INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS 2.0

2015 EDITION

FACTORY INTEGRATION

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FACTORY INTEGRATION

1 INTRODUCTION

The Factory Integration (FI) focus area of the ITRS is dedicated to ensuring that the semiconductor 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 ITRS focus areas 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, 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.

Societal driving forces and trends such mobile devices and the internet of things (IoT) are impacting all areas of the ITRS, however, as shown in Figure FI-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 FI-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.
- *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 Environmental Safety and Health (ESH) objectives such as contamination waste reduction be an integral part of FI factory operation objectives.
- *Big Data:* The data explosion in manufacturing provides both challenges and opportunities for FI; a section of the FI chapter was created in 2013 and enhanced in 2015 that describes these in detail.

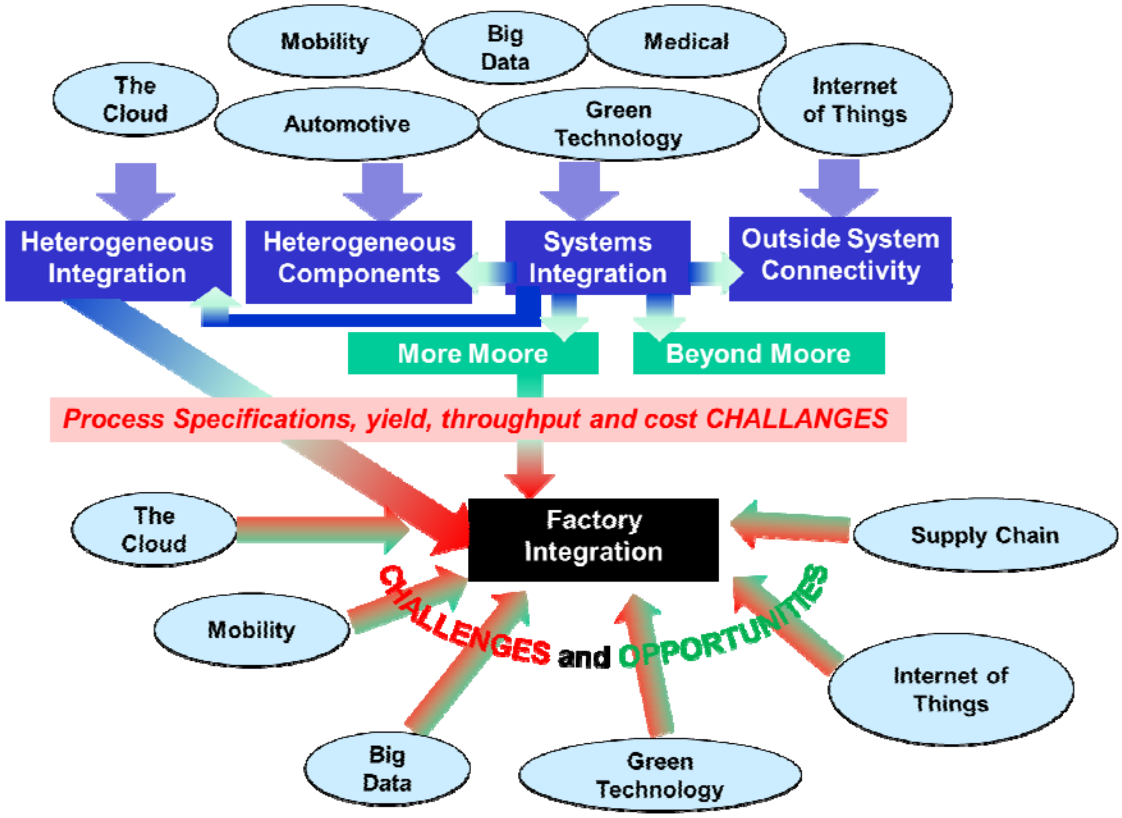

Figure FI-1: Societal forces impacting challenges and opportunities in FI

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 semiconductor 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. *Migration of Factory Ecosystem from Mobile Era to IoT and Large Memory for Big Data*—According to Bell's Law every ten years, a new generation of technology appears, and mobile will be succeeded by the era of IoT and sensors. The predictions show a very large number of these devices produced at a very low cost. The forecasts suggest a continued fast rate of bit and transistor count growth. In this era, significantly more memory will be provided in the cloud, and the relative growth of microprocessor and logic may slow

by comparison. One immediate impact of this is predicted by Industry 4.0, namely, the Smart Factory and Smart Manufacturing.[1]

5. *Significant productivity improvement either by next wafer size manufacturing paradigm or through 300mm manufacturing technology improvement*—the industry needs to review the productivity losses in 300mm and improve prior to the next wafer size transition so to make this transition more cost-effective.

6. *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.

7. *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 vertical (e.g., internal tool fault detection) 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.

8. *Supply chain integration and 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 yield correlation, warranty traceability and cost reduction).

9. *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.

10. *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 FDC, PdM, APC, etc. at more granular levels (e.g., lot based to single wafer oriented for maximizing productivity), protection of data and IP within data will become more complicated and sometimes contradictive 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, OEMs and 3rd party suppliers

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[1] *See for example*

[1] Project of the Future: Industry 4.0 (Germany Ministry of Education and Research, http://www.bmbf.de/en/19955.php.)

[2] INDUSTRIE 4.0 – Smart Manufacturing for the Future (Germany Trade & Investment , http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Brochures/Industries/industrie4.0-smart-manufacturing-for-the-future-en.pdf)

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 factory operation issues

d. Achieving balance between data availability (e.g., log-data for improved equipment performance) and IP protection of Device Manufacturer 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 antivirus software operations

g. Protection of the facility's instrumentation and control systems from attack

h. Protecting quality and integrity of Big Data and application of Big Data analytics to identifying security issues

i. Protecting fab and equipment operation control systems from unauthorized operation or alteration from both inside fab and outside

11. *Challenges and Issues associated with increased integration of FI with Yield Enhancement (YE) and Environmental Safety and Health (ESH) solutions* — As noted above FI challenges and solutions directly impact aspects of ESH and YE 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.

2 BACKGROUND INFORMATION

2.1 ACRONYMS

The following acronyms are used in this chapter:

Table FI-1 Acronyms Used in this Chapter

Acronym	***Meaning***	***Acronym***	***Meaning***
AMC	Airborne Molecular Contamination	NPW	Non-Product Wafer
AMHS	Automated Material Handling System	NTP	Networked Time Protocol
APC	Advanced Process Control	OEM	Original Equipment Manufacturer
ARP	Augmenting Reactive with Predictive	PCS	Process Control Systems
BD	Big Data	PdM	Predictive Maintenance
CIP	Continuous Improvement Program	PE	Production Equipment
CSA	Control Systems Architectures	PHM	Prognostic Health Management
DFM	Design for Manufacturing	PIC	Physical Interface and Carriers
DS	Decision Support	PM	Preventative Maintenance
EFEM	Equipment Front-End Module	PPM	Predictive and Preventative Maintenance
EFM	Equipment Front-End Module	PTP	Precision Time Protocol
EHM	Equipment Health Monitor	R2R	Run-to-Run (control)
EMI	ElectroMagnetic Interference	ROI	Return On Investment
EOW	Equipment Output Waste	RUL	Remaining Useful Life
ESA	ElectoStatic Attracted	SCOR	Supply Chain Operations Reference
ESD	ElectroStatic Discharge	SEMI	Semiconductor Equipment and Materials International
ESH	Environmental Safety and Health	SHL	Super Hot Lots
EUV	Extreme UltraViolet	SiC	System in a Package
FC	Fault Classification	SMC	Surface Molecular Contamination
FD	Fault Detection	SOAP	Simple Object Access Protocol, Service Oriented Architeure Protocol
FDC	Fault Detection and Classification	SoC	System on a Chip
FI	Factory Integration	SoS	Software as a Service
FICS	Factory Information and Control System	SPC	Statistical Process Control
FO	Factory Operations	TR	Technical Requirements
FP	Fault Prediction	TWG	Technical Working Group
IDM	Integrated Device Manufacturer	UPW	Ultra-Pure Water
IM	Integrated Measurement	VM	Virtual Metrology
IP	Intellectual Property	W2W	Wafer-to-Wafer (control)
ISMI	International SEMATECH Manufacturing Initiative	WIP	Work in Process
ISO	International Standards Organization	WIW	Within Wafer (control)
ITWG	ITRS Technology Working Group	WTW	Wait Time Waste
MES	Manufacturing Execution System	XML	eXtensible Markup Language
MHS	Material Handling System	YMS	Yield Management System
MSL	Maximum Forseeable Loss		

2.1 STANDARDS

A number of standards fall within the scope of the FI chapter that are important to the realization of the FI roadmap. 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 FI-2 Standards Important to the Factory Integration Roadmap

Number	Title
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
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 Products Recipe Tasks
SEMI E171	Predictive Carrier Logistics
SEMI E30	Generic Model for communication and Control of Manufacturing Equipment (GEM)
SEMI E33	Specification for Semiconductor Manufacturing Facility Electromagnetic Compatibility
SEMI E37	High-Speed SECS Message Services (HSMS)
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 Documention
SEMI E78	Electrostatic Compatibility – Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment
SEMI S2	Environmental, Health, and Safety Guidline for Semiconductor Manufacturing Equipment
SEMI S23	Guide for Conservation of Energy, Utilities and Materials Used by Semiconductor Manufacturing Equipment

3 SCOPE

3.1 OVERVIEW

Semiconductor manufacturing extends across several manufacturing domains. FI's scope is wafer manufacturing or fabrication in front-end and back-end. In addressing the evolution of FI, the ITRS community realized that FI challenges and solutions directly impact aspects of the Environmental Safety and Health (ESH) and Yield Enhancement (YE) roadmaps, and requirements of ESH and YE roadmaps placed requirements and provide direction for FI. Thus it became clear that improved integration of these three areas was needed; this is a fundamental goal of the FI Focus area.

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 (3) provides for improved integration of ESH and a portion of YE objectives, requirements and solution. The scope of the roadmap is summarized in Figure FI-2.

3.2 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 four functional areas, corresponding to physical boundaries that are required to perform semiconductor manufacturing. They are Production Equipment (PE), Material Handling Systems (MHS), Factory Information & Control Systems (FICS), and, Factory Facilities (Facilities). With the advent of the information age the Factory Integration 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 Factory Integration roadmap chapter has been restructured to capture this paradigm shift. Specifically, additional functional areas have been added to 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), Environmental Safety and Health (ESH), and Yield Enhancement (YE). 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 ten 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 (FO)* provides many of the key drivers of requirements and actions for the other four thrusts 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.
- *Production Equipment (PE*) covers process and metrology equipment and their interfaces to other factory elements. It also focuses on addressing equipment related productivity losses.
- *Material Handling Systems (MHS)* 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 (FICS)* 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 (ARP)* 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 (BD)* 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 (CSA)* 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 and Health (ESH)* relationship to FI addresses a trend noted in the move to ITRS 2.0, namely the closer relationship and interdependency of many issues and solutions in ESH with FI. This includes how many FI tools can be used to provide or enhance ESH solutions, and how ESH solutions will be more fully integrated in the factory.
- *Yield Enhancement (YE)* relationship to FI addresses a trend noted in the move to ITRS 2.0, namely the closer relationship and interdependency of many issues and solutions in YE with FI. This includes how many FI tools such as prediction can be used to improve yield and how yield objectives will be more closely integrated into FI solutions.

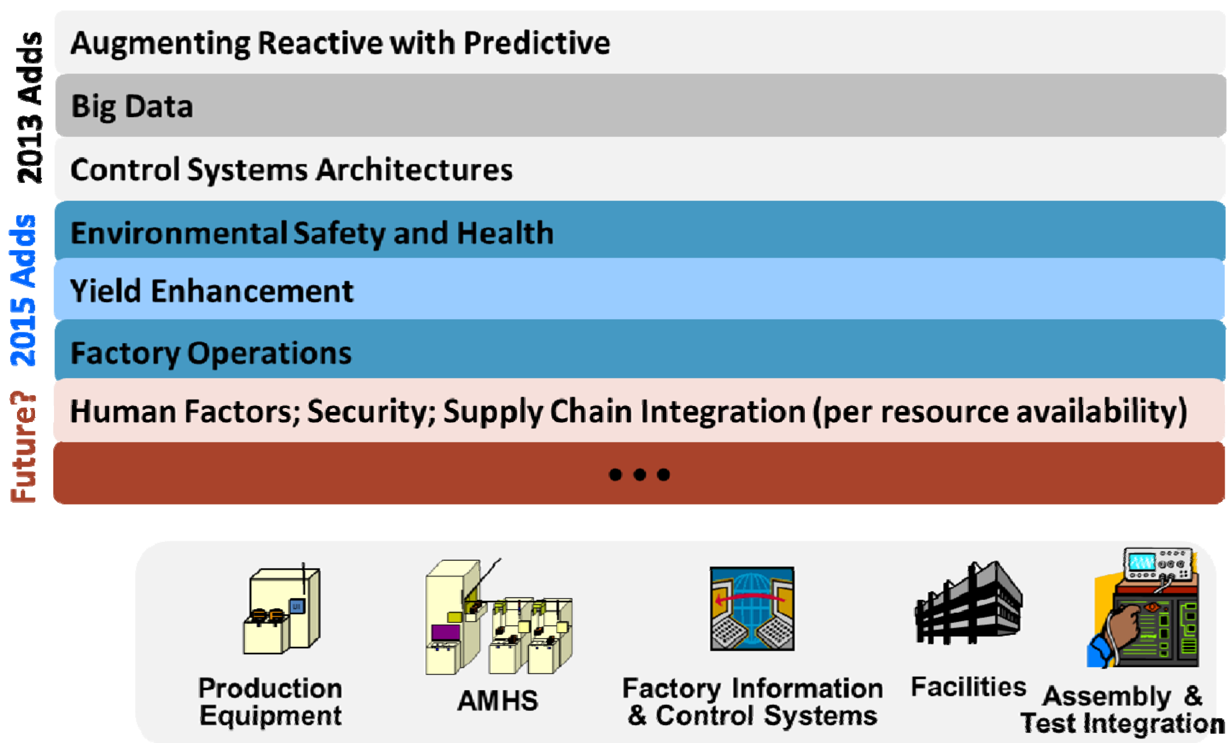

Figure FI-2 Factory Integration Scope

In addition to these functional areas, the Factory Integration chapter also addresses the cross-cut issues that cut across all of these functional areas.

3.3 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 (3) provides for improved integration of ESH and a portion of YE objectives, requirements and solution (see below).

Improving integration of FI with Environmental Safety and Health (ESH), and Yield Enhancement (YE)— In addressing the evolution of FI, the ITRS community realized that FI challenges and solutions directly impact aspects of the ESH and YE roadmaps, and requirements of ESH and YE roadmaps placed requirements and provide direction for FI. Thus it became clear that improved integration of these three areas was needed; this is a fundamental goal of the FI Focus area.

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. 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 300mm and 450mm. Other FI issues such as challenges in AMHS and facilities will have solution components that are similar for 300mm and 450mm, but other components that are different. This distinction is delineated in this chapter.

Impact of non-nano-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 nano-manufacturing FI roadmap. Thus the FI roadmap will increasingly define the roadmap for many technology solutions through reference to general manufacturing trends.

4 WHAT IS NEW WITH THE 2015 EDITION

4.1 ADDITION OF SECTIONS ON ENVIRONMENTAL SAFETY AND HEALTH (ESH) AND YIELD ENHANCEMENT (YE) AS THEY RELATE TO FI

As part of the move to ITRS 2.0, sections have been added to the 2015 FI chapter to describe the strengthening relationship between ESH, YE and FI. Note that the FI sections complement and reference the full ESH and YE chapters that can still be found in the ITRS. The scope of this integration and the plan for migration to ITRS 2.0 is described in the white paper “Factory Integration Focus Area” (see www.itrs2.net).

4.2 ENHANCEMENT OF BIG DATA SECTION

A major addition to the 2013 edition was a new sub-chapter on Big Data (BD). The fab is continually becoming more data driven and requirements for data volumes, communication speeds, quality, merging, and usability need to be understood and quantified. Challenges and solutions associated with these issues are provided in the BD sub-chapter. For 2015 this chapter has been enhanced to include more information on the migration to Hadoop or similar big data-friendly ecosystems and algorithm advancements to support the “value” aspect of big-data.

4.3 Enhancement of Augmenting Reactive with Predictive Section

A major addition to the 2013 edition was a new sub-chapter on Augmenting Reactive with Predictive (ARP). Solutions such as predictive maintenance, predictive scheduling and planning, virtual metrology and yield prediction are all part of this evolution to prediction. It is expected that all of these technologies will begin to play a significant role in productivity improvement and waste reduction over the next seven years, with the roadmap indicating a migration towards an integrated predictive extension of all systems. Because prediction is important to all aspects of factory integration, the basic ARP roadmap concepts are moved to the APR sub-chapter, with specific ARP items retained in the respective sub-chapters. In 2015 the ARP section has been enhanced to include information on the role of equipment in providing prediction information and capabilities.

4.4 Expansion of Narrative on Supply Chain Integration, FI for Assembly and Test, and Security

Tighter integration of FI with the supply chain, both upstream and downstream, will be required to better achieve directives of productivity, quality and cost reduction, by supporting concepts such as lean manufacturing, yield correlation, part tracking (e.g., to pursue warranty recall isolation), and coordinated ESH directives. As the importance of supply chain integration grows, its specification in the ITRS FI chapter is increasing accordingly. In this roadmap, key challenge and solution areas for supply chain integration are overviewed; in the future it is expected that "Supply Chain Integration" will become a function area of FI. A distinct environmental (ESH) initiative in Multi-Stakeholder Life Cycle Risk Assessment of materials used in the Semiconductor Industry is underway as described in Fig ESH 2 of our ESH section of the ITRS Roadmap.

The FI chapter has traditionally been focused on front-end processing, however with the advent of More-than-Moore, heterogeneous integration and the related impacts on yield and need for single device traceability, tighter integration with assembly and test is now required. Further, many of the ITRS FI concepts defined for front-end processes can be extended to assembly and test. The FI chapter is evolving to capture this increased importance of integration of assembly and test. In this roadmap, key challenge and solution areas for assembly and test integration are overviewed; in the future it is expected that "Assembly and Test Integration" will become a function area of FI.

Security is an increasingly important topic that permeates through all aspects of manufacturing disciplines. While it is expected that a security roadmap in semiconductor manufacturing will rely heavily on advancements in other manufacturing areas, a framework for security in semiconductor 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 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. Future roadmap versions will seek to better define an evolving FI security framework.

4.5 Enhancement of Production Equipment (PE) Specification

The Production Equipment (PE) specification has been enhanced with a new section focusing on communication between host and PE in support of PE energy and utility savings. In the future, this specification may extend to the communication with subsystems inside the equipment. The specification is aligned with work being done in SEMI standards.

4.6 Advanced Process Control as an Equipment and Fab Design Requirement

Advanced Process Control (APC), which includes run-to-run process control, fault detection, fault classification, fault prediction and statistical process control technologies, and often leverages integrated metrology for process control) has evolved past the state of being an add-on capability to being a design-in requirement both at the equipment and fab-wide level. This does not mean the equipment will necessarily have embedded APC, but it does mean that the equipment will need to leverage APC capabilities (either internally or externally) to meet productivity and cost reduction targets. This is further emphasized in 2015 with the addition of a Control Systems Architecture (CSA) sub-chapter in FI.

5 Difficult 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.

Table FI-3 Factory Integration Difficult Challenges

Difficult Challenges through 2023	***Summary Of Issues***
1. Responding to rapidly changing, complex business requirements	• Increased expectations by customers for faster delivery of new and volume products (design → prototype and pilot → volume production) • Rapid and frequent factory plan changes driven by changing business needs • Ability to load the fab within manageable range under changeable market demand, e.g., predicting planning and scheduling in real-time • Enhancement in customer visibility for quality assurance of high reliability products; tie-in of supply chain and customer to Factory Information and Control Systems (FICS) operations • 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 • 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.
2. Managing ever increasing factory complexity	• Quickly and effectively integrating rapid changes in process technologies • Complexity of integrating next generation equipment into the factory • 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, (3) managing load on tools • Manufacturing knowledge and control information needs to be shared as required among factory operation steps and disparate factories in a secure fashion • Need to concurrently manage new and legacy FICS software and systems with increasingly high interdependencies • Ability to model factory performance to optimize output and improve cycle time for high mix factories • Need to manage clean room environment for more environment susceptible processes, materials, and, process and metrology tools • 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 • Comprehending increased purity requirements for process and materials • 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. • Communication protocols developed for semiconductor manufacturing are not aligned with trends in information technology communication such as web services. • 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. • Addressing factory integration challenges to assess and integrate EUV systems into the factory infrastructure • Address process hazard management issues

	• Addressing Airborn 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). • 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) • Linking yield and throughput prediction into factory operation optimization; incorporating incoming disturbances such as power and materials purity variability into the prediction equation. • Achieving real-time simulation of all fab operations as an extension of existing system with dynamic updating of simulation models • Understanding and managing queue times (time between operations/segments) and production of product within those times to achieve acceptable product quality • Managing and protecting IP, avoiding security issues such as malware attacks, and protection of the facility's instrumentation and control systems from attack • 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 • Achieving compatibility of existing systems that are largely reactive with emerging predictive paradigms of operation, such as Predict Maintenance and yield prediction • Addressing shifting focus from line width pitch shrinks, to 3D and emerging disruptive technologies
3. Achieving financial growth targets while margins are declining	• Developing metrics on performance of factory integration systems and understanding how these metrics translate to factory financial information • 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
4. Meeting factory and equipment reliability, capability, productivity and cost requirements per the Roadmap	• 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 (R2R control, FD , FC and 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 NPW (non-product wafers) 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, FD and C criteria, equipment engineering best known methods
5. Cross leveraging factory integration technologies across boundaries such as 300mm and 450mm to achieve economy of scale	• Addressing the potential data explosion and other big data issues associated with crossing a technology boundary • Ensuring that we take 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. 450mm era: Effecting architectural and other changes as necessary at an affordable cost to maintain or improve wafer-throughput-to-footprint levels in migration to 450mm
6. Addressing unique challenges in the move to 450mm (where 300mm technologies cannot always be leveraged)	• Understanding and addressing 450mm 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 must be leveraged to achieve 450mm quality and production goals.
Difficult Challenges Beyond 2023	***Summary of Issues***
1. Meeting the flexibility, extendibility, and scalability needs of a cost-effective, leading-edge factory	• 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 450mm 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.

2. Increasing global restrictions on environmental issues	• Addressing the move towards global regulations • Developing methods for increasing material reclamation • Proactively addressing future material shortages, such as non-renewable chemicals
3. Post-conventional Semiconductor manufacturing uncertainty	• 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

6 TECHNOLOGY REQUIREMENTS

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

Table FI-4 provides a summary of key focus areas and issues for each of the factory integration functional areas beyond 2015.

Table FI-4 Key Focus Areas and Issues for FI Functional Areas Beyond 2015

Functional Area	***Key technology focus and issues***
Factory Operations (FO)	1. Systematic productivity improvement methodology of the current “lot-based” manufacturing method prior to 450mm insertion 2. Challenges in moving to smaller lot and single wafer aspects of factory operations 3. Interdisciplinary factory productivity improvement method such as systematic factory waste visualization of manufacturing cycle times and factory output opportunity losses 4. Extendable and reconfigurable factory service structure
Production Equipment (PE)	1. 450mm production tool development 2. for integration into the factory information system; supporting bridge capabilities to 450mm 3. Determining context data set for equipment visibility 4. Equipment health monitoring (EHM) and fingerprinting to support improved uptime. 5. Run rate (throughput) improvement and reduction of equipment output waste that comes from NPW and other operations 6. Improving equipment data quality and data accessibility to support capabilities such as APC and e-Diagnostics 7. 7) 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 equipment health monitoring (EHM) and reporting. 8. Migrate to a mode of operation where APC is mandatory for proper execution of process critical steps 9. 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 (AMHS)	1. Reduction in average delivery times, 2. Avoid tool starvation 3. More interactive control with FICS and PE for accurate scheduled delivery, including (predictive) scheduling/dispatch, maintenance management, and APC 4. Aim for continuous improvement in reliability and corresponding minimization of downtime 5. 450mm specific AMHS issues 6. AMHS interaction with other wafer transport and storage systems such as sorter and load port
Factory Information and Control Systems (FICS)	1. Increased reliability of FICS systems such as maintenance management 2. Increased FICS performance for more complex factory operation, such as decision speed and accommodating larger data sets 3. Enhanced system extendibility including extensibility across fabs 4. Utilize FICS information to achieve waste-reduction (e.g., wait-time waste, unscheduled downtime, and

	wafer scrap) and sustainability (e.g., resource conservation) 5. Facilitate enhancement of reactive with predictive approach to operations (e.g., planning and scheduling, maintenance, virtual metrology and yield prediction and feedback) 6. Determining approaches to control (e.g., distributed versus centralized) and when to institute disruptive control systems changes (e.g., at 450mm introduction) 7. Achieving minimum downtime, seamless transition, and uninterrupted operations in production throughout the software upgrade process
Facilities	1. Continuous improvement to maintain facility systems viability 2. Minimization of facilities induced production impacts 3. Facility cost reduction 4. Determining and addressing emerging technology requirements such as AMC (Airborne Molecular Contamination) control, 450mm, 3D, etc. 5. Maintaining safety in facilities operations (e.g., in response to a seismic event) 6. Even more aggressive focus on environmental issues and optimization to environmental targets. Facility utility reduction
Augmenting Reactive with Predictive (ARP)	1. Improved data quality to support effective prediction 2. Prediction solutions tied to application financials for optimized benefit 3. Integration of predictive functions (data, algorithm, user interface, and cross-leveraging capabilities) as an augmentation of existing systems 4. Move to real-time simulation of all fab operations occurring as an extension of existing system with dynamic updating of simulation models
Big Data (BD)	1. Optimization of data storage volumes and data access to achieve FI objectives and enable applications to plug and play 2. Speed improvement in collecting, transferring, storing and analyzing data 3. Software optimization to gather data from multiple systems and sources for analysis resulting on actionable decisions 4. 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 5. Migrating from relational data storage infrastructure to largely big data friendly infrastructure such as Hadoop, along with small relational component. 6. Algorithm development and implementation to support emerging capabilities such as predictive and machine learning
Control Systems Architecture (CSA)	1. Addressing evolutionary aspects of control system and control system architectures such as granularity, speed, quality, and capability. 2. 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 3. Addressing the framework to integrate monitoring and closed loop control tied to all semiconductor manufacturing key performance indices – including engineering and manufacturing control levels. 4. Addressing the capability to integrate with supply-chain framework for value chain control.
Environmental Safety and Health (ESH)	1. The roadmapping process will continue to quantify factory environmental factors 2. Roadmapping from 2015 will include, new materials, sustainability and green chemistry 3. Provide proactive engagement with stakeholder partners and reset strategic focus on the roadmap goals. 4. Continue focus on factory, and supply chain safety for employees and the environment
Yield Enhancement (YE)	1. The road mapping focus will move from a technology orientation to a product/application orientation. 2. Airborne molecular contamination (AMC), packaging, liquid chemicals and ultra-pure water were identified as main focus topics for the next period. 3. Electrical characterization methods, Big Data and modeling will become more and more important for yield learning and yield prediction.

7 Factory Operations

7.1 FO Challenges

7.1.1 *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 ~~its~~ 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 ITWG has concluded that such metrics are expressed as productivity waste. As of 2011, FI adopted Waste Reduction as one of the focus area topics. Readers should refer to the Focus Areas section for more detail.

7.1.2 *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 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, WIP and line throughput are becoming more important.

7.1.3 *High Granularity and Proactive Services*

Finer material handling operation is required due to strong demand on cycle time reduction. More real-time control of production equipment (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 equipment health monitor (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.

7.1.4 *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 ~~so~~ 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.

7.1.5 *Integration of Facilities Requirements into Factory Operations*

The increasing pressure of achieving goals such as environmental, safety and 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 sub-chapter.

7.1.6 SIGNIFICANT PRODUCTIVITY IMPROVEMENT

A major change in the FO Technology Requirements Table is the planned insertion of significant productivity improvement of the current technology preceding the 450mm insertion. Based on the preceding 5-year discussion the FI ITWG came to a conclusion that the industry is to work on systematic productivity waste reduction in order to maximize the current manufacturing technology productivity.

This waste reduction is to meet 30% 300mm 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.

7.1.7 FUTURE MANUFACTURING REQUIREMENTS

A large scale productivity improvement scheme (formerly known as "300mm Prime") has been sought in the industry since 2007. It was known as 300mm Prime technology. Today, this technology guidance is provided primarily by two resources: (1) the ISMI Unified 300mm and 450mm Guidelines published in 2007[2], (2) the G450C guidance for production equipment and (3) G450C general statements on Factory Integration in industry briefings.

The industry can focus on common technology development for 300mm and 450mm. 450mm factories would benefit by adaption of improved technology validated for 300mm. FO metrics were reviewed and modified to reflect the future manufacturing, including 450mm needs. Industry should study the implication of the FO Technical Requirements (TR) Table and other FI TR Tables.

7.1.8 WASTE REDUCTION METRICS

The 2011 FI ITWG decided to introduce two waste reduction metrics; Wait Time Waste (WTW) and Equipment Output Waste (EOW), into the FO TR Table 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 ITWG's 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.

7.1.9 CYCLE TIME METRICS

The most significant factory operational metrics are a pair of cycle time metrics. This is not only because cycle time recently is gaining more importance both in high mix and low mix manufacturing, but also it is considered to represent how the factory is operated. One of the cycle time metrics is for 25 wafer lot size, and the other one is for 12 wafer lot size. This set of requirement metrics can differentiate between two kinds of factories: low mix fab and high mix fab, respectively.

With such characterization along with the lot size it would be possible to determine if there is any pronounced deterioration due to the varying or small lot sizes. This would promote factory performance improvement in dynamic conditions and the relevant factory operations as well as equipment availability and agility. Such visualization of the dynamic factory characteristics is also effective and applicable to low mix production characteristics.

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[2] *See "ISMI Next Generation Factory Vision," Unified 450mm/300mmPrime Factory Guidelines Workshop, ISMI, (July 2007).*

7.1.10 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" sub-chapter. 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.

7.1.11 450MM RELATED METRICS

450mm specific requirement has been discussed in order to seek any FO TR Table items. Although the factory services requirements specific to 450mm manufacturing have not been identified in the 2015 edition, 300mm factory services are expected to be applicable to 450mm and so do the FO requirements captured. There may be different requirements in 450mm 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 litho exposure tools and inspection tools inevitably have a longer cycle times compared to the similar 300mm tools (since the process time is proportional to the area of treatment (beamscan).

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

7.1.12 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 twenty-five (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 semiconductor 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 (1) wafer throughout the fab. Thus, both single wafer processing and single wafer transport are employed. It is unclear whether the industry will adopt the single wafer manufacturing system paradigm. The FI TWG may consider eliminating this as a roadmap item in the future.

FO roadmaps and FI roadmaps in general must address the challenges and potential solutions associated with the operational paradigms that are adopted.

7.1.13 ASSEMBLY TEST INTEGRATION

As we move forward in semiconductor 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 & test operation and integration with each other and front-end operations. In the past semiconductor 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 which 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 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 & 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 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 FE into and with the BE.

7.1.14 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 FI-3)[3]. Besides continuous improvement of factory deviation control to improve manufacturing performance, there are other sources of deviation from the overall supply chain into factory which also require good control to reduce the deviation and improve the complexity management. There are several key parameters which 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 (for example: MAPE), there are no known methods to assure quality of demand forecast.

2. Demand Deviation: The semiconductor 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: Semiconductor devices could be packed into high-value added packages and installed into higher-value product. For example: the chips could be packed into the IGPT 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, components and final product are

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[3] *One source of information on SCOR is the APICS Supply Chain Council, which "advances supply chains through research, benchmarking, and publications". www.apics.org*

important. It requires a robust FI system to automatically collect, store and trace all supply chain operations.

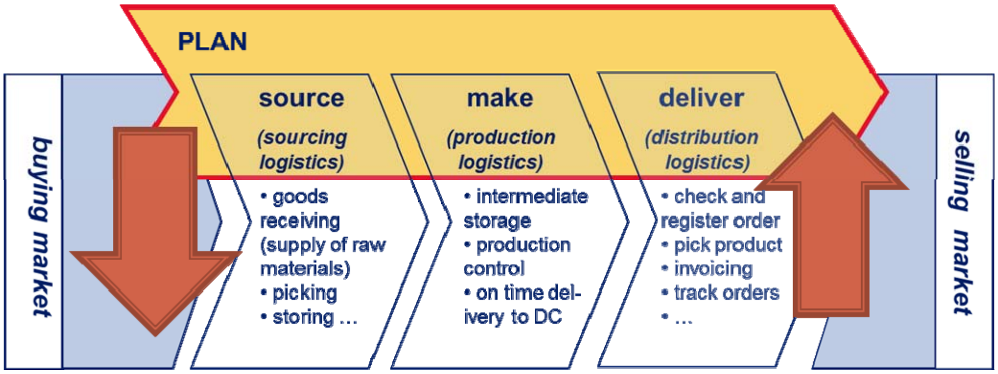

Figure FI-3 Supply Chain Model SCOR

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 semiconductor 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.

7.2 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.

Table FI-5 Factory Operations Technology Requirements

Year of Production	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
DRAM ½ Pitch (nm) (contacted)	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7	??	??
Wafer Diameter (mm)	*300*	*300*	*300*	*300*	*300*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*
Factory Cycle Time (days/ mask layer) of product lots																
for 25 wafer lots, 300mm	1.37	1.33	1.31	1.29	1.28	1.27	1.27	1.27	1.26	1.26	1.26	1.26	1.26	1.26	??	??
450mm, XX wafer lots				1.61	1.60	1.59	1.59	1.58	1.58	1.58	1.58	1.58	1.57	1.57	??	??
Super hot-lot (average top 1% of lots)	0.31	0.30	0.30	0.30	0.30	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.28	0.28	0.28	0.27
Factory Wait Time Waste (WTW) (days /mask layer)																
WTW for 25 wafer lots, 300mm	0.91	0.80	0.72	0.63	0.54	0.47	0.40	0.34	0.29	0.24	0.20	0.16	0.13	0.10	TBD	TBD
WTW for 450mm, XX wafer lots				0.54	0.48	0.42	0.33	0.27	0.24	0.24	0.18	0.18	0.18	0.18	TBD	TBD
X factor				2.50	2.50	2.20	2.20	2.00	2.00	2.00	1.80	1.80	1.80	1.80	TBD	TBD
Factory Equipment Output Waste (EOW)	25%	25%	25%	25%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	TBD	TBD
Bottle neck equipment																
Utilization	94%	94%	94%	94%	95%	95%	95%	95%	94%	94%	94%	94%	94%	94%	TBD	TBD
Availability	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	TBD	TBD
Average delivery time (minutes); Same for 300mm and 450mm	4	4	4	4	3	3	3	3	4	4	4	4	4	4	4	4
Per cent of NPW to product wafers	23%	21%	20%	18%	16%	15%	15%	13%	12%	11%	10%	10%	< 10%	<10%	<10%	<10%
Overall NPW activities versus production wafers activities (wafer move count ratio)	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%	<5%

Manufacturable solutions exist, and are being optimized (white)
Manufacturable solutions are known (yellow)
Interim solutions are known (yellow with red diamond)
Manufacturable solutions are NOT known (red)

Explanation of Items for Factory Operations Requirements

Item	*Explanation*
Wafer diameter	All the values are for 300mm wafer. Values beyond 2014 will be amended as more 450mm requirements become available. Factory cycle time, for an example, is thought to become considerably longer than 300mm due to longer process time of beam equipment (litho, ion implantation, inspection, etc.) for 450mm
Factory cycle time per mask layer (days) 25 wafer lot *Factory cycle time per mask layer (days) 12 wafer lot*	A key metric of time to money and measure of total time to process is a lot cycle time per mask layer. For example, if a process has 30 masking layers, and cycle time per mask layer is 1.5, then total factory (fabrication) cycle time based on 25 wafers per lot is: 30 × 1.5 = 45 days. Cycle time for a 12 wafer lot would be calculated accordingly.
Single wafer processing	Processing one wafer at a time through the process chamber, independent of lot size.
Super hot-lot (average top 1% of lots) factory cycle time per mask layer	Assume ~ 5 wafers per lot. Factories typically prioritize these lots over any other lots, tools downstream are reserved for the super hot lot. As a result, the cycle time for super hot lots is considered as the fastest speed of that fab line and for that product.
Wait Time Waste (days): 25 wafers in a carrier	Factory Wait Time Waste can be expressed as follows; WTW (average) = Σ (wait time)/ N [day/mask layer], Where N: # of total masks. Since the factory cycle time for SHL can represent the least Wait Time Waste cycle time, the equation can be rewritten with using cycle time values in FO TR Table as the difference between the factory cycle time of

	production lots (of 25 wafers) and the super hot lot cycle time. $= \Sigma\ (CT_{25}\text{-}CT_{SHL})$ [days/mask layer] where; CT : Cycle Time for production lots [days/mask layer] CT_{SHL} : Cycle Time for super hot lots/mask [days/mask layer] The subtraction needs to be compensated with the number of wafers between production lots and super hot lots. Waite Time Waste indicator is adapted for more direct visualization of waste or room to improvement in terms of factory cycle time.
Wait Time Waste (days): 12 wafers in a carrier	Waite Time Waste for 12 wafer lot would be calculated accordingly as description above.
X factor	X-factor is the total cycle time (queue time + hold time + raw process time + travel time) divided by the Raw Process Time (RPT). Raw process time for a lot at a tool is the time it takes to process a lot on the tool. Generally this time will be from when the tool starts to process the lot (and thus cannot be moved to another tool for processing) until the lot is finished and can be moved to the next operation. X-factor is shown for continuous improvement. Actual X-Factor values will depend heavily on WIP and raw process time for a given process technology or generation. X factor deteriorates if raw process time is shorten. X factor improves with lower WIP.
Equipment Output waste (%): 25 wafers in a carrier, high mix production	Equipment Output Waste is defined as normalized difference between instantaneous throughput and throughput averaged over a period that contains a usual production equipment usage cycle that includes maintenance procedure (such as 1 week to 1 month period). The instantaneous throughput (TH_0) is such that observed during continuous runs of wafers without process changes before and after. EOW for a single equipment can be defined as; $EOW = (TH_{25}-TH_0)/TH_0 \times 100$ [%] Where TH_{25} is averaged throughput in a 25 wafers per a carrier manufacturing environment. Factory EOW is defined as a total sum over all the production tools used for that product divided by N the # of total tools [%]. Factory $EOW = \Sigma((TH_{25}-TH_0)/ TH_0) / N \times 100$ [%] FI ITWG conducted a preliminary survey on limited production tools. Factory EOW may be refined as more EOW data become available. The values are for 25 wafers in a carrier, high mix production.
High mix operation	High mix is defined as the followings: • Running more than three technology generations concurrently in the same Fab • Running more than ten process flows within the same technology generation • Running more than 50 products concurrently through the Fab • Many of small lots of 1–10 wafers in size • Running an average of less than 50 wafers between reticle changes for each lithography expose equipment • Lot starts are based on customer orders. There is a daily variation in the number of lots you start with different products and process flows • At least five large volume products (product flows) with no one product having >50% of production volume
Bottle neck equipment utilization and availability	A bottleneck tool usually refers to a lithography tool. Availability is defined in SEMI E10 as "the probability that the equipment will be in a condition to perform its intended function when required." Utilization is defined in SEMI E10 as "the percentage of time the equipment is performing its intended function during a specified time period." Availability includes setup, idle and processing time, utilization is considered as time directly adding value of constraint equipment (usually lithography tools) measured in % without sacrificing cycle time. Constraint equipment utilization (normally lithography) is the pulse of the Fab and usually determines the output capacity.
Average delivery time (minutes)	The time begins at the request for carrier movement from the factory system and ends when the carrier arrives at the load port of the receiving equipment.
Per cent of NPW to product wafers	NPW are the non-production wafers includes dumay wafer, process qualitification wafer and equipment calibration wafers and so on. And the percentage of NPW to product wafers is the ratio of NPW wafers count compared to total production wafer counts in production floor at any time.
Overall NPW activities versus production wafers activities	Total equipment-driven non-production wafers processed on equipment divided by total production wafers processed on equipment, for the same time period, assuming that equipment is running at designed availability and planned utilization rates. Typical non-production wafers include test wafers, monitor wafers, calibration wafers. The requirement as shown is for all production (non-metrology) equipment.
Bidirectional equipment functional visualization	Equipment functional performance should be bi-directionally visible to validate equipment capability performance at the time of equipment delivery to both the equipment supplier and the user, and it should be visible to the user during that equipment is being used for production. Bidirectional visibility ensures equipment performance quality traceability and efficient technical information exchange between relevant equipment users and suppliers. Such bi-directionality is assured by standardized equipment data models and quality. Partial implementation means such as the equipment data available through SECS where equipment capability behaviors are usually not intended to be visualized. So-called second equipment data port is expected to provide such visibility.

Single wafer manufacturing system	Wafer manufacturing system that utilizes carriers with extremely small wafer capacities, or, in some cases, handles individual wafers is thought to be an enabler for the least WIP manufacturing method. 2015 Factory Integration roadmap captures such manufacturing method to become feasible due to the strong demand on very short product cycle time for 2015 implementation. The factory cycle time is expected to be reduced significantly although more future study is needed to represent appropriate cycle time requirements that meet the cost criteria.

8 PRODUCTION EQUIPMENT

8.1 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 300mm transition standardization. Further the factory operation driven metrics have been moved to the FO TR Table for clarity. The PE (Production Equipment) TR Table has metrics only on availability for process tools and metrology tools together with electric statics field requirements.

8.2 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 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 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.

8.3 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, predictive maintenance (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 TR Table is also responsible to the intended significant productivity improvement preceding 450mm insertion. Although the FO TR Table owns the EOW requirement EOW metrics may be broken down to EOW for the PE section to address waste reduction in 2011 and after. The waste due to non-product wafer (NPW) operations and the frequent recipe changes can be the killer of EOW especially in high product mix operations. The information of NPW operations needs to be made visible.

8.4 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 300mm to 450mm 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 sub-chapter). 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 be 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 FI-6 Context Data Importance for Good Equipment Visibility

Data Usages	***Data Usage "Key" Information***	
	Equipment activity context	***Time stamp for host observation***
R2R control FDC, FICS data usages	■ *Tool name* ■ *Chamber index / STS* ■ *Processing index* ■ *Recipe ID* ■ *Recipe Step Number* ■ *Product ID*	Inter factory-level (Factory wide)
Tool-to-facility combination activity	■ *Tool name* ■ *Chamber index / STS* ■ *Eq status* ■ *Processing index* ■ *ID to indicate interactive control events*	Inter-Tool-level External sensors need their own time stamps
Additional sensor data utilization	*T.B.D.*	Conditional
Within-tool activity data utilization	■ *Task ID* ■ *Processing index / Wafer locations* ■ *Internal control events*	Intra-Tool-level +/- equipment heart beat frequency

8.5 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 it's 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 R&D (Research and Development) environments compared to HVM (High Volume Manufacturing) because it is likely that the wafer processing tools are likely 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 is 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 FI-4. 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 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.

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 innovate solutions is the preventive control of Airborne Molecular Contamination (AMC). Lastly, efficient and cost-effective equipment development will be a critical milestone in the industry transition to the next wafer processing size.

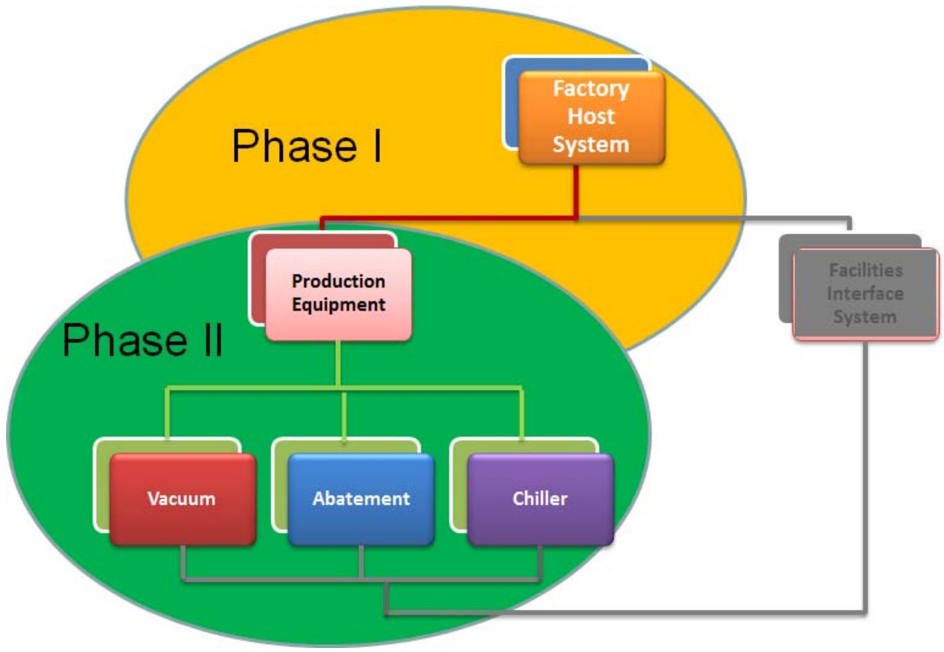

Figure FI-4 Phased scope of SEMI standards work to support PE energy savings

8.6 Data Integration in Production Equipment

As diagnostics and control of equipment processing becomes more critical in terms of (1) process targets, (1) 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 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.

8.7 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 potentially 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 while 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 semiconductor 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.

8.8 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 450mm as well as movement to new process materials will present challenges. The movement to 450mm 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 sub-chapter. 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.

Table FI-7 Production Equipment Technology Requirements

Year of Production	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
DRAM ½ Pitch (nm) (contacted)	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7	??	??
Wafer Diameter (mm)	*300*	*300*	*300*	*300*	*300*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*
Process equipment availability (A80)--300mm	>95%	>95%	>95%	>95%	>96%	>96%	>96%	>96%	>96%	>96%	>96%	>96%	>96%	>96%	>96%	>96%
Process equipment availability (A80)--450mm				93%	93%	> 93%	> 93%	> 93%	> 93%	> 93%	> 93%	> 93%	> 93%	> 93%	> 93%	> 93%
Metrology equipment availability (A80)--300mm	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%	>98%
Metrology equipment availability (A80)--450mm				> 95%	> 95%	> 96%	> 96%	> 96%	> 96%	> 96%	> 96%	> 96%	> 96%	> 96%	> 96%	> 96%
Maximum allowed electrostatic field on wafer and mask surfaces (V/m) for ESD prevention	2,600	2,200	2,000	1,800	1,550	1,400	1,300	1,100	1,000	900	775	700	650	550	TBD	TBD
Maximum recommended electrostatic field at chrome mask surfaces (V/m) for EFM	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Minimum equipment data output rates (Hz) from a tool	10Hz	10Hz	100Hz	100Hz	100Hz	100Hz	1kHz	1kHz	1kHz	1kHz	>1kHz	>1kHz	>1kHz	>1kHz	TBD	TBD
Pervasiveness of APC as an integral part of equipment design and operation	Partial	Partial	All	All	All	All	All	All	All	All	All	All	All	All	All	All
Pervasiveness of predictive technologies such as virtual metrology PdM, ~~PHM,~~ yield prediction and predictive scheduling in certain equipment components (e.g., vacuum, abatement, gas supply systems) feeding into overall equipment predictive solution, to support improvements such	Partial	Partial	Partial	Partial	Partial	Partial	All	All	All	All	All	All	All	All	All	All
Pervasiveness of Equipment Health Monitoring capability as a common health indication capability across tools	Partial	Partial	All	All	All	All	All	All	All	All	All	All	All	All	All	All

Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known
Manufacturable solutions are NOT known

Explanation of Items for Production Equipment Requirements

Item	*Explanation*
Process equipment availability (A80)	Availability is defined as 100% minus (scheduled downtime% + unscheduled downtime %). The metric in the table is the requirement for an 80% confidence (i.e., equipment is at or above this value 80% of the time) for each individual process (non-metrology) equipment, over a period of one week of 7 × 24 operations. Scheduled and unscheduled downtimes are defined in SEMI E10. Note: The value shown in the process equipment table is the minimum A80 value for all equipment - please refer to the Factory Operations requirements table for availability requirements specific to factory bottleneck equipment. Process equipment availability of 450mm is expected to approach that of 300mm over time.
Metrology availability (A80)	Availability is defined as 100% minus (scheduled downtime% + unscheduled downtime%). The metric in the table is the requirement for an 80% confidence (i.e., equipment is at or above this value 80% of the time) for each individual metrology equipment, over a period of one week of 7 × 24 operations. Scheduled and unscheduled downtimes are defined in SEMI E10
Maximum allowed electrostatic field on wafer and mask surfaces (V/m) for ESD (Electric static discharge) prevention	Refer SEMI standards E78 and E43 for measurement methods. This guidance does not apply to EFM prevention. (SEMI E78: Electrostatic Compatibility – Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment. SEMI E43: Guide for Measuring Static Charge on Objects and Surfaces.)
Maximum recommended electrostatic field at chrome mask surfaces (V/m) for EFM	EFM causes cumulative migration of chrome onto clear areas of the mask. Reducing the frequency of exposure to electric field, especially low level transients and alternating fields that are too weak to present an ESD risk, is just as important as reducing the field strength. Masks should not be connected to ground. Refer to SEMI Standard E163 for more details. 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. NB: Permanently reducing the humidity of a reticle is believed to reduce the rate of reticle degradation by EFM and also other continuously operating mechanisms (i.e. 193nm haze

	formation and the "Sun Effect").
Pervasiveness of predictive technologies such as virtual metrology PdM, yield prediction and predictive scheduling in certain equipment components (e.g., vacuum, abatement, gas supply systems) feeding into overall equipment predictive solution, to support improvements such as reduction in unscheduled downtime and improved yield.	Pervasiveness is defined as a percentage of tools and tool components that will benefit from the application that have been outfitted with all of these technologies or are providing data to support all of these technologies. Minimal is defined as less than 25%. Partial is defined as 25-75% and All is defined as greater than 75%.
Pervasiveness of Equipment Health Monitoring capability as a common health indication capability across tools	Pervasiveness is defined as a percentage of tools that will benefit from the application that have been outfitted with this technology or are providing data to support this technology Minimal is defined as less than 25%. Partial is defined as 25-75% and All is defined as greater than 75%.

9 MATERIAL HANDLING SYSTEMS

9.1 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. Automated Material Handling Systems (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 technology requirements table 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 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 prepositioning 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.

9.2 450MM

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.

Single wafer transportation or very small lot size transportation for lean manufacturing is to be investigated for the possible efficient implementations in areas such as between specific tool sets or a specific part of the process as shown in the long-term requirements.

Table FI-8 Material Handling Systems Technology Requirements

Table FI-8 Material Handling Systems Technology Requirements														
Year of Production	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*
DRAM ½ Pitch (nm) (contacted)	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7
Wafer Diameter (mm)	*300*	*300*	*300*	*300*	*300*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*
Transport E-MTTR (minutes) per SEMI E10	10	10	10	5	5	5	5	5	5	5	5	5	5	5
Storage E-MTTR (minutes) per SEMI E10	20	20	20	10	10	10	10	10	10	10	10	10	10	10
Transport MMBF (mean moves)	25k	35k	35k	50k	65k	65k	65k	65k	65k	65k	65k	65k	65k	65k
Storage MCBF (mean cycles)	100k	150k	150k	200k	300k	300k	300k	300k	300k	300k	300k	300k	300k	300k
Mean carrier removal time (sec)	30	25	25	20	20	20	20	20	20	20	20	20	20	20
Mean carrier delivery time (sec)	300	270	270	240	240	240	240	240	180	180	180	180	180	180
Downtime to extend system capacity when previously planned (minutes)	15	10	10	5	5	5	0	0	0	0	0	0	0	0
Time required to integrate process tools to AMHS (minutes per LP)	15	5	5	5	5	5	5	5	5	5	5	5	5	5

Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known
Manufacturable solutions are NOT known

Explanation of Items for Material Handling Systems Requirements

Item	*Explanation*
Transport E-MTTR (min per SEMI E10)	Mean time to repair equipment-related failures (AMHS Transport); the average time to correct an equipment-related failure and return the equipment to a condition where it can perform its intended function; the sum of all equipment-related failure time (elapsed time, not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not maintenance delay downtime), divided by the number of equipment-related failures during that period. Notes: Refers to unscheduled, supplier dependent failures. Includes interbay and intrabay transport systems. Offline repair of components is not included in this time. Includes embedded software control systems (transport controllers). Does not include storage AMHS equipment or errors induced by the storage equipment. Does not include load port, FOUP carrier, or MES level software issues. Does not include reticle system.
Storage E-MTTR (min per SEMI E10)	Mean time to repair equipment-related failures (AMHS Storage); the average time to correct an equipment-related failure and return the equipment to a condition where it can perform its intended function; the sum of all equipment-related failure time (elapsed time, not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not maintenance delay downtime), divided by the number of equipment-related failures during that period. Notes: Refers to unscheduled, supplier dependent failures. Includes storage equipment load ports and embedded software. Does not include interbay or intrabay transport or incidents induced by these errors. Does not include FOUP carrier or MES level software issues. Does not include reticle system.
Transport MMBF (mean moves between failure)	Average number cycles (delivery from point A to point B) made by AMHS interbay or intrabay transport equipment before a person has to intervene to fix a failure. Number of transport moves / Number of supplier dependent unscheduled failures. Reference transport MPH definition for details on move.
Storage MCBF (mean cycles between failure)	Average number cycles (delivery from point A to point B) made by AMHS storage equipment before a person has to intervene to fix a failure. Number of storage cycles / Number of supplier dependent unscheduled failures per quarter. Reference cycle time definition for details on stocker cycle.
Mean carrier removal time (sec)	Mean time vehicle system picks up carrier from loadport after bottleneck EQ sends out “ready to unload” to MES or MES sends “pick up carrier command” to MCS, whichever happens later.
Mean carrier delivery time (sec)	Mean time vehicle system delivers carrier to loadport ,after bottelneck EQ sends out “ready to load” to MES or MESS sends “deliver carrier command” to MCS, whichever happens later.
Downtime to extend system capacity when previously planned (minutes)	Impact to material handling system in terms of downtime, in minutes, of the material handling system, required for making connections to system track extensions or a new storage when previsions for this expansion were incorporated in the original design.

Time required to integrate process tools to AMHS (minutes per LP)	The downtime to the transport system when a process tool is integrated to the AMHS. Addition of tool occurs on a track with existing vehicle traffic (no bypass units around tools). Assume tool is placed correctly and physical tool move in does not impact the AMHS. System not stopped for PIO install (tool side). Time includes: hardware install on track, teaching LP, software updates, and delivery testing. Scope ends when all vehicles have capability to deliver to new LP.

10 Factory Information and Control Systems

10.1 Scope

The scope of Factory Information and Control Systems (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 ITRS; including Yield, Factory Operations, Production Equipment, and Material Handling control and management.

10.2 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., SOAP[4] / XML[5] and web services) that enable this level of integration.

10.3 Improve Factory Yield and Minimize Waste

Yield improvement and waste minimization will rely heavily on FICS solutions. Process Control Systems (PCS) which utilize Advanced Process Control (APC) technologies including Run-to-run (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

[4] *SOAP: Simple Object Access Protocol, Service Oriented Architecture Protocol*

[5] *XML: Extensible Markup Language*

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 the automated material handling system (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 and 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.

10.4 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 BD sub-chapter.

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.

10.5 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 TR Table. Mission critical FICS components, both software and hardware, must provide fault tolerant solutions that eliminates 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 intellectual property (IP) within the equipment. Semiconductor 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 FI-9 Factory Information and Control Systems Technology Requirements

Year of Production	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
DRAM ½ Pitch (nm) (contacted)	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7	??	??
Wafer Diameter (mm)	*300*	*300*	*300*	*300*	*300*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*
# Masks Count*—DRAM [(EUV by 2013) - updated by Litho TWG in 2011 to reflect actual trends and survey data; and the effects of multi-patterning and introduction of EUV]		33		38	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
# Masks Count*—DRAM [(EUV by 2013) scenario based on an ICK model (see notes) extended through 2024 by the 2009-10 ITRS assumptions; and the estimated effects of	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39
Unscheduled downtime of a mission critical application (minutes per year)	**<10 min**	**<10 min**	**<10 min**	**<10 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**	**?5 min**
Scheduled downtime of a mission critical application (minutes per year)	**<15 min**	**<15 min**	**<15 min**	**<15 min**	**0 min**	**0 min**	**0 min**	**0 min**	**0 min**	**0 min**	**0 min**	**0 min**	**T.B.D.**	**T.B.D.**	**T.B.D.**	**T.B.D.**
Wafer-level (within-lot) recipe / parameter adjustment, e.g., for W2W control	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**
Within-wafer recipe / parameter adjustment	**Partial (Litho+)**	**Partial (Litho+)**	**Partial (Litho+)**	**Partial (Litho+)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**	**Yes (All)**
Relative accuracy of mission critical FICS clocks to fab-level time authority	**5ms**	**5ms**	**1ms**	**1ms**	**1ms**	**1ms**	**1ms**	**1ms**	**1ms**	**1ms**	**< 1ms**	**< 1ms**	**< 1ms**	**< 1ms**	**< 1ms**	**< 1ms**
FICS design to support peak equipment data transfer rates (production rate for each variable)	**10HZ**	**10HZ**	**100Hz**	**100Hz**	**100Hz**	**100Hz**	**1kHz**	**1kHz**	**1kHz**	**1kHz**	**> 1kHz**	**> 1kHz**	**> 1kHz**	**> 1kHz**	**> 1kHz**	**> 1kHz**
FICS design to support peak factory data transfer rates (Bytes / second)	**>1.6 MHz**	**>1.6 MHz**	**>2 MHz**	**>2 MHz**	**>10 MHz**	**>10 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**	**>16 MHz**

**Refer to Table ORTC5 mask counts' scenarios and notes*

Manufacturable solutions exist, and are being optimized (white)
Manufacturable solutions are known (yellow)
Interim solutions are known (yellow with red diamond)
Manufacturable solutions are NOT known (red)

Explanation of Items for Factory Information and Control Systems Requirements

Item	*Explanation*
Downtime of mission critical applications (minutes per year)	The time when mission critical applications is not in a condition, or is not available, to perform its intended function. Mission critical applications are those required to keep the entire wafer factory operational. Depending on factory configuration, these include: MES, scheduler / dispatcher, MCS, PCS, recipe download, reticle system, and facilities control systems. Hardware, system, and software upgrades are part of non-scheduled time as defined in SEMI E10-0304E, Section 5.10.1, and are not included in downtime.
Unscheduled downtime of mission critical applications (minutes per year)	The time when the equipment is not available to perform its intended function due to planned down time events as defined in SEMI E10-0304E. Scheduled down time includes maintenance delay, production test, preventive maintenance, change of consumables, setup, and facilities related events.
Scheduled downtime of mission critical applications (minutes per year)	The time when the equipment is not available to perform its intended function due to unplanned down time events as defined in SEMI E10-0304E. Scheduled down time includes maintenance delay, repair, change of consumables, out-of-spec inputs, and facilities related events.
Wafer-level recipe / parameter adjustment	Ability for factory information and control systems to run a different recipe and/or parameters for each wafer within a carrier. Adjustments for later wafers can be made as earlier wafers complete processing (i.e., wafer-to-wafer). This facilitates wafer-to-wafer recipe and parameter adjustment and supports the ability to have multiple lots per carrier.
Within-wafer recipe / parameter adjustment	The granularity to which the factory information and control systems are kept synchronized to a central reliable source. This enables time-critical process control to take place in a distributed architecture. This requirement does not necessarily require the increase in production tool's control "heart beat" frequency.
FICS design to support peak equipment data transfer rates (Production rate for each variable)	The peak rate of variable production that the factory information and control systems shall be required to support in collecting information from a single piece of processing equipment and transport to central storage. Note that there may be special cases where higher data rates are required for specific sensors or applications, such as ESD detection.

FICS design to support peak factory data transfer rates (Bytes / second)	The peak rate of data (in variables / second) that the factory information and control systems shall collect from all processing equipment and transport to central storage, where the average variable size is four bytes or less; if variable size averages are higher, the FICS peak rate requirements are adjusted so that the byte/sec rate requirement remains constant. This number is calculated assuming 20 variables / tool, and 200 tools / fab. So for example, if each tool produces a value for each variable at 10 Hz, then fab data rates are (10 reports / variable / second) X(4 bytes / report) X 20 variables / tool) X 200 tools / fab = 160K bytes / second across the fab. Peak data rates may grow to support higher peak equipment data rates and to support the production of more variables / tool.

11 FACILITIES

11.1 SCOPE AND FACILITY MISSION

Facilities include the overall physical buildings, cleanroom and facility infrastructure systems, including tool hook up. The ITRS 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

11.2 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 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
- facility spaces/volumes.

11.3 Complexity and Costs of Facilities Services Rising

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

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

11.3.1 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.

11.3.2 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 FI-5

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.

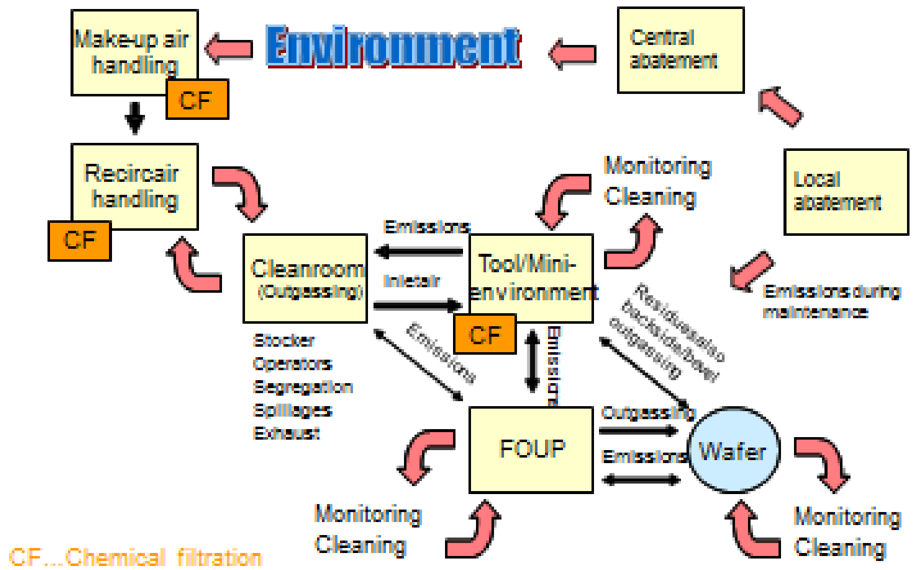

Figure FI-5: Total AMC concept

11.3.3 Meeting Static Charge Requirements

Electrostatic charge adversely impacts every phase of semiconductor 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, change in the frequency of compliance verification, and other forms of ESD monitoring, such as ESD event detection.. (ESD) Technology Roadmap.

11.3.4 Meeting Electromagnetic Interference Control Requirements

Electromagnetic Interference (EMI) (see the standard SEMI E33 for definition)[12] causes variety of problems for semiconductor 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 semiconductor 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.

As feature sizes decrease, the impacts described above are likely to become more pronounced, particularly for metrology equipment that utilizes beam-based processes 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.
To control and reduce the negative impact of EMI on wafers, materials and equipment, more comprehensive studies, advanced methods and measurement tools are needed.

11.4 Semiconductor 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 the pending use of 450mm 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
- nano materials ESH management
- Energetics Materials ESH 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.

11.5 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 semiconductor 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 be 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 increases 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 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.

11.6 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 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 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.

11.7 450MM 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, single wafer processing etc.), will have an impact on future factory requirements. The high cost of a 450mm 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 FI-10 Facilities Technology Requirements

Year of Production	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*	*2029*
DRAM ½ Pitch (nm) (un-contacted Poly) (f) [2]	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7	??
Wafer Diameter (mm)	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Wafer Diameter (mm)						450	450	450	450	450	450	450	450	450	450
# Mask Levels—DRAM	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39
Manufacturing (clean room) area m2/wafer starts per month/number / of mask layers (300mm)	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
Manufacturing (clean room) area m2/wafer starts per month/number of mask layers (450mm)				0.013	0.011	0.009	0.0075	0.0075	0.0075	0.0075	0.0075	0.007	0.0065	0.0065	??
SubFab to Fab ratio (see definition)	0.6	0.6	0.6	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	??
Facility cleanliness level (ISO 14644)	Class 6 at rest	Class 6 at rest	Class 6 at rest	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?	Class 6 at rest?
Facility cleanliness level (Airborne molecular contamination AMC)	Discussed in Yield Enhancement Chapter								Discussed in Yield Enhancement Chapter						
Design Criteria for Facility critical vibration areas (lithography, metrology, other) (μm/sec)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)	6.25 (VC D)
Design Criteria for Facility non-critical vibration areas (μm/sec)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)	50 (VC A)
Temperature and Humidity Specifications	Discussed in Yield Enhancement Chapter								Discussed in Yield Enhancement Chapter						
Maximum allowable electrostatic field on facility surfaces (V/m) for ESD prevention	2700	2400	2200	2050	1850	1700	1550	1450	1350	1200	1100	1000	900	850	??
Continuous Radiated emission Limit for Facility Allowable Low Frequency (0-30kHz) Magnetic Field (nT/) for EMI sensitive area	80	70	60	50	40	30	20	10	10	9	8	7	6	5	??
Continuous Radiated emission Limit for Facility Allowable Low Frequency (0-30kHz) Magnetic Field (nT/) for very EMI sensitive area	8	7	6	5	4	3	2	1	1	1	1	1	1	1	??
Continuous Radiated emission Limit for Facility Allowable High Frequency (30MHz - 3GHz) Electric(/Magnetic) Field (V/m) for EMI sensitive area (Far Field)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	??
Continuous Radiated emission Limit for Facility Allowable High Frequency (30MHz - 3GHz) Electric(/Magnetic) Field (V/m) for EMI sensitive area (Near Field)	1.0	1.0	0.8	0.8	0.7	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.5	??
Transient Radiated emission Limit for Facility Allowable Spectrum (30MHz - 3GHz) Electric(/Magnetic) Field (V/m) for EMI sensitive area (Far Field)	1	1	1	1	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.6	0.5	0.5	??
Transient Radiated emission Limit for Facility Allowable Spectrum (30MHz - 3GHz) Electric(/Magnetic) Field (V/m) for EMI sensitive area (Near Field)	2	2	2	2	1.5	1.5	1.5	1.2	1.0	1.0	1.0	0.8	0.8	0.7	??
Continuous Conducted Emission Limit Allowable Continuous Noise (9kHz - 30MHz) Level (dBuV)	90	90	90	90	80	80	80	80	70	70	70	70	70	70	??
Transient Conducted Emission Limit Allowable transient signal Level (V) for regular environment	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	??
Transient Conducted Emission Limit Allowable transient signal Level (V) for sensitive environment	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	??
Gas, water, chemical purity	Discussed in Yield Enhancement Chapter								Discussed in Yield Enhancement Chapter						
Facility power and water consumption.	Discussed in ESH Chapter								Discussed in ESH Chapter						
Energy Consumption Total Fab Support System (kWh/cm ² per wafer out)	Discussed in ESH Chapter								Discussed in ESH Chapter						
Ratio of Tool Idle vs. Processing Energy Consumption (kW/kW)	0.60	0.60	0.60	0.50	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	??

Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known ◆
Manufacturable solutions are NOT known

Explanation of Items for Facilities requirements:

Item	*Explanation*
Manufacturing (cleanroom) area (m^2)	Manufacturing (cleanroom) area is defined as the gross space in square meters containing the process and metrology equipment used for direct manufacturing processes such as photolithograph, diffusion, etch, thin films, CMP, excluding subfab spaces containing support equipment and facility infrastructure systems. This includes all space within the Fab cleanroom envelope containing process tools, bays and corridors.
Wafer starts per month (WSPM)	Wafer starts per month is defined as the number of wafers introduced into production for processing during a given 30 day period.
# of mask layers	This refers to number of mask layers of DRAM.
Sub-Fab to Fab ratio	Sub-Fab to Fab ratio is defined as the footprint of the support equipment area to the main frame manufacturing area above. The 25% reduction in floor space allows for columns and safety equipment in the subfab that is required by the facility. Relates to factory operations "floor space effectiveness." Note- Some tools have a higher ratio and others have no sub-Fab equipment. This represents an average of all tools in a full DRAM factory toolset.
Facility cleanliness class (ISO 14644)	Cleanliness classification of wafer factory manufacturing (cleanroom) area as defined by ISO 14644-1[1].

Design Criteria for Facility critical vibration areas (litho, metro, other) (micrometers per second)	"Vibration critical" is defined as area of the primary manufacturing floor in which a significant portion of the equipment is highly sensitive to floor vibration, the mitigation was not provided at the tool itself, and excessive vibrations can have serious deleterious effects on product. Extensive measures may be required in the facility's structural and mechanical equipment design based upon the needs of this space category. Vibration criteria are limits on vibration amplitudes at the floor or other support of a tool, given as VC-x, where x is a letter designation from A through E, each corresponding to a specific vibration amplitude spectrum. Refer to IEST-RP-CC0012.2[2]
Design Criteria for Facility non-critical vibration areas (micrometers per second)	"Vibration non-critical" is defined as area of the primary manufacturing floor in which all or some of the equipment is only moderately vibration sensitive, and the structural system performance can be reduced. Vibration criteria are limits on vibration amplitudes at the floor or other support of a tool, given as VC-x, where x is a letter designation from A through E, each corresponding to a specific vibration amplitude spectrum. Refer to IEST-RP-CC0012.2.
Maximum allowable electrostatic field on facility surfaces (V/m) for ESD prevention.	Facility surface electric field limits apply to all factory materials-construction materials, furniture, people, equipment, and carriers Refer to SEMI standards E129[3], E78,[4] and E43[5] for measurement methods. Note: This guidance may not apply to EFM prevention for chrome masks. See field limits listed in FAC 5 and comments in sections 6, 9 and 11; See also SEMI E163-0212
Design criteria for "EMI sensitive area"	"EMI sensitive areas" are defined as areas of primary manufacturing floor, where EMI sensitive tools like SEM (Scanning Electron Microscope) TEM (Tunneling Electron Microscope), e-beam, Focused Ion Beam and metrology tools are located. Listed limits cover typical tool requirements. Specific application can require tighter limits
Design criteria for "very EMI sensitive areas"	"Very EMI sensitive areas" are defined as areas, not inline connected with the normal production process. These are typically labs or research areas. In these areas specific measurements requiring very high resolution are necessary and therefore also the limits concerning EMI are tighter compared to normal production area. Sensitive Tool are SEM, TEM , Focused Ion Beam, e-beam and specific metrology tools. Listed limits cover typical tool requirements. Specific application can require tighter limits
Radiated emission Limit for Facility	Radiated emission is electromagnetic fields (a combination of electric and magnetic fields) - similar to the fields used in wireless communication and radio broadcast. Electric field is generated by voltage; magnetic - by current. Similarly, these fields generate undesirable voltages and currents in wires and traces on board in other electronic equipment. These undesirable signals may cause interference with normal operation of equipment and can alter process parameters by interfering with the sensors and controls. Radiated emission' strength diminishes with the distance, meaning that it presents less of a problem to the equipment located far from the source. Mitigation of radiated emission includes selecting low-emission equipment compliant with EMC (electromagnetic compliance) standards, properly grounding it, reducing length of wires that act as antennae and improving shielding, including closing all the covers on the equipment.
Conducted Emission Limit for Facility	Conducted emission is undesirable electrical signal on wires and in the metal structure of equipment. It is typically caused by electrical commutation, servo and variable frequency motors, actuators, RF sources in the FAB, noisy power supplies and alike. Unlike radiated emission, conducted signals can propagate quite far through the wires with minimal attenuation and capable of causing significant operational problems far away from the source. Mitigation of conducted emission includes EMI filters, proper routing of power lines and ground and selection of low-noise equipment. Often, emission is mixed - power cables and ground that may carry conducted signal become antennae for radiating such signal, and the opposite - radiated field creates electrical signal in cables and wires that enter equipment becoming conducted emission interference. Mitigation of such interference typically involves shortening and proper routing of cables and EMI filtering.
Ratio of tool idle versus processing energy consumption (kW/kW)	Ratio of energy consumption of process tool and support equipment when not processing wafers over energy consumption while tool is processing wafers per SEMI S23 application guide.

References for Table FI-10:

[1] ISO 14644-1.: Cleanrooms and controlled environments, Part 1: Classification of air cleanliness
[2]IEST-RP-CC012.2: Considerations in Cleanroom Design.
[3] SEMI E129: Guide to Assess and Control Electrostatic Charge in A Semiconductor Manufacturing Facility.
[4] SEMI E78: Electrostatic Compatibility – Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment.
[5] SEMI E43: Guide for Measuring Static Charge on Objects and Surfaces.
[6] SEMI E163-0212 Guide for the handling of reticles and other extremely electrostatic sensitive (EES) items within specially designated areas.

12 AUGMENTING REACTIVE WITH PREDICTIVE

12.1 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.
- *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.

12.2 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. The prediction vision generally is the same for 300mm and 450mm 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. This 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 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; 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. Real-time simulation of fab operations as an extension of existing system is a long-term vision that will necessarily require the successful implementation of the individual prediction capabilities followed by their integration on a common prediction platform.

12.3 TECHNOLOGY REQUIREMENTS

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

Table FI-11 Augmenting Reactive with Predictive (ARP) Technology Requirements

Year of Production	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
DRAM ½ Pitch (nm) (contacted)	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7
Wafer Diameter (mm)	300	300	300	300	300	450	450	450	450	450	450	450	450	450
Predictive Scheduling: fab-wide solutions	Partial	Partial	Partial	Partial	All	All	All	All	All	All	All	All	All	All
EHM: fab-wide solutions (common health indicator across tools)	Partial	Partial	All	All	All	All	All	All	All	All	All	All	All	All
PdM: fab-wide solutions	None	None	Minimal	Minimal	Partial	Partial	Partial	All	All	All	All	All	All	All
VM: fab-wide solutions	None	None	Minimal	Minimal	Partial	Partial	Partial	All	All	All	All	All	All	All
Yield Prediction: fab-wide solutions	None	None	Minimal	Minimal	Partial	Partial	Partial	Partial	All	All	All	All	All	All
Simulation as an extension of existing with real-time update: all-systems, fab-	None	None	Minimal	Minimal	Partial	Partial	Partial	Partial	Partial	All	All	All	All	All

Manufacturable solutions exist, and are being optimized (white)
Manufacturable solutions are known (yellow)
Interim solutions are known (yellow with red diamond)
Manufacturable solutions are NOT known (red)

Explanation of Items for Augmenting Reactive with Predictive (ARP) requirements:

Item	*Explanation*
Predictive Scheduling	Prediction scheduling is aleady being implemented for lithography. Similar solutions could be utilized for other processes Fab-wide predictive scheduling is being considerd, but not yet implemented. Improvements in prediction capabilties will occur in parallel with deployment expansion; improvements will include incorporation of prediction accuracy into prediction strategy.
EHM	EHM technology will rely heavily on anamoly detection. EHM fab-wide deployment will require some form of standarization on EHM dashboard design and functionality. Reference: J. Moyne, J. Iskandar, P. Hawkins, T. Walker, A. Furest and B. Pollard, D. Stark and G. Crispieri, "Deploying an Equipment Health Monitoring Dashboard and Assessing Predictive Maintenance," Proceedings of the 24th Annual Advanced Semiconductor Manufacturing Conference (ASMC 2013), Saratoga Springs, New York, (May 2013).
PdM	PdM solutions address the entire maintenance cycle, from predicting maintenance through addressing recovery from maintenance events towards returning to production. PdM technology is being deployed on selected tool types. Solutions consistency has not been achieved. Improvements in data quality (especially maintenance data systems) will be required for widespread deployment of PdM . SEMI standards for data quality should be leveraged (e.g, E151 and E160). Standards for "PdM ready" systems will eventually be required for cost-effective fab-wide deployment.

	Effective PdM systems will require a conjoining of stastical (e.g., historical data) analysis and process/equipment knowledge; this in-turn will require closer cooperation between PdM solution provide, user and tool provider. Algorithm improvements in PdM may leverage other prediction technologies (e.g., VM and Yield Prediction).
VM	VM technology is being deployed on selected tool types. Solution consistency has not been achieved. VM will have a number of uses ranging from "smart metrology" to enabling wafer-to-wafer control. The roadmap for these capabiltiies will largely be a function of the VM accuracy requirements for each capabiltiies and the underlying data quality and prediction capabilities. Algorithm improvements in VM may leverage other prediction technologies (e.g., PdM and Yield Prediction).
Yield Prediction	Yield prediction will strongly leverage VM prediction techniques. It is expected that yield prediction will follow VM.
Simulation as an extension of existing with real-time update: all-systems, fab-wide	This capability will require the confluence of all prediction technologies on a common framework. Challenges include real-time update of simulation models, determining prediction quality, extending existing systems (Uis, data stores, etc) to support simulation, and providing standardized methods for incorporation of simulation components.

13 BIG DATA

13.1 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 semiconductor 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". 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)[6]. 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.

13.2 SCOPE

The scope of this Big Data (BD) section is to identify the challenges and potential solutions associated with Big Data attributes of: volume, velocity, variety, veracity and value.

13.3 TECHNOLOGY REQUIREMENTS

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

[6] *http://bigdatawg.nist.gov/home.php*

13.3.1 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.

13.3.2 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.

13.3.3 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.

13.3.4 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 used 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.

13.3.5 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 though 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.

13.4 General Big Data Areas of Concern

13.4.1 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-realtime[7] 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 semiconductor 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.

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—FD[8]). Oftentimes 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 systems 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

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[7] *"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.*

[8] *"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 by on the order of less than 1 second.*

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.

13.4.2 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.

13.4.3 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

13.4.4 Data Retention

Data retention in Big Data will be required as needs grow for proper analytics and availability. 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.

13.4.5 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.

13.4.6 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.

13.4.7 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.

Table FI-12 Big Data (BD) Technology Requirements

Year of Production	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*
DRAM ½ Pitch (nm) (contacted)	23.8	21.9	20	18.4	16.9	15.5	14.2	13	11.9	10.9	10	9.2	8.4	7.7
Wafer Diameter (mm)	*300*	*300*	*300*	*300*	*300*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*	*450*
Volume BD Requirements:														
Daily data collection volume across fab (Terabytes)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data retention in fab: Maintenance Data (Months)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data retention in fab: Diagnostic Output Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Data retention in fab: Trace Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data retention in fab: Process Control and Metrology Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data retention in fab: Yield Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data retention in fab: Execution Log Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data archive length: Maintenance Data (Years)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data archive length: Diagnostic Output Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data archive length: Trace Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data archive length: Process Control and Metrology Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data archive length: Yield Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Minimum data archive length: Execution Log Data	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Velocity BD Requirements:														
FICS design to support peak equipment data transfer rates (production rate for each variable)	10HZ	10HZ	100Hz	100Hz	100Hz	100Hz	1kHz	1kHz	1kHz	1kHz	> 1kHz	> 1kHz	> 1kHz	> 1kHz
FICS design to support peak factory data transfer rates (Bytes / second)	>1.6 MHz	>1.6 MHz	>2 MHz	>2 MHz	>10 MHz	>10 MHz	>16 MHz	>16 MHz	>16 MHz	>16 MHz	>16 MHz	>16 MHz	>16 MHz	>16 MHz
Variety BD Requirements:														
Relative accuracy of mission critical FICS clocks to fab-level time authority	5ms	5ms	1ms	1ms	1ms	1ms	1ms	1ms	1ms	1ms	> 1ms	> 1ms	> 1ms	> 1ms
Time accuracy and context of human entered data	None	None	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Standards to support automatic merging of data stores (Maintenance, Diagnostic ouptut, Trace, Process Control/Metrology, Yield and Execution Log) across FI space	None	None	Partial	Partial	Partial	Partial	Full	Full	Full	Full	Full	Full	Full	Full
Veracity BD Requirements:														
Specification of the data quaility of data stores per data quality standard metrics	Partial	Partial	Partial	Partial	Full	Full	Full	Full	Full	Full	Full	Full	Full	Full
Quality of human entered data	None	None	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Value BD Requirements:														
Standardized mechanism to determine benefit of data, e.g., in $ / TeraByte of storage	Developed	Developed	Partial Implementation	Partial Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation	Full Implementation
Cloud and Integration BD Requirements:														
Enterprise-wise Integration of fab and facility data stores	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Performance of Data I/O to/from the cloud	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Data integration up and down the supply chain	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Standards for secure cloud data access	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Migration to Big Data Friendly Ecosystem (E.g., Hadoop)														
Used for offline analysis and modelling	Miminal	Miminal	Partial	Partial	Partial	Partial	Full	Full	Full	Full	Full	Full	Full	Full
Used for "Real-time" on-line diagnostics and control	None	None	Miminal	Miminal	Miminal	Miminal	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Partial

Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known
Manufacturable solutions are NOT known

Explanation of Items for Big Data (BD) requirements:

Item	*Description*
Volume BD Requirements:	See narrative for Volume definition
Daily data collection volume across fab (Terabytes)	Data collection volumes to support capabilities such as diagnostics and prediction will likely grow exponentially; new methods to manage these data volumes will have to be developed.
Minimum data retention in fab: Maintenance Data (Months)	Increased data retention will be required to support future capabilities such as predictive maintenance (PdM)
Minimum data retention in fab: Diagnostic Output Data	Increased data retention will be required to support future capabilities such as predictive maintenance (PdM)
Data retention in fab: Trace Data	As equipment data collection rates increase, trace data amounts will correspondingly increase; mechanisms for managing these data volumes in real time will have to be developed.

Minimum data retention in fab: Process Control and Metrology Data	Increased data retention will be required to support future capabilities such as Virtual Metrology (VM)
Minimum data retention in fab: Yield Data	Increased data retention will be required to support future capabilities such as Yield prediction (YP)
Minimum data retention in fab: Execution Log Data	Increased data retention will be required to support future capabilities such as fab simulation / emulation
Minimum data archive length: Maintenance Data (Years)	Capabilities such as PdM will benefit from significantly increased archive length of maintenance and diagnostic output data
Minimum data archive length: Diagnostic Output Data	Capabilities such as PdM and VM will benefit from significantly increased archive length of maintenance and diagnostic output data
Minimum data archive length: Trace Data	Increased archiving of trace data will allow for improved data mining of recurring issues and to develop improved models such as VM and PdM
Minimum data archive length: Process Control and Metrology Data	Capabilities such as PdM and VM will benefit from significantly increased archive length of maintenance and diagnostic output data
Minimum data archive length: Yield Data	Increased archiving of yield data will allow for improved data mining of recurring issues and to develop improved yield prediction models, as well as better relate issues to other events in the fab
Minimum data archive length: Execution Log Data	Increased archiving of execution log data will allow for improved data mining of execution issues and to develop improved fab simulation models
Velocity BD Requirements:	See narrative for Velocity definition
FICS design to support peak equipment data transfer rates (production rate for each variable)	See FICS Requirements table for definition
FICS design to support peak factory data transfer rates (Bytes / second)	See FICS Requirements table for definition
Variety BD Requirements:	See narrative for Variety definition
Relative accuracy of mission critical FICS clocks to fab-level time authority	See also FICS Requirements table; Clock schronization per SEMI E148
Time accuracy of human entered data	Human data entry will continue to be a major issue in achieving data quality levels necessary to support emerging capabilities such as PdM; time accuracy of human entered data will have to be greatly improved and be verifiable
Standards to support automatic merging of data stores (Maintenance, Diagnostic ouptut, Trace, Process Control/Metrology, Yield and Execution Log) across FI space	Emerging capabilities are increasingly requiring the merging of dissimilar data stores; standards will allow for the automated merging of these data stores to reduce the cost of capability implementation
Veracity BD Requirements:	See narrative for Veracity definition
Specification of the data quaility of data stores per data quality standard metrics	Standard have been developed for Data Quality Metrics (SEMI E160) however these standards must be enforced and baselines of minimimum data quality for various data stors (e.g., Maintenance) established
Value BD Requirements:	See narrative for Value definition
Standardized mechanism to determine benefit of data, e.g., in $ / TeraByte of storage	Improving the value of data will first require a standardized method and metric for determining that value
Cloud and Integration BD Requirements:	See narrative for Cloud definition
Enterprise-wise Integration of fab and facility data stores	Future capabilities such as fab optimization to production and waste management goals simulataneously, will require integration of fab and facility data stores; integration will move from fab-wide to enterprise-wide
Performance of Data I/O to/from the cloud	The cloud must meed increasingly stringent requirements of data velocity
Data integration up and down the supply chain	Benefits will increasingly be achieved through optimization of the supply chain, both up and downstream; this in-turn will require data integration across the supply chain
Standards for secure cloud data access	Emerging cloud security capabilities will have to be leveraged to allow the use of the cloud in the face of increasingly stringent security requirements
Migration to Big Data Friendly Ecosystem (E.g., Hadoop)	See narrative for big data ecosystem discussion
Used for offline analysis and modelling	Initially big data friendly eco-systems will be suited for off-line analysis of large archives of data
Used for "Real-time" on-line diagnostics and control	As response times are assessed and matched to "real-time" requirements of on-line decision making, big data friendly eco-systems will begin to be used in on-line solutions; see narrative for discussion of "real-time".

14 Control Systems Architectures

14.1 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.

14.2 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.

14.3 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.

14.4 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 PTP[9], 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.

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

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.

14.5 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 be continually addressed. In both cases technologies not specific to semiconductor 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.

14.6 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 (SOS). 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 semiconductor 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 semiconductor manufacturing following this general manufacturing trend.

14.7 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.

15 Environmental Safety and Health

15.1 Scope

The Environment, Safety, and Health (ESH) activities, strategies and vision for the overall 2015 ITRS Roadmap continues the progressive work of 2013 and 2014 with an aim of projecting the principles of a successful, sustainable, long range, global, industry-wide ESH program. Execution remains largely independent of the specific technology thrust advances to which the principles are applied. Thus, many ESH Roadmap elements, such as the Difficult Challenges and the Technology Requirements, feed directly into the Focus Group Roadmaps of ITRS 2.0, notably Factory Integration. The six basic and overarching ESH 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 perspective in regards 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 Semiconductor Industry continues to be an ESH leader as well as an overall technology leader. Semiconductor manufacturers have adopted a business approach to ESH 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.

15.1.1 ESH and Factory Integration Synergy

As part of the move to ITRS 2.0, the ESH activities and output will become more integrated with FI as part of the Factory Integration “thrust” activities. This section in the FI chapter represents the first step in that integration focus. In the future the ESH chapter may be fully included in the Factory Integration thrust chapter. In the interim, the reader is encouraged to refer back to the full ESH chapter when reading this section to understand the full ESH roadmap.

The increased synergy between ESH and FI efforts in 2015 can be summarized with the following ESH strategies:

- The roadmap process will continue to quantify factory environmental factors
- Roadmap 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

15.2 Alternative Assessment Methodologies

Consistent with the principles and concepts of Green Chemistry, are the application of Alternative Assessment Methodologies, which enable the selection of less ESH impactful materials, proactively. Such methods can be viewed as a practical implementation vehicle for Green Chemistry. In the fall of 2015, a project team completed work on a comprehensive evaluation of review of Alternative Assessment Evaluation Methods, based on key criteria, using several representative materials of process and product significance to the semiconductor and electronics industries. This effort was sponsored by The International Electronics Manufacturing Initiative (iNEMI), a not-for-profit, R&D consortium of ~100 leading electronics manufacturers, suppliers, associations, government agencies and universities. They develop roadmaps for the global electronics industry, describing future technology requirements, identifying and prioritizing technologies and infrastructure gaps, in a similar way to how the ITRS does this for the semiconductor industry. Given the increasing focus on product content regulations globally, INEMI was motivated to support this work, to promote processes and emphasize the value of tools which enable the selection of more benign materials. As part of this effort, the project team examined existing environmental/toxicology assessment tools, methods and frameworks which have been developed by various sources (industry, NGOs, academia and government agencies), with the goal of identifying their applicability to both current and future electronics manufacturing and products. Given that there is no universally applicable or accepted tool, this effort strove to conduct limited benchmark testing/evaluation of key alternative assessment tools, resulting in a gap analysis in matrix form, with pros/cons of each methodology. The completion of this first project phase, resulted in the development of an Alternative Assessment Framework, which was a stakeholder aligned methodology that represents a stakeholder aligned approach, forming the basis for a common industry approach to performing alternative assessments, and was based on the National Academies Report. Moreover, the 14 alternative assessment tools that were evaluated represented tools that have been shown to have future potential regulatory interest, and which can be used in the context of the aforementioned framework. These were also grouped into like categories, which can be useful to electronics manufacturers and upstream by the semiconductor industry. Utilization of these tools by semiconductor manufacturers and their suppliers upstream will provide greater insight and better decision making for materials design and selection. This proactive look ahead can be of significant value downstream, in terms of designing out product content issues. The second phase of this work is now being developed and should be finalized in early 2016.

16 Yield Enhancement (YE)

16.1 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 alone with AMC requirements will be jointly worked out by Factory Integration and Yield ITWGs.

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.

16.1.1 YE AND FACTORY INTEGRATION SYNERGY

As part of the move to ITRS 2.0, the YE activities and output will become more integrated with FI as part of the Factory Integration "thrust" activities. This section in the FI chapter represents the first step in that integration focus. In the future the YE chapter may be fully included in the Factory Integration thrust chapter. In the interim, 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 in 2015 can be summarized with the following ESH 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.

16.2 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 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.

16.3 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 semiconductor 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 semiconductor 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.

16.4 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 ~~to~~ 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 the 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.

16.5 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 is 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"[10] 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.

16.6 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.

16.7 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 TWG activities are envisaged, connections with More Moore (MM), Heterogeneous Integration (HI) and Heterogeneous Components (HC) are necessary.

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[10] *"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).*

17 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*," and "*Qualification/pre-production*", 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.

Research Required

Development Underway

Qualification/Pre-Production

Continous Improvement

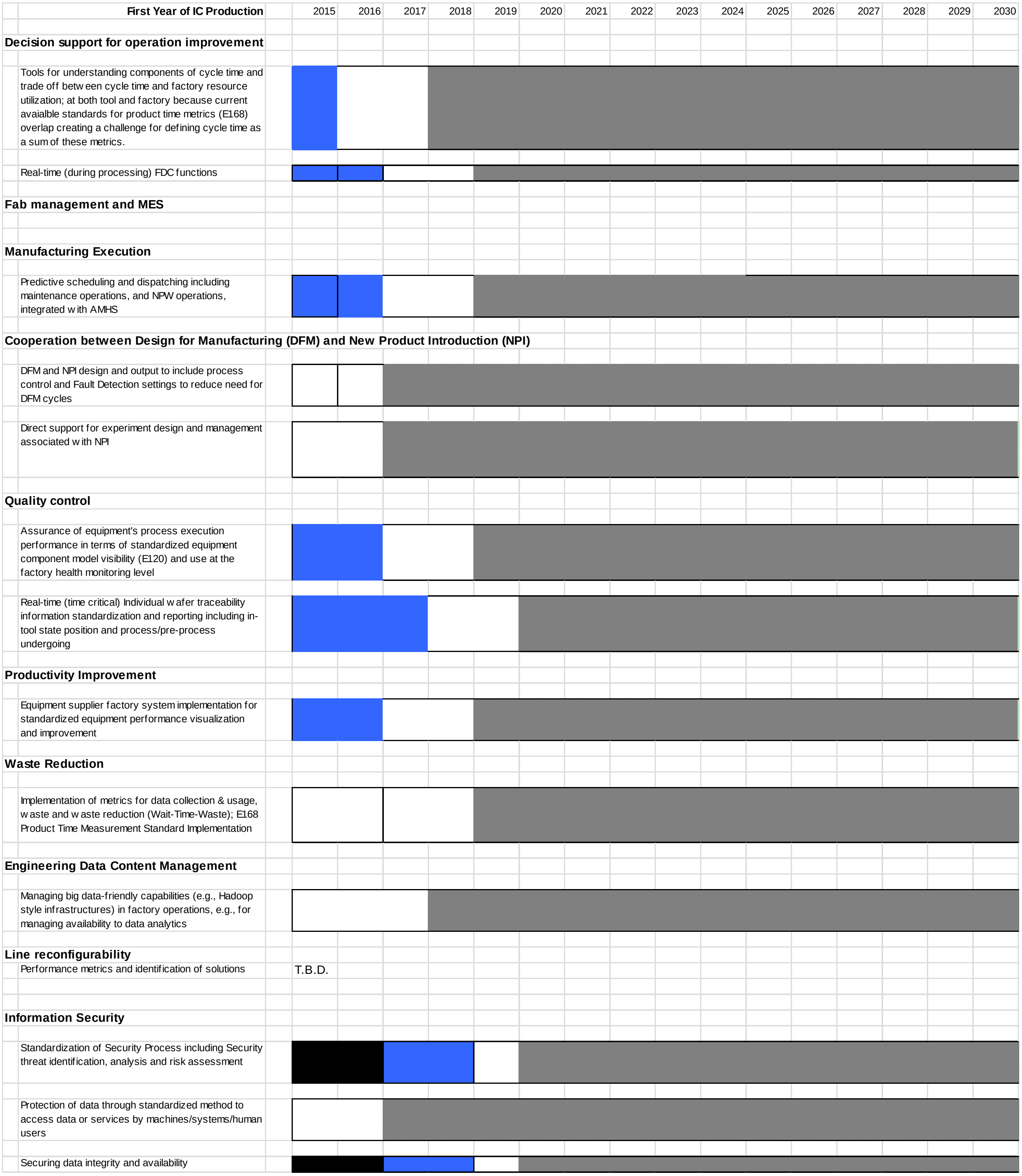

Figure FI-6 Factory Operations Potential Solutions

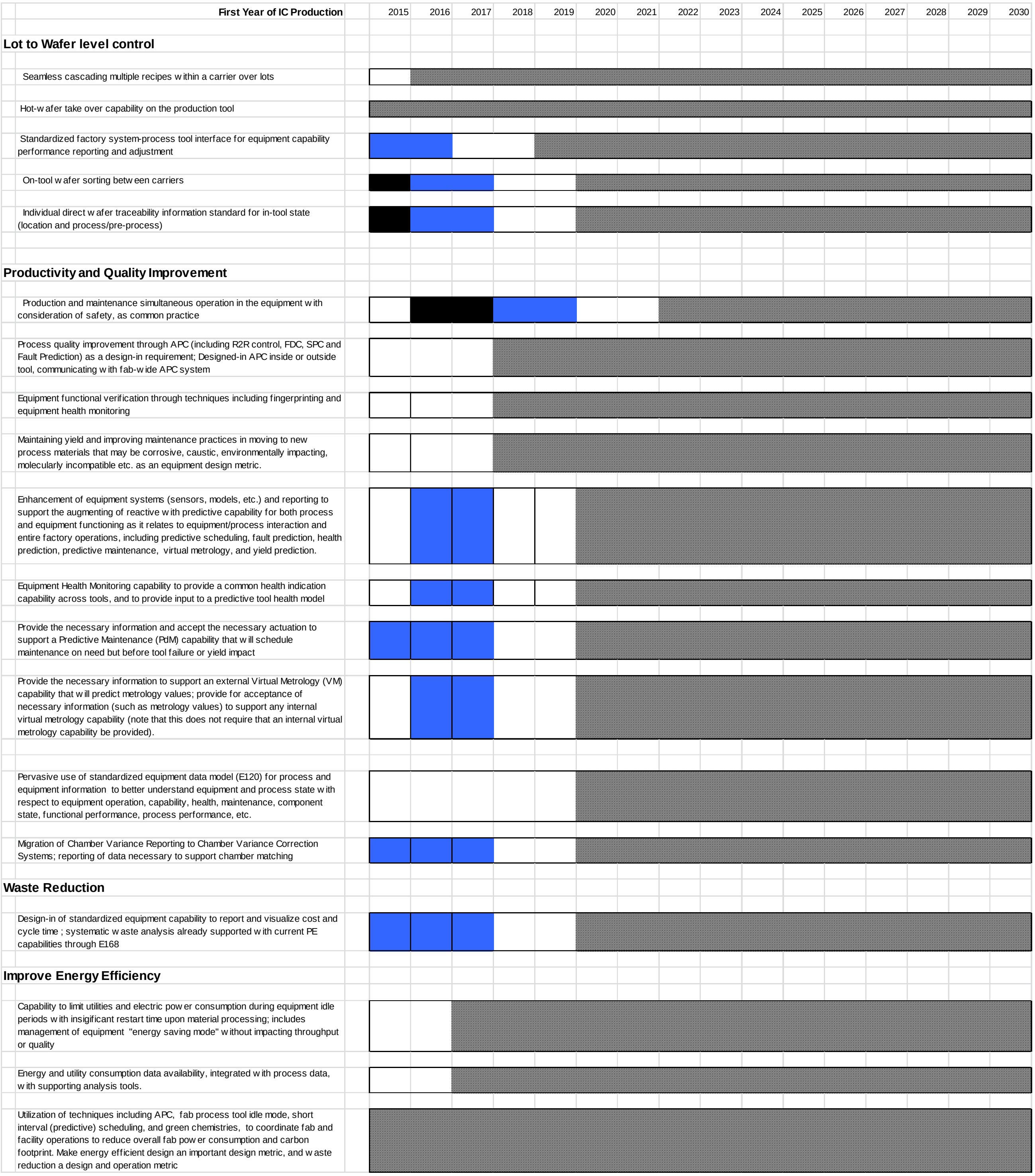

Figure FI-7 Production Equipment Potential Solutions

First Year of IC Production	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
450mm AMHS																
450mm Interface standards development																
450mm automated material handling system configurations																
Easily extendible transport system																
Automated or zero field hardware alignment and positioning	300mm					450mm										
Automated software configuration (HW independent structure and parameter setting)	300mm					450mm										
Uninterrupted extended transport system rail	300mm					450mm										
Uninterrupted software upgrade	300mm					450mm										
High Reliability																
Automated preventative/predictive maintenance, and e-Diagnostics	300mm					450mm										
Visualization of AMHS information	300mm					450mm										
High Perfromance																
Integrate the transport/storage of near tool (Near tool buffer, shared EFEM, on-tool storage, etc.)	300mm					450mm										
Integrate WIP scheduling and dispatching systems with storage and transport systems	300mm					450mm										
Traffic-jam prediction and control capability; elimination of flocking risk	300mm					450mm										
The prediction allocation of the vehicle (a processing completion prediction), as part of a predictive scheduling/dispatching system	300mm					450mm										

Figure FI-8 Material Handling Potential Solutions

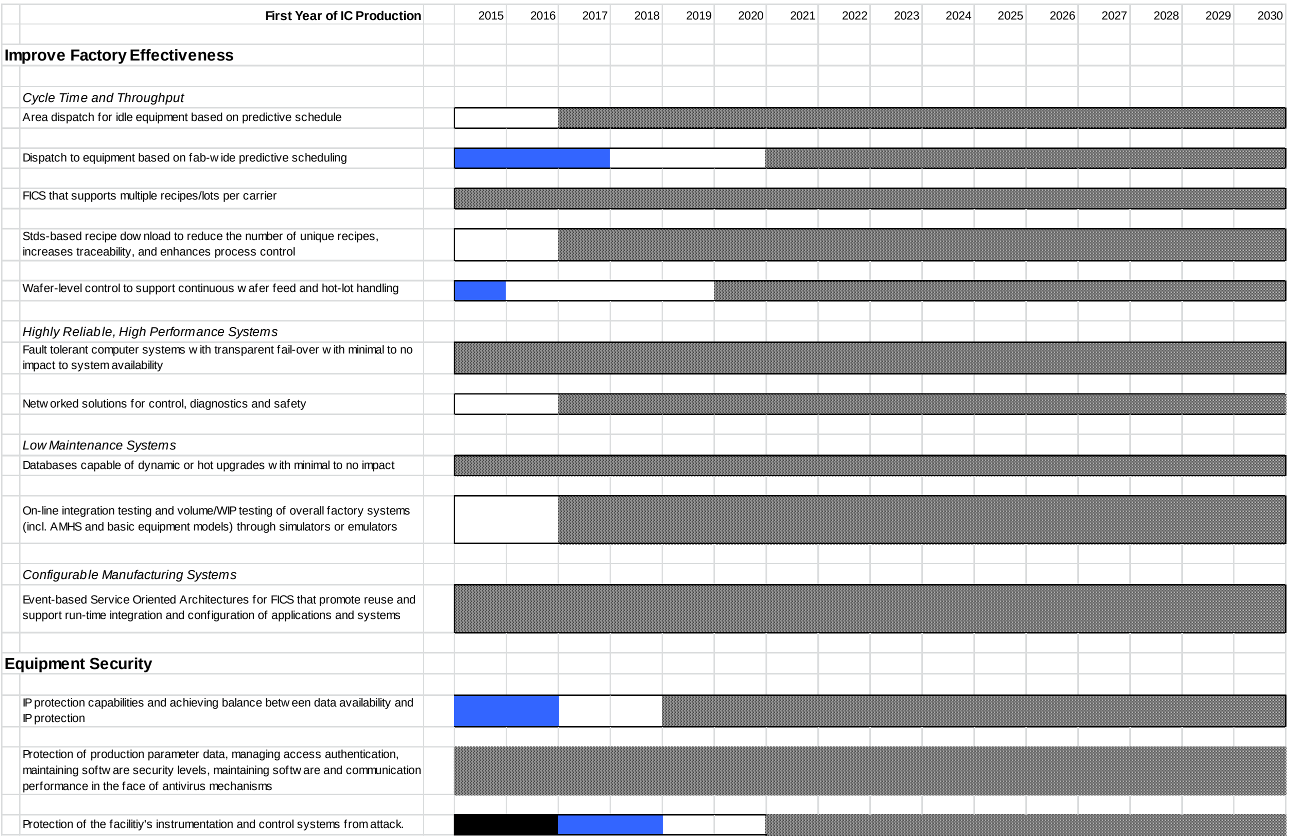

Figure FI-9 Factory Information and Control Systems Potential Solutions

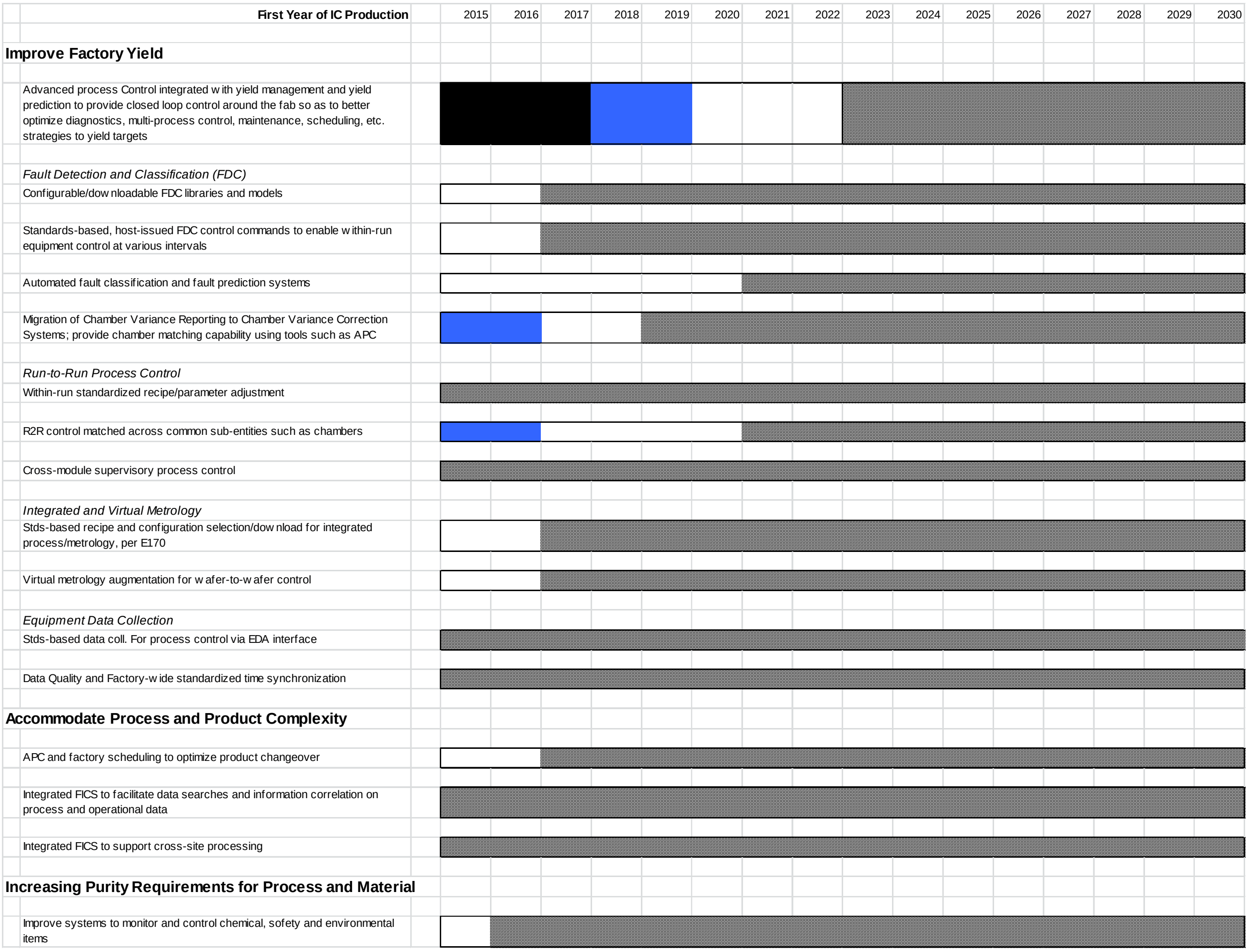

Figure FI-9 Factory Information and Control Systems Potential Solutions (continued)

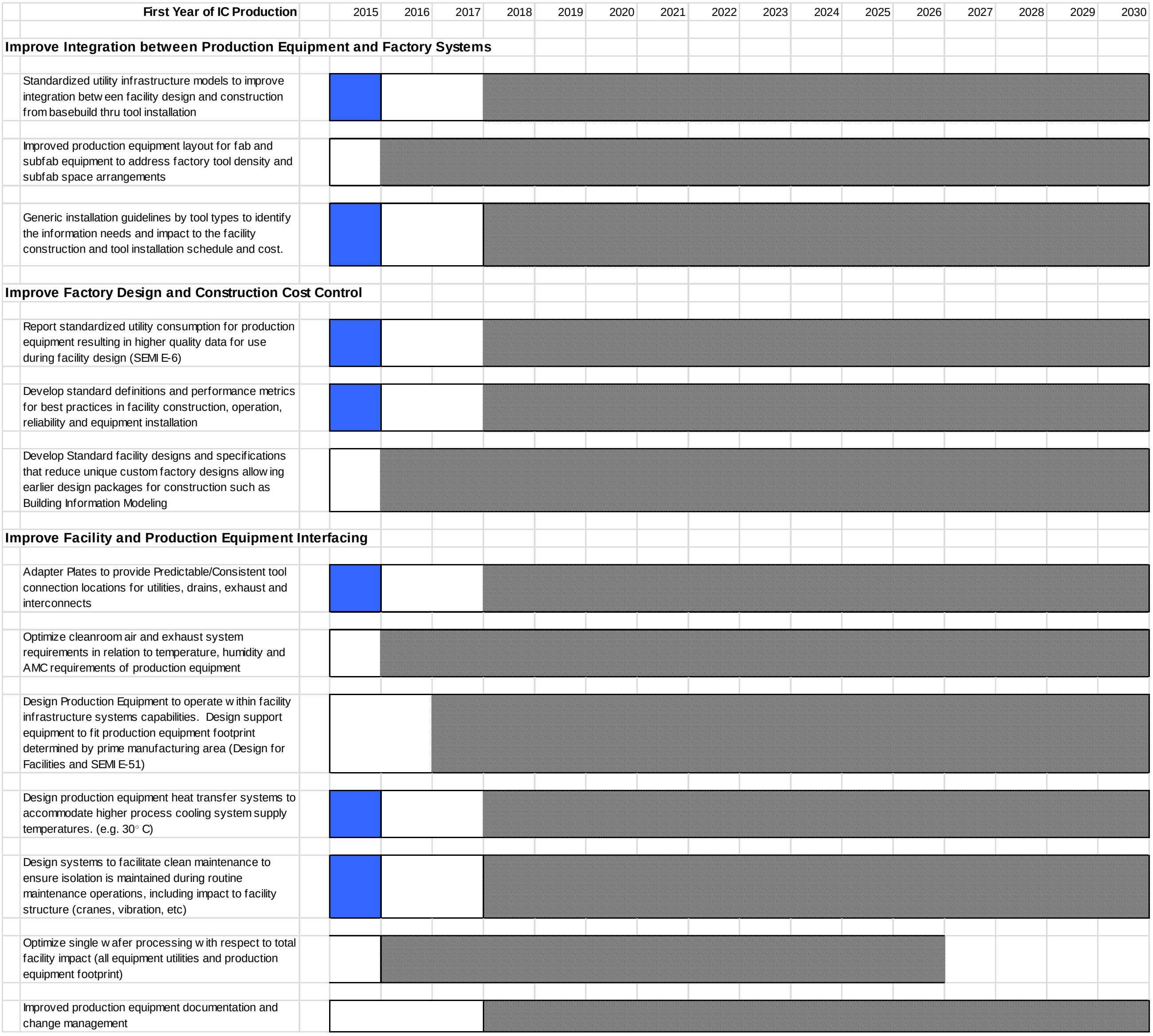

Figure FI-10 Facilities Potential Solutions

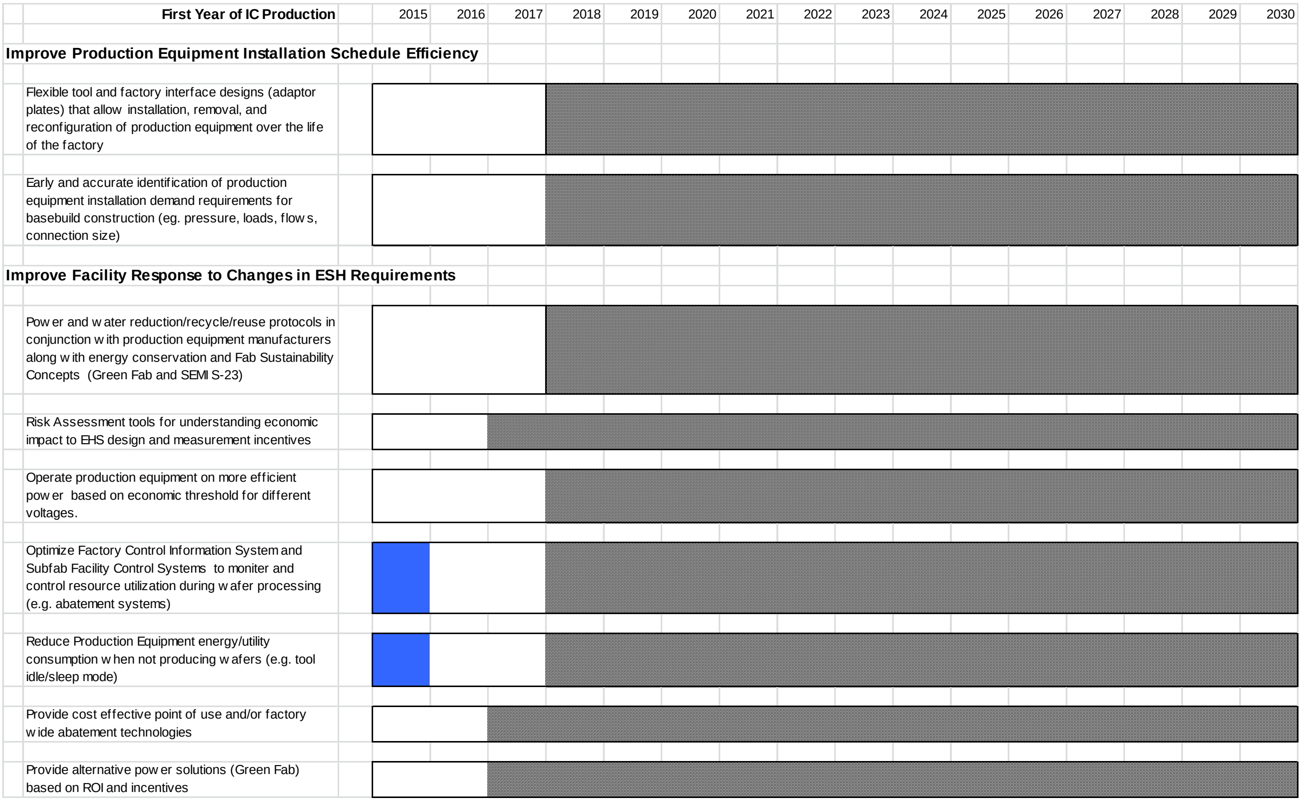

Figure FI-10 Facilities Potential Solutions (continued)

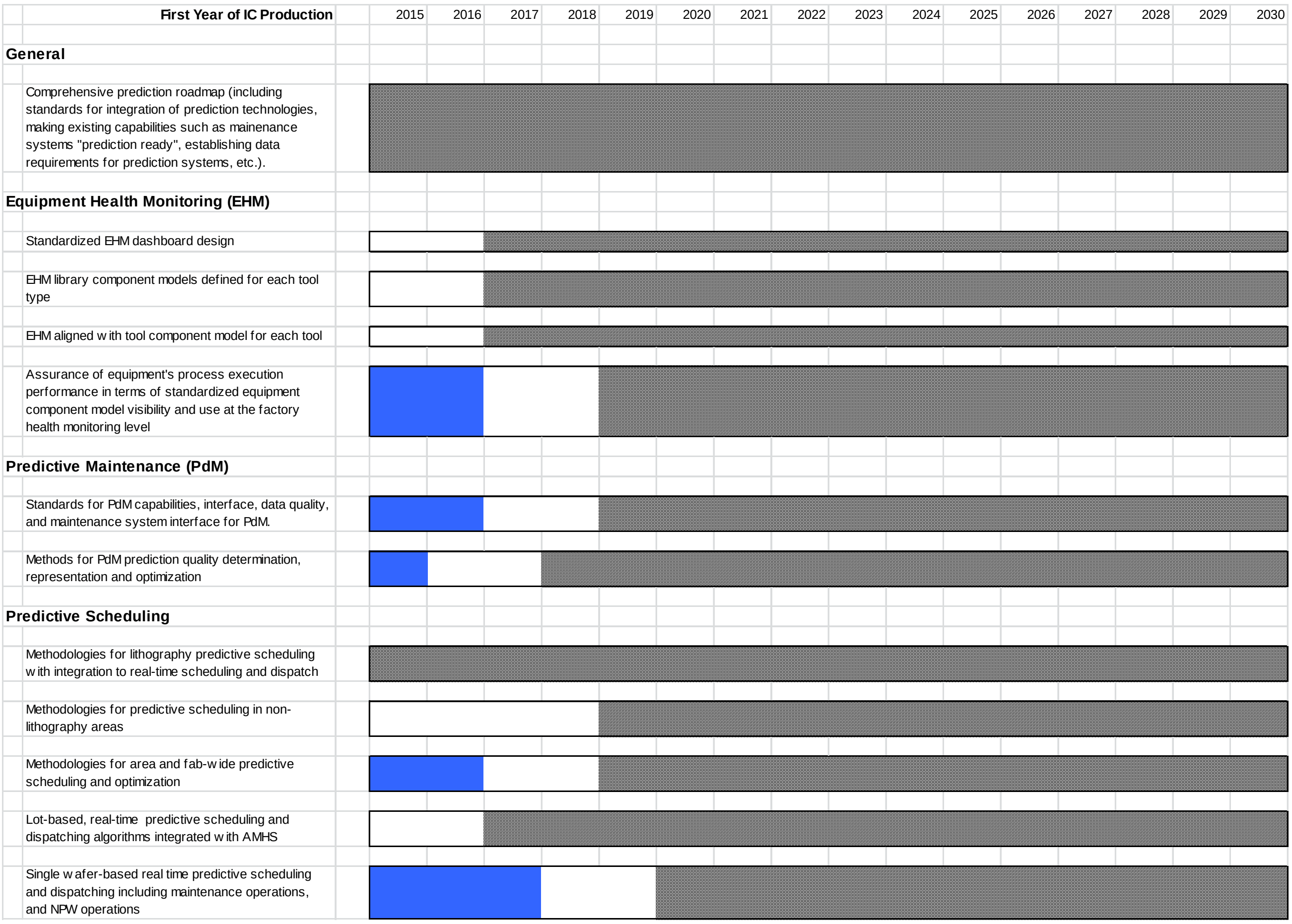

Figure FI-11 Augmenting Reactive with Predictive Potential Solutions

Figure FI-11 Augmenting Reactive with Predictive Potential Solutions (continued)

	First Year of IC Production	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Volume																	
	Capabilities in place to support required data retention both resident and archived																
	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 control/metrology, yield and Execution Log.																
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																

Roadmap to be Determined

Figure FI-12 Big Data Potential Solutions

18 CROSSCUT ISSUES

FI technology requirements are often driven by the device, processing, yield, metrology, ESH, lithography, and other technology working group (TWGs) requirements. In order to understand the crosscut issues fully, the FI TWG interfaces with the other TWGs and puts together a list of key crosscut challenges and requirements as shown below. FI will continue to address these key crosscut challenges and requirements.

Table FI-13 Crosscut Issues Relating to Factory Integration

Crosscut Area	***Factory integration related key challenges***
Front end Process (FEP)	Factory and FEP teams will continue to work on AMC requirements. FEP and Factory Integration will work on 450 mm challenges. Energy conservation effort: such as equipment sleep mode for energy conservation and the 1.5 mm wafer edge exclusion for long term challenge to starting material and SOI. 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
Lithography	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 due to small lots. AMC relative to the reticle and tighter process control needs. Lithography DFM needs. EFM may be added as it is confirmed as mask quality detractor. Predictive scheduling is important to lithography as it is often the critical process to maintaining throughput.
ESH	See new ESH subsection in FI chapter
Metrology	Comprehensive metrology roadmap to be jointly defined. AMC, temperature, and humidity control remain crosscut issues 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 FI targets
Yield Enhancement	See new YE subsection in FI chapter
Test	Big data and prediction requirements and solutions will impact and provide solutions for Test.

18.1 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 impact on reticle. Refer to *Lithography chapter* for a more information.

18.2 ENVIRONMENTAL, SAFETY AND HEALTH (ESH)

ESH continues to play a very important role in factory design and operation. Decisions made at the earliest stages of factory planning will have a dramatic impact on the ability of that factory to meet rigorous safety and environmental requirements economically.

As part of the move to ITRS 2.0, the ESH activities and output will become more integrated with FI as part of the Factory Integration "thrust" activities. Section 15 in this FI chapter represents the first step in that integration, providing a summary of the synergy between ESH and FI, and referencing the full ESH ITRS chapter. In the future the YE chapter may be fully included in the Factory Integration thrust chapter. In the interim, the reader is encouraged to read the ESH section in this chapter and refer back to the full ESH chapter to fully understand ESH to FI cross-cut issues.

18.3 Yield Management

Development of good yield management strategies reduces costs and investment risks. As a result of the increased synergy of some of the Yield Enhancement topics with Factory Integration (e.g., big data, yield prediction and yield enhancement), *section 16 of this document* reflects yield management systems. Due to the changed structure of ITRS 2.0 several cross TWG activities are envisaged, connections with More Moore (MM), Heterogeneous Integration (HI) and Heterogeneous Components (HC) are necessary. Refer to the *Yield Enhancement subchapter* for a more comprehensive discussion on YMS.

18.4 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 will become an important solution to augment existing metrology for improving quality without negatively impacting cost in terms of capital and lost throughput. 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 ITWGs will continue to work on the Virtual Metrology (VM) and IM requirements. Refer to the *Metrology chapter* for overall metrology topics.

18.4.1 Static Charge and Electromagnetic Interference Control

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

1. Electrostatic attracted (ESA) contamination increases as particle size decreases. ESA 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.
3. Equipment malfunctions due to ESD-related electromagnetic interference (EMI) reduce OEE, and have become more frequent as equipment microprocessor operating speeds increase.

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.

Influences of electromagnetic fields on sensitive electron optical devices have been known for many years (Microprocessor lockup, data errors, reduced optical resolution, reduced power stability, screen jitter, mask writing problems). But in the past these influences were limited to applications in research. Now, due to ongoing shrinking of structures and on the other hand the explosive increase of applications using wireless communication techniques, the influence of EMI effects in semiconductor manufacturing Fabs can no longer be neglected. Areas where uncontrolled electromagnetic fields are a very sensitive concern are SEM/TEM, e-beam and metrology tools. In order to reach acceptable electromagnetic field limits in the production area, the topic has to be discussed and considered at the very beginning of the design of a new Fab. The electromagnetic field limits listed in table FAC 10 are an average value which covers most of the known process tool requirements. Nevertheless for specific applications and specific process tools also tighter limits can be required.

19 Additional Factory Integration Focus Areas

In addition to working on the eight factory integration sub-sections and cross-ITWG challenges, the FI ITWG also evaluated key technology focus areas that impact the factory integration near-term and long-term needs and also cuts across all the FI thrusts. This section provides details on the four key focus areas of 1) Waste Reduction, 2) Energy Conservation, 3) Security, 4) Supply Chain Management, and 5) Migrating to a more cooperative service-based approach to FI deployment and maintenance. While these areas are mentioned throughout the FI chapter, they may deserve increased consideration in future versions of the roadmap, perhaps in the form of their own sub-chapter.

19.1 Waste Reduction

As the cost of manufacturing increases, it is becoming imperative to focus on other areas of cost reduction in parallel with Si scaling. The FI ITWG discussed cost driving concept and the relevant metrics in the preceding 5 years and concluded that waste reduction is a critical concept to drive manufacturing to meet the Moore’s Law cost trend.

Waste is the most common sense of productivity loss and can be a metric that will drive comprehensive effort in each ITWG to attain high productivity and cost reduction. The ultimate goal for waste reduction is that all the TR Tables in ITRS roadmap adapt waste reduction scheme, i.e., as a new driving axis in addition to the Si scaling cost reduction.

2011 version of the ITRS introduced waste reduction scheme for the first time. Waste reduction is included only in The Factory Integration Chapter and it has been incorporated only in the FO TR Table and not in thrust team TR Tables. The FI chapter’s waste reduction guidance values are not yet related to the individual technology areas of ITRS Roadmap.

The ITRS needs to discuss, firstly, on the target setting for waste reduction deduced from Moore’s Law or equivalent derivatives, secondly, how each ITWG can incorporate this new theme into their activities, and, finally, how TR Tables can express their requirements along with the waste reduction. This discussion should include comprehensiveness of the metrics needed for the roadmap. Apparently energy and resource waste reduction is becoming another axis in addition to the Si scaling.

One of the most effective waste reduction areas is production equipment’s operations which are peripheral and preparatory to the main thread of production operations. These operations can be classified into three logical areas; (1) those residing in the production equipment, (2) those residing in the interface between the production equipment and factory, and, (3) those residing in factory operation. The first area is to be dealt with by the equipment supplier and device maker collaboratively. “In-situ chamber cleaning” and “chamber seasoning” are well known example affiliated to this logical area. Carrier and/or lot exchange is a known waste in the 2nd area. The frequent change of process recipes due to small lot operation is known to cause considerable waste in tool operation and it is affiliated to the third logical area.

19.2 Energy Conservation

The primary goal of energy conservation is to reduce facility operation cost by enabling facility demand based utilization model in which energy conservation plays a pivotal role. Factory Integration team worked on several initiatives within the facilities and production equipment sub-team to define energy conservation related challenges and the outcome of this work is reflected as a metric (tool idle versus processing energy consumption) in the Facilities technology requirements table. Equipment sleep mode means that the equipment support units such as pumps will be shut down when no wafers are processed (i.e., when the tool is idle).

19.3 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 semiconductor manufacturing space includes 1) protection of data from unauthorized viewing or changing, 2) access authentication mechanism against both human and non-human accesses 3) managing user class read-write privileges, 4) maintaining software security levels, 5) addressing viruses and associated performance associated with antivirus practices (including production equipment capability to communicate with host). 6) protecting quality and integrity of Big Data, 7) Application of Big Data analytics to identify security issues, 8) balancing data availability with IP protection, 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 semiconductor 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 analysis risk analysis and mitigation cycles on security challenges.

These issues are not unique to semiconductor manufacturing, and many of the issues go even beyond manufacturing in general. Thus any roadmap for security in the ITRS 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 semiconductor manufacturing specific issues should be delineated and related gaps with the general manufacturing security roadmap identified.

19.4 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 and cost reduction). Supply chain integration and management is thus a necessary part of the FI roadmap. Developing this roadmap will require and understanding of both semiconductor 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 and 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 has been improved in the 2015 roadmap (see Section 7.1.14). In the future Supply Chain Management may be one of the focus areas of the FI thrust.

19.5 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.

20 SUMMARY

The Factory Integration chapter of the ITRS 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 2015 Factory Integration chapter has the following highlights;

1. Restructuring of vision somewhat to address the changing FI environment and the move to ITRS 2.0 (see Sections 1, 3 and 4.
2. Incorporation of sections on ESH and YE to address the stronger connection between FI and these areas, as well as the directives of ITRS 2.0.
3. An expanded discussion of security, Assembly and Test Integration, and Supply chain integration as these topics follow the general FI trend of increased integration across the enterprise.
4. Expanded discussion of capabilities for communication with equipment to support energy savings.
5. An expanded discussion of big data focusing on 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.

The FI ITWG should continue to work towards the following goals:

1. Promoting integration and commonality with perhaps new thrust areas defined in the future, such as security and supply chain integration. These new areas will have their own challenges and solutions which may be documented as new FI sub-chapters.
2. Addressing the FI component of the challenges cited in the ITRS 2.0 description of semiconductor manufacturing (see for example Figure FI-1).
3. Supporting cost per unit area requirements of silicon and increasing factory flexibility to changing technology and business needs and the FI ITWG should identify the needed factory services and technologies along with the corresponding potential solutions.

For more information and details on Technology Requirements and Potential Solutions, access the electronic chapter links for Factory Integration highlighted as links throughout this chapter and online at *http://www.itr2s.net*.