



INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

INTERNATIONAL
ROADMAP
FOR
DEVICES AND SYSTEMS

2017 EDITION

FACTORY INTEGRATION

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Table of Contents

Acknowledgments	iv
1. Introduction	1
1.1. Current State of Technology	1
1.2. Drivers and Technology Targets.....	2
1.3. Vision of Future Technology	3
1.4. Background Information.....	4
2. Scope of Report.....	7
2.1. Introduction.....	7
3. Summary and Key Points.....	9
3.1. What Is New in the Transition from the International Technology Roadmap for Semiconductors (ITRS) 2.0 to the IRDS?	9
4. Challenges.....	10
5. Technology Requirements	14
5.1. Summary	14
5.2. Factory Operations Needs	18
5.3. Production Equipment Needs	21
5.4. Material Handling Systems Needs	25
5.5. Factory Information and Control Systems Needs	25
5.6. Facilities Needs.....	27
5.7. Augmenting Reactive with Predictive Needs.....	32
5.8. Big Data Needs	34
5.9. Control Systems Architectures Needs.....	38
6. Potential Solutions.....	39
6.1. Factory Operations Potential Solutions	41
6.2. Production Equipment Potential Solutions	42
6.3. Material Handling Systems Potential Solutions.....	45
6.4. Factory Information and Control Systems Potential Solutions.....	46
6.5. Facilities Potential Solutions	47
6.6. Augmenting Reactive with Predictive Potential Solutions.....	48
6.7. Big Data Potential Solutions	50
6.8. Control Systems Architectures Potential Solutions	51
7. Cross Teams	51
7.1. Environmental, Safety, Health, and Sustainability (ESH/S)	52
7.2. Yield Enhancement.....	53
7.3. Metrology.....	55
7.4. Lithography.....	55
7.5. Multi-IFT Issue: Wafer Defect Metrology	56
7.6. Multi-IFT Issue: Yield Management for Packaging and Assembly	56

8.	Emerging Concepts and Technologies	56
8.1.	Smart Manufacturing and Industry 4.0	56
8.2.	Security	57
8.3.	Supply Chain Management	58
9.	Conclusions and Recommendations.....	58
10.	References	59

List of Figures

Figure FAC1	Societal Forces Impacting Challenges and Opportunities in FI	3
Figure FAC2	Factory Integration Scope.....	7
Figure FAC3	Supply Chain Model SCOR	21
Figure FAC4	Phased Scope of SEMI Standards Work to Support PE Energy Savings.....	24
Figure FAC5	Total AMC concept	28
Figure FAC6	Example of Defining the Dimensions of Analytics Capabilities [3].....	37
Figure FAC7	Factory Operations Potential Solutions	42
Figure FAC8	Production Equipment Potential Solutions	44
Figure FAC9	Material Handling Systems Potential Solutions.....	45
Figure FAC10	Factory Information and Control Systems Potential Solutions.....	46
Figure FAC11	Facilities Potential Solutions	47
Figure FAC12	Augmenting Reactive with Predictive Potential Solutions.....	49
Figure FAC13	Big Data Potential Solutions	50

List of Tables

Table FAC1	Acronyms Used in This Report.....	4
Table FAC2	Standards Referenced in This Report	5
Table FAC3	Difficult Challenges	10
Table FAC4	Key Focus Areas and Issues for FI Functional Areas Beyond 2017	14
Table FAC5	Stabilized FI Metrics with Recommended Values (Critical but Educational Values)	17
Table FAC6	Factory Operations Technology Requirements.....	21
Table FAC7	Context Data Importance for Good Equipment Visibility.....	23
Table FAC8	Production Equipment Technology Requirements.....	25
Table FAC9	Material Handling Systems Technology Requirements	25
Table FAC10	Factory Information and Control Systems Technology Requirements	27
Table FAC11	Facilities Technology Requirements	32
Table FAC12	Augmenting Reactive with Predictive (ARP) Technology Requirements	34
Table FAC13	Big Data Technology Requirements.....	38
Table FAC14	Stabilized FI Potential Solutions with Description	40
Table FAC15	Crosscut Issues Relating to Factory Integration Delineated by IFT	51

[Link to Factory Integration tables in Excel](#)

ACKNOWLEDGMENTS

Factory Integration International Focus Team (IFT) active members— Daniel Babbs, Jonathan Chang, Gino Crispieri, Peter Csatory, Mike Czerniak, Astrid Gettel, Ramond Goss, David Gross, Chih-Wei (David) Huang, Vladimir Kraz, Slava Libman, Les Marshall, Supika Mashiro, Rick McKee, Steve Moffatt, Chris Muller, Andreas Neuber, Kevin Pate, Markus Pfeffer, Lothar Pfitzner, Gavin Rider, Dave Roberts, Ines Thurner, Brad van Eck, and Makoto Yamamoto.

The Factory Integration IFT would also like to thank Semiconductor Equipment and Materials International (SEMI), the Advanced Semiconductor Manufacturing Conference 2017 organizers, and the Advanced Process Control (APC) 2017 Conference organizers for supporting execution of our security survey; and the APC 2017 Conference organizers for hosting the APC Council meeting in which security survey responses were consolidated and consensus was reached on Factory Integration security challenges.

FACTORY INTEGRATION

1. INTRODUCTION

The Factory Integration (FI) chapter of the IRDS is dedicated to ensuring that the microelectronics manufacturing infrastructure contains the necessary components to produce items at affordable cost and high volume. Realizing the potential of Moore's Law requires taking full advantage of device feature size reductions, new materials, yield improvement to near 100%, wafer size increases, and other manufacturing productivity improvements. This in turn requires a factory system that can fully integrate additional factory components and utilize these components collectively to deliver items that meet specifications determined by other IRDS international focus teams (IFTs) as well as cost, volume and yield targets. Preserving the decades-long trend of 30% per year reduction in cost per function also requires capturing all possible cost reduction opportunities. These include opportunities in front-end as well as back-end production, facilities, yield management and improvement, increased system integration such as up and down the supply chain, and improving environmental health and safety. FI challenges play a key role realizing these opportunities and many FI technology challenges are becoming limiters to achieving major technology milestones.

1.1. CURRENT STATE OF TECHNOLOGY

The overall FI scope addresses several challenges/issues that threaten to slow the industry's growth, including:

1. *Complex business models with complex factories*—Rapid changes in microelectronics technologies, business requirements, and the need for faster product delivery, high mix, and volatile market conditions continue to make effective and timely factory integration to meet accelerated ramp and yield targets more difficult over time. The factory now must integrate an even larger number of new and different equipment types, software applications and data to meet complex market objectives and customer requirements. High mix and low-volume product runs are making mask cost, fabrication, and FI extremely difficult in a market where average selling prices are declining.
2. *High potential of waste generation and inclusion in factory operations*—Continuous improvement of factory productivity with more comprehensive visualization and inclusion of waste and resource utilization targets is necessary to achieve growth and cost targets.
3. *Production equipment utilization and extendibility*—Production equipment is not keeping up with reliability, availability, and, utilization targets, which has an enormous impact on capital and operating costs. Reliability, availability and especially utilization are also impacted by factory operation factors.
4. Significant productivity improvement either by next wafer size manufacturing paradigm or through 300 mm manufacturing technology improvement—the industry needs to review the productivity losses in 300 mm and improve prior to the next wafer size transition so to make this transition more cost-effective. Due in-part to the challenges associated with transition to the next wafer size, the projected date for transition has been moved out to 2025.
5. *Augmenting reactive with predictive operations*—The industry needs to augment the existing reactive mode of operation, changing reactive operations to predictive operations wherever possible, but continuing to be able to support reactive operation. This will provide significant opportunities for cost reduction and quality and capacity improvement. Examples include predictive maintenance (PdM), metrology prediction via virtual metrology (VM), fault prediction, predictive scheduling, and yield prediction.
6. *Control system evolution*—Control systems will continue to become more granular (e.g., lot-to-lot, to wafer-to-wafer, to within wafer), and higher speed (e.g., run-to-run to real-time quality parameter control). Centralized versus various levels of distributed control is also being evaluated, both in a horizontal (e.g., distributed applications and control optimized across the supply chain) and vertical (e.g., internal tool fault detection tied to higher level maintenance activities) sense. Big data characteristics including veracity (i.e., data quality including accuracy, synchronization and context richness), value (including algorithms) and velocity (i.e., rates) must improve to support the evolution of control systems and will also serve to realize new control system concepts.
7. *Supply chain integration and management*—FI connectivity up and down the supply chain leveraging the accelerated information technology (IT) trends will be necessary to support tightening of production methods (e.g., associated with lean manufacturing) and addressing business requirements (e.g., for yield correlation, warranty traceability, and cost reduction).

2 Introduction

8. *Ramp-up of new technologies*—Closer integration of the industry is required for successful ramp-up of new technology nodes and device architectures. There is a need for improved hardware and software capabilities as well as more rapid reliable deployment of these capabilities. Examples include process characterization involving nascent device materials, chemicals, gases, and consumables; where the wafer process environments are far better protected to prevent productivity degradation.
9. *Security*—Information security will be more challenging with the increase of data shared across the factory integration space. For example, the concept of the “connected Fab,” which is one of central concepts of Industry 4.0/Smart Manufacturing, even indicates potential direct data exchanges beyond the factory integration space. While data must be made available to promote fault detection and classification (FDC), predictive maintenance (PdM), advanced process control (APC), etc. at more granular levels (e.g., lot based to single wafer oriented for maximizing productivity), protection of data and intellectual property (IP) within data will become more complicated and sometimes contradictory to needs of data availability. Key challenges are listed below: (Note that some of these challenges are addressed in SEMI E169-0616: Guide for Equipment Information and System Security, however this is a guide and thus does not contain any specific standards requirements.)
 - a. Protection of crucial production parameter data (e.g. recipe, equipment parameters) from unauthorized viewing or changing within the factory including between factory, original equipment manufacturers (OEMs) and 3rd party suppliers [1]
 - b. Managing access authentication mechanisms for both human and non-human entities (e.g., software program)
 - c. Managing user class read-write privileges to support user capabilities while preventing access that would result in breach of IP security or factory operation issues
 - d. Achieving balance between data availability (e.g., log-data for improved equipment performance) and protection of device manufacturer’s manufacturing IPs and equipment suppliers’ proprietary information (e.g., equipment design and control)
 - e. Maintaining software security levels when interacting with 3rd parties on the factory floor
 - f. Maintaining software and communication performance in the face of security measures such as antivirus software operations or compartmentation firewalls.
 - g. Protecting quality and integrity of big data and application of big data analytics to identifying security issues
 - h. Protection of the facility’s instrumentation and control systems from attack
 - i. Protecting fab and equipment operation control systems from unauthorized operation or alteration from both inside fab and outside
10. Challenges and issues associated with increased integration of FI with Yield and ESH solutions—As noted above FI challenges and solutions directly impact aspects of ESH/S and Yield roadmaps and these roadmaps in turn place requirements and provide direction for FI. This is exemplified in areas such as yield prediction and energy savings.

1.2. DRIVERS AND TECHNOLOGY TARGETS

Societal driving forces and trends such mobile devices and the internet of things (IoT) are impacting all areas of the IRDS, however, as shown in Figure FAC-1, these factors impact the evolution of FI from two perspectives, namely:

1. Requirements they place on product technologies that are delineated in roadmaps associated with other focus areas; these technology requirements indirectly influence FI in terms of tighter process requirements with acceptable yields, throughputs and costs.
2. Requirements they place on FI technologies that directly impact FI in terms of aligning with these trends and effectively leveraging these capabilities.

An analysis of perspective 1) can be found by studying the roadmaps found in other focus groups as illustrated in Figure FAC-1, and then determining how the FI roadmap addresses the related tighter process requirements. With respect to perspective 2), the following is an example of how some of these drivers directly impact FI:

- *The Cloud*: The advent of the cloud and cloud-based technologies provides tremendous opportunities in terms of analytics, addressing data volumes, coordination, enterprise-wide sharing and commonality and leveraging capabilities across industries. However, it also presents challenges in terms of security from attack, security for IP protection, and performance.
- *Big Data*: The data explosion in manufacturing provides both challenges and opportunities for FI; a section of the FI chapter was created in the ITRS 2013 Edition and enhanced in the ITRS 2.0 2015 Edition, as well as in the IRDS 2017 whitepaper that describes these in detail.

- *Mobility*: Mobile devices have and will continue to enhance the capabilities of FI systems in terms of accessibility, ergonomics and human-machine interaction, flexibility, portability, etc., but also can present many security challenges as well as performance challenges.
- *Green Technology*: The movement towards greener technologies and subsequent requirements for reduction in energy costs and “carbon footprint” significantly impact FI. First and foremost, they require that facilities objectives such as energy consumption and ESH/S objectives such as contamination waste reduction be an integral part of FI factory operation objectives.
- *IoT*: The definition of IoT varies in detail however the definition from Wikipedia is applicable in the context of this report: “The internet of things is the network of physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to connect and exchange data.” [2]. IoT technologies provides opportunities in terms of flexible connectivity and interoperability strategies for dissimilar system across the FI infrastructure. This connectivity could be used for non-time critical and human-in-the-loop activities when the communication is the internet, however issues of security and response time variability must be considered. The connectivity could be used for more time critical applications such as control with intranet connectivity.
- *Supply Chain*: An important trend in FI is tighter integration up and down the supply chain for improved quality, traceability, efficiency, etc. This is discussed in further detail in sections 5.2.13 and 8.3.

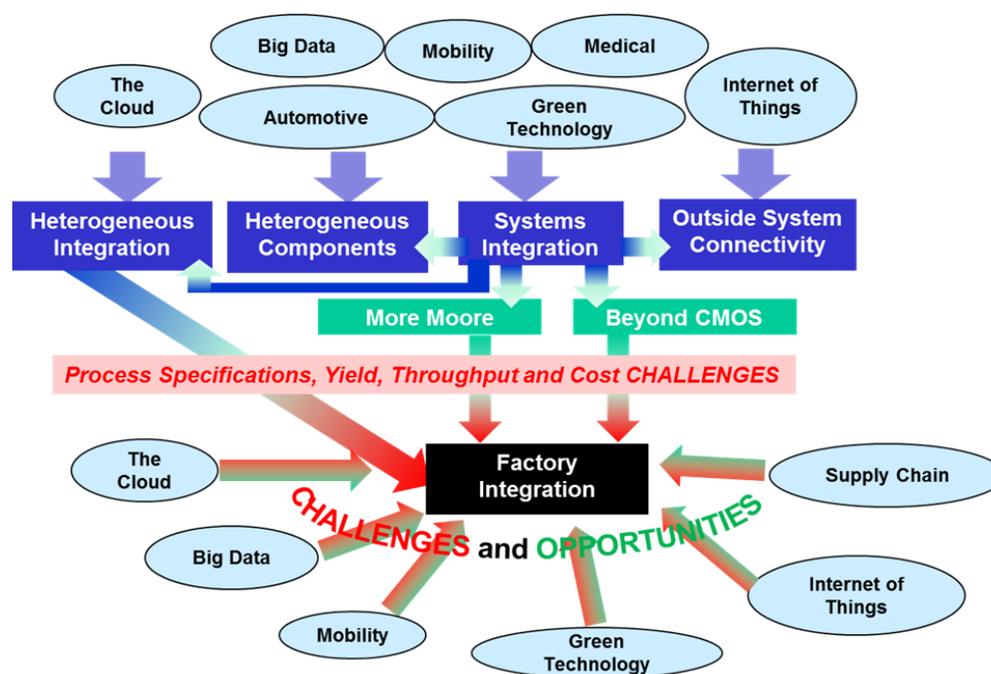


Figure FAC1 Societal Forces Impacting Challenges and Opportunities in FI

1.3. VISION OF FUTURE TECHNOLOGY

The future of microelectronics manufacturing FI is imbued in large part in the tenants of “Smart manufacturing” (SM) and Industry 4.0 (I4.0). “Smart Manufacturing” is a term “generally applied to a movement in manufacturing practices towards integration up and down the supply chain, integration of physical and cyber capabilities, and taking advantage of advanced information for increased flexibility and adaptability” [3–5]. It is often equated with “Industry 4.0”, a term that originated from a project in the German government that promotes a 4th generation of manufacturing that uses concepts such as cyber-physical systems, virtual copies of real equipment and processes, and decentralized decision making to create a smart factory [6,7]. Key tenants of this migration include leveraging big data infrastructures, integrating with the supply chain network, leveraging advanced analytics, improving use of cyber-physical systems (CPS), improving the use of real-time simulation through realizing the “digital twin,” and reliance on a knowledge network for using subject matter expertise (SME) in an increasingly collaborative environment. These terms are expounded upon through this document. This migration is associated with a number of challenges ranging from moving from reactive to predictive/prognostic mode of operation to addressing security associated with data sharing.

4 Introduction

1.4. BACKGROUND INFORMATION

Important information that can be referenced to help in the understanding of the Factory Integration Roadmap report is found below. This includes a listing of acronyms used, standards referenced and an introduction to table types that are not necessarily found in other IRDS reports. Note that documents cited in this report can be found in Section 10.

1.4.1. ACRONYMS

The following acronyms are used in this report:

Table FAC1 Acronyms Used in This Report

<i>Acronym</i>	<i>Meaning</i>	<i>Acronym</i>	<i>Meaning</i>
ACSEC	Advisory Committee (AC) on Information Security and Data Privacy	FDC	Fault Detection and Classification
AMC	Airborne Molecular Contamination	FEP	Front end Process
AMHS	Automated Material Handling System	F-GHG	fluorinated greenhouse gases
APC	Advanced Process Control	FI	Factory Integration
ARAMS	Automated Reliability, Availability, and Maintainability Standard	FICS	Factory Information and Control System
ARP	Augmenting Reactive with Predictive	FO	Factory Operations
BD	Big Data	FOUP	Front Opening Unified Pod
BEP	Back End Process	FP	Fault Prediction
BKMs	Best Known Methods	GEM	Generic Equipment Model
CIP	Continuous Improvement Program	HSMS	High-Speed SECS Message Services
CPS	Cyber-Physical System(s)	HVM	High Volume Manufacturing
CPU	Central Processing Unit	I/O	Input/output
CSA	Control Systems Architectures	I4.0	Industry 4.0
CVD	Chemical Vapor Deposition	IC	Integrated Circuit
DFM	Design for Manufacturing	ID	Identity
DM	Data Mining	IDM	Integrated Device Manufacturer
DOT	Deliver-On-Time	IFT	International Focus Team
DS	Decision Support	IGPT	Insulated-Gate Bipolar Transistor
EES	Extremely Electrostatic Sensitive	IM	Integrated Measurement
EESM	Equipment Energy Saving Mode	iNEMI	International Electronics Manufacturing Initiative
EFEM	Equipment Front-End Module	IP	Intellectual Property
EFM	Electric Field Induced Migration	IRDS	International Roadmap for Devices and Systems
EHM	Equipment Health Monitor	ISMI	International SEMATECH Manufacturing Initiative
EMI	ElectroMagnetic Interference	ISO	International Standards Organization
EOW	Equipment Output Cycle Time Waste	IT	Information Technology
EPT	Equipment Performance Tracking	ITRS	International Technology Roadmap for Semiconductors
ESA	Electrostatic Attracted, Electrostatic Attraction	JIT	Just-In-Time
ESD	Electrostatic Discharge	LEED	Leadership in Energy and Environmental Design
ESH/S	Environmental, Safety, Health, and Sustainability	LP	Low Power
EUV	Extreme Ultraviolet	MES	Manufacturing Execution System
EUVL	Extreme Ultraviolet Lithography	MFL	Maximum Foreseeable Loss
ExD	Excursion Detection (VM capability)	MHS	Material Handling System
FC	Fault Classification	NGOs	Non-Government Organizations
FD	Fault Detection	NIST	National Institute of Standards and Technology

<i>Acronym</i>	<i>Meaning</i>	<i>Acronym</i>	<i>Meaning</i>
NPW	Non-Product Wafer	SECS	SEMI Equipment Communication Standard
NTP	Networked Time Protocol	SEM/TEM	Scanning Electron Microscopy/Transmission Electron Microscopy
OEE	Overall Equipment Efficiency	SEMI	Semiconductor Equipment and Material International
OEM	Original Equipment Manufacturer	SESMC	Subsystem Energy Saving Mode Communication
PCL	Predictive Carrier Logistics	SFORMS	Secured Foundation of Recipe Management Systems
PCS	Process Control Systems	SHL	Super Hot Lots
PdM	Predictive Maintenance	SM	Smart Metrology (a VM capability), Smart Manufacturing
PE	Production Equipment	SMC	Surface Molecular Contamination
PFC	Perfluorocarbon	SME	Subject Matter Expertise, or Subject Matter Expert
PIC	Physical Interface and Carriers	SOAP	Simple Object Access Protocol
PM	Preventative Maintenance	SOS	Software as a Service
POC	Point of Connection	SPC	Statistical Process Control
POD	Point of Delivery	TH	Throughput
POE	Point of Entry	TR	Technical Requirements
POP	Point of Process	UF	Ultra-Filtration
POS	Point of Supplier	UPW	Ultra-Pure Water
POU	Point of Use	VM	Virtual Metrology
PPM	Predictive and Preventative Maintenance	W2W	Wafer-to-Wafer (control)
PTP	Precision Time Protocol	WIP	Work in Process
R&D	Research and Development	WIW	Within Wafer (control)
R2R	Run-to-Run (control)	WTW	Wait Time Waste
RAM	Reliability, Availability, and Maintainability	XML	eXtensible Markup Language
RM	Real Metrology	YEx	Yield Excursion
ROI	Return on Investment	YMS	Yield Management System
RUL	Remaining Useful Life	YP	Yield Prediction
SCOR	Supply Chain Operations Reference		

1.4.2. STANDARDS

A number of standards fall within the scope of the FI report and are important to the realization of the FI roadmap, as shown in Table FAC-2. These standards are listed here. Note that this list is not meant to be comprehensive; for a complete listing of SEMI standards, refer to www.semi.org/standards.

Table FAC2 Standards Referenced in This Report

<i>Number</i>	<i>Title</i>
IEST-RP-CC012.2	Considerations in Cleanroom Design
ISO 14644-1	Cleanrooms and controlled environments, Part 1: Classification of air cleanliness
SEMI E10	Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM) and Utilization
SEMI E116	Specification for Equipment Performance Tracking
SEMI E120	Specification for the Common Equipment Model
SEMI E125	Specification for Equipment Self Description
SEMI E126	Specification for Equipment Quality Information Parameters

6 Introduction

<i>Number</i>	<i>Title</i>
SEMI E129	Guide to Assess and Control Electrostatic Charge in A Semiconductor Manufacturing Facility
SEMI E132	Specification for Equipment Client Authentication
SEMI E133	Specification for Automated Process Control
SEMI E134	Specification for Data Collection Management
SEMI E138	XML Semiconductor Common Components
SEMI E147	Guide for Equipment Data Acquisition
SEMI E148	Specification for Time Synchronization and Definition of the TS-Clock Object
SEMI E151	Guide for Understanding Data quality
SEMI E160	Specification for Communication of Data Quality
SEMI E163	Guide for the Handling of Reticles and Other Extremely Electrostatic Sensitive (EES) Items Within Specially Designated Areas
SEMI E164	Specification for EDA Common Metadata
SEMI E167	Specification for Equipment Energy Saving Mode Communications (EESM)
SEMI E169	Guide for Equipment Information System Security
SEMI E170	Specification for Secured Foundation of Recipe Management Systems (SFORMS)
SEMI E171	Specification for Predictive Carrier Logistics (PCL)
SEMI E175	Specification for Subsystem Energy Saving Mode Communication (SESMC)
SEMI E176	Guide to Assess and Minimize Electromagnetic Interference (EMI) in a Semiconductor Manufacturing Environment
SEMI E30	Specification for the Generic Model for communications and Control of Manufacturing Equipment (GEM)
SEMI E33	Specification for Semiconductor Manufacturing Facility Electromagnetic Compatibility
SEMI E37	High-Speed SECS Message Services (HSMS) Generic Services
SEMI E43	Guide for Measuring Static Charge on Objects and Surfaces.
SEMI E5	SEMI Equipment Communications Standard 2 Message Content (SECS-II)
SEMI E51	Guide for Typical Facilities Services and Termination Matrix
SEMI E54	Specification for Sensor/Actuator Network
SEMI E58	Specification for Automated Reliability, Availability, and Maintainability (ARAMS)
SEMI E6	Guide for Semiconductor Equipment Installation Documentation
SEMI E78	Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment
SEMI S2	Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment
SEMI S23	Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment

1.4.3. EDUCATIONAL TABLES

Some of the technical challenges that had been identified in previous roadmap efforts have become more routine technical requirements. Although their challenging natures are somewhat diminished they still need close observation and continuous improvement. Such items are summarized in the Educational FI Metrics Table FAC-5

Similarly, some of the potential solutions that were considered to address the technical challenges that had been identified in previous roadmap efforts have been adopted but they are still in need of continuous improvement. Such former “potential” solutions are summarized in the Educational Solutions Table FAC-14.

2. SCOPE OF REPORT

2.1. INTRODUCTION

Microelectronics manufacturing extends across several manufacturing domains. FI’s scope is microelectronic manufacturing or fabrication in front-end and back-end. The FI Focus team has addressed evolution of FI by providing an extensible roadmap that 1) focuses on the commonality of certain functional areas, 2) supports roadmaps for specific functional and physical areas, 3) addresses societal drives identified above, and 4) provides for improved integration of Environmental, Safety, Health, and Sustainability (ESH/S) and a portion of Yield) objectives, requirements and solution. The scope of the roadmap is summarized in Figure FAC2.

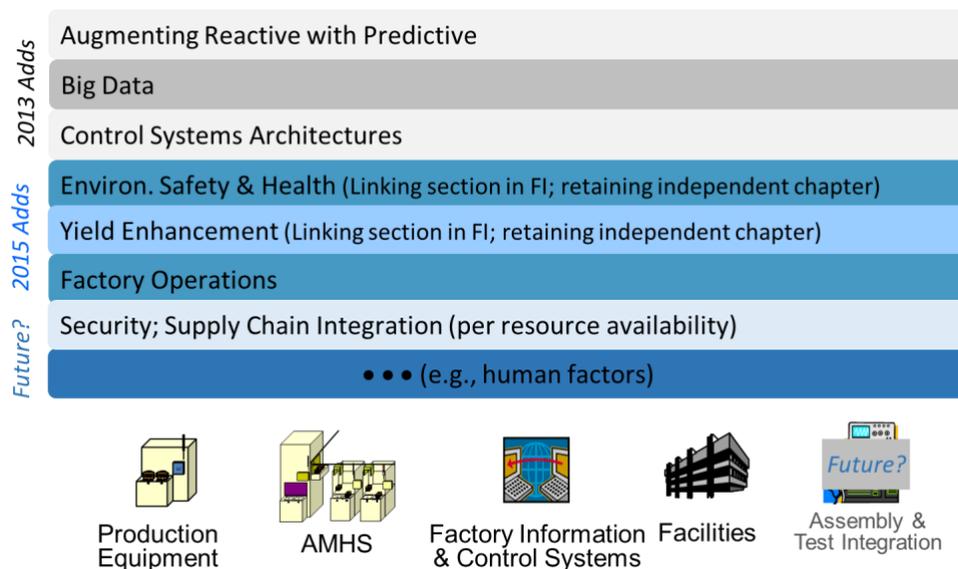


Figure FAC2 Factory Integration Scope

2.1.1. FUNCTIONAL AREAS WITHIN FACTORY INTEGRATION

In order to clearly understand the integrated factory requirements and at the same time define measurable and actionable metrics, the factory integration chapter defines functional areas, corresponding to physical boundaries that are required to perform microelectronics manufacturing. They are Production Equipment (PE), Material Handling Systems (MHS), Factory Information and Control Systems (FICS), and, Factory Facilities (Facilities), with Assembly and Test interaction identified as a potential future functional area. With the advent of the information age, the FI space has seen a dramatic evolution over the past decade due to factors such as data driven operations, distributed applications, cloud computing and integration. A common theme is gradual elimination of integration boundaries such as operating systems, physical systems and application spaces. This FI roadmap chapter captures this paradigm shift by defining additional areas that correspond to functionality that is common across the factory integration space. These additional function areas are Factory Operations (FO), Augmenting Reactive with Predictive (ARP), Big Data (BD), Control Systems Architectures (CSA), ESH/S, and Yield Enhancement. Additional across-space functional areas may be added in the future as technology roadmaps are devised. These include areas such as security and supply chain integration.

Overall, these functional areas are used to clarify how difficult challenges translate into technology requirements and potential solutions. The scope of these functional areas is as follows:

- *Factory Operations* provides many of the key drivers of requirements and actions for the other functional areas with associated factory business models. FO has most of the original requirements that are deduced required factory service provision viewpoints driven by the business needs.

8 Scope of Report

- *Production Equipment* covers process and metrology equipment and their interfaces to other factory elements. It also focuses on addressing equipment related productivity losses.
- *Material Handling Systems* covers transport, storage, identification, tracking, and control of direct and indirect materials. MHS covers requirements for the automated MHS hardware and control systems.
- *Factory Information and Control Systems* includes computer hardware and software, manufacturing execution and decision support systems, factory scheduling, control and diagnostics associated with control of equipment and material handling systems, and process control. FICS also covers decision making support systems for the productivity waste visualization and reduction.
- *Facilities* include the infrastructure of buildings, utilities, and monitoring systems.
- *Augmenting Reactive with Predictive* covers augmenting of existing reactive technologies with predictive technologies while retaining the reactive capabilities. These predictive technologies include Predictive Maintenance (PdM), Fault Prediction (FP) Virtual Metrology (VM), predictive scheduling, yield prediction and augmenting predictive capabilities of the factory with simulation and emulation.
- *Big Data* identifies the challenges and potential solutions associated with the increases in data generation, storage and usage, and capabilities for higher data rates and additional equipment parameter data availability. It specifically addresses the big data attributes of: volume, velocity, variety, veracity and value.
- *Control Systems Architectures* covers general trends in control that are common across the FI space. This includes control solutions that directly interface with the equipment, such as process run-to-run control, but also higher-level control solutions such as control of cycle time deviation, productivity deviation and on-time delivery deviation. Control inside the equipment is generally not within the CSA scope. Trends addressed include the move to more granular control (e.g., lot-to-lot, to wafer-to-wafer, to within wafer), higher speed control, higher quality control methods, increase in control systems capabilities, the advent of new control paradigms such as fully distributed (autonomous) control and machine learning, and new control platforms such as cloud-based.
- *Environmental, Safety, Health, and Sustainability* relationship to FI addresses a trend, namely the closer relationship and interdependency of many issues and solutions in ESH/S with FI. This includes how many FI potential solutions can be used to provide or enhance ESH/S solutions, and how ESH/S solutions will be more fully integrated in the factory.
- *Yield* relationship to FI addresses a trend, namely the closer relationship and interdependency of many issues and solutions in YE with FI. This includes how many FI potential solutions such as prediction can be used to improve yield and how yield objectives will be more closely integrated into FI solutions.

In addition to these functional areas, the Factory Integration chapter also addresses the cross-cut issues associated with other IFT efforts that cut across all of these FI functional areas.

2.1.2. FACTORS CONTRIBUTING TO DEFINING FACTORY INTEGRATION SCOPE

The following are key factors impacting the scope of FI

Addressing the evolution of Factory Integration—The FI Focus team has addressed evolution of FI by providing an extensible roadmap that 1) focuses on the commonality of certain functional areas, 2) supports roadmaps for specific functional and physical areas, 3) addresses societal drives identified above, and 4) provides for improved synergy with ESH/S and YE objectives, requirements and solution (see below).

Improving integration of FI with ESH/S and Yield—In addressing the evolution of FI, the IRDS community realized that many FI challenges and solutions directly impact aspects of the ESH/S and Yield roadmaps, and many of the requirements of ESH/S and Yield roadmaps placed requirements and provide direction for FI. Thus, it became clear that improved integration of these three areas was needed; as a result, sub-sections are included in the FI chapter cross-team section that discuss the synergy with the ESH/S and Yield roadmaps, respectively.

Cross-leveraging 300 mm and 450 mm factory challenges—We have addressed several 300 mm challenges, but it is still necessary to continue to address these challenges as we migrate to 450mm (circa 2025, as discussed in the Introduction). We need to provide solutions that can be used in both domains as much as possible so as to leverage economy of scale and resource pooling. FI issues such as: 1) cycle time improvement, 2) yield improvement, 3) productivity waste reduction, 4) higher process controllability, and, 5) reduction in utilities, power consumption and emission with even more progressive targets, should have very similar solutions and roadmaps in 300 mm and 450 mm. Other FI issues such as challenges in AMHS and facilities will have solution components that are similar for 300 mm and 450 mm, but other components that are different. This distinction is delineated in this report.

The re-emergence of 200 mm—The increased heterogeneity and variety of devices combined with market pressures such as those associated with IoT solutions has given rise to 200 mm production as an important component of microelectronics ecosystem. While basic tenants of FI challenges and potential solutions associated with 300 mm translate well to 200 mm, there are specific FI challenges, such as connectivity, variability, and availability of replacement components that must be addressed so that 200 mm can remain as a viable production capability in the ecosystem.

Impact of non-microelectronics-manufacturing FI technologies – As we move forward in Factory Integration, technology solutions such as big data, supply chain integration, cloud-based computing and security developed across industries will increasingly impact the microelectronics manufacturing FI roadmap. Thus, the FI roadmap will increasingly define the roadmap for many technology solutions through reference to general manufacturing trends.

3. SUMMARY AND KEY POINTS

The FI chapter of the IRDS is dedicated to ensuring that the microelectronics manufacturing infrastructure contains the necessary components to produce items at affordable cost and high volume. This report summarizes the challenges and potential solutions associated with that objective and plots a roadmap for addressing the challenges and incorporating the potential solutions. These challenges and solutions are broken down by functional area, with some of the functional areas aligned with a physical component of factory integration, such as PE or AMHS, and others aligned with overarching areas such as ARP and big data. A signification portion of the FI roadmap addresses trends associated with smart manufacturing and Industry 4.0, components of which are described throughout this report.

3.1. WHAT IS NEW IN THE TRANSITION FROM THE INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS (ITRS) 2.0 TO THE IRDS?

The Factory Integration chapter of the IRDS evolved from its counterpart in the ITRS 2.0 chapter [8,9]. This section highlights some of the major efforts and changes associated with that evolution over the past year.

3.1.1. ENHANCEMENT OF BIG DATA SECTION

The big data evolution is occurring faster than originally anticipated. As a result, this trend as well as an improved understanding of the big data trend, roadmap timelines have been updated and new and refined challenges and potential solutions have been identified. As an example, it has been determined that limitations on length of data store archives will disappear, thus an objective for data retention of “ALL” has been identified, which means that all historical data for that data store is retained.

Additionally, there has been a significant increase in focus on analytics in FI, and this trend is better captured in the current version of the IRDS FI roadmap, both in the big data and augmenting reactive with predictive sections.

3.1.2. EXPANSION OF NARRATIVE AND ROADMAP ITEMS ASSOCIATED WITH SECURITY

Security is an increasingly important topic that permeates through all aspects of manufacturing disciplines. While it is expected that a security roadmap in microelectronics manufacturing will rely heavily on advancements in other manufacturing areas, a framework for security in microelectronics manufacturing factory integration is still needed. E169-0615: Guide for Equipment Information System Security (mentioned earlier) might contribute to a portion of this framework (focusing on production equipment security). Although limited to production recipes executed in production equipment, the current efforts associated with the development and expansion of E170 might also contribute elevated security environment regarding recipe handling between FICS and production equipment. The current FI roadmap summarizes basic security challenges and solution areas, such as data partitioning and IP security. Future roadmap versions will seek to better define an evolving FI security roadmap by providing a security section in the roadmap that includes technology challenges and potential solutions tables.

3.1.3. IMPROVED DISCUSSION OF VIRTUAL METROLOGY AND CROSS-CUT INTERACTION WITH IRDS METROLOGY CHAPTER

As part of the cross-cut activities with the Metrology IFT, it was determined that more information was needed from the community as to the role, state-of-the-art, and trends in virtual metrology. In response the Metrology and FI IFTs worked together to execute a survey on virtual metrology in microelectronics manufacturing. The results of that survey are captured in a white paper [10]. Key findings that relate to virtual metrology’s impact on FI challenges and solutions have been incorporated into the ARP FI section as well as the crosscut table metrology entry.

4. CHALLENGES

Difficult challenges associated with factory integration span multiple technology generations and often cut across the factory functional areas. Near-term difficult challenges for the factory integration include business, technical, and productivity issues that must be addressed, as shown in Table FAC-3.

Table FAC3 Difficult Challenges

<i>Near-Term Challenges: 2017–2024</i>	<i>Description</i>
Responding to rapidly changing, complex business requirements	<ul style="list-style-type: none"> Increased expectations by customers for faster delivery of new and volume products (design à prototype and pilot à volume production)
	<ul style="list-style-type: none"> Rapid and frequent factory plan changes driven by changing business needs
	<ul style="list-style-type: none"> Ability to load the fab within manageable range under changeable market demand, e.g., predicting planning and scheduling in real-time
	<ul style="list-style-type: none"> Enhancement in customer visibility for quality assurance of high reliability products; tie-in of supply chain and customer to FICS operations
	<ul style="list-style-type: none"> Addressing the big data issues, thereby creating an opportunity to uncover patterns and situations that can help prevent or predict unforeseeable problems difficult to identify, such as current equipment processing/health tracking and analytical tools
	<ul style="list-style-type: none"> To strengthen information security: Maintaining data confidentiality (the restriction of access to data and services to specific machines/human users) and integrity (accuracy/completeness of data and correct operation of services), while improving availability (a means of measuring a system's ability to perform a function in a particular time) contradictive to needs of data availability.
Managing ever-increasing factory complexity	<ul style="list-style-type: none"> Quickly and effectively integrating rapid changes in process technologies
	<ul style="list-style-type: none"> Complexity of integrating next generation equipment into the factory
	<ul style="list-style-type: none"> Increased requirements for high-mix factories. Examples are 1) significantly short life of products that calls frequent product changes, 2) the complex process control as frequent recipe creations and changes for process tools and frequent quality control criteria due to small lot sizes, and 3) managing load on tools
	<ul style="list-style-type: none"> Manufacturing knowledge and control information needs to be shared as required among factory operation steps and disparate factories in a secure fashion
	<ul style="list-style-type: none"> Need to concurrently manage new and legacy FICS software and systems with increasingly high interdependencies
	<ul style="list-style-type: none"> Ability to model factory performance to optimize output and improve cycle time for high mix factories
	<ul style="list-style-type: none"> Need to manage clean room environment for more environment susceptible processes, materials, and, process and metrology tools
	<ul style="list-style-type: none"> Addressing need to understand and minimize energy resource usage and waste; determining what the energy usage profile actually is; e.g., need to integrate fab management and control with facilities management and control
	<ul style="list-style-type: none"> Comprehending increased purity requirements for process and materials

	<ul style="list-style-type: none"> • Providing a capability for more rapid adaptation, re-use and reconfiguration of the factory to support capabilities such as rapid new process introduction and ramp-up. This includes a challenge of supporting evolution of a FI communication infrastructure to support emerging capabilities beyond interface A.
	<ul style="list-style-type: none"> • Communication protocols developed for semiconductor manufacturing are not aligned with trends in information technology communication such as web services.
	<ul style="list-style-type: none"> • Meeting challenges in maintaining yield and improving maintenance practices resulting from movement to new process materials that may be corrosive, caustic, environmentally impacting, molecularly incompatible, etc.
	<ul style="list-style-type: none"> • Addressing factory integration challenges to assess and integrate extreme ultraviolet (EUV) systems into the factory infrastructure
	<ul style="list-style-type: none"> • Address process hazard management issues
	<ul style="list-style-type: none"> • Addressing Airborne Molecular Contamination (AMC) challenges through possibly changing factory operation approach (e.g., maintaining vacuum in specific areas), as well as providing necessary interfaces, information and technologies (e.g., virtual metrology and APC).
	<ul style="list-style-type: none"> • Maintaining equipment availability and productivity, and minimizing equipment variability, while managing increase in sensors and systems, and associated data volume increases within and outside the equipment, coordinated to support new paradigms (e.g., management of energy expended by the equipment and the fab in general, augmenting reactive capabilities with predictive)
	<ul style="list-style-type: none"> • Linking yield and throughput prediction into factory operation optimization; incorporating incoming disturbances such as power and materials purity variability into the prediction equation.
	<ul style="list-style-type: none"> • Achieving real-time simulation of all fab operations as an extension of existing system with dynamic updating of simulation models
	<ul style="list-style-type: none"> • Understanding and managing queue times (time between operations/segments) and production of product within those times to achieve acceptable product quality
	<ul style="list-style-type: none"> • Managing and protecting IP, avoiding security issues such as malware attacks, and protection of the facility's instrumentation and control systems from attack
	<ul style="list-style-type: none"> • Addressing FI issues associated with implementing emerging technology revolutions (rather than evolutions) in achieving production targets, including rapid integration of new tools, components and materials, leveraging existing infrastructure, ramping up on new technology ramp-up
	<ul style="list-style-type: none"> • Achieving compatibility of existing systems that are largely reactive with emerging predictive paradigms of operation, such as predictive maintenance and yield prediction
	<ul style="list-style-type: none"> • Addressing shifting focus from line width pitch shrinks, to 3D and emerging disruptive technologies
	<ul style="list-style-type: none"> • Developing metrics on performance of factory integration systems and understanding how these metrics translate to factory financial information

12 Challenges

Achieving financial growth targets while margins are declining	<ul style="list-style-type: none"> • Achieve waste reduction continuous improvement targets, e.g., through equipment cycle time reduction, and reduction in power consumption • Improving efficiency of factory operations through tighter integration with supply chain, e.g., to achieve lean manufacturing targets • Incorporating product priority into factory integration planning and operations to achieve financial objectives
Meeting factory and equipment reliability, capability, productivity, and cost requirements per the roadmap	<ul style="list-style-type: none"> • Increased impacts that single points of failure have on a highly integrated and complex factory • Achieving better communication between equipment suppliers and users with respect to equipment requirements and capabilities • Improved bi-direction information exchange between equipment and factory systems to achieve equipment and factory reliability, capability and productivity objectives • Design-in of equipment capability visualization in production equipment; design-in of APC (run-to-run (R2R) control, FD, FC and statistical process control (SPC)) to meet quality requirements • Equipment data, analytics and visualization to support equipment health monitoring (EHM) • Developing and implementing methods that reduce the use of non-product wafers (NPWs) and the associated lost production time • Reducing undesired wait-time waste; developing wait-time waste reporting for tools; providing standardized equipment wait-time waste metrics reporting to support fab-wide equipment wait-time waste management • Augmenting reactive with a predictive paradigm for scheduling, maintenance and yield management • Meeting tighter and more granular control requirements such as wafer-to-wafer (e.g., single-wafer oriented) and within wafer utilizing technologies such as virtual metrology • Yield mining techniques that support root cause analysis for determination of contributions to yield loss in the process stream. • Addressing the move towards "lights out" human-less operation in the fab to meet goals such as contamination levels. • More comprehensive traceability of individual wafers to identify problems to specific process areas • Standards for supply chain traceability of spares, e.g., for better understanding of lifetime of spares • Standards and best practices to support providing degradation characteristics of components from suppliers for improved tracking and predicting of failures • Comprehensive management that allows for automated sharing and re-usages of complex engineering knowledge and contents such as process recipes, APC algorithms, fault detection and classification (FD and C) criteria, equipment engineering best known methods
Cross leveraging factory integration technologies across boundaries such	<ul style="list-style-type: none"> • Addressing the potential data explosion and other big data issues associated with crossing a technology boundary

as 300 mm and 450 mm to achieve economy of scale	<ul style="list-style-type: none"> • Ensuring the industry takes advantage of the technology change to implement the appropriate factory integration enhancements such as control system paradigm shift. • Understanding the software roadmap for moving across these technology boundaries. • 450 mm era: Effecting architectural and other changes as necessary at an affordable cost to maintain or improve wafer-throughput-to-footprint levels in migration to 450 mm
Addressing unique challenges in the move to 450 mm (where 300 mm technologies cannot always be leveraged)	<ul style="list-style-type: none"> • Understanding and addressing 450 mm implications on issues such as product logistics (e.g., AMHS), utility usage and factory design and layout • Determining and specifying what technologies (such as prediction) become required (as opposed to just desired) as they <i>must</i> be leveraged to achieve 450 mm quality and production goals.
<i>Long-Term Challenges: 2025–2032</i>	<i>Description</i>
Meeting the flexibility, extendibility, and scalability needs of a cost-effective, leading-edge factory	<ul style="list-style-type: none"> • Evaluating and implementing revolutionary disruptive technologies such as distributed autonomous control at the appropriate time to maximize cost competitiveness • Determining the appropriate time to move to 450 mm for all high-volume commodity production • Consider the possibility of self-evolving and self-configuring FI technologies such as data analysis and prediction where software (re-)configuration tasks are greatly reduced • Adoption of augmented reality capabilities for enhanced human machine interaction • Cost and task sharing scheme on industry standardization activity for industry infrastructure development • Achieving the “prediction vision” of a state of fab operations where (1) yield and throughput prediction is an integral part of factory operation optimization, and (2) real-time simulation of all fab operations occurs as an extension of existing system with dynamic updating of simulation models.
Increasing global restrictions on environmental issues	<ul style="list-style-type: none"> • Addressing the move towards global regulations • Developing methods for increasing material reclamation • Proactively addressing future material shortages, such as non-renewable chemicals
Post-conventional Semiconductor manufacturing uncertainty	<ul style="list-style-type: none"> • Uncertainty of novel device types replacing conventional CMOS and the impact of their manufacturing requirements on factory design • Timing uncertainty to identify new devices, create process technologies, and design factories in time for a low risk industry transition • Potential difficulty in maintaining an equivalent 0.7’ transistor shrink per year for given die size and cost efficiency

5. TECHNOLOGY REQUIREMENTS

5.1. SUMMARY

The evaluation of the technology requirements and identification of potential solutions were performed to achieve the primary goals listed above by breaking up the discussion into the integrated and complementary functional areas as explained earlier.

Table FAC4 provides a summary of key focus areas and issues for each of the factory integration functional areas beyond 2017. It also includes a discussion of synergistic issues with ESH/S and Yield IFTs as well as issues that may be the topic of future focus areas.

Table FAC4 Key Focus Areas and Issues for FI Functional Areas Beyond 2017

<i>Functional Area</i>	<i>Key technology focus and issues</i>
Factory Operations	<ul style="list-style-type: none"> • Systematic productivity improvement methodology of the current “lot-based” manufacturing method prior to 450 mm insertion
	<ul style="list-style-type: none"> • Challenges in moving to smaller lot and single wafer aspects of factory operations
	<ul style="list-style-type: none"> • Interdisciplinary factory productivity improvement method such as systematic factory waste visualization of manufacturing cycle times and factory output opportunity losses
	<ul style="list-style-type: none"> • Extendable and reconfigurable factory service structure
Production Equipment	<ul style="list-style-type: none"> • 450 mm production tool development for integration into the factory information system; supporting bridge capabilities to 450 mm
	<ul style="list-style-type: none"> • Determining context data set for equipment visibility
	<ul style="list-style-type: none"> • EHM and fingerprinting to support improved uptime
	<ul style="list-style-type: none"> • Run rate (throughput) improvement and reduction of equipment output waste that comes from NPW and other operations
	<ul style="list-style-type: none"> • Improving equipment data quality and data accessibility to support capabilities such as APC and e-diagnostics
	<ul style="list-style-type: none"> • Develop equipment capabilities to support the move to a predictive mode of operation (including virtual metrology, predictive maintenance, predictive scheduling and yield prediction and feedback); examples include reporting equipment state information, time synchronization, and EHM and reporting.
	<ul style="list-style-type: none"> • Migrate to a mode of operation where APC is mandatory for proper execution of process critical steps
	<ul style="list-style-type: none"> • Design, develop and implement (standardized where appropriate) capabilities for utility (e.g., electricity) reduction such as support for idle mode, improved scheduling, and communication between host and equipment for energy savings
Automated Material Handling Systems	<ul style="list-style-type: none"> • Reduction in average delivery times
	<ul style="list-style-type: none"> • Avoid tool starvation
	<ul style="list-style-type: none"> • More interactive control with FICS and PE for accurate scheduled delivery, including (predictive) scheduling/dispatch, maintenance management, and APC
	<ul style="list-style-type: none"> • Aim for continuous improvement in reliability and corresponding minimization of downtime
	<ul style="list-style-type: none"> • 450 mm specific AMHS issues

Functional Area	Key technology focus and issues
	<ul style="list-style-type: none"> • AMHS interaction with other wafer transport and storage systems such as sorter and load port
Factory Information and Control Systems	<ul style="list-style-type: none"> • Increased reliability of FICS systems such as maintenance management
	<ul style="list-style-type: none"> • Increased FICS performance for more complex factory operation, such as decision speed and accommodating larger data sets
	<ul style="list-style-type: none"> • Enhanced system extensibility including extensibility across fabs
	<ul style="list-style-type: none"> • Utilize FICS information to achieve waste-reduction (e.g., wait-time waste, unscheduled downtime, and wafer scrap) and sustainability (e.g., resource conservation)
	<ul style="list-style-type: none"> • Facilitate enhancement of reactive with predictive approach to operations (e.g., planning and scheduling, maintenance, virtual metrology and yield prediction and feedback)
	<ul style="list-style-type: none"> • Determining approaches to control (e.g., distributed versus centralized) and when to institute disruptive control systems changes (e.g., at 450 mm introduction)
	<ul style="list-style-type: none"> • Achieving minimum downtime, seamless transition, and uninterrupted operations in production throughout the software upgrade process
Facilities	<ul style="list-style-type: none"> • Continuous improvement to maintain facility systems viability
	<ul style="list-style-type: none"> • Minimization of facilities induced production impacts
	<ul style="list-style-type: none"> • Facility cost reduction
	<ul style="list-style-type: none"> • Determining and addressing emerging technology requirements such as airborne molecular contamination (AMC) control, 450 mm, 3D, etc.
	<ul style="list-style-type: none"> • Maintaining safety in facilities operations (e.g., in response to a seismic event)
	<ul style="list-style-type: none"> • Even more aggressive focus on environmental issues and optimization to environmental targets.
	<ul style="list-style-type: none"> • Facility utility reduction
Augmenting Reactive with Predictive	<ul style="list-style-type: none"> • Improved data quality to support effective prediction
	<ul style="list-style-type: none"> • Prediction solutions tied to application financials for optimized benefit
	<ul style="list-style-type: none"> • Integration of predictive functions (data, algorithm, user interface, and cross-leveraging capabilities) as an augmentation of existing systems
	<ul style="list-style-type: none"> • Move to real-time simulation of all fab operations occurring as an extension of existing system with dynamic updating of simulation models
Big Data	<ul style="list-style-type: none"> • Optimization of data storage volumes and data access to achieve FI objectives and enable applications to plug and play
	<ul style="list-style-type: none"> • Speed improvement in collecting, transferring, storing and analyzing data
	<ul style="list-style-type: none"> • Software optimization to gather data from multiple systems and sources for analysis resulting on actionable decisions
	<ul style="list-style-type: none"> • Data quality improvements to address issues of time synchronization, accurate compression/uncompression, and merging of data form multiple sources collected at potentially varying data rates

16 Technology Requirements

<i>Functional Area</i>	<i>Key technology focus and issues</i>
	<ul style="list-style-type: none"> • Migrating from relational data storage infrastructure to largely big data friendly infrastructure such as Hadoop, along with small relational component. • Algorithm development and implementation to support emerging capabilities such as predictive and machine learning
Control Systems Architecture	<ul style="list-style-type: none"> • Addressing evolutionary aspects of control system and control system architectures such as granularity, speed, quality, and capability. • Addressing potentially revolutionary aspects of control systems and control systems architectures such possible moves to cloud computing, distributed/autonomous control, and artificial intelligence enhanced control • Addressing the framework to integrate monitoring and closed loop control tied to all semiconductor manufacturing key performance indices—including engineering and manufacturing control levels. • Addressing the capability to integrate with supply-chain framework for value chain control.
Environmental, Safety, Health, and Sustainability (ESH/S)	<ul style="list-style-type: none"> • The roadmapping process will continue to quantify factory environmental factors • Roadmapping from 2015 will include, new materials, sustainability, and green chemistry • Provide proactive engagement with stakeholder partners and reset strategic focus on the roadmap goals. • Continue focus on factory and supply chain safety for employees and the environment
Yield Enhancement (YE)	<ul style="list-style-type: none"> • The roadmapping focus will move from a technology orientation to a product/application orientation. • AMC, packaging, liquid chemicals, and ultra-pure water were identified as main focus topics for the next period. • Electrical characterization methods, big data and modeling will become more and more important for yield learning and yield prediction.
Information Security	<ul style="list-style-type: none"> • The roadmap will begin to define challenges and potential solutions for information security including secure data partitioning and IP separation. Initial focus is on defining the current challenges.
Smart Factory	<ul style="list-style-type: none"> • The roadmap will continue to provide increased focus on Industry 4.0 and smart factory concepts such as integration up and down the supply chain, and CPS concepts such as the increased focus on simulation and emulation to support concepts such as “digital twin.”

5.1.1. STABILIZED FACTORY INTEGRATION METRICS AND RECOMMENDED VALUES

As FI challenges become addressed and solutions are continually being optimized, it is often important to capture the challenge stabilization metric and provide an indication of the value. As a result, the FI IFT reviewed the technology requirements tables and captured these stabilized metrics in education Table FAC5, delineated by focus area. As technical challenges in focus areas are addressed and reach a state of continuous optimization, they may be removed from their respective challenge tables and moved to this education table.

Table FAC5 Stabilized FI Metrics with Recommended Values (Critical but Educational Values)

Functionality Area	Metric/Requirement	Recommended Value/level	Year of Stabilization	Justification
Factory Operations	N/A			
Production Equipment	Maximum recommended electrostatic field at chrome mask surfaces (V/m) for electric field-induced migration (EFM)	0	2017	No amount of electric field exposure can be regarded as safe for a chrome reticle. The recommended field value should reduce the risk of degradation to an acceptable level over the normal production lifetime of a reticle. Additional information is provided in Section 5.6.3.
Automated Material Handling Systems	Time required to integrate process tools to AMHS (minutes per low power (LP) (300 mm)	5	2014	The value is important to keep disruption to production minimum, but it doesn't need roadmap as it already reaches practical limit with currently adopted interface between PE and AMHS
Factory Information and Control Systems	Wafer-level (within-lot) recipe/parameter adjustment, e.g., for wafer-to-wafer (W2W) control	YES	2015	This metric indicates FICS capability to facilitate wafer-to-wafer recipe and parameter adjustment and supports the ability to have multiple lots per carrier, which have been widely realized.
Facilities	Facility cleanliness level (ISO 14644)	Class 6	2013	Wide adoption of mini-environment for the critical areas/systems eased facility cleanliness level requirement
	Design criteria for facility critical vibration areas (lithography, metrology, other) (mm/sec)	6.25 (VC D)	circa 2011	Observing the value is critical for area of the primary manufacturing floor in which a significant portion of the equipment is highly sensitive to floor vibration. But required measures are known and have been implemented.
	Design criteria for facility non-critical vibration areas (mm/sec)	50 (VC A)	circa 2011	The metric is for the area where all or some of the equipment is only moderately vibration sensitive. No need for special consideration to realize the value.
Augmenting Reactive with Predictive	N/A			
Big Data	N/A			

5.2. FACTORY OPERATIONS NEEDS

5.2.1. **SYSTEMATIC FAB PRODUCTIVITY IMPROVEMENT**

One of the most important missions of FI is to assist fab productivity improvement effort by providing productivity information to those who are responsible at each of the hierarchical operation responsibility layers and providing means to evaluate the improvement before and after implementation. There should be methodologies to identify the room for improvement as Continuous Improvement Program (CIP) and the planning of strategic improvement. For these methodologies to be effective the factory activity information is to be designed to have rationalized structures to facilitate high data utilization for decision makings. It is also imperative to define commonly usable productivity metrics so that the productivity improvement activities can cooperate among many. The FI IFT has concluded that such metrics are expressed as productivity waste.

5.2.2. **AGILITY AND FLEXIBILITY IN FACTORY SERVICES**

Factory services are numerous but are required to change in a short period of time to accommodate various business demands. The process control methods change as a new process generation is introduced. Process recipes are changed as a new product or technology is introduced. The line capacity is re-optimized upon a new product introduction. Fab capacity control and corresponding decision makings need to be agile and flexible. Decision making support capabilities such as predictive visualization of cycle time, work in progress (WIP) and line throughput are becoming more important.

5.2.3. **HIGH GRANULARITY AND PROACTIVE SERVICES**

Finer material handling operation is required due to strong demand on cycle time reduction. More real-time control of PE is required to meet elaborated process control requirements such as wafer-to-wafer and within wafer APC. Frequent confirmation of production equipment healthiness using capabilities such as EHM is required to reduce the potential of wafer scrap. Finer wafer-level product quality traceability is required while lot-based manufacturing is employed. All of these trends are associated with a general trend of finer and more proactive (predictive) process and quality control.

5.2.4. **HIERARCHICAL OPERATION STRUCTURE AND MANUFACTURING CONTROL OPERATION**

Hierarchical structure in the manufacturing control operation is required to provide a counter-measure to the increased complexity in manufacturing decision makings and fast control execution. FO structure needs to be designed to enable the comprehensive optimization of FO for the required productivity. A good example is the *hierarchical quality assurance* in which the wafer fabrication execution control and process outcome control are hierarchically delineated with aid of increased visibility of the individual hierarchical layers.

The manufacturing control paradigm may change over time as capabilities such as cloud computing, application-based integration and control (“apps”), and autonomous and semi-autonomous control are explored and evaluated for various FO applications. Trends will be more closely aligned with other manufacturing arenas (than in the past) in order to leverage technology innovation and economy of scale. At this time a roadmap for the evolution and paradigm shift of manufacturing control cannot be fully realized because directions are not yet clear. These concepts are explored further in the Control Systems Evolution section.

5.2.5. **INTEGRATION OF FACILITIES REQUIREMENTS INTO FACTORY OPERATIONS**

The increasing pressure of achieving goals such as environmentally benign and safe operation of fabs as well as utility cost reduction will require that factory and facilities operations be coordinated. This will require increased attention to facility objectives in factory objective functions. See also the Facilities section.

5.2.6. **SIGNIFICANT PRODUCTIVITY IMPROVEMENT**

A focus of the FO Technology Requirements Table FAC-6 is challenges associated with significant productivity improvement of the current technology preceding the 450 mm insertion.

This waste reduction is to meet 30% 300 mm wafer cost reduction and 50% cycle time reduction. The implementation of such significant improvement will be somewhat delayed due to the current economic situation and the speed of development and adoption of standards for wait-time-waste and related metrics.

Equipment variation reduction will be a source of productivity improvement. In the future this may be quantified in table entries in this section as metrics are agreed upon for the quantification of this source of improvement.

5.2.7. **FUTURE MANUFACTURING REQUIREMENTS**

The industry can focus on common technology development for 300 mm and 450 mm. 450 mm factories would benefit by adaption of improved technology validated for 300 mm. FO metrics were reviewed and modified to reflect the future

manufacturing, including 450 mm needs. Industry should study the implication of the FO Technology Requirements Table FAC-6 and other FI technology requirements tables.

5.2.8. WASTE REDUCTION METRICS

Equipment Output Waste (EOW) is in the FO Technology Requirements Table FAC-6 with intent of aligning the significant productivity improvement scheme. It is beyond the FI's task to capture all of the waste types in the roadmap. It is important to introduce more comprehensive waste metrics for FI so as to address the direction of overall productivity optimization of highly complicated manufacturing system. These need to be comprehensive and measurable factory-level waste metrics. Addressing the issue of waste reduction metrics will promote new manufacturing concepts, manufacturing control models, and algorithms.

It is also the FI IFTs mission to induce the environment where the industry can collaboratively address the waste visualization and reduction needs. Metrics definition and measurement method standardization are good examples of these efforts.

5.2.9. DATA USAGES

The stringent engineering requirement is driving need for more data that would result in so-called data explosion. This is explored in detail in the FI "Big Data" section. It is critical not only to collect necessary data but also to develop intelligent analysis and algorithms to identify and use the right signals to make data driven decisions and reuse such intelligence as models in later occasions. The factory data shall be designed in accordance to these models with usages for high data utilization efficiencies.

5.2.10. 450 MM RELATED METRICS

450 mm specific requirement has been discussed in order to seek any FO Technology Requirements Table items. Although the factory services requirements specific to 450 mm manufacturing have not been identified in the current roadmap, 300 mm factory services are expected to be applicable to 450 mm and so do the FO requirements captured. There may be different requirements in 450 mm for the FO. The distinct example is cycle time requirement. The longer factory cycle time requirements are expected since the beam production equipment such as lithography exposure tools and inspection tools inevitably have a longer cycle times compared to the similar 300 mm tools (since the process time is proportional to the area of treatment (beamscan)).

Readers are encouraged to read the FO Technology Requirements Table FAC-6 with wafer size dependency in mind, but should not read all the same fab operation characteristic values as 300 mm being required for 450 mm. From the waste reduction view point, there should be much similarity between 300 mm and 450 mm requirements, but more study is needed for WTW as discussed earlier. As 450 mm factory services requirements and physical ones become available IRDS FI will capture 450 mm specific items into respective FI technology requirements tables.

5.2.11. OPERATIONAL PARADIGMS RELATED TO LOT SIZE

Production goals that include flexibility, cycle time reduction and demand optimization in high-mix environments have led to the consideration of a number of operational paradigms that facilitate these goals. The paradigms include:

- *Single wafer processing*—which is defined in this chapter as processing one wafer at a time in an equipment chamber. Wafer transport is not specified (and may be wafer-based or lot-based). Single wafer processing is prevalent in many processes today and allows for increased flexibility in scheduling to demand as well as improved effectiveness of FI capabilities such as process control and fault detection.
- *Multi-product mixed-lots processing*—is defined in this chapter as a type of single wafer processing where wafer transport is multi-wafer lot-based, however multiple products can exist within the lot. The total number of wafers in the lot is not fixed and can be less than 25 or variable. The impact is optimal AMHS capacity and decreased cycle time, especially in high-mix environments that include low running products (i.e., having a relatively small percentage of the overall product mix) along with high running products (i.e., having a relatively large percentage of the overall product mix). Multi-product mixed-lots processing is relatively rare in current microelectronics manufacturing practice but should become more prevalent over time as the need for flexibility increases and FI systems become better equipped to manage this processing paradigm.
- *Single wafer manufacturing*—is defined in this chapter to mean a lot size equal to one wafer throughout the fab. Thus, both single wafer processing and single wafer transport are employed.

20 Technology Requirements

The paradigm shift to single wafer manufacturing is not occurring as soon as originally expected, and it is unknown if this paradigm shift will ever take place on a large scale. FO roadmaps and FI roadmaps in general must address the challenges and potential solutions associated with the operational paradigms that are adopted.

5.2.12. ASSEMBLY TEST INTEGRATION

As the industry moves forward in microelectronics manufacturing there is an increased focus on integration in and with backend processes, with the goal of improving final product performance. As a result, there are increased opportunities for product improvement coming from potential solutions in assembly and test operation and integration with each other and front-end operations. In the past microelectronics manufacturing pursued advanced manufacturing methods to support advanced FE process technology (e.g., e-Manufacturing SEMATECH initiatives in 2003), which have been defined and implemented providing performance improvement in areas such as FICS, AMHS and equipment engineering control. However, FE e-Manufacturing leverages a number of standards that requires a high cost to implement. Recent developments such as Industry 4.0/Smart Manufacturing (references provided earlier) cite technologies including IoT, big data, and robotics as enablers for new capabilities to support back-end (BE) manufacturing. These capabilities would support potential solutions that address issues such as huge deviation in product, production and equipment in BE areas to achieve manufacturing excellence in cost-effective way. Examples include leveraging IoT to enable data collection for all objects in factory and using big data capabilities to enable advanced manufacturing intelligence and prediction capabilities. Industry 4.0 concepts will enable improved assembly and test with e-Manufacturing performance with lower cost. FI will identify the potential opportunities from emerging technologies such as those cited in Industry 4.0 to enable advanced e-Manufacturing in assembly and test for advanced manufacturing excellence. So, the focus on providing potential solutions in assembly and test in the future will be 1) increased focus on assembly test to support new devices which rely more heavily on BE excellence, 2) leverage new concepts such as those cited in Industry 4.0 in formulating BE potential solutions, and 3) leveraging potential solutions already identified for front-end (FE) into and with the BE.

5.2.13. SUPPLY CHAIN INTEGRATION

Factory performance depends on overall deviation control of all factors (man, machine, material, method). The factory is part of the overall supply chain (see Supply Chain Operations Reference—SCOR model in Figure FAC3)¹. Besides continuous improvement of factory deviation control to improve manufacturing performance, there are other sources of deviation from the overall supply chain into factory that also require good control to reduce the deviation and improve the complexity management. There are several key parameters that should be considered in the control formulation; the inclusion of these parameters in the control does not necessarily mean that these factors are under control:

1. Demand Forecast Deviation: the demand is considered the beginning of the downstream supply chain; forecast of demand is not easy to determine because the demand has high complexity. Even if we could define the measure to detect the deviation of demand forecast, there are no known methods to assure quality of demand forecast.
2. Demand Deviation: The microelectronics factory operating near capacity requires a long lead time for preparation and qualification of equipment and processes. Demand deviation can thus result in extra cost associated with lost capacity. The complexity of demand change control depends on the scale of overall supply chain. Having more suppliers or customers for any given factory will increase the complexity and further increase the difficulty of controlling the demand. There can be no automatic control of demand deviation; the factory role is to provide a better response to this deviation.
3. Supply Chain Operation Deviation in the downstream supply chain: Microelectronics devices could be packed into high-value added packages and installed into higher-value product. For example: the chips could be packed into the insulated gate bipolar transistor (IGBT) modules and finally installed into electric cars. Any deviation from supply chain will cause high cost. To assure good control of these deviations, the traceability of these chips (in the downstream supply chain), components and final product are important. It requires a robust FI system to automatically collect, store, and trace all supply chain operations.
4. Supply Chain Operation Deviation in the upstream supply chain; It is important to maintain traceability in the upstream supply chain to manage part and consumable inventory as well as quality, for improved production quality, reliability, and yield.

¹ One source of information on SCOR is the APICS Supply Chain Council, which “advances supply chains through research, benchmarking, and publications”. www.apics.org

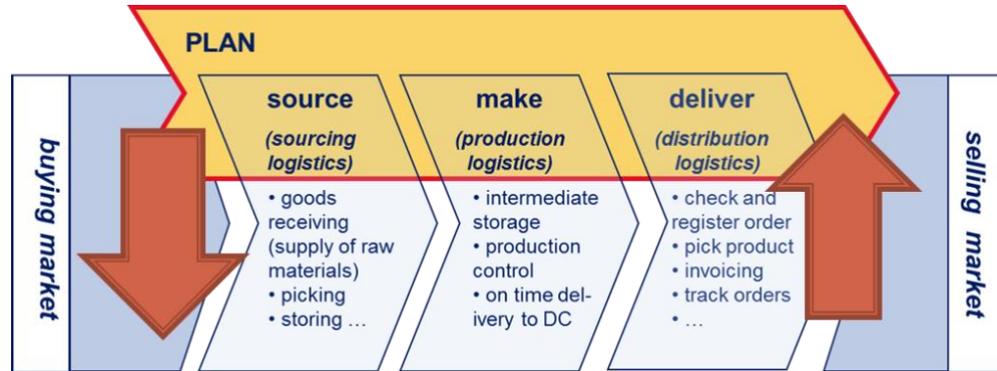


Figure FAC3 Supply Chain Model SCOR

Also, key parameters in the factory are required for feedback to the supply chain for robust operation:

1. **Delivery accuracy:** To ship the right product at right time to customer is a commitment from the factory. Deviation of delivery will result into loss of revenue and cost of production. With the cumulative knowledge in the microelectronics industry, it is simpler to maintain good delivery accuracy if an extra buffer is reserved or good manufacturing system is in place to reduce all manufacturing deviations. One form of solution is to have real-time predictive delivery schedule for all order from real-time operation status from factory.
2. **Cycle time:** Good cycle time control will increase the control capability of both supply chain and factory. The factory cycle time results from overall factory operation performance for all output. Good (matched to plan) factory cycle time does not necessarily imply good delivery accuracy, but good cycle time mean does imply relatively stable operation according to the original plan. Supply chain optimization does not require detailed information on the material process cycle time inside the factory, but only the overall factory cycle time to support supply chain delivery demand (requirements or estimates). New device introduction can have special supplier demand requirements. The complexities are increasing with higher product mix and tighten production specifications. Real-time dynamic cycle time integration will improve factory operation to support supply chain delivery demand requirements.
3. **Yield:** High yield is a basic objective for products shipping to the supply chain. The complexity of yield is very high and subject to strong deviation as this control depends on the production process capability. There are many controls put in place for the machines—daily monitoring, maintenance, FDC; material—inspection, metrology; man—training, certification, operation procedure, scheduling and dispatching. Although these controls are not directly incorporated in supply chain calculations their operation does impact the supply chain thus the control objectives will be impacted by the supply chain in the future. The real-time integration of product yield data will also help improve the responsiveness of the supply chain.

Table FAC6 Factory Operations Technology Requirements

5.3. PRODUCTION EQUIPMENT NEEDS

5.3.1. SCOPE

The original scope of the production equipment section includes all factory integration requirements relevant to the process and metrology equipment. Also included are tool embedded controllers, front-end module (EFEM) and load ports, carrier, and wafer handling, software and firmware interfaces to host systems, and all facilities interfaces of the equipment. The most of PE and factory interfaces have been standardized as the result of 300 mm transition standardization. Further the factory operation driven metrics have been moved to the FO Technology Requirements Table FAC-6 for clarity. The PE Technology Requirements Table FAC-8 has metrics only on availability for process tools and metrology tools together with electric statics field requirements.

5.3.2. DATA VISIBILITY (INTO AND OUT OF THE EQUIPMENT)

An important aspect of PE and specification of requirements in this document is visibility “into” the equipment and visibility from the equipment to the outside world. In order to achieve the potential solutions described here the equipment will have to provide visibility of information such as state and health through standardized communication interfaces. Requirements

22 Technology Requirements

for this visibility will increase in the future. Similarly, equipment will have to have access to information outside the traditional domain to achieve capabilities. This visibility includes upward (e.g., into the factory systems) as well as downward (e.g., into tool components). An example of upward visibility would be predictive scheduling where the equipment would need to know upstream WIP and possibly processing times to provide an optimum schedule and dispatch as part of a fab-wide throughput optimization strategy. An example of downward visibility would be coordination of pump states to support an equipment move to an “idle” mode (described later in this chapter) to save on power resources without sacrificing throughput. It is an important PE requirement that equipment properties such as health and process capability be validated with data; this validation process represents a method by which users and equipment suppliers can communicate issues such as tool readiness and capability. The data that represents the visibility into and out of the equipment will also be used to validate equipment; this validation will be performed by an equipment supplier prior to delivery with respect to equipment functionality.

Tool data visibility must address the following important use case. To achieve good device yields, the process tools used to create the device must be in statistical control. That is, key process settings must be in control during a run as deviations will impact the final product yield. To help integrated device manufacturers (IDMs) accomplish this parameter control, tool manufacturers should provide a reference set of parameters and values for a properly operating tool. The tool manufacturers can then test that tools perform to these values prior to shipment and IDMs can then check basic tool health by monitoring these parameters over time. If there is a performance discrepancy, the IDM and tool manufacturer can use the reference parameter values compared to target values as a starting point for problem diagnosis.

5.3.3. WASTE REDUCTION

Waste reduction is a combination of efforts aimed at reducing waste in a number of areas including wait-time (cycle time), operation waste, wafer scrap, consumable use, downtime, and energy and natural resource consumption. While technologies such as APC (Fault Detection and R2R control) are currently important to improving waste reduction metrics, predictive solutions such as virtual metrology, PdM, and predictive scheduling will also be key technologies for the reduction of waste moving forward, addressing such issues as wait-time waste, unscheduled downtime, and wafer scrap. Further equipment energy saving solutions such as coordinated “idle” mode will address energy waste issues.

The industry’s growth rate will not be sustainable in the future if increasing capitalization cost trends continue without significant improvement in productivity. The PE Technology Requirements Table FAC-8 is also responsible to the intended significant productivity improvement preceding 450 mm insertion. Although the FO Technology Requirements Table FAC-6 owns the equipment output cycle time waste (EOW) requirement EOW metrics may be broken down to EOW for the PE section to address waste reduction. The waste due to NPW operations and the frequent recipe changes can significantly increase EOW especially in high product mix operations. The information of NPW operations needs to be made visible.

5.3.4. PRODUCTIVITY REQUIREMENTS

The requirement for high degree of wafer traceability implementation exists. This includes the process path, process parameters, and preceding operations. The move from 300 mm to 450 mm in PE should have no negative impact on any facet of equipment productivity. Factories will have to move to full wafer-level control to support productivity requirements.

The process control in the equipment is controlled by event-driven method (see also CSA section). Information that determines what event should be triggered includes internal equipment context data. Time stamping information is another source of context data that is needed to identify the happenings in the PE because high accuracy time stamping is required by the factory system; the factory system provides an accurate time synchronization capability across the factory. The equipment activity data should be provided together with driver events such as “Task ID” since equipment internal control is usually associated with such driver events to show the context of equipment internal events.

Sustaining productivity improvements will necessitate the tighter coupling of software capabilities, such as APC, maintenance, and scheduling/dispatch, with the PE. As such, some of these capabilities, such as APC, may be designed into the equipment (e.g., to facilitate more elaborate and fast or adaptive control implementation), or the equipment may be designed to require functionality with external APC systems. Further, PE will be required to produce the necessary data in a timely fashion and accept the appropriate actuation to enable the tight coupling with these software systems. These requirements will become even stronger as the industry moves towards a predictive (rather than reactive) mode of operation. Such predictive and self-running PE are the prerequisites for a single-wafer manufacturing system where very high degree of control synchronization for tools and factory and/or for tool to tool level is indispensably needed.

As environmental sustainability issues continue to play a larger role in the design and operation of PE, PE will have to implement and/or support environmentally-aware solutions at the equipment and integrated-factory levels. “Support” could

mean providing embedded solutions or solution components or providing the necessary data and supporting the necessary actuation capability for participation in fab-wide solutions. Examples of these solutions include support for “idle” mode of operations, integration with facilities management systems, and providing necessary data to support waste reduction capabilities such as PdM.

Table FAC7 Context Data Importance for Good Equipment Visibility

<i>Data Usages</i>	<i>Data Usage “Key” Information</i>	
	<i>Equipment activity context</i>	<i>Time stamp for host observation</i>
R2R control FDC, FICS data usages	<ul style="list-style-type: none"> • Tool name • Chamber index • Processing index • Recipe ID • Recipe Step Number • Product ID • Wafer ID 	Inter factory-level (Factory wide)
Tool-to-facility combination activity	<ul style="list-style-type: none"> • Tool name • Chamber index • Eq status • Processing index • ID to indicate interactive control events 	Inter-tool-level External sensors need their own time stamps
<i>Additional Sensor Data Utilization</i>		
Within-tool activity data utilization	<ul style="list-style-type: none"> • Task ID • Processing index/wafer locations • Internal control events 	Intra-tool-level +/- equipment heart beat frequency

5.3.5. ENERGY SAVINGS AND FACTORY ENVIRONMENT

In order to minimize consumption rate of energy and other utilities of production equipment when it is not needed to perform its intended function (i.e., processing wafers), production equipment needs to have ‘Smart’ energy-saving modes capabilities, which enable automatic energy and other utilities shutoff or reduction control while maintaining quick startup for returning to production readiness, with the goal of no added productivity penalties at equipment re-start. The potential savings depend on the scenario, with greater potential savings during fab start-up/ramp and research and development (R&D) environments compared to high-volume manufacturing (HVM) because it is likely that the wafer processing tools are to spend more time in a non-wafer-processing state. Even at HVM, not all equipment types are utilized to their full capacity due to bottleneck and other reasons, thus ‘Smart’ energy-saving modes are expected to be effective in such cases.

Realizing these ‘Smart’ energy-saving modes requires coordination between fab host and production equipment as well as between production equipment and sub-fab supporting equipment as shown in Figure FAC4. Standardization of communication protocols is being pursued in both of these areas with the fab host to production equipment communication standard completed (SEMI E167). This standard specifies methods for communicating between fab host and equipment: the expected timing and length of period in which the production equipment (and in turn supporting sub-fab equipment) takes to return to normal operation, is not to be utilized, the timing for returning to normal operating condition is expected, and to report transition between normal operation modes and energy-saving modes become necessary. A SEMI Standards Task Force is working on specifying standardized communication between production equipment and sub-fab supporting equipment to realize energy savings.

24 Technology Requirements

Energy savings is also achieved through energy-efficient equipment designs, which are achieved through the use of higher efficiency power distribution systems within the tool, more efficient tool-heat-load removal methods, and optimized recycling and reuse of water.

An additional emerging focus area requiring innovative solutions is the preventive control of AMC. Lastly, efficient and cost-effective equipment development will be a critical milestone in the industry transition to the next wafer processing size.

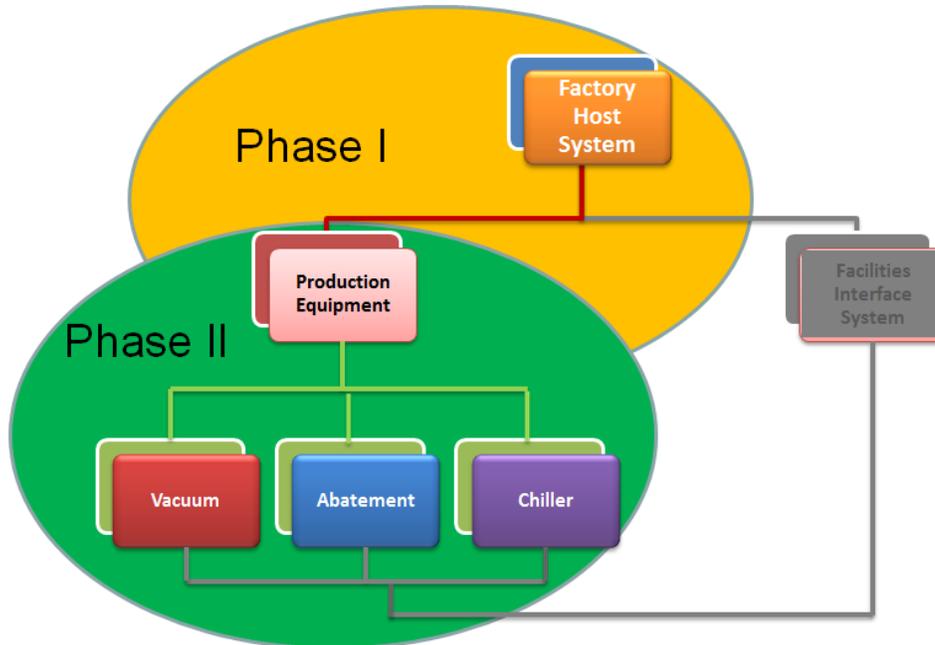


Figure FAC4 Phased Scope of SEMI Standards Work to Support PE Energy Savings

5.3.6. DATA INTEGRATION IN PRODUCTION EQUIPMENT

As diagnostics and control of equipment processing becomes more critical in terms of 1) process targets, 2) frequency and type of control actions, and 3) equipment and process health, and as newer technologies such as predictive maintenance begin to play a more important role in optimization of equipment productivity, data from equipment components and sub-systems will play an increasing role in the operation of these control solutions. As an example, vibration data from pumps can be used to estimate pump remaining useful life (RUL), but also can be an important contributor to process diagnostics. As such it is important that the data from the components and sub-systems be made available to higher level equipment and process diagnostics systems so that a holistic approach to equipment process diagnostics and control can be achieved.

5.3.7. PREDICTION CAPABILITIES IN PRODUCTION EQUIPMENT

Future equipment capabilities will include predictive capabilities as described in the Augmenting Reactive with Predictive (ARP) section of this chapter. Equipment will benefit from capabilities such as excursion prediction to avoid mis-processing, scrap, and potential equipment damage. Scheduling prediction will result in increased capacity and reduce waste. Virtual metrology could be leveraged for improved process control and reduced cycle time. While the predictive scope will be fab and even enterprise-wide, and much of the predictive capabilities will exist outside of the equipment, the equipment will play an important role in providing predictive capabilities. First and foremost, it will provide crucial data required for the development, execution, and maintenance of prediction models. Data must be provided of sufficient quality (e.g., accuracy, freshness, speed) to support these prediction models and thus requirements will be equipment and data producers. Equipment will also provide some predictive capabilities directly. This is because equipment has access to information not always available outside of the equipment or at the data rates that can be found inside of the equipment. Equipment suppliers may have specialized algorithms for prediction. Inside equipment predictions or prediction information as available must be coordinated with outside equipment prediction capabilities that have access to a much larger pool of data (types, archival length, process capabilities, etc.) and can more readily support big data concepts often required to develop and maintain prediction models.

New specifications and standards on aspects of equipment prediction will be developed. As an example, SEMI E171 addressed “Specification for Predictive Carrier Logistics (PCL)”; the purpose of the standard is “...to provide a

communication scheme for exchanges of carrier logistics related information, especially predictive information, between equipment and the factory system in order to support seamless cascading of carriers for continuous processing of equipment in microelectronics fabrication systems or similar ones”.

Further detail on inside-equipment prediction systems and their role in the prediction vision can be found in the *Augmenting Reactive with Predictive* and *Big Data* sections of this chapter.

Table FAC8 Production Equipment Technology Requirements

5.4. MATERIAL HANDLING SYSTEMS NEEDS

5.4.1. OVERALL

Ergonomic and safety issues coupled with the need for efficient and rapid material transport are the major drivers in defining material handling systems for the 300 mm wafer generation and beyond. AMHS must have acceptable return on investment (ROI) and must interface directly with all inline (i.e., used in normal process flow) production and metrology equipment. AMHS must deliver material in a timely fashion to support critical equipment in order to minimize wait time waste. Furthermore, the material handling system needs to be designed so that it can accommodate the extendibility, flexibility, and scalability demands on the factory with minimum down time.

The AMHS Technology Requirements Table FAC-9 is based on the premise that as demands on the material handling system continue to increase while supporting fab operations with decreased down time and reduced lot wait-time waste on bottleneck equipment. In order to achieve the requirements, AMHS may be composed of interoperable sub-systems from multiple (best of breed) suppliers.

Solutions to provide better utilization of floor space through optimization of tools layout of the factory, integration of process and metrology equipment, etc. must be developed. It is also necessary to investigate the potential impact of increasingly larger factory sizes that require AMHS transport between multiple buildings and floors.

For efficient production, there will be a need to integrate WIP scheduling and dispatching systems with storage and transport systems for the goal of reducing wait time waste (WTW). This is especially true as scheduling and dispatching systems become predictive. For example, correctly predicting/scheduling pending and completed jobs on tools enables the repositioning of carries and transport close to tools when jobs on tools are finished.

The potential impact of high-mix operations and smaller lot sizes must be investigated. The tradeoff between lot size and MPH increase also needs to be evaluated. The adoption of automated reticle transport systems by IC makers will depend on the business model for the factory. Potential solutions for reticle transport systems must not negatively impact the lithography equipment's footprint, run rate, and ease of installation or de-installation.

5.4.2. 450 MM

Investigation and evaluation of the 450 mm physical interface and carriers (PIC) have been developed. The AMHS design may have to be revisited along with investigation into the wafer transport/storage (near tool) capabilities (i.e., EFEM, shared EFEM, on-tool storage). Other items that will impact AMHS design will be the 450 mm factory size, factory layout, AMC needs and factory throughput and cycle time requirements.

Table FAC9 Material Handling Systems Technology Requirements

5.5. FACTORY INFORMATION AND CONTROL SYSTEMS NEEDS

5.5.1. SCOPE

The scope of FICS includes computer hardware and software, manufacturing execution, decision support systems, factory scheduling, control of equipment and material handling systems, and process control. FICS serves as an essential infrastructure and technology enabler to a number of critical functional areas addressed by the IRDS—including yield, factory operations, production equipment, and material handling control and management.

5.5.2. IMPROVE FACTORY EFFECTIVENESS

Factories must be able to adjust schedules and dispatching schemes rapidly to quickly respond to unexpected equipment downs or product scrap to maximize productivity and maintain target production rates and production times of high priority (hot) lots as well as the production lots. This calls for optimization and prediction models that include predicting impacts

of operational or configuration changes to other FICS applications. The objective is to make the best choice of what to process looking beyond the boundaries of a single tool or cluster tool. With a global view of factory activity, the scheduling component can make decisions beyond a small area in the factory. The effect will be greater factory utilization, higher throughput, and reduced cycle time variability. Integration of FICS applications with business-level software systems provides accurate factory floor data for supply management, and improved product tracking. Potential solutions will require the standardization of technologies (e.g., Simple Object Access Protocol, Service Oriented Architecture Protocol (SOAP) and Extensible Markup Language (XML) and web services) that enable this level of integration.

5.5.3. IMPROVE FACTORY YIELD AND MINIMIZE WASTE

Yield improvement and waste minimization will rely heavily on FICS solutions. Process control systems (PCS) which utilize APC technologies including R2R control, fault detection (FD), fault classification (FC), fault prediction (FP) and statistical process control (SPC) will become more pervasive and an integral part of FICS solutions. SEMI standard E133 should be leveraged for definitions, identifying capabilities and possible identifying interface requirements for PCS solutions. SEMI standard E126 should be leveraged for specifying R2R control capabilities specific to a process type. Highly integrated PCS solutions will enable yield and process capability improvement, while reducing cycle time, ramp-up (re)qualification time, scheduled and unscheduled downtime, non-product wafers, scrap, and rework levels. R2R control at the wafer and increasingly the sub-wafer level will utilize virtual metrology and efficiently adapt to product changes, and maintenance events. Module and cross-module control solutions such as litho-to-etch CD control will become more prominent and R2R control capabilities will be linked to fab-level parameter targets such as yield, throughput, and electrical characteristics.

Fault detection systems will continue to trigger at recipe step boundaries but as equipment data sampling rates increase real-time alarming will see greater utilization and also provide input for virtual metrology systems tied to R2R control. Fault classification and fault prediction can reduce problem resolution time and the severity of process excursions, but widespread use will evolve slowly due to technology and standards hurdles. Chamber variance tracking and reporting will become an increasingly important tool for identifying yield and throughput issues, with APC assisted chamber variance control eventually taking the place of variance reporting. SPC is a mature technology with its current use rate and domain space continuing. Over the longer term, PCS solutions will leverage virtual metrology and other technologies to provide for real-time yield prediction with feedback into FICS for improved scheduling/dispatch, process control, and maintenance management that is better tied to productivity and waste objectives.

The FICS will provide collaborative integration between APC, manufacturing execution system (MES), equipment performance tracking (EPT), factory scheduler/dispatcher, maintenance management, and AMHS. This level of system integration is required to ensure delivery of the right material, lot, and wafers at the right time at the right locations maximizing equipment utilization. It will be enabled by event-driven, reconfigurable supervisory control capabilities at the heart of the FICS; common data warehouse and data models; adoption of Interface 'B' and associated standards for application integration; proliferation of networks for control diagnostics, and safety signals across the fab.

5.5.4. DATA UTILIZATION

Increasing levels of collaborative integration and exchange of data between key FICS system components, smaller lot sizes, and tighter process windows will lead to increased message and data load that must be managed by the FICS. Production equipment will be providing increased volumes of data: sensor data required for fault detection, advanced process control data, and tool performance data; including critical equipment actuators such as mass flow, pressure, and temperature controllers. The FICS must be scalable to accommodate increasing data rates and manage the collection, storage, and retrieval of this increase in data collection. While distributed systems are not novel; FICS architectures will increasingly distribute data and applications below the factory level. Distributed data and applications will decrease factory bandwidth competition and enhance the FICS ability to filter through large quantities of data, to identify the specific set of information required to make decisions for factory operation and business-level decisions. Additional information big data issues of this type are discussed in the Big Data section.

Achieving these FICS requirements will necessitate alignment to industry standards for data acquisition, data interchange, and recipe management. Specific tool, supplier, or manufacturing-defined proprietary interfaces will increase implementation time and cost to both the IC manufacturer and the FICS supplier. Time to develop these new standards must be decreased, through collaboration between IC makers, equipment suppliers, and FICS suppliers. Ultimately the standards-compliant applications will reduce time and cost of integration, allowing IC makers and suppliers to focus on improved capabilities rather than customized integration. This will decrease the risk of new applications integration into an existing factory system.

5.5.5. HIGHLY RELIABLE, HIGH PERFORMANCE SYSTEMS

The increasing reliance of the factory on the FICS infrastructure will continue to drive increased factory system complexity. There will be increased attention to maintaining the gains to overall factory system availability and to further decreasing the occurrence of full fab downtime incidents caused by a failure of a single, mission critical application as shown in the FICS Technology Requirements Table FAC-10. Mission-critical FICS components, both software and hardware, must provide fault tolerant solutions that eliminate unscheduled factory system failures as well as scheduled downtime to install or upgrade. Potential solutions include software applications and databases that are capable of dynamic upgrades; software applications that can monitor health of factory systems and that can induce load-balancing, and fault tolerant computer systems with transparent hardware switching for failovers.

Cyber security continues to remain a high priority from the factory operations perspective. Cyber security guidelines were first published by ISMI in March 2005 documenting available methods for cyber security. The security focus is also on protecting IP within the equipment. Microelectronics equipment is now well integrated into the FICS infrastructure with engineers and technicians. Ensuring IP protection is critical to overall financial success in an environment where there is a significant amount of operations-level overlap.

Table FAC10 Factory Information and Control Systems Technology Requirements

5.6. FACILITIES NEEDS

5.6.1. SCOPE AND FACILITY MISSION

Facilities include the overall physical buildings, cleanroom and facility infrastructure systems, including tool hook up. The IRDS Facilities scope does not include adjacent general office spaces and corporate functional areas. It is important to note that the following requirements will affect the facility and support facility infrastructure system with respect to their complexity and costs:

- production equipment
- manufacturing goals
- management philosophies
- environmental, safety, and health (ESH) goals
- building codes and standards
- defect-reduction and wafer cost reduction targets
- disruptive manufacturing technology migration

5.6.2. DEMAND ON FACILITIES SERVICES INCREASES

The industry continues to demand facilities that are increasingly flexible, environmentally benign, extendable and reliable, services that come online more quickly, and are more cost-effective. However, production equipment requirements, ESH/S compliance and factory operational flexibility continue to drive increased facility capital and operating costs. Production and support equipment are becoming more complex, larger, and heavier, thereby driving the need for a continuous increase in factory size and tool packing density.

New and different process steps are increasing the growth of the cleanroom's size faster than the increases in factory production output. A focus on environmental issues such as carbon footprint reduction added constraints on the facilities operational objective function. Consequently, the increasing size and complexity of the factory, the production equipment and material handling systems, as well as the pressure to reduce time-to-market and facility costs, will make compliance with many of the current requirements a greater challenge. Better coordination among the items listed below are necessary to achieve these goals, improve system and space utilization, and control facility capital and operating costs:

- production equipment operation
- maintenance
- environmental requirements
- facility infrastructure system design
- handling new process chemicals throughout facility (source supply to exhaust treatment)
- installed utility capacities vs. load

28 Technology Requirements

- facility spaces/volumes

5.6.3. COMPLEXITY AND COSTS OF FACILITIES SERVICES RISING

Facility complexity and costs are also rising due to impacts from many areas including:

- rising utility costs
- need of better control on AMC (airborne molecular contamination)
- the greater variety of gases/chemicals
- disruptive factory requirements to meet emerging technology needs for 450 mm, EUV, 3D, etc.
- more stringent ESH/S regulations
- improved electrostatic charge and electromagnetic interference controls
- acoustic controls

5.6.3.1. MEETING PRODUCTION EQUIPMENT REQUIREMENTS AT POINT-OF-USE TO REDUCE COSTS

Meeting production equipment requirements (such as vibration and air, gas, and liquid purity levels) at the point-of-use may be a more cost-effective approach to meeting future requirements without increasing facility costs or sacrificing flexibility. For example, reducing facility vibration requirements and then working with production equipment manufacturers to ensure proper vibration control at the tool could reduce overall costs without decreasing the facility's flexibility. Reduction of air, gas, and chemical purity and piping installation specifications on central supply systems and introducing localized purification systems to the specific equipment or areas requiring such measures can also help control costs, improve flexibility and enhance operating reliability.

5.6.3.2. MEETING AMC REQUIREMENTS

An increasing impact on the AMC levels in the fabs is observed for the local scrubbers due to fugitive emissions during maintenance, e.g. for dopants, besides the impact of removal efficiency and the resulting reintroduction of exhaust gases back into the make-up air. The total AMC concept is illustrated in Figure FAC5.

Reductions of this cross contamination can be achieved by applying BKMs to abatement maintenance as well as improving the overall removal efficiency for the abatement and central facility scrubbers.

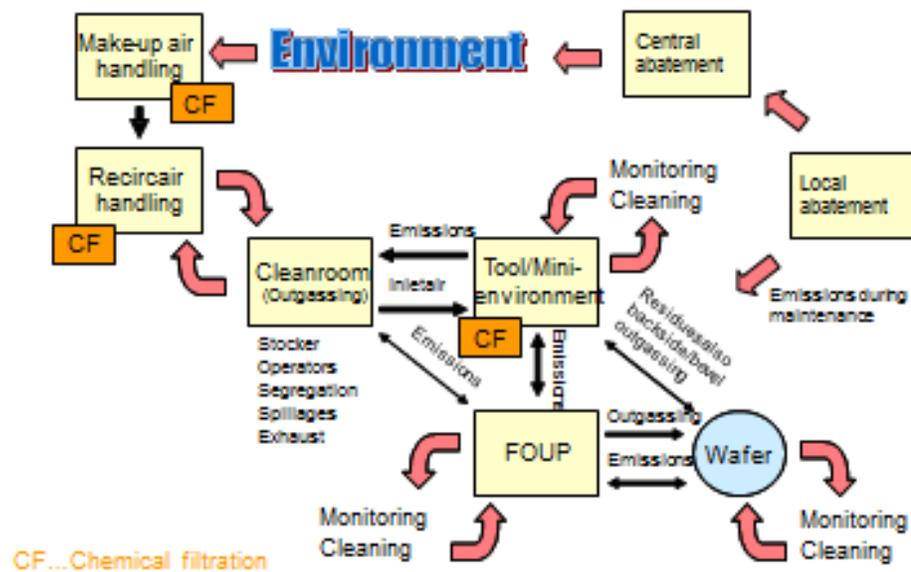


Figure FAC5 Total AMC concept

5.6.3.3. MEETING STATIC CHARGE REQUIREMENTS

Electrostatic charge adversely impacts every phase of microelectronics manufacturing, causing three basic problems, as follows:

1. Electrostatic attracted (ESA) contamination increases as particle size decreases, making defect density targets more difficult to attain. Electrostatic attraction of particles to masks will become a more serious problem if future lithography methods eliminate the pellicle used to keep particles away from the mask focal plane.
2. Electrostatic discharge (ESD) causes damage to both devices and photo-masks. Shrinking device feature size means less energy is required in an ESD event to cause device or mask damage. Increased device operating speed has limited the effectiveness of on-chip ESD protection structures and increased device sensitivity to ESD damage.
3. Equipment malfunctions due to ESD-related electromagnetic interference (EMI) reduce OEE and have become more frequent as equipment microprocessor operating speeds increase.

Electrostatic discharge (ESD) sensitivity trends will have larger impact on manufacturing process yields as the device feature size decreases. Companies will need to increase their efforts to verify that the installed ESD controls are capable of handling these devices and to make any necessary improvement in ESD control methods. This could include changes in the ESD control item limits, changes in the frequency of compliance verification, and other forms of ESD monitoring, such as ESD event detection.

It should be noted that progressive reticle pattern degradation in photomasks can be caused by electric fields that are very much weaker than those that induce ESD damage. This damage phenomenon is called EFM (Electric Field Induced Migration). Transient or rapidly changing electric fields that are not strong enough to induce ESD are particularly problematic because they will cause cumulative EFM. This may escape detection until defective devices are being produced.

5.6.3.4. GUIDANCE ON RETICLE ELECTROSTATIC PROTECTION

When controlling ESD was the primary objective, limiting the field strength to which a reticle could be exposed was a valid countermeasure. But it is now known that other damage mechanisms operate several orders of magnitude below the ESD threshold and they are capable of causing even more significant losses in microelectronics production than reticle ESD. They operate cumulatively every time the field passing through a reticle changes, so every change in the field experienced by a reticle, even at a very low level, has the potential to add to the degradation.

This leads to the deduction that it is no longer appropriate to address the electrostatic risk to a reticle in the IRDS by simply tabulating a maximum recommended field strength year by year, as has been customary for ESD prevention. The number of reticle moves taking place while any electric field may be present and the degree of a reticle's exposure to transient or oscillating fields may be more significant risk factors. The sensitivity of reticles to these difficult-to-quantify risk factors will, however, inevitably increase over time.

For this reason, the recommendation for reducing reticle electrostatic damage is now to minimize a reticle's exposure to any strength of electric field, not to move reticles while any electric field may be present, and especially to prevent transient and oscillating fields from reaching a reticle. Achieving this will require the increased adoption of metallic shielding to keep electric fields and especially fast field transients away from reticles. Measures that were developed to address the ESD risk, but which do not protect reticles against these risks, such as equipotential bonding (grounding) and the use of static dissipative materials for making reticle boxes, may need to be replaced with more protective approaches. Guidance about this is provided in SEMI Standard E163.

5.6.3.5. MEETING ELECTROMAGNETIC INTERFERENCE CONTROL REQUIREMENTS

It has been known for many years that Electromagnetic Interference (EMI) (see the standard SEMI E33 for definition)¹² causes a variety of problems for microelectronics manufacturing, including, but not limited to, equipment lockup and malfunction, sensor misreading, metrology errors, sensitive component damage and others. There are many sources of EMI in microelectronics environment that include electromagnetic emission from ESD, operation of equipment, especially high-energy tools, motors and actuators, wireless communication and alike. Co-location of sensitive equipment with high-energy tools, cabling, ground problems, improper maintenance of equipment and others further aggravate EMI problems.

In the past these influences were limited to applications in research. Now, due to ongoing shrinking of structures and the explosive increase of applications using wireless communication techniques, the influence of EMI effects in microelectronics manufacturing Fabs becomes more pronounced, particularly in areas where uncontrolled electromagnetic fields are a very sensitive concern as in SEM/TEM, e-beam and metrology tools to perform its intended functions. Therefore, understanding EMI phenomena, its impacts, and how to mitigate it in a cost-effective fashion become more important as process technology progresses into the future. Currently EMI is not well understood by the end user and thus leads to misdiagnosed problems and misapplied EMI mitigation/controls. This needs to be addressed at a global level to prepare for what is expected to be more electromagnetic-related impacts in the future.

30 Technology Requirements

To control and reduce the negative impact of EMI on wafers, materials and equipment, more comprehensive studies, advanced methods and measurement tools are needed.

5.6.4. MICROELECTRONICS INDUSTRY FUTURE CHANGES AND REQUIREMENTS

Despite the continuous device feature size shrinkage and increase of process complexity in process technology according to Moore's Law, the drive towards the reduction in manufacturing cost will result in the introduction of larger wafer sizes, such as 450 mm wafers. Such a change will also have implications on the design and construction of a wafer manufacturing facility due to increases in overall size, height, and weight of process equipment, their utility consumption, and other process-driven facility requirements such as AMC, EMI, ESD and acoustic controls.

With more production support equipment placed in the sub-fab, a utility sub-fab may be required to house additional equipment. For example, the addition of local purification and reclaim systems at the support equipment level will require more sub-fab area. These challenges will continue to drive the need for further facility technology development in such areas as:

- PFC abatement
- structural design
- AMHS facility integration
- chemical delivery facility integration
- Ultra-pure Water (UPW) delivery
- energy efficiency
- communication challenges (energy, water, waste, emissions, management) infrastructure
- Airborne Molecular Contamination (AMC) control
- EMI/ESD controls
- microelectronics materials ESH/S management
- Energetics Materials ESH/S management and facility consideration

Such considerations must also be evaluated in the case of a planned conversion of an existing wafer manufacturing facility to the next wafer size.

5.6.5. RESOURCE CONSERVATION CONSIDERATIONS

The need to reduce resource consumption is an area that requires greater attention. This will necessitate the integration of new technologies in the design and construction of facilities as well as different operational strategies.

For example, reduction of the cleanliness within the manufacturing space to ISO Class 7 could reduce the recirculation air volume requirements. (Consider widening temperature, humidity, and pressurization requirements) This would have a ripple effect on the exhaust and make-up air systems; which would lead to reduction in power consumption. Process equipment idle and sleep modes can also reduce energy consumption during non-processing times. Heat recovery systems can reuse heat otherwise dissipated to the atmosphere. Using more process cooling water will further reduce the amount of recirculation air required to remove heat generated by the process equipment.

These are just some examples requiring further consideration. Green technologies must also be considered for integration into the design and construction of future facilities. For example, by incorporating concepts such as those outlined by the US Green Building Council's LEED program into the design of the facility, energy and water conservation strategies would need to be more widely adopted.

With the new technologies and the introduction of mega fabs the energy and water footprints become significant when considering the local available infrastructure. Seasonal draughts and geography specific water availability in some advanced microelectronics fab locations further exacerbate the concern.

The infrastructure itself will be a serious limiting factor for many locations both with regard to water and power availability, quality and cost. It will become an increasingly important site selection constraint for new fab construction or expansions of the existing facilities.

Technology development needed to be driven both for energy and water consumption to reduce the external utility footprint. But this task is much more complex than it looks at the first glance.

1. Water recycling and reuse will require substantial investment in either complex segregation of the industrial wastewater streams with subsequent treatment or sophisticated end-of-pipe solutions.
2. Increased water recycling at same consumption level will reduce the external water supply needs but will increase energy and potentially also chemical consumption.
3. Water reuse may also increase parameters in the site outfall posing the risk of environmental compliance
 - a. Chemical consumption has dramatically increased in latest technology generations. Unless the chemical consumption is reduced dramatically, or the chemical waste segregation is not improved, increased water recycling excursions in waste water concentration and issues environmental compliance and external water reuse will be the result.
4. Process requirements such as lithography needs (EUV or multiple patterning) as well as the need to reduce F-GHG and N₂O emissions will drive power consumption even further. Increased energy consumption adds cooling load, which results in higher water evaporation in the cooling towers. The effect is similar to recycling, increasing concentrations of the contaminants in the site effluent.

More development is needed to address these complex and interconnected issues.

5.6.6. INDUSTRY COLLABORATION FOR FACILITIES

To reduce the time from groundbreaking to the first full loop wafer out, a paradigm shift in the way facilities are designed and constructed will be required to meet the following demands

- the fabrication process and the production equipment will increase in complexity
- factory operations will seek more flexibility
- global codes, standards, and regulations will increase in variability

This shift entails complete integration of the IC manufacturer, the factory designers/builders and the production equipment manufacturers into the entire project team. At a minimum, the project team must be assembled at an early stage with process engineers, manufacturing engineers, facility engineers, design consultants, construction contractors, ESH/S personnel, as well as manufacturers of process equipment and facility components.

Development of building information models, standardized design concepts, generic fab models, and off-site fabrication will be required to meet desired cost reduction goals to deliver a facility capable of meeting both current and future process technology requirements. Challenging the production equipment suppliers and factory design teams to develop and conform to a standardized utility infrastructure will also help control capital cost and reduce time-to-market.

Development of sustainability concepts for factory construction and operation will improve resource usage and reduce the environmental impact, for example:

- Production equipment installation costs and time continue to be driven higher by increasing gas, chemical and utility connections, energy conservation methodologies, and process-driven facility and ESH/S compliance requirements. Earlier awareness of new production equipment designs, standardization of production equipment connections, and the materials of construction, and the availability of measured utility consumption flow data in a standardized database system would allow for appropriate construction of the base build with an emphasis on “Design for Facilities”.
- Construction costs can be substantially reduced by lowering exhaust /make-up air requirements, raising non-critical process equipment’s cooling water inlet temperatures to a level where no central chiller plant is required for this equipment and using higher voltage power for production equipment as much as feasible.
- Operating costs can be reduced by innovative reuse and recycling concepts for Ultra-Pure Water (UPW), implementing equipment “sleep” mode during idle periods, raising process cooling water temperatures.

Although reliability of facility infrastructure systems is currently sufficient to support manufacturing, much of it has been achieved through costly redundancy. Improvements are still required in the design and operation of individual electrical, mechanical, chemical delivery, and telecommunications and facility control components and systems to reduce manufacturing interruptions. Collaboration with facility component manufacturers and equipment suppliers may modify the N+1 philosophy for redundancy, and positively affect costs without sacrificing reliability.

5.6.7. 450 MM CONSIDERATIONS

Any significant change in the production equipment, both for post-CMOS or for the next generation wafer size, such as new chemistries, the wafer environment or handling requirements (nitrogen or vacuum atmospheres, transition of an

32 Technology Requirements

equipment type from batch processing to single wafer manufacturing, etc.), will have an impact on future factory requirements. The high cost of a 450 mm Fab will increase the capital investment risk and drive more focus on loss prevention mitigation such as increased fire protection, more robust building materials and MFL (maximum foreseeable loss) separation walls within the Fab.

The table below outlines facilities technology requirements.

Table FAC11 Facilities Technology Requirements

5.7. AUGMENTING REACTIVE WITH PREDICTIVE NEEDS

5.7.1. SCOPE

The scope of Augmenting Reactive with Predictive (ARP) is all FI technologies that can have a predictive component. This section addresses the challenges and solutions associated with the augmenting of existing reactive technologies with predictive technologies while retaining the reactive capabilities. These predictive technologies include, but are not limited to, Predictive Maintenance (PdM), Equipment Health Monitoring (EHM), Fault Prediction (FP), Virtual Metrology (VM), predictive scheduling, yield prediction and augmenting predictive capabilities of the factory through simulation and emulation. The following definitions are used for purposes of discussion in this document; these definitions should be replaced by standardized definitions as they become available in the industry.

- *Predictive Maintenance (PdM)* – Also referred to previously as Predictive and Preventative Maintenance (PPM) and Prognostic Health Management, PdM is the technology of utilizing process and equipment state information to predict when a tool or a particular component in a tool might need maintenance, and then utilizing this prediction as information to improve maintenance procedures. This could mean predicting and avoiding unplanned downtimes and/or relaxing un-planned downtime schedules by replacing schedules with predictions. PdM solutions as defined herein address the entire maintenance cycle, from predicting maintenance through addressing recovery from maintenance events towards returning to production. Note that PdM for equipment or a particular equipment component could be managed at the equipment level or fab level, while other PdM activities require fab level management.
- *Equipment Health Monitoring (EHM)* – The technology of monitoring tool parameters to assess the tool health as a function of deviation from normal behavior. EHM is not necessarily predictive in nature but is often a component of predictive systems.
- *Virtual Metrology (VM)* – (standardized definition from SEMI E133) is the technology of prediction of post process metrology variables (either measurable or nonmeasurable) using process and wafer state information that could include upstream metrology and/or sensor data.
- *Fault Prediction (FP)* – (standardized definition from SEMI E133) is the technique of monitoring and analyzing variations in process data to predict anomalies.
- *Predictive Scheduling* – Is the technology of utilizing current and projected future information on tool and factory state, capabilities, WIP, schedule, dispatch and orders to predict and improve scheduling of a system (tool, group of tools, fab, etc.).
- *Yield Prediction* – Is the technology of monitoring information across the fab (e.g., tool and metrology) to predict process or end of line yield.

5.7.2. PREDICTION VISION

The prediction vision is a state of fab operations where 1) yield and throughput prediction is an integral part of factory operation optimization; and 2) real-time simulation of all fab operations occurs as an extension of existing system with dynamic updating of simulation models—this concept is often referred to as “digital twin” [11,3]. The prediction vision generally is the same for 300 mm and 450 mm facilities and full implementation of the vision is expected to become a requirement for remaining cost competitive in both facility types. Prediction capabilities will likely be required first and have more impact on certain tool types such as bottleneck tools.

Achievement of this vision will place a number of *requirements* on the roadmap for all prediction technologies.

1. Roadmaps for each of the predictive technologies must be structured to support their eventual merging in terms of sharing data and capabilities. This is because the prediction vision can only be achieved through the cost-effective collaboration of all prediction technologies.

2. Prediction technologies should be structured wherever possible to be strictly value add. In other words, there must be a clear understanding that the value provided by the successes of the prediction engine (e.g., correct predictions) is larger than the cost associated with the failure of the prediction engine (e.g., missed or false predictions). This in-turn requires that prediction solutions provide not only predictions, but indications of quality of predictions, and prediction solution implementation must incorporate quality of prediction information into solution design and optimization.
3. Prediction technologies must be structured to augment rather than strictly replace their reactive counterparts. This is because prediction will never be 100% accurate or 100% comprehensive. The reactive capabilities should complement the predictive capabilities by providing support to fab operations where prediction fails or is not implemented, and by providing input to future prediction capabilities such as predictive models.
4. Predictions systems will include aspects of prediction from equipment. Equipment has access to information not always available outside of the equipment or at the data rates that can be found inside of the equipment. Inside equipment predictions or prediction information as available must be coordinated with outside equipment prediction capabilities that have access to a much larger pool of data (types, archival length, process capabilities, etc.). Further detail on inside-equipment prediction systems can be found in the *Production Equipment* section of this chapter.
5. Data quality of systems must be improved to better support predictive capabilities. Data quality of existing systems is a function of the requirements for these systems. Because these systems are (today) generally not designed with prediction in mind, they don't always have the necessary data quality to support cost-effective prediction capabilities. Examples include inaccurate human-entered and missing context data in maintenance management systems, and insufficient archiving of data necessary to realize robust predictive models. The data quality issue is especially true of maintenance management systems (e.g., with human data entry). A roadmap for improvement of data quality of these systems to make them "prediction ready" is needed. Data quality guidelines and standards such as SEMI E151 and E160 should be leveraged.
6. Prediction solutions must be robust to support long-term application. The required accuracy of prediction solutions is application dependent. Knowledge of prediction accuracy (the second requirement) is thus necessary for determining robustness of the prediction engine. The prediction engine may need to be updated to support changes in the application environment. Thus, a roadmap for successful application of prediction solutions necessarily requires that these prediction solutions be robust to continuously adapt to their application environment. As part of this requirement, methods will have to be developed to maintain robustness as prediction quality continually improves and thus less "mistakes" (such as false positives or missed events) are available to update the predictor; for example, if the predictor results in zero unscheduled downtime, it may be due to high accuracy of the predictor or an overly conservative prediction.
7. Prediction solutions must provide predictions of required accuracy in a timely manner with respect to the application for which they are being used. This means that the prediction engine can be constrained by a maximum time for prediction (e.g., response time, or event occurrence), a required accuracy for prediction, or some combination of time and accuracy. Prediction solutions will have to be designed to support configuration to these constraints, depending on the application.

The roadmap for application of the prediction technologies varies among tool types. Predictive scheduling will initially focus on bottleneck tool types such as lithography where the benefit potential is high, however, longer term it will result in coordinated predictive scheduling of all tool types. EHM can be applied to any tool type where FD data collection is available, so the focus will be guided by need for health monitoring. VM focus has initially been on tool types where higher quality models can be realized, such as CVD and etch. Initial VM is focused on its use as an aid in excursion detection (ExD). This will be expanded to more widespread use to support "smart metrology" (SM), where real and virtual metrology work together to maximize the effectiveness of metrology given cycle time optimization requirements. Longer term VM will be used to augment process control, e.g., converting lot-to-lot control to W2W control, by providing predicted metrology values to supplement both pre and post process metrology. Additionally, in the longer term, fab-wide approaches to VM will be leveraged and prediction quality will be incorporated into VM application optimization. PdM will initially focus on maintenance events that are costly, occur more frequently (so more events are available for developing/maintaining models), and generate higher quality models; as with VM, longer term PdM will incorporate prediction quality in the decision process allowing for more widespread application and adoption. Yield prediction will likely leverage many of the same prediction technologies used for VM but will require coordination across the fab and improved data quality. As such, this technology will likely not become widespread until successes with VM and PdM become more widespread. Initially the focus will be on yield excursion detection (YEx) with root cause analysis via data mining (DM). Real-time simulation of fab operations as an extension of existing system (i.e., digital twin) is a long-term vision that will necessarily require the

34 Technology Requirements

successful implementation of the individual prediction capabilities followed by their integration on a common prediction platform.

5.7.3. TECHNOLOGY REQUIREMENTS

Achievement of the prediction vision places requirements in the individual prediction technologies as well as the comprehensive prediction strategy.

Table FAC12 Augmenting Reactive with Predictive (ARP) Technology Requirements

5.8. BIG DATA NEEDS

5.8.1. INTRODUCTION

To improve factory operations and traceability companies must invest in solutions to effectively manage their data growth. Data generation, storage and usage have increased in the factory because of the improvements of microelectronics equipment computer interfaces that provide higher rates for data collection and additional equipment parameter data availability. In addition to the increase of equipment generated data, manufacturing data analysis requires more complex data integration because the needed data comes from multiple sources and databases. Traditional database and file systems processing capabilities are being exceeded by transactional volumes, velocity responsiveness, quantity, variety, and veracity of data created. This explosion of data growth in manufacturing has created a set of requirements which are commonly referred to as “Big Data” (BD). As a result, there are significant efforts across industry to define big data and the big data problem. A consolidated effort is being headed by NIST (National Institute of Standards and Technology) [12]. Big data is characterized by an increase in: data volume, velocity of generation (as well as variability in collection and storage rates), variety of data sources, difficulty in verifying the veracity, or “quality”, of the data, and difficulty in obtaining maximum value from the data through efficient analytics and processing. From an information technology perspective, Big data represents data sets whose size, type, speed of creation, or data quality make them impractical to process and effectively analyze with traditional database technologies and related tools in a cost- or time-effective way.

5.8.2. SCOPE

The scope of this big data section is to identify the challenges and potential solutions associated with big data attributes of: volume, velocity, variety, veracity and value in microelectronics manufacturing environment.

5.8.3. TECHNOLOGY REQUIREMENTS

Big data technology requirements can be categorized according to the big data issues identified above, namely volume, velocity, variety, veracity and value.

Volume

With the increase of data collected per tool and per wafer, storage of large amounts of data (petabytes) places considerable load and cost on existing infrastructure, such as analyzing, storing, processing and cleansing data. Algorithms to optimize the storage of data are needed. Data models that enable access of the data in an optimal and reliable way must be developed and standardized for applications to plug and play.

Velocity

Velocity issues with data include speed of generation, speed of compression as needed for transmission, speed of transferring, speed for pre-processing for storage, speed of storage and speed of analyzing. The rate of data generation is exceeding the ability to store it in the underlying systems. For example, sensor networks are able to generate vast data sets and at rates that exceed the storage capability of traditional SQL databases.

Variety

Merging different data sources and data types is often difficult, time-consuming and results in data quality degradation (Veracity). For example, wafer image data (from visual inspections) is not easily stored with numeric data types in the same database table. A factory must make huge volumes of data meaningful to the product flow and process steps such that multiple applications can take advantage of the data to create meaningful and actionable information.

Veracity

Veracity refers to the accuracy or truthfulness of the data. For example, data store reduction can be accomplished by new and emerging techniques used to compress data without impacting the quality of the data and ensuring no loss of information. These tools or applications may not be sufficient or could be limited by the type of application used by the

factory. Retrieving the compressed data by those applications may also impact the accessibility and quality of potential predictions from that big data.

Another common issue is using data timestamps from multiple sources to merge data. These timestamps are often unsynchronized resulting in low data quality of merged data, thus impacting the factory's ability to use data from multiple sources reliably. The scope and/or resolution of the data collected from multiple sources and often at different rates further complicates the merging of data. For example, merging metrology with Fault-Detection Control (FDC) data and maintenance data provides many unique challenges.

Data that depends on or is created by personnel (i.e., "human entered data") can often be associated with many data quality issues such as accuracy, timeliness or freshness, availability and clarity. Challenges arise from merging different types of data (such as a context data) with continuous tool data-sets. In this area standards may be required to reduce errors created by humans. Correlation of personnel actions to resolve problems with the process tool would also likely benefit from standardization with the goal of optimizing the quality of the data.

Value

The cost of big data needs to be balanced with its potential value. Costs include collection, storage, and processing of the data. This is weighed against the benefits—both quantifiable and unknown. The unknown benefits refer to data that might be collected with the thought of data exploration and/or future event analysis (the event hasn't yet happened, but the data might provide insight into how the event would occur).

To help determine the value of data there are often statistical applications specific to particular groups of data consumers. For example, factories are often interested in fault detection, condition-based health monitoring and prognostics information to the factory. These applications can become bottlenecks in their attempt to analyze and provide information in near real time of high-volume, high-velocity data. Factory specific applications need to provide plug and play means to access the data or information they generate such that data analysis can be done at different layers and with different types of data. Applications need easy access to the data, in the right format, for efficient analysis to occur.

Big Data Decision Support Systems and Expert Systems used for analysis in manufacturing and operations are becoming part of the factory. Access to data from yield management, scheduling, dispatching and/or maintenance applications will require appliances to allow big data analytics. These all must be considered when determining the value of the data.

A solution area that determines and can enhance the value of data over time is the algorithms or analytics used for providing value, such as predicting an event, and supporting investigation of data through data mining. Big data environments will allow for the application of these algorithms more efficiently over much larger data sets. These environments will also encourage the development of more complex multivariate algorithmic approaches for data quality improvement, partitioning/ordering, clustering and analysis. Much of this development will be pioneered in other industries. The relatively rapid evolution in this area will require analysis solutions that are modular to support evolution, rapid prototyping and plug-n-play of analysis capabilities.

5.8.4. GENERAL BIG DATA AREAS OF CONCERN

Migration to Hadoop or Similar Big Data-Friendly Ecosystems

Moving to big data solutions involves addressing any number five Vs at various levels. Currently this is often accomplished by enhancing existing systems, e.g., to support larger data volumes or improved data quality. However, over the longer term it is anticipated that all of manufacturing will move to include more big-data friendly solutions such as those that contain Hadoop Ecosystem components. Initially these solutions will be used primarily for off-line, non-realtime² applications such as off-line data mining to support generation and maintenance of prediction models. In these areas, the move to big data-friendly solutions will be motivated by reduced cost of ownership with respect to data volumes, improved analysis processing speeds, and increased analysis capabilities resulting largely from the parallel processing capabilities of the ecosystem. Over the longer term some of these solutions will likely be used for on-line non-real-time applications; the development to support this capability will likely come from outside of the microelectronics industry. The level of real-time response capability of these systems over the longer term is unclear, however there will continue to be pressures from other industries to push Hadoop and similar capabilities into the real-time response realm.

² "Real-time" response as used in this section is a response that is prompt enough so that the application does not result in delay of processing. Thus, real-time response for a fault detection—FD analysis application at the end of the "run" (e.g., recipe or recipe step) would require that the analysis be completed and necessary action taken before processing begins on the next run.

36 Technology Requirements

Traditional relational and other transactional data management capabilities will continue to exist to support capabilities that are highly transactional in nature (versus data volumes) as well as real-time and near real-time capabilities that require response times that cannot be reliably achieved by big data friendly solutions (e.g., in-process fault detection—FD³). Often the big data-friendly ecosystems will represent a historical data warehousing extension of (near) real-time data management systems. For example, a transactional database component for an FD system might support housing control rules, report formats, etc., as well as a few days of trace data for analysis. Thus, it could support short term and small data size analysis queries. The corresponding big data-friendly ecosystem system would house all trace data and would support longer term, larger size data analysis, e.g., for development of prediction models. The data collection and analysis infrastructure would have to support populating and data mining across both infrastructures. The determination of the historical data size in the transactional component will be a function of a number of factors including a comparative analysis of transaction speeds.

A migration path will facilitate the move to big data friendly systems. The migration path will allow operation across composite systems consisting of both big data friendly and relational ecosystem components. In many cases this will allow for a gradual increase in the role of the big data friendly component over time. Capabilities from other industries will be leveraged in facilitating the migration path.

Prediction capabilities will be one of the primary beneficiaries of the move to big data-friendly ecosystems, as many of the big data challenges associated with ARP, such as Volume, Veracity (data quality), and Value (analytics) will be addressed in-part by the move to Hadoop ecosystem solutions. However, many other capabilities will benefit. These include capabilities that leverage 1) data volume, such as root cause analysis, 2) data variety or multi-dimensional data analysis, such as yield enhancement, factory operations, supply chain management and OEE, and 3) data value or analytics, such as new analysis for fault detection and classification.

Cloud Computing

The infrastructure needs for cloud computing for the factory can be borrowed from commercial computer clouds. An adequate architecture to integrate factory data from multiple locations for a holistic analysis is needed. Cloud computing requires that effective security is in place and that the speed of data access over the network is not a problem. Processing costs associated with cloud computing if the services are contracted versus using private resources must be compared in cost and security to protect the intellectual property and cost of ownership.

Data Security

Making data available for advanced analytics will likely be challenging because of multiple levels of user data accessibility needs. Determination of standardized policies will be applied to big data to make sure internal and external users have access to the data. Empowerment in the organization to explore and discover uncovered patterns and trends in the factory will likely be performed by internal resources. Big data will need to be secured and managed by the factory but access to it may be limited by security policies or firewalls inherent to the computer or server infrastructure

Data Retention

Data retention in big data will be required as needs grow for proper analytics and availability. In many cases it may be beneficial to retain ALL data in some systems such as maintenance management, in order to support capabilities such as predictive maintenance. Archival and availability of data is user specific but best practices are not. Methods for purging, storing, archiving and managing big data retention may be required. Additionally, looking at how often data is accessed and consumed may help tailor retention policies.

Algorithm Choices

The highly complex and precise production environment in microelectronics has resulted in a heavy focus on analytics to support enhancement of existing solutions such as FDC, and the realization of newer predictive solutions such as VM and PdM. This industry is somewhat unique when it comes to the application of analytics because 1) equipment and processes are highly complex, oftentimes with many interacting variables; 2) the cost of a false or missed positive (alarm) in applying analytics can oftentimes be very high; 3) processes are highly dynamic with continuous drift and frequent shifts; 4) processes environment changes are associated with a relatively large number of context variables such as product/recipe type and maintenance event type and time; 5) processes are often poorly visible with only a subset of the parameters necessary to fully quality the process being available, and 6) the industry favors factory-wide re-usable solution approaches versus point solutions. As a result, analytical techniques successfully applied in other non-microelectronics manufacturing

³ “In-process FD” is used here to mean FD that that is providing analysis and response during processing. An example might be an endpoint detection mechanism. The response time requirement is dependent on the speed of processing, but can often be on the order of less than 1 second.

domains may not be directly transferrable to widespread use in microelectronics manufacturing. Specifically, purely data driven or statistical techniques will continue to be less successful than techniques that incorporate SME in terms of process, equipment and component knowledge relative to the analysis. Big data-friendly techniques such as deep learning may have utility in highly complex environments such as wafer topography and defect mapping analysis [13,14]. The progress of algorithms applied to specific problem analysis should be tracked especially where approach-to-approach comparative analysis is provided. Algorithmic approach progressions in roadmaps should be assessed with respect to dimensions of capability, e.g., as shown in Figure FAC6[3].

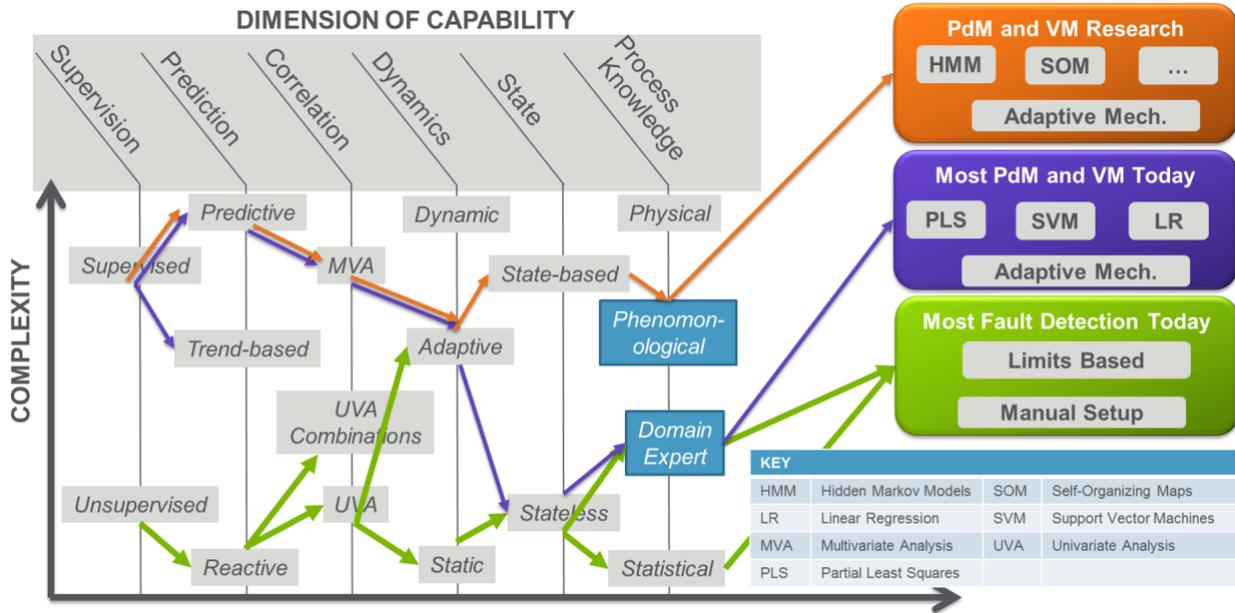


Figure FAC6 Example of Defining the Dimensions of Analytics Capabilities [3]

Data Visualization

Better visualization tools that can work with the analysis tools against the databases are needed. Plug and play applications are highly desirable. Some analytical tools used for big data are likely to be part of the analytical software, but their flexibility or features may not be as advanced as the factory needs.

The following are the selected aspects of big data. Each describes a particular problem in relation to the scope of big data.

Production Tool Data

Production tools need to provide more data as data collection requirements increase for process control, traceability and performance tracking applications which are used today as an integral part of manufacturing. Means to effectively export data from the production tool are needed. A second data collection port on a tool may be the best option, although it comes at a price because the interface may not use the protocol or data format used to collect other information from the tool. A second port to export the data should not impact other operations on the tool while it is running. The I/O and CPU cycles needed to collect and communicate with the tool must not impact the tool processing or intended use. Sensor Bus data access and/or embedded health monitoring tool capabilities can decrease data collection to mitigate and reduce the amount of data being collected and stored by the factory. Data from the equipment may need to be moved from inside of the factory to other systems to allow other applications to consume the data in a safe and secure manner. Systems communicating with the tool and distributing the data across the applications are likely to be affected by big data.

Network Issues

Network stress with big data often occurs when data is collected from multiple sources, in particular from the tools in the factory. Usually, data is consolidated from different sources (facilities, maintenance, yield, etc.) such that it can be used for analysis. Raw data is used to calculate values and requires context data to associate it to the right manufacturing and process step, material, equipment used, etc. These issues have the potential to overload the existing networks and infrastructure requiring special appliances to mitigate the network usage.

5.9. CONTROL SYSTEMS ARCHITECTURES NEEDS

5.9.1. SCOPE

The scope of Control Systems Architectures (CSA) is control aspects that are common across FI technologies. It does not include low level control such as Mass Flow Control inside a tool, but rather covers control at the higher levels such as process run-to-run control and control associated with manufacturing execution systems. This section addresses the challenges associated with both the evolution and potential revolution of these control systems. Evolutionary items include more granular control, higher speed control, higher control quality, and higher levels of control capability. Potentially revolutionary items include the possibility of new control paradigms and new control platforms.

5.9.2. CONTROL SYSTEMS VISION

The overall control systems vision is not concisely defined here because it isn't clear how new control technologies might be embraced, and the pace of control system evolution is so rapid that unforeseen technologies might appear over the next few years. However evolutionary aspects of the vision can be specified, such as granularity, speed, quality and capabilities.

5.9.3. CONTROL SYSTEMS GRANULARITY

Control systems granularity will increase for capabilities such as run-to-run (R2R) control as the concept of a controllable "run" evolves from a lot to a wafer (i.e., wafer-to-wafer (W2W) control) to within wafer (WIW) control. An example of WIW control in this context is "shot-to-shot" control in lithography. Achieving this level of granularity will require that equipment and metrology provide the necessary feed forward and feedback information in an equally granular fashion, but also in a timely fashion. This is especially true for the feed forward component of control as controllers generally treat this information as a disturbance rather than a component for model adaptation. Issues of throughput impact and reporting delay of metrology systems will be addressed in-part by the augmentation of these systems with virtual metrology. These augmented metrology systems will have to balance speed and quality to meet the requirements of the control systems; reporting of measurement and predicted measurement quality along with measurement value will be required for optimization of the consuming control systems.

5.9.4. CONTROL SYSTEMS SPEED AND QUALITY

As noted above, there will be constant pressure on many control systems solutions to provide control advices at higher speeds (both in terms of response time and frequency) in the face of increasing amounts of data to process (and other big data issues) and increasingly complex control algorithms. Improvements in computing power will address this requirement to some extent, however new control approaches will also be explored. One example is time-synchronized control, where the control network is synchronized using capabilities such as NTP or PTP⁴, and the control capability utilizes this synchronization and time stamping of data. Another example is just-in-time style control systems decision making where the controller is given a time deadline for providing an advice and the controller determines the "best" advice given that deadline, thereby balancing speed and quality for a particular application.

Another dimension of control system quality improvement will be the speed of control system solution delivery, qualification and deployment, for both new systems and system updates. As an example, the move to event-based control (e.g., business rules or control "strategies") allows for the relatively easy addition of new "control rules" as new capabilities are deployed. Modularity and "plug-and-play" capability (i.e., rapid and modular software exchange) of control algorithms will allow for improved comparative analyses and more rapid deployment of control systems improvements.

5.9.5. CONTROL SYSTEMS CAPABILITIES

Control systems capabilities will continue to improve in a number of common ways such as 1), addressing the big data issues in control, thereby allowing for the use of more and higher quality data in control decisions, 2), development of improved algorithms for control in general and for control related to a specific control task, and 3), movement to control software architectures that allow for cost-effective enhancement of control capabilities.

A second dimension in which control capabilities will increase is in the area of mobile computing. This includes mobile computing units (e.g., tablets) for monitoring and control of systems (e.g., maintenance logging) as well as mechanisms for remote monitoring and control of systems (e.g., outside of the cleanroom). In both cases issues of security and safety must

⁴ Networked Time Protocol and Precision Time Protocol: Please see SEMI E148—Specification for Time Synchronization and Definition of the TS-Clock Object

be continually addressed. In both cases technologies not specific to microelectronics manufacturing will increasingly be leveraged.

A third dimension in which control capabilities will increase is through the effective combination, capture, storage and sharing/access of control system technology combined with process and equipment expertise. Control systems capability improvement in many areas will increasingly rely on the collective use of control, equipment and process knowledge. For example, statistical models for R2R control will, in many cases, be replaced by phenomenological model forms that are stochastically tuned. Methods for capture and reuse of these capabilities and the associated knowledge will be developed. Development of these methods will require addressing technical, standardization, and intellectual property issues depending on the scope of re-use.

5.9.6. FUTURE CONTROL PARADIGMS

The future of control in many aspects of FI is unclear and is evolving quickly. Some control paradigms that are being or will be considered are:

- *Cloud-based storage with secure global access methods:* The advent of cloud-based technologies will impact control systems architectures. This will include cloud-based software delivery/update/support mechanisms, hosted services and more movement towards software as a service (SaaS). The cloud will enhance the capability for cooperation between user, OEM and control systems supplier, however use of these capabilities will require the addressing of number of security and IP issues.
- *Distributed control and autonomous control:* The advent of technologies such as web-based services and tablets has resulted in the enabling of a highly distributed control environment where disparate capabilities and suppliers can be brought together to achieve control objectives, moving away from the centralized control concept. This technology trend is already being harnessed in many FI domains (e.g., mobile computing units for maintenance management or process monitoring), however the level and timing of impact on the FI control approach as a whole is unclear. It is likely that movement to this control paradigm will be guided by trends across manufacturing in general rather than trends specific to microelectronics manufacturing.
- *Machine learning and artificial intelligence:* This paradigm in control systems architectures involves the enhancement of these systems so that they can “learn” from the environment as reported through the data. Adaptive model-based control systems (e.g., R2R controllers) may be thought of as learning from the environment; predictive control systems (see ARP section) might also be thought of as learning to some extent as predictive models are tuned. It is expected that more comprehensive learning techniques will be explored and applied to control systems architectures; these techniques and their application will likely be a trend observed across manufacturing in general with microelectronics manufacturing following this general manufacturing trend.

5.9.7. TECHNOLOGY REQUIREMENTS AND POTENTIAL SOLUTIONS

Achievement of the control system architectural vision is associated with a number of technology requirements which have been presented in the previous section. These requirements will be further quantified in a CSA requirements table in future versions of this document. A quantified roadmap for potential solutions in the CSA area will also be provided in future versions of this document.

6. POTENTIAL SOLUTIONS

The principal goals of factory integration are maintaining cost per unit area of silicon, decreasing factory ramp time, and, increasing factory flexibility to changing technology and business needs. The difficult challenges of 1) responding to complex business requirements; 2) High potential of waste generation and inclusion in factory operations and resources due to the high operation complexity; 3) managing the high factory complexity; 4) meeting factory and equipment reliability needs, 5) meeting the fab flexibility, extendibility, and scalability needs; 6) meeting the complex process and its control requirements for the leading edge device at production volumes; 7) comprehending ever increasing global restrictions on environmental issues; 8) preparing for the emerging factory paradigm and next wafer size must be addressed to achieve these goals. Potential solutions are identified for Factory Operations, Production Equipment, Material Handling Systems, Factory Information and Control Systems, and Facilities. Note that the bars containing wafer diameter data represent potential solutions that are wafer-size specific.

Potential solutions are shown as “*Research required*,” “*Development underway*,” “*Qualification/pre-production*”, or “*Continuous improvement*”, coded in potential solutions tables as shown below. The purpose is to provide guidance to researchers, suppliers, and IC makers on the timing required to successfully implementing solutions into factories. In some

40 Potential Solutions

cases, the IFT determined that there is insufficient information either in the IFT or in the industry in general to provide specifics on the timing of a potential solution; in these cases, the code *To be determined* is used.

	Research Required
	Development Underway
	Qualification/Pre-Production
	Continuous Improvement
	To Be Determined (TBD)

As the industry develops potential solutions, they often reach a point of continuous improvement and capturing their progress in a potential solutions roadmap is not necessary. However, in many cases it is still important to describe these solutions from an educational perspective. These solutions are captured in Table FAC144 delineated by functional area.

Table FAC14 Stabilized FI Potential Solutions with Description

Functionality areas	Solutions	Year of entering CIP	Justification to regard the item "educational"
Factory Operations (FO)	<i>NO Entry</i>		
Production Equipment (PE)	Seamless cascading multiple recipes within a carrier over lots	2016	Viable solution to improve utilization but can't be called "potential" solution anymore.
	Hot-wafer take over capability on the production tool	2015	Important solution for keeping cycle time as short as possible for critical reasons (e.g., send ahead metrology, important sample) but can't be called "potential" solution anymore
	On-tool wafer sorting between carriers in select tools	2017	Having been realized where it is necessary, or at least known as viable solution.
	Process quality improvement through APC (including R2R control, FDC, SPC and Fault Prediction) as a design-in requirement; the APC that is leveraged could be inside or outside of the equipment	2011	APC has been implemented for some time. There is a lot of room for improvement, but it is not "potential" solution anymore.
	Equipment functional verification through techniques including fingerprinting and equipment health monitoring	2017	Dashboard function for equipment fingerprinting and health data becomes prevalent.
	Capability to limit utilities and electric power consumption during equipment idle periods; includes management of equipment "energy saving mode" without impacting throughput or quality	2017	Standards to support equipment sleep mode coordination with FICS became available.
	To make energy efficient design an important equipment design metric, and waste reduction equipment design and operation performance metrics	2015	There is a SEMI Standard that provides metrics for equipment energy efficiency. It can also be used to evaluate utility use efficiency.
Automated Material Handling Systems (AMHS)	450 mm Interface standards development	2016	Physical interface Standards Suite for AMHS and 450 Carriers/production equipment had completed and stabilized. It is expected, however, once 450mm systems implementation for quantitative production starts the Standards Suite may need some more revisions.

Functionality areas	Solutions	Year of entering CIP	Justification to regard the item "educational"
	Uninterrupted software upgrade	2017	This solution is not wafer diameter dependent and has already been available.
	Visualization of AMHS information	2017	This solution is not wafer diameter dependent and has already been available.
Factory Information & Control Systems (FICS)	Cross-module supervisory Run-to Run process control	2015	Have already been implemented for critical processes
	Stds-based equipment data collection for process monitoring and diagnostics via EDA interface	2015	Have already been implemented for critical equipment
	Data Quality and Factory-wide standardized time synchronization	2015	Standards are available
	Integrated FICS to facilitate data searches and information correlation on process and operational data	2015	Correlation is possible, but speed can be improved
	Integrated FICS to support cross-site processing	2015	already been implemented
Facilities	Early and accurate identification of production equipment installation demand requirements for basebuild construction (e.g. pressure, loads, flows, connection size)	From 300 mm tools	SEMI E6 and other Standards are available to specify and communicate production equipment installation demand between supplier and user. Without quantifying how early or accurate these cannot be solutions.
Augmenting Reactive with Predictive (ARP)	<i>NO Entry</i>		
Big Data (BD)	<i>NO Entry</i>		

6.1. FACTORY OPERATIONS POTENTIAL SOLUTIONS

The Factory Operations potential solutions are classified into planning Decision Support (DS) tools at the strategic level and tools for running the factory at the tactical or execution level. The solution components for these two levels are quite different but are essential in order to manage high-mix factories effectively. The tactical tools need quick access to transactional data whereas the DS tools need large sets of data with several analysis/reporting options.

Successful determination of where, when, and in what quantities the products are needed is essential for improving manufacturing productivity. The cost of capital equipment is significantly increasing and now constitutes more than 75% of wafer Fab capital cost and via depreciation a significant fraction of the fixed operating costs as well. Reducing the wafer costs requires improvements in equipment utilization, availability, and capacity loss due to set up, tool dedication, etc. Effective factory scheduling also plays a key role in improving equipment utilization and it also leads to improved cycle time and on-time-delivery. A real-time predictive scheduling and dispatching tool integrated with AMHS and incorporating predictive maintenance (PdM), preventive maintenance (PM) scheduling, Equipment Health Monitoring (EHM) and resource scheduling policies are required to reduce WIP, improve on-time-delivery, and improve capacity utilization.

42 Potential Solutions

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Decision Support for Operation Improvement																
Real-time (during processing) FDC functions	█															
Manufacturing Execution																
Predictive scheduling and dispatching including maintenance operations, and NPW operations, integrated with AMHS	█															
Cooperation between Design for Manufacturing (DFM) and New Product Introduction (NPI)																
DFM and NPI design and output to include process control and Fault Detection settings to reduce need for DFM cycles	To Be Determined (TBD)															
Direct support for experiment design and management associated with NPI	█															
Quality Control																
Real-time (time critical) Individual wafer traceability information standardization and reporting including in-tool states such as wafer position and process pre-process / post-process condition	█															
Productivity Improvement																
factory system implementation for equipment performance visualization, tracking, and improvement																
Waste Reduction																
Implementation of metrics for data collection & usage, waste and waste reduction (Wait-Time-Waste); E168 Product Time Measurement Standard Implementation	█															
Engineering Data Content Management																
Managing big data-friendly capabilities (e.g., Hadoop style infrastructures) in factory operations, e.g., for managing availability to data analytics	█															
Information Security																
Development of industry standards for each category of data in a fab and the standard security level for that category	█	█														
To balance data confidentiality and integrity with availability by partitioning datas with IP protections and standardizing data encryption.	█															
Adoption of IT standards for identity and access management including human and non-human access, to facilitate single sign-on and central management on user accounts management throughout Fab including production equipment	█															

Figure FAC7 Factory Operations Potential Solutions

6.2. PRODUCTION EQUIPMENT POTENTIAL SOLUTIONS

The PE interface with factory is expected to facilitate such factory operations such as Just-In-Time (JIT) or Deliver-On-Time (DOT) operation of carriers for seamless processing, coordination of APC capabilities such as Fault Detection and Run-to-run Process control both inside and outside of the tool, wafer or lot processing queue manipulation for hot lot handling, energy management within the equipment as well as part of the entire fab infrastructure, and, increasingly, predictive capabilities such as predictive scheduling, predictive maintenance (PdM) and Virtual Metrology. This will require production of more and more equipment information and increasingly higher rates including equipment state information, designs that accommodate control information and recommendations from external sources, and adherence to SEMI standards for data communication as well as state representation.

For the same type of recipes in which the same process resources are used almost for the same process settings the PE should behave as it is processing wafers under the same process recipe so to keep the seamless processing. This requirement implies that the PE needs to be capable of understanding the contents of the recipes, or, that the factory system sends a flag to PE to make PE accept any recipe without any NPW operations. More discussion is required to understand the requirement of such control and implementation methodology.

It is noteworthy that many operation controls become heavily dependent on scheduling in order to reduce WIP, to facilitate reasonable scheduled maintenance of PE, and, to gain flexibility against unexpected events in the fab. Predictive scheduling will become an integral part of equipment operation to optimize scheduling and reduce wait-time waste. It is also noteworthy to highlight that process controls need to become more model-based for higher reusability and to reduce the engineering burden and time consumption. Equipment should be designed with APC in mind. In some cases, this will mean that APC will be an integral part of the delivered tool solution, while in other cases it will mean that the equipment is produced to be “APC ready”, provide the necessary timely data and allowing the appropriate control to support APC. Research can be better focused toward the innovations required to achieve these objectives.

The movement to 450 mm as well as movement to new process materials will present challenges. The movement to 450 mm should not result in a reduction of any operations or product quality metrics.

Just as with the fab in general, equipment operations will gradually evolve from reactive to reactive augmented with predictive operations. This is discussed in detail in the ARP section. Corrective maintenance will be augmented with predictive maintenance. Fault detection and scrap reduction shall be augmented with fault prediction and scrap avoidance. Reactive scheduling shall be augmented with predictive scheduling. Metrology will be supplemented with virtual metrology. This change in mindset shall have an impact on equipment design and operations.

44 Potential Solutions

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Lot to Wafer level control																
Standardized factory system-process tool interface for equipment capability performance reporting and adjustment																
Implementation of standardized individual direct wafer traceability information for in-tool state (location and process/pre-process)																
Productivity and Quality Improvement																
Production and maintenance simultaneous operation in select equipment with consideration of safety, as common practice																
Equipment Health Monitoring capability to provide a common health indication capability across tools, and to provide input to a predictive tool health model																
Provide the necessary information and accept the necessary actuation to support a Predictive Maintenance (PdM) capability that will schedule maintenance on need based on higher level (above equipment) objectives but before tool failure or yield impact																
Provide the necessary information to support an external Virtual Metrology (VM) capability that will predict metrology values; provide for acceptance of necessary information (such as metrology values) to support any internal virtual metrology capability (note that this does not require that an internal virtual metrology capability be provided).																
Migration of Chamber Variance Reporting to Chamber Variance Correction Systems; reporting of data necessary to support chamber matching																
Waste Reduction																
Design-in of standardized equipment capability to report and visualize cost and cycle time																

Figure FAC8 Production Equipment Potential Solutions

6.3. MATERIAL HANDLING SYSTEMS POTENTIAL SOLUTIONS

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
450 mm AMHS																
450mm automated material handling system configurations																
Easily extendible transport system																
Automated or zero field hardware alignment and positioning	300 mm								450 mm							
Automated software configuration (HW independent structure and parameter setting)	300 mm								450 mm							
Uninterrupted extended transport system rail	300 mm								450 mm							
High Reliability																
Automated preventative/predictive maintenance, and e-Diagnostics	300 mm								450 mm							
High Performance																
Integrate the transport/storage of near tool (Near tool buffer, shared EFEM, on-tool storage, etc.)	300 mm								450 mm							
Integrate WIP scheduling and dispatching systems with storage and transport systems	300 mm						To Be Determined		450 mm							
Traffic-jam prediction and control capability; elimination of flocking risk	300 mm								450 mm							
The prediction allocation of the vehicle (a processing completion prediction), as part of a predictive scheduling/dispatching system	300 mm								450 mm							

Figure FAC9 Material Handling Systems Potential Solutions

6.4. FACTORY INFORMATION AND CONTROL SYSTEMS POTENTIAL SOLUTIONS

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Improve Factory Effectiveness																
<i>Cycle Time and Throughput</i>																
Area dispatch for idle equipment based on predictive schedule																
Dispatch to equipment based on fab-wide predictive scheduling																
Wafer-level control to support continuous wafer feed and hot-lot handling																
<i>Highly Reliable, High Performance Systems</i>																
<i>Low Maintenance Systems</i>																
<i>Configurable Manufacturing Systems</i>																
Equipment Security																
IP protection capabilities and achieving balance between data availability and IP protection																
Protection of the equipment's instrumentation and control systems from attack.																
Improve Factory Yield																
Advanced process Control integrated with yield management and yield prediction to provide closed loop control around the fab so as to better optimize diagnostics, multi-process control, maintenance, scheduling, etc. strategies to yield targets																
<i>Fault Detection and Classification (FDC)</i>																
Migration of Chamber Variance Reporting to Chamber Variance Correction Systems; provide chamber matching capability using tools such as APC																
<i>Run-to-Run Process Control</i>																
R2R control matched across common sub-entities such as chambers																
<i>Integrated and Virtual Metrology</i>																
Stds-based recipe and configuration selection/download for integrated process/metrology, per E170																
Virtual metrology augmentation for wafer-to-wafer control																
<i>Equipment Data Collection</i>																

Figure FAC10 Factory Information and Control Systems Potential Solutions

6.5. FACILITIES POTENTIAL SOLUTIONS

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Improve Integration between Production Equipment and Factory Systems																
Standardized utility infrastructure models to improve integration between facility design and construction from basebuild thru tool installation																
Improve Factory Design and Construction Cost Control																
Develop standard definitions and performance metrics for best practices in facility construction, operation, reliability and equipment installation																
Improve Facility and Production Equipment Interfacing																
Improve Production Equipment Installation Schedule Efficiency																
Improve Facility Response to Changes in ESH Requirements																
Optimize Factory Control Information System and Subfab Facility Control Systems to monitor and control resource utilization during wafer processing (e.g. abatement systems)																
Reduce Production Equipment energy/utility consumption when not producing wafers (e.g. tool idle/sleep mode)																

Figure FAC11 Facilities Potential Solutions

6.6. AUGMENTING REACTIVE WITH PREDICTIVE POTENTIAL SOLUTIONS

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
General																
Comprehensive prediction roadmap (including standards for integration of prediction technologies, making existing capabilities such as maintenance systems "prediction ready", establishing data requirements for prediction systems, etc.).	[Shaded]															
Equipment Health Monitoring (EHM)																
Standardized EHM dashboard design	[Shaded]															
EHM library component models defined for each tool type	[Shaded]															
EHM aligned with tool component model for each tool	[Shaded]															
Assurance of equipment's process execution performance in terms of standardized equipment component model visibility and use at the factory health monitoring level	[White]	[Shaded]														
Predictive Maintenance (PdM)																
Standards for PdM capabilities, interface, data quality, and maintenance system interface for PdM.	[White]	[Shaded]														
Methods for PdM prediction quality determination, representation and	[White]	[Shaded]														
Predictive Scheduling																
Methodologies for lithography predictive scheduling with integration to real-time scheduling and dispatch	[Shaded]															
Methodologies for predictive scheduling in non-lithography areas	[White]	[Shaded]														
Methodologies for area and fab-wide predictive scheduling and optimization	[White]	[Shaded]														
Lot-based, real-time predictive scheduling and dispatching algorithms integrated with AMHS	[Shaded]															
Single wafer-based real time predictive scheduling and dispatching including maintenance operations, and NPW operations	[Blue]	[White]	[Shaded]													

Figure FAC12 Augmenting Reactive with Predictive Potential Solutions

First Year of IC Production	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Virtual Metrology																
Standards for virtual metrology capabilities and interfaces																
Re-usable VM methods for excursion detection to support across- fab implementation																
Re-usable VM methods for smart metrology to support across- fab implementation																
Re-usable VM methods to support W2W process control, NPW reduction, PM recovery, etc.																
Predictive Yield																
Methods for effective fab-wide yield prediction overcoming factors such as fab data quality																
Standards for specification and integration of yield prediction solutions																
Simulation in Lock-step with Reality																
Methods for real-time simulation update and extension of existing systems (UI, data stores, etc.) to support simulation / emulation / digital twin.																
Standards for integration of simulation systems with existing systems																
Area solutions (e.g., tool) for simulation in lock-step with reality																
Fab-wide solutions for simulation in lock-step with reality																

Figure FAC12 Augmenting Reactive with Predictive Potential Solutions (continued)

6.7. BIG DATA POTENTIAL SOLUTIONS

First Year of IC Production		2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Volume																	
	Capabilities in place to support required data retention which could be ALL																
	Methods of data storage optimized to data analysis methods (e.g., via standardized data models)																
Velocity																	
	Solutions to support peak equipment and peak factory data transfer rates																
Variety																	
	Standards for data models of key FI data stores including maintenance, diagnostic, Process control/metrology, yield and Execution Log.																
Veracity																	
	Data quality baseline specifications provided as standardized metric values for key FI data stores including including maintenance, diagnostic, Process																
Value																	
	Standardized mechanisms in place used to determine benefit of data, e.g., in \$ / TeraByte of storage																
Other																	
	Communication standards, data models, high-speed integration methods, and security protocols in place to support Cloud Computing as a solution for FI systems																
	Fab-wide big data ecosystem																

Figure FAC13 Big Data Potential Solutions

6.8. CONTROL SYSTEMS ARCHITECTURES POTENTIAL SOLUTIONS

Achievement of the control system architectural vision is associated with a number of technology requirements which have been presented in the previous section. These requirements will be further quantified in a CSA requirements table in future versions of this document. A quantified roadmap for potential solutions in the CSA area will also be provided in future versions of this document.

7. CROSS TEAMS

FI technology requirements are often driven by other IFT requirements as shown in Figure FAC1. In order to understand the crosscut issues fully, the FI IFT interfaces with the other IFTs and puts together a list of key crosscut challenges and requirements as shown in Table FAC15, delineated by IFT area. This is followed by a discussion of interactions with specific IFTs or interactions around specific issues. FI will continue to address these key crosscut challenges and requirements.

Table FAC15 Crosscut Issues Relating to Factory Integration Delineated by IFT

<i>Crosscut Topic</i>	<i>Counterpart IFT(s)</i>	<i>Factory Integration Related Key Challenges</i>
<i>Front end Process (FEP)</i>	<i>More Moore Beyond CMOS Outside System Connectivity</i>	(Common across counterparts IFTs) Facility to support material (e.g., chemical distribution to abatement systems) and production environment (e.g., AMC, ESD,) for novel device structure including materials used in them.
		FICS to support increased number of parameters, detailed controls with FB from metrology and other support tool and systems.
		ARP will impact all FE process in some way; coordinate roadmaps to make sure FEPs are moving toward “prediction ready”, e.g., by providing necessary data
		Novel devices and their production processes may require more extensive data collection and its utilization for improvement of process performance. Getting to know FEP's BD data requirements (identification of 5V) is prerequisite for preparedness of BD system
<i>Back end Process (BEP)</i>	<i>More Moore Beyond CMOS Outside System Connectivity Packaging Integration</i>	(Common across counterparts IFTs) FICS for backend may need optimization including customization of supporting standards to allow full integration of data through processes (i.e., FEP-BEP integration)
		Tests needs (sampling rates and frequency) must be optimized by utilizing BD based analytics; BEP may impose higher data rate and bandwidth requirements in FICS
		Better integration between BEP and FEP will be required both to meet device design requirements and to achieve yield and productivity objectives
<i>Lithography</i>	<i>Lithography</i>	Continuing to understand EUVL (power, consumables) requirements from FI perspective; completely different factory design is expected.
		Fast reticle change; reticle storage issues and reticle buffering to support practical cycle time (especially for small lots operation)
		Facility to support production environment (e.g., AMC, ESD) for reticle and tighter process control needs.
		Predictive scheduling is important to lithography as it is often the critical process to maintaining overall throughput of the Fab.

<i>Crosscut Topic</i>	<i>Counterpart IFT(s)</i>	<i>Factory Integration Related Key Challenges</i>
		Lithography DFM needs. EFM may be added as it is confirmed as mask quality detractor.
<i>Sustainable Manufacturing Green Chemistry</i>	<i>ESH/S</i>	ESH/S to identify required Fab/equipment capabilities to measure resource consumption and release/emission to environment.
		FI to provide necessary metrics/methodology/data systems /infrastructure to accommodate ESH/S objectives
<i>Real and Virtual Metrology</i>	<i>Metrology</i>	Comprehensive metrology roadmap to be jointly defined.
		Virtual Metrology is an emerging cross-cut issue. The role of VM in metrology will be increasing; VM may become an integral part of some metrology offerings. Metrology capabilities will become part of the prediction engine input (e.g., for throughput projections) and output (e.g., for VM tuning).
		Metrology requirements on ESD and EMI could impact Facility targets
<i>Yield Enhancement</i>	<i>Yield Enhancement</i>	Facility/PE needs to contemplate necessary capabilities for supporting YE related requirements at different interface points (i.e., POS, POD, POC, POE, POU, POP)
		Facility need to support AMC, temperature, humidity and other environment controls as required by YE
		Facility need to support AMC, temperature, humidity and other environment controls as required by YE FI and YE to discuss opportunities to optimize tests (frequencies, condition to do/skip test) by utilizing BD and predictions
		YE to benefit from yield excursion detection and analysis and ultimately yield prediction provided as part of FICS, ARP and BD capabilities.
<i>Big Data</i>	<i>All</i>	Big data and prediction requirements and solutions will impact and provide solutions for Test.
		Big data and associated enabling of prediction technologies and advanced analytics will allow for improvement of and innovation in YE techniques, metrology and real + VM metrology capabilities, and better integration of FEP and BEP.
		Big data and its better enabling of prediction and other analytics will improve all aspects of FI allowing for realization of production capabilities to support emerging production requirements from IFTs such as More Moore and Beyond CMOS

7.1. ENVIRONMENTAL, SAFETY, HEALTH, AND SUSTAINABILITY (ESH/S)

7.1.1. SCOPE

The Environmental, Safety, Health, and Sustainability (ESH/S) activities, strategies and vision has an aim of projecting the principles of a successful, sustainable, long range, global, industry-wide ESH/S program. Execution remains largely independent of the specific technology thrust advances to which the principles are applied. Thus, many ESH/S Roadmap

elements, such as the Difficult Challenges and the Technology Requirements, feed directly into the other IFTs in the IRDS, notably Factory Integration. The six basic and overarching ESH/S Roadmap strategies are:

- To fully understand (characterize) processes and materials during the development phase;
- To use materials that are less hazardous or whose byproducts are less hazardous;
- To design products and systems (equipment and facilities) that consume less raw materials and resources;
- To make the factory, and fundamental industry supply chain safe for employees and the environment;
- To provide clear global ESH/S perspective in regard to new materials, sustainability and green chemistry;
- To provide proactive engagement with stakeholder partners and customers and reset strategic focus on the roadmap goals.

By applying these six core strategies as the essential elements to success, the Microelectronics Industry continues to be an ESH/S leader as well as an overall technology leader. Microelectronics manufacturers have adopted a business approach to ESH/S which uses principles that are deeply integrated with factory manufacturing technologies, supply chain, products, and services. Product Lifecycle and Green Chemistry outlines are added for 2015.

ESH/S and Factory Integration Synergy

In aligning with the industry trend towards tighter integration of ESH/S and FI activities, the ESH/S IFT contributes this section in the FI chapter. The reader is encouraged to refer back to the full ESH/S chapter when reading this section to understand the full ESH/S roadmap.

The increased synergy between ESH/S and FI efforts can be summarized with the following ESH/S strategies:

- The roadmap process will continue to quantify factory environmental factors
- Roadmap will include, new materials, sustainability and green chemistry
- Provide proactive engagement with stakeholder partners and reset strategic focus on the roadmap goals.
- Continue focus on factory, and supply chain safety for employees and the environment

7.2. YIELD ENHANCEMENT

7.2.1. SCOPE

Development of good yield management strategies reduces costs and investment risks. A factory yield model defines typical operational performance and permits a Pareto of performance and yield detractors. A factory model based on experimental mapping of process parameters and process control strategies reduces the need for increased metrology tools and monitor wafers. It is also critical to determine tolerance variations for process parameters and interactions between processes to reduce reliance on end-of-line inspections. Factory models should also be capable of handling defect reduction inputs to assure efficient factory designs for rapid construction, rapid yield ramp, high equipment utilization, and extendibility to future technology generations. Temperature and humidity metrics along with AMC requirements will be jointly worked out by Factory Integration and Yield IFTs.

Over the longer term yield prediction will be utilized along with feedback to factory systems such as scheduling/dispatch, maintenance management and process control to provide for better control to yield and throughput objectives. Realization of these yield prediction with feedback systems will require tighter coordination between yield and factory operation data management systems.

Yield management systems (YMS) must be developed that can access and correlate information from multiple data sources. YMS should also work with measurement/metrology equipment from multiple suppliers using pre-competitive standards-based data models and structures. Longer term Augmenting Reactive with Predictive technologies will result in a capability for yield prediction; the challenges and potential solutions for this capability will be coordinated with the Yield Management group. Refer to the Yield Enhancement chapter for a more comprehensive discussion on YMS.

YE and Factory Integration Synergy

In aligning with the industry trend towards tighter integration of YE and FI activities, the YE IFT contributes this section in the FI chapter. The reader is encouraged to refer back to the full YE chapter when reading this section to understand the full YE roadmap.

The increased synergy between YE and FI efforts can be summarized with the following ESH/S strategies:

- The road mapping focus will move from a technology orientation to a product/application orientation.
- Airborne molecular contamination (AMC), packaging, liquid chemicals and ultra-pure water were identified as main focus topics for the next period.
- Electrical characterization methods, big data and modeling will become more and more important for yield learning and yield prediction.

7.2.2. AIRBORNE MOLECULAR CONTAMINATION

The presence of Airborne Molecular Contamination (AMC) within the processing areas has played a more significant role as device geometries for integrated circuits shrink. Yield problems caused by AMC are well documented and occur at a host of different process steps.

Airborne molecular contamination (AMC) control may be implemented either fab-wide or locally at certain critical processes, potentially also at different levels for different processes. All cleanroom components, such as filters, partition, electric wire, etc., should be designed and selected considering their outgassing properties. Also, cross-contamination within the wafer carriers (FOUPs) should be considerable. Visualization, modeling and simulation tools are required to determine and validate the most appropriate integrated AMC control solutions. Furthermore, these tools should deliver a fair basis to estimate the cost effectiveness of the proposed solutions.

The “Wafer Environment Contamination Control” tables of the Yield Enhancement Chapter provide recommended contamination control levels which should be maintained at the interface between cleanroom environment and the part of the manufacturing equipment (mini-environments) as follows:

- AMC as measured/monitored in the cleanroom air and /or purge gas environment
- Surface Molecular Contamination (SMC) on monitoring wafers

These values reflect the need to reduce AMC from the ambient environment as well as to keep the out-gassing emissions in the clean room environment at low level.

It is noteworthy that there is a second contamination path regarding AMC that needs to be managed. Wafers leaving process covered with residues are out-gassing and over time any minienvironment in which processed wafers are temporally staying or kept for certain duration such as the wafer carrier (FOUP) will be contaminated. These adsorbed contaminations on the FOUP wall have been observed to re-contaminate cleaned wafers and subsequently contaminate equipment including expensive metrology equipment. This cross-contamination mechanism has been primarily identified for volatile acids after dry etching processes but cannot be neglected for other equipment and for other contaminants, such as caustics, organics and dopants. This cross contamination depends thereby by many factors. There is a need to monitor the FOUP contamination level as well as the interface between equipment and wafer carriers.

FOUP purging has been proven extremely difficult due to the dead-end type internal design of air spaces between the wafers as well as the limited possible flow rate. New methods such as vacuum/N₂ purge cycles can support faster cleaning times and overcoming the long dead legs. Nevertheless, further development is needed to establish suitable control limits of FOUP status and purging efficiency with on-line and off-line methods. Refer to *Yield Enhancement Chapter* for more information. Meeting AMC requirements is also addressed from a facilities perspective in the *Facilities* section of this chapter.

7.2.3. ULTRA-PURE WATER

Ultrapure water (UPW) is purified water with most of the quality parameters below or near their detection limits of the most advanced metrology. Specific definitions of the water quality requirements to enable future technology are presented.

Particle levels are reduced using the best available ultra-filtration (UF) technology, but today’s particle counting technology is not able to keep up with critical particle node due to continued scaling of critical microelectronics devices.

The focus will turn to critical parameters such as particles, metals, and organic compounds and the corresponding characterization methods. Particles remain a high and growing risk, critical for implementing future microelectronics technology; due to its high sensitivity to reducing line widths. On-line metrology for particles in liquid does not address killer particle size (sensitivity problem), and therefore, filtration efficiency for killer particles provides limited information. At the same time, it is apparent that the killer size of the particles has approached filtration capability of the most advanced final filters. Statistical process control is increasingly being used to monitor the consistency of process parameters. Process variation of fluid purity can be as critical to wafer yield as the absolute purity of the fluids. Therefore, it is important that measurement methods detect sufficient number of events to ensure confidence in measured particle concentrations.

Development of other statistically significant particle counting methods or a higher sample volume particle counter is needed to improve confidence in reported particle counts. Refer to *Yield Enhancement Chapter* for more information.

7.2.4. ELECTRICAL CHARACTERIZATION METHODS AND VIRTUAL METROLOGY FOR YIELD CONTROL

In order to overcome the problems of missing sensitivity and high effort consuming metrology for yield control one focus of the YE group will be the partial replacement of physical based metrology with electrical diagnosis and virtual metrology wherever feasible. The use of all available data sources and approaches for data analysis will be further elaborated for yield monitoring. Hereby, a better balance of defect/contamination detection and fault diagnostics/control of electrical characteristics should be established by including statistical and systematic approaches into YE activities.

Furthermore, virtual metrology becomes more and more essential for yield considerations. Virtual metrology is defined as the prediction of post process metrology variables (either measurable or non-measurable) using process and wafer state information that could include upstream metrology and/or sensor data.

Refer to *Yield Enhancement Chapter* and the *Augmenting Reactive with Predictive (ARP)* section of this chapter for more information.

7.2.5. THE MOVE TOWARDS YIELD PREDICTION

As noted in the *ARP* section of this chapter, part of the prediction vision is a state of fab operations where “yield and throughput prediction are an integral part of factory operation optimization”. Yield prediction will also become an integral part of yield control and enhancement. Big data capabilities will be leveraged to develop and maintain yield prediction models. These models will provide indications of potential yield excursions as part of the process flow, so as to provide “real-time”⁵ indications of issues to avoid quality issues associated with the delay between processing associated with the yield excursion and the end-of-line e-test and yield analysis (a delay that can often be days or even weeks). Analytics will identify culprits of yield excursions in terms of process and process parameters; analytics from other prediction technologies, notably virtual metrology, will be leveraged. Eventually control actions will be defined to allow the evolution from real-time yield excursion detection to real-time yield excursion control, and then real-time yield continuous optimization.

7.3. METROLOGY

Metrology systems must be fully integrated into the factory information and control systems to facilitate run-to-run process control, yield analysis, material tracking through manufacturing, and other off-line analysis. The scope of measurement data sources will extend from key suppliers (masks and silicon wafers) through Fab, probe, assembly, final test and be linked to business enterprise level information. Data volumes and data rates will continue to increase dramatically due to wafer size increases, process technology shrinks, and the big data problem. Virtual metrology (VM) will become an important solution to augment existing metrology for improving quality without negatively impacting cost in terms of capital and lost throughput. Refer to the *ARP* section of this chapter for the VM roadmap. In factories, review and classification tools may eventually appear in clusters or integrated clusters to create a more efficient factory interface. Some process equipment will include integrated measurement (IM) capabilities to reduce cycle time and wafer-to-wafer process variance. The FI and Metrology IFTs will continue to work on the VM and IM requirements. Refer to the *Metrology chapter* for overall metrology topics.

7.4. LITHOGRAPHY

The Lithography chapter deals with the difficulties inherent in extending optical methods of patterning to physical limits, and also evaluates the need to develop entirely new, post-optical lithographic technologies capable of being implemented into manufacturing. Key challenges that need to be addressed by the Factory Integration team are to ensure the infrastructure (power and water) readiness for EUVL to improve Advanced Process Control (APC) for lithography equipment (e.g., tighter control is needed for overlay and edge roughness), and to improve predictive scheduling/dispatch potential solutions for lithography as it is usually the bottleneck process. Other issues to be addressed include Design for Manufacturing (DFM) and temperature variation inside the tools, and, AMC and ESD impact on reticle. Refer to *Lithography chapter* for a more information.

⁵ “Real-time” as used here is a response time of sufficient promptness so that process flow is not impacted, and yield is not impacted as a result of analysis delays. For example, the yield prediction should occur before the next wafer or lot is processed (i.e., seconds or minutes).

7.5. MULTI-IFT ISSUE: WAFER DEFECT METROLOGY

Defect metrology continues to be important towards smaller nodes, especially considering new yield challenges like multiple patterning. The main way to detect yield impacting defects in the production is defect inspection. Therefore, the most important requirements for inspection and review are now incorporated in the More Moore chapter.

For Heterogenous Integration not small dimensions but 3D integration is the challenge. To find the right solutions for those inspection requirements and challenges will be the focus.

7.6. MULTI-IFT ISSUE: YIELD MANAGEMENT FOR PACKAGING AND ASSEMBLY

As technology requirements in the assembly and packaging area increase, yield loss and therefore yield improvement methodologies become essential. In this situation a clear benefit can be drawn from the experience in the FE. Yet the most appropriate methodologies have to be selected and FE yield tools need to be adapted to BE requirements. The task will be to define a dedicated roadmap.

Due to the changed focus of Yield Enhancement several cross IFT activities are envisaged, connections with More Moore (MM), Heterogeneous Integration (HI) and Heterogeneous Components (HC) are necessary.

8. EMERGING CONCEPTS AND TECHNOLOGIES

In addition to working on the factory integration sub-sections and cross-IFT challenges, the FI IFT also evaluated key emerging concepts and technologies that will impact the FI roadmap and cut across all FI areas. This section provides details on these concepts and technologies which may represent opportunities, but also risks. Some of these concepts and technologies may deserve increased consideration in future versions of the roadmap, perhaps in the form of their own needs and potential solutions roadmap subsections.

8.1. SMART MANUFACTURING AND INDUSTRY 4.0

As noted earlier Smart manufacturing (SM) is a term “generally applied to a movement in manufacturing practices towards integration up and down the supply chain, integration of physical and cyber capabilities, and taking advantage of advanced information for increased flexibility and adaptability” [3–5]. It is often equated with “Industry 4.0” (I4.0), a term that originated from a project in the German government that promotes a 4th generation of manufacturing that uses concepts such as cyber-physical systems, virtual copies of real equipment and processes, and decentralized decision making to create a smart factory [6,7].

8.1.1. THE SMART MANUFACTURING AND INDUSTRY 4.0 VISION

A number of SM and I4.0 common themes are expected to impact the FI roadmap. Some of these already addressed in the existing FI roadmap include:

- Leveraging big data infrastructures (see section 5.8)
- Integrating the supply chain network (see section 5.2.13 and 8.3)
- Leveraging advanced analytics (see section 5.8.4)

Other aspects of SM and I4.0 that will be addressed in greater detail in future FI roadmap reports include [15]

Improving use of cyber-physical systems (CPS):

CPS refers to the “tight conjoining of and coordination between computational and physical resources” [16]. This is not a new concept as systems that integrate computational and physical resources have been in existence for some time. However future SM systems will continue to improve from a CPS perspective in terms of “adaptability, autonomy, efficiency, functionality, reliability, safety, and usability.”

Improving the use of real-time simulation through realizing the “digital twin”:

“A digital twin refers to a digital replica of physical assets, processes and systems that can be used for various purposes” [11]. This concept is further refined in this report in section 5.7.2 as “a state of fab operations where ... real-time simulation of all fab operations occurs as an extension of existing system with dynamic updating of simulation models”. Many of the predictive applications being developed in the industry today will likely continue to evolve to more directly support this vision.

Business Paradigm Change: Migration to Cooperative Services-based Approach to FI

The rapid increase in FI requirements (e.g., big data) and capabilities (e.g., prediction) in recent years has led to a change in the approach to implementing and maintaining FI capabilities. Development and maintenance of emerging capabilities such as PdM, VM, waste management, and utilities management incorporation into fab objectives, requires intimate knowledge of the fab objectives, process, equipment and the capabilities themselves. Thus, it has become clear that cost-effective development and maintenance of these capabilities will require increased and continuous cooperation of users, OEMs and 3rd party FI capability suppliers. As an example, in a PdM deployment and maintenance effort, the user provides knowledge of objectives, costs, and metrics of success, along with process and equipment domain expertise. The OEM provides intimate knowledge of the equipment and PdM best practices for the equipment and serves as a conduit for longer term enhancement of equipment capabilities based on PdM results. The 3rd party PdM solution provider provides the PdM solutions which includes a fab-wide integration infrastructure and addresses issues such as security and big data in a standardized supportable way. During PdM solution maintenance the user leverages the PdM solution and may determine when enhancements are needed. The OEM continues to provide equipment knowledge and perhaps hardware and software updates to 1) address new PdM downtime event types as they occur or are addressed, and 2) perhaps reduce the cost of downtime event types currently addressed by the PdM system. The 3rd party PdM solution provider develops and maintains the state-of-the-art PdM capability, e.g., implementing improved algorithms and leveraging solution libraries to guide cost-effective enhancement the PdM capability. This new paradigm of increased cooperation between user, OEM and 3rd party FI capability supplier will place stronger requirements on issues such as security, IP protection and all big data issues. These issues will have to be addressed in the FI roadmap.

8.2. SECURITY

The three primary goals of security are to maintain confidentiality (the restriction of access to data and services to specific machines/human users) and integrity (accuracy/completeness of data and correct operation of services) and improve availability (a means of measuring a system's ability to perform a function in a particular time).

As mentioned in the Introduction section of this chapter, the scope of security in microelectronics manufacturing space includes 1) protection of crucial manufacturing data from unauthorized viewing or changing, 2) access authentication mechanism against both human and non-human entities 3) managing user class read-write privileges, 4) achieving balance between data availability and protection of both Microelectronics Manufacturer's manufacturing IPs and equipment suppliers proprietary information, 5) maintaining software security levels, 6) maintaining performance of equipment control system, software and communication (e.g. production equipment capability to communicate with host in timely fashion) while addressing security threats (e.g., viruses) and vulnerability of system 7) protecting quality and integrity of big data, 8) Application of big data analytics to identify security issues, and 9) protection of fab and equipment operation control systems from unauthorized operation or intentional alteration including destruction of control systems themselves.

Further advancement of the "connected Fab", which is one of center concepts of 'Industry4.0/Smart Manufacturing', even indicates potential direct data exchanges beyond factory integration space such as uses of distributed systems for specialized services including remote diagnosis or predictive analytics provided through data network beyond Fab intranet. While it is unknown to what extent the "connected Fab" concept prevails in microelectronics manufacturing space, it is certain information security will become more challenging with the increase of data shared across the factory integration space.

Attention is also drawn to the fact that Security functions and other important aspect of Fab/equipment operation controls such as safety may have conflicting objectives (example of fire safety wants normally-open control, i.e., to keep door open/available, while security may want normally-closed control). Also pointed out is that management of these functions may also be required.

At the moment in manufacturing in general, IT security issues are often only raised reactively once the development process is over and specific security related problems have already occurred. However, such belated implementation of security solutions is both costly and also often fails to deliver reliable solution to the relevant problem. Consequently, it is deemed necessary to take a comprehensive approach as a process including implementation of security threat identification and risk analysis and mitigation cycles on security challenges.

These issues are not unique to microelectronics manufacturing, and many of the issues go even beyond manufacturing in general. Thus, any roadmap for security in the IRDS should be developed and presented through reference to challenges and potential solutions across the manufacturing space. As an example, the IEC has set up and Advisory Committee (AC) on Information Security and Data Privacy (ACSEC, www.iec.ch/acsec). Any microelectronics manufacturing specific issues should be delineated and related gaps with the general manufacturing security roadmap identified.

8.3. SUPPLY CHAIN MANAGEMENT

FI connectivity up and down the supply chain leveraging the accelerated IT technology trends will be necessary to support tightening of production methods (e.g., associated with lean manufacturing) and addressing business requirements (e.g., for warranty traceability, improved quality, improved productivity, and cost reduction). Supply chain integration and management is thus a necessary part of the FI roadmap. Developing this roadmap will require an understanding of both microelectronics supplier and consumer sectors. For example, with respect to suppliers it will require an understanding of methods for specifying, bidding and ordering to support lean manufacturing inventory management requirements. With respect to customer, it will require an understanding of traceability requirements to support customer sector warranty and cost reduction requirements. Ultimately there should be an effort to consolidate requirements capabilities, best practices and standards across the supplier and customer environments for reduced costs and increased capabilities. The description of Supply Chain Management and its relation to FI can be found in Section 5.2.13. In the future Supply Chain Management may be one of the focus areas of the FI thrust.

9. CONCLUSIONS AND RECOMMENDATIONS

The Factory Integration chapter of the IRDS focuses on integrating all the factory components needed to efficiently produce the required products in the right volumes on schedule while meeting cost targets. The Factory Integration chapter provides the technical requirements categorized by functional areas and also the proposed potential solutions. It also provides Factory Integration related challenges from the crosscut issues and key focus areas that need to be addressed in order to keep up with the technology generation changes, productivity improvements and at the same time maintaining decades-long trend of 30% per year reduction in cost per function.

The 2017 Factory Integration report evolved from ITRS 2.0 FI chapter [8,9]. The 2017 report has the following highlights:

1. Restructuring of narrative to align with IRDS structure.
2. Identification of smart manufacturing (SM) and Industry 4.0 (I4.0) tenants as key components of the FI roadmap, including big data infrastructures, supply chain integration, advanced analytics, cyber-physical systems, simulation and “digital twin”, and reliance on a knowledge network for leveraging SME into solutions.
3. An expanded discussion of security, identifying data partitioning and IP security as a key gating factory in moving forward in many of the SM and I4.0 tenants. Security will likely become an FI focus area in future FI roadmap reports.
4. Continued emphasis on addressing the 5 “Vs” of big data and data management, recognizing that the big data revolution is occurring faster than previously envisioned. Determination that a potential exists for retention of ALL data in archival fashion with respect to particular data stores, and this may be desirable in future scenarios, e.g., to support predictive analytic model development.
5. An expanded discussion of the big data ecosystem, including Hadoop, big data algorithms / analytics, and the increased role of prediction which is enabled by big data advancements.
6. An expanded discussion of the prediction vision especially with respect to specific capabilities of VM and yield prediction and how they will evolve over time.
7. A presentation of an algorithm analytics roadmap component defining the requirements that shape algorithm choices and explaining the requirement for incorporation of SME into most analytics solutions in microelectronics FI.
8. An identification of the reemergence of 200mm as an important component of the FI ecosystem moving forward.

The recommended next steps for the microelectronics manufacturing FI ecosystem community are as follows:

1. Embrace the tenants of SM and I4.0. Pursue big data solutions as a complement to existing transactional solutions. Pursue advanced analytics for solutions, with a focus on incorporating SME into solutions. Consider comparative study of analytical solutions and determining an analytics roadmap as part of the decision process. Understand expanding role of simulation/emulation and the emergence of the digital twin concept. Identify opportunities up and down the supply chain and consider potential solutions for increased integration.
2. Understand that data partitioning and IP security will be a growing challenge. Look towards emerging potential solutions including standards in this and other industries that can be leveraged.
3. Pursue increasing granularity of diagnostics and control systems. FDC will continue to be primarily end of recipe or recipe step but will include more in-situ “real-time” FDC. R2R control will continue to move from lot to wafer to within wafer, and ultimately to include in-situ control.

10. REFERENCES

- [1] Moyne, J., Mashiro, S., Gross, D., “Determining a Security Roadmap for the Microelectronics Industry” (submitted to) *Proceedings of the 27th Annual Advanced Semiconductor Manufacturing Conference (ASMC 2017)*, Saratoga Springs, New York, May 2017.
- [2] Wikipedia: Internet of things. Available online: https://en.wikipedia.org/wiki/Internet_of_things
- [3] J. Moyne and J. Iskandar, “Big Data Analytics for Smart Manufacturing: Case Studies in Semiconductor Manufacturing,” *Processes Journal*, Vol. 5, No. 3, July 2017. Available on-line: <http://www.mdpi.com/2227-9717/5/3/39/htm>.
- [4] Wikipedia: Smart Manufacturing. https://en.wikipedia.org/wiki/Smart_manufacturing
- [5] Davis, J., Edgar, T; Porter, J., Bernaden, J., and Sarli, M. Smart manufacturing, manufacturing intelligence and demand-dynamic performance,” *Computers & Chemical Engineering*, 2012, vol. 47, pp. 145–156.
- [6] *Project of the Future: Industry 4.0*, Germany Ministry of Education and Research, Available on-line: <http://www.bmbf.de/en/19955.php>.
- [7] Kagermann, H.; Wahlster, W. INDUSTRIE 4.0 Smart Manufacturing for the Future. *Germany Trade and Invest*, 2016.
- [8] *International Roadmap for Devices and Systems, 2016 Edition: Factory Integration White Paper*. Available online: https://irds.ieee.org/images/files/pdf/2016_FI.pdf .
- [9] *International Technology Roadmap for Semiconductors, 2.0*. Available online: <http://www.itrs2.net/>
- [10] International Roadmap for Devices and Systems: Virtual Metrology White Paper – 2017.
- [11] Wikipedia: Digital Twin. Available online: https://en.wikipedia.org/wiki/Digital_twin
- [12] NIST Big Data Working Group. Available online: <http://bigdatawg.nist.gov/home.php>
- [13] Najafabadi, M. N., et al., “Deep learning applications and challenges in big data analytics”, *Journal of Big Data* (2015) 2:1.
- [14] Vogel-Walcutt, J.J, Gebrim, J.B., C. Bowers, Carper, T.M., Nicholson, D., “Cognitive Load Theory vs. Constructivist Approaches: Which Best Leads to Efficient, Deep Learning?” *Journal of Computer Assisted Learning*, 2010.
- [15] Armacost, M. and Moyne, J. “Moving towards the ‘smart factory’ in microelectronics manufacturing”, *Nanochip*, vol. 12, N. 2, 2017.
- [16] Cyber-Physical Systems (CPS) Program Solicitation NSF 10-515. Available online: <https://www.nsf.gov/pubs/2010/nsf10515/nsf10515.htm>