualizations of MC theory; also, fundamental requirements for developing a basic MC framework composed from eight generic levels of MC were thoroughly discussed in [54]. Further, as information technologies evolves, Fogliatto et al. [55] updated the latest successful MC applications among various fields, including the food industry, electronics, large engineered products, mobile phones, and personalized nutrition; or special MC applications such as homebuilding and the production of foot orthoses. They clearly identified required conditions in different fields and situations of implementing a suitable MC platform from the view of economics, success factors, enablers, and customer-manufacturer interactions.

For manufacturers, two mandatory factors of agility and quick responsiveness to manufacturing changes are expected to minimize the escalating costs [51, 53, 55]. They have to ensure the production facility must be flexible enough for switching between complex variants with some delay and be agile enough to adapt to changes in customized products at a low cost, thereby retaining economic benefits [55, 56]. For customers, after the emergence of Industry 4.0, the state-of-the-art of IoT/CPS replaces traditional MC scenarios, and gives customers more chances to actively participate in a collaborative design of customized products.

However, no matter how production technologies are improved in the era of Industry 4.0, the ultimate aim for manufacturing has not changed, which is the manufacturing quality of products. Manufacturers are imperative to ensure that the manufacturing quality of deliverables conforms to the design specifications before delivering them to customers. Thus, "quality control" is also listed as one of the promising areas to be achieved for future research in MC [55]. Namely, how to effectively minimize the defective product cost is still the biggest challenge of MC. As such, a fully automated and real-time total-inspection method is needed to withstand a global requirement on increasing product quality and reducing production cost.

1.2.3 Zero Defects – Vision of Industry 4.1

Since the late 1960s, ZD has been one of the quality-improvement objectives for accomplishing manufacturing quality [57]. Through prevention methods, ZD aims to boost production and minimize waste. ZD is based on the concept that the amount of mistakes a worker makes doesn't matter since inspectors will catch them before they reach customers [57].

Industry 4.0, since its first presentation at the Hannover Messe 2014, is set to be one of the new manufacturing objectives and, most of all, keep the faith of achieving nearly ZD state in the manufacturing industry [58, 59]. The current Industry 4.0 related technologies emphasize on productivity improvement but not on quality enhancement; in other words, they can only keep the faith of achieving nearly ZD state without realizing this goal. The key reason for this inability is the lack of an affordable online and real-time Total Inspection technology. By adopting the Automatic Virtual Metrology (AVM) technology that has been certified with the invention patents from six countries (Taiwan ROC, USA, Japan, Germany, China, and Korea) developed by the research team of Fan-Tien Cheng, the Editor and main author of this book, ZD can be achieved as AVM can provide the Total Inspection data of all products online and in real time. A defective product will be discarded once it is detected by AVM; in this way, all of the *deliverables* will be ZD. Further, the Key-variable Search Algorithm (KSA) of the Intelligent Yield Management (IYM) system developed by Fan-Tien Cheng's research team can be utilized to find out the root causes of the defects for continuous improvement on those defective products. As such, ZD of all *products* can be achieved. Therefore, once AVM and IYM are integrated into the successfully developed Industry 4.0 platform, the state of ZD can be realized, which is defined as Industry 4.1 by Fan-Tien Cheng. The concepts of Industry 4.1 were disclosed in *IEEE Robotics and Automation Letters* in January 2016 [60]. The technical details of AVM and IYM will be elaborated in Chapters 8 and 10, respectively.

1.2.3.1 Two Stages of Achieving Zero Defects

Generally speaking, two stages are involved for achieving Zero Defects in Industry 4.1:

- Stage I: accomplish Zero Defects of all the *deliverables* by applying efficient and economical total-quality-inspection techniques.
- Stage II: ensure Zero Defects of all the *products* gradually by improving the yield with big data analytics and continuous improvement.

Stage I can be accomplished by directly applying AVM to perform Total Inspection on all the possible deliverables. If any defects are found in a possible deliverable, then this one should not be delivered to customers. As a result, the goal of ZD for all the deliverables is achieved.

The manufacturing-related data of all the defective products found in Stage I should be collected such that the KSA in IYM can be performed on those data to find out the root causes that result in the defects. Then, those root causes should be fixed for reducing possible defects that may occur in the subsequent production run. As such, the goal of nearly ZD for all the products can be accomplished by continuous improvements. The process mentioned in this paragraph is the so-called Stage II.

1.3 Development Strategy of Intelligent Manufacturing with Zero Defects

As semiconductor manufacturing technologies advance, semiconductor manufacturing processes are becoming more and more sophisticated. Thus, how to maintain their feasible production yield becomes an important issue. As shown in Figure 1.12, during the product life cycle, the product yield (blue solid line) gradually rises up in the research-and-development (RD) phase and ramp-up phase and then keeps steady in the mass-production (MP) phase. On the contrary, the product cost (red solid line) continuously decreases during the production life cycle. If a company can improve its changing curves of yield and cost from the solid lines into their corresponding segmented lines, the company's competitiveness would be enhanced effectively. This implies that rapidly increasing the yield in the RD phase to transfer products into the MP phase, and then assuring the yield in the MP phase while promptly finding out and resolving the root causes of yield losses is a feasible

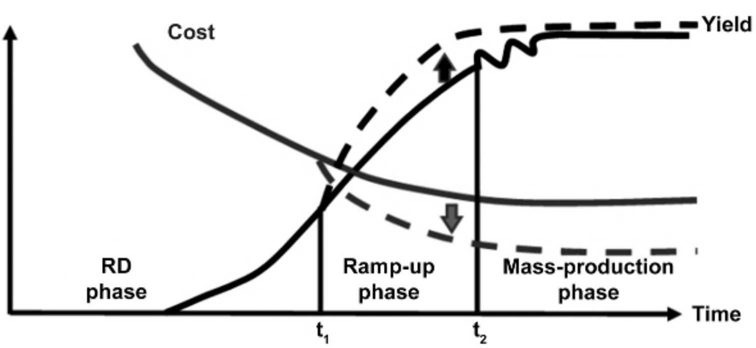

Figure 1.12 Changing curves of yield and cost during the product life cycle. *Source:* Reprinted with permission from Ref. [61]; © 2017 IEEE.

strategy for increasing the company's competitiveness. However, no literature has proposed a systematic approach of enhancing and assuring production yield, which targets both the RD phase and the MP phase of the product life cycle.

In the following, a five-stage approach as shown in Figure 1.13 for enhancing production yield and assuring nearly ZD, taking a semiconductor bumping process as an illustrative example, is proposed.

1.3.1 Five-Stage Strategy of Yield Enhancement and Zero-Defects Assurance

As shown in Figure 1.13, a five-stage approach for enhancing yield and assuring ZD of a manufacturing process is proposed. This five-stage approach involves RD, ramp-up, and MP phases. Observing the left portion of Figure 1.13, the RD and ramp-up phases cover the first two stages; while the right portion of Figure 1.13 contains the last three stages for the MP phase.

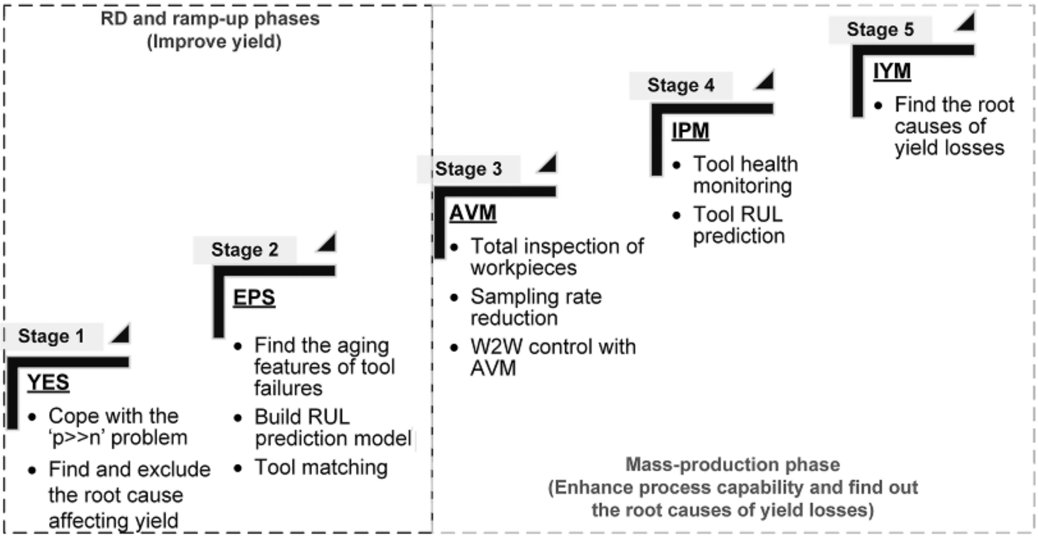

Figure 1.13 Five-stage strategy for increasing yield in RD/ramp-up and MP phases of a manufacturing process.

The production line of the bumping process shown in Figure 1.14 consists of two sub-processes, i.e. Re-Distribution Layer (RDL) and Under Bump Metallurgy (UBM). In the following, UBM is selected as the illustrative manufacturing process, as depicted at the bottom of Figure 1.14. The UBM bumping process contains the following stations: Sputtering Deposition, Photoresist (including Positive Photoresist Coating, Edge Bead Remover, Exposure, and Developing), Cu Plating, Striping, Etching, Ball Mount, Reflow, and Flux Clean.

The proposed actions at Stages 1 and 2 and associated challenges are described below.

Stage 1: developing a yield enhancement system (YES) to cope with the ‘p>>n’ problem to find and exclude the root cause affecting yield

In the illustrative bumping process, there are roughly 25 production stations, each station has 10 tools, each tool has 4 chambers, and each chamber has 100 sensors. Thus, there are totally about 100,000 parameters affecting the yield of the bumping process. If the information of tool maintenance and different material sources is also considered, the number of yield-affecting parameters, i.e. p, is even higher. In the RD phase of the product life cycle, the number of samples, i.e. n, is relatively small, thereby leading to a challenge of finding the root causes of poor yield under the condition ‘*p*>>*n*.’ This is the so-called high dimensional regression problem [61]. Thus,the developed YES should be able to promptly find the root causes affecting yield from the enormous number of parameters (*p*) under the constraint of small number of samples (*n*) and exclude them so as to effectively enhance the yield in the RD phase.

Stage 2: developing an equipment prognosis system (EPS) to find the aging features of tool failures and perform tool matching

While the YES at Stage 1 can be used to identify the problematic tool affecting yield, an equipment prognosis system (EPS) shall be developed to facilitate assuring the capability of the tool. Specifically, by creating the cause-effect relationship of failure and prognosis model of equipment, the developed EPS should be able to observe the variation trend of key aging features and further estimate the remaining useful life (RUL) of equipment. Accordingly, the problematic tool can be maintained at proper time before it fails. Consequently, the possibility of tool’s abnormality can be reduced, and the yield in the RD phase can be enhanced. Moreover, after building a successful pilot production line, a tool matching scheme shall be applied for rolling out the pilot production line to multiple lines.

The right portion of Figure 1.13 shows the last three-stage (Stages 3, 4, and 5) actions for assuring good yield in the MP phase. The proposed actions at Stages 3, 4, and 5 and associated challenges are described below.

Stage 3: conducting a fab-wide deployment of AVM to achieve the goal of Total Inspection and to perform workpiece-to-workpiece (W2W) control with AVM

The AVM system is capable of converting off-line sampling measurement into on-line and real-time Total Inspection of all workpieces to timely detect abnormalities during production. Also, the sampling rate of real measurements can be reduced by applying AVM. Accordingly, fab-wide AVM applications can effectively reduce the production cost and achieve the goal of nearly ZD of all the deliverables in the MP Phase. In addition, due to the ability of achieving Total Inspection of all the workpieces, the outputs of AVM can be applied to support W2W control for fulfilling the goal of enhancing manufacturing process capability.

Stage 4: constructing the IPM system to perform tool health monitoring and execute tool RUL prediction

At this stage, the IPM system is constructed to detect abnormality on key components of all the manufacturing tools and to predict the RULs of all the key components so as to improve the tool availability and prevent unscheduled down of all the manufacturing tools.

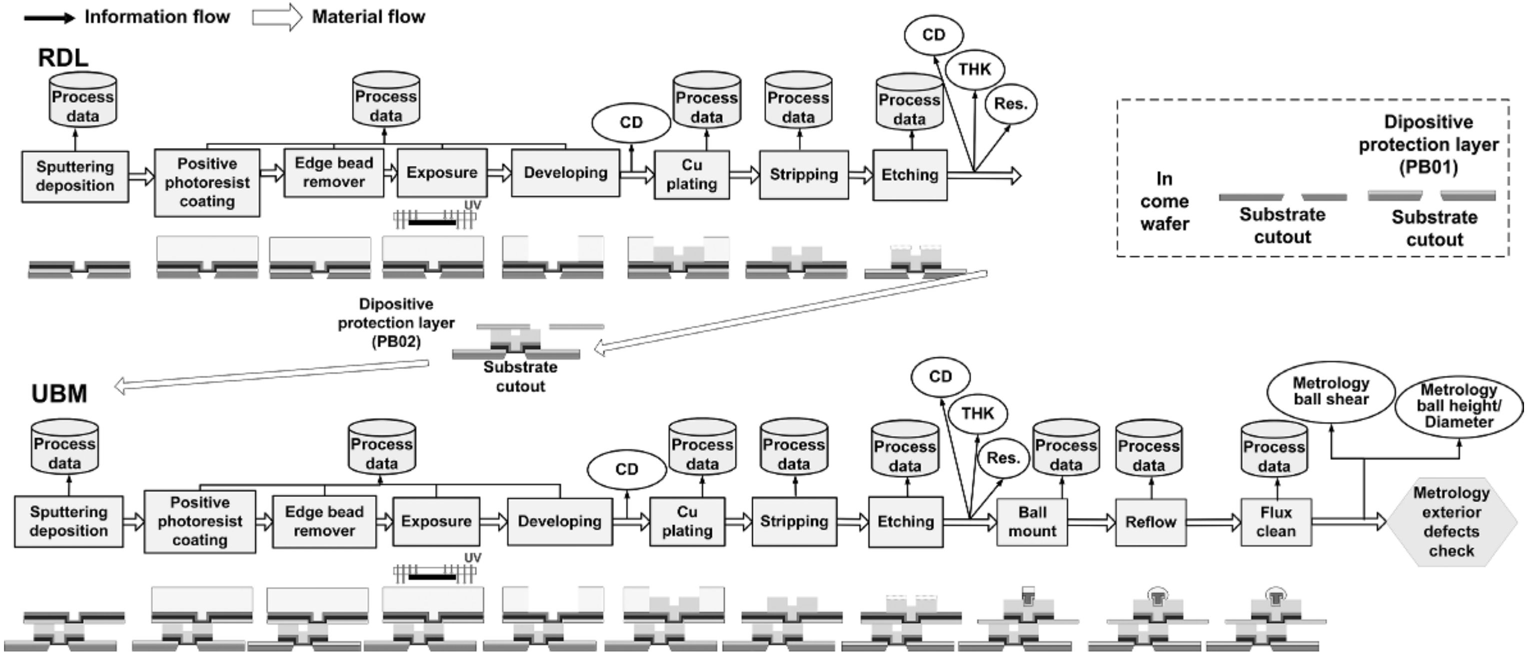

Figure 1.14 Production line of the bumping process.

Stage 5: developing the IYM system to promptly find the root causes of yield losses

In the MP phase, the IYM system is developed to promptly find out the root causes which affect the yield so as to reduce the trouble shooting time and improve the yield. As such, the goal of nearly ZD of all products can be achieved in the MP phase.

1.4 Conclusion

The evolution of automation is surveyed in this chapter, including e-Manufacturing and Industry 4.0. Then, the importance of ZD, which is the vision of Industry 4.1 is presented. Finally, the five-stage strategy of yield enhancement and ZD assurance is proposed. This five-stage strategy is the guideline for developing the Intelligent Manufacturing System with ZD. As a result, an Intelligent Factory Automation (iFA) System Platform is designed and elaborated in Chapter 6 to realize the proposed five-stage approach of yield enhancement and ZD assurance.

Appendix 1.A – Abbreviation List

APC	Advanced Process Control
ATP	Available-to-Promise
AVM	Automatic Virtual Metrology
BDA	Big Data Analytics
CASD	Capacity-Allocated-Support Demand
CIM	Computer-Integrated Manufacturing
CMfg	Cloud-based Manufacturing
CORBA	Common Object Request Broker Architecture
CPS	Cyber-Physical Systems
EC	Engineering Chain
ECMS	Engineering-Chain-Management System
EECs	Equipment Engineering Capabilities
EE	Equipment Engineering
EES	Equipment Engineering System
EPS	Equipment Prognosis System
ERP	Enterprise Resource Planning
ESCM	Electronic Supply Chain Management
FDC	Fault Detection and Classification
FOUP	Front Opening Unified Pod
FICS	Free Internet Chess Server
GEDs	Generic Embedded Devices

GEM	Generic Equipment Model
GH	Generic Holon
GUI	Graphical User Interface
HMES	Holonic Manufacturing Execution System
HSCS	Holonic Supply-Chain System
HSMS	High-Speed SECS Message Services
IC	Integrated Circuit
ICT	Information and Communication Technology
iFA	Intelligent Factory Automation
IoT	Internet of Things
IP	Internet Protocol Address
IPM	Intelligent Predictive Maintenance
ISMT	International SEMATECH
IT	Information Technology
ITRS	International Technology Roadmap of Semiconductor
IYM	Intelligent Yield Management
KSA	Key-variable Search Algorithm
L2L	Lot-to-Lot
MC	Mass Customization
MCS	Material Control System
MES	Manufacturing Execution System
MP	Mass Production
MPS	Master Production Schedule
NACFAM	National Coalition for Advanced Manufacturing
O2D	Order-to-Delivery
OEE	Overall Equipment Effectiveness
PdM	Predictive Maintenance
PO	Purchase Order
R2R	Run-to-Run
RD	Research and Development
RDL	Re-Distribution Layer
RM	Recipe Management
RUL	Remaining Useful Life
SC	Supply Chain
SECS	SEMI Equipment Communications Standard

SOAP	Simple Object Access Protocol
SPC	Statistical Process Control
SSL	Secure Sockets Layer
T2M	Time-to-Market
tsmc	Taiwan Semiconductor Manufacturing Company
UBM	Under Bump Metallurgy
VM	Virtual Metrology
W2W	Wafer-to-Wafer
W2W	Workpiece-to-Workpiece
WIP	Work in Process
WSDL	Web Services Description Language
YES	Yield Enhancement System
YMS	Yield Management System
ZD	Zero Defects

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