INTERNATIONAL
ROADMAP
FOR
DEVICES AND SYSTEMS

2021 EDITION

FACTORY INTEGRATION

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Factory Integration International Focus Team (IFT) active members— Daniel Babbs, Eric Collart, Neil Condon, Terry Cox, Gino Crispieri, Peter Csatary, Mike Czerniak, Wolfgang Eissler, Rudy Federici, Russell Fitzpatrick, Albert Fuchigami, Astrid Gettel, Raymond Goss, Alrev Green, David Gross, Ken Harris, Parris Hawkins, Karey Holland, Chih-Wei (David) Huang, David Huntley, Leo Kenny, Vladimir Kraz, Chris Jones, Slava Libman, Tom Linton, John Maline, Supika Mashiro, Mitsuhiro Matsuda, Chuck McCain, Rick McKee, Jason Mechler, Steve Moffatt, Jairo Moura, James Moyne, Chris Muller, Phil Naughton, Andreas Neuber, Kevin Pate, Markus Pfeffer, Lothar Pfitzner, Gavin Rider, Inna Skvortsova, Doug Suerich, Ines Thurner, Mitsuya Tokumoto, Tadamasa Tominaga, Don Yeaman

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FACTORY INTEGRATION

1. INTRODUCTION

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

1.1. CURRENT STATE OF TECHNOLOGY

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

1. *Complex business models with complex factories*—Rapid changes in microelectronics technologies, business requirements, and the need for faster product delivery, high mix, and volatile market conditions continue to make effective and timely factory integration to meet accelerated ramp and yield targets more difficult over time. The factory now must integrate an even larger number of new and different equipment types, software applications and data to meet complex market objectives and customer requirements. High mix and low-volume product runs are making mask cost, fabrication, and FI extremely difficult in a market where average selling prices are declining.
2. *High potential of waste generation and inclusion in factory operations*—Continuous improvement of factory productivity with more comprehensive visualization and inclusion of waste and resource utilization targets is necessary to achieve growth and cost targets.
3. *Production equipment utilization and extendibility*—Production equipment is not keeping up with reliability, availability, and utilization targets, which has an enormous impact on capital and operating costs. Reliability, availability and especially utilization are also impacted by factory operation factors.
4. Significant productivity improvement either by next wafer size manufacturing paradigm or through 300 mm manufacturing technology improvement—the industry needs to review the productivity losses in 300 mm and improve prior to the next wafer size transition so to make this transition more cost-effective. Due in-part to the challenges associated with transition to the next wafer size including wafer size transition under continued More Moore 2D scaling trends, the projected date for transition has been moved out to 2029.
5. *Augmenting reactive with Predictive and Prescriptive operations*—The industry needs to augment the existing reactive mode of operation, changing reactive operations to predictive operations wherever possible, but continuing to be able to support reactive operation. This will provide significant opportunities for cost reduction and quality and capacity improvement. Examples include predictive maintenance (PdM), metrology prediction via virtual metrology (VM), fault prediction, predictive scheduling, and yield prediction.
6. *Control system evolution*—Control systems will continue to become more granular (e.g., lot-to-lot, to wafer-to-wafer, to within wafer), and higher speed (e.g., run-to-run to real-time quality parameter control). Centralized versus various levels of distributed control is also being evaluated, both in a horizontal (e.g., distributed applications and control optimized across the supply chain) and vertical (e.g., internal tool fault detection tied to higher level maintenance activities) sense. Big data characteristics including veracity (i.e., data quality including accuracy, synchronization and context richness), value (including algorithms) and velocity (i.e., rates) must improve to support the evolution of control systems and will also serve to realize new control system concepts.
7. *Supply chain integration and management*—FI connectivity up and down the supply chain leveraging the accelerated information technology (IT) trends will be necessary to support tightening of production methods (e.g., associated with lean manufacturing) and addressing business requirements (e.g., for yield correlation, warranty traceability, and cost reduction).

8. *Ramp-up of new technologies*—Closer integration of the industry is required for successful ramp-up of new technology nodes and device architectures. There is a need for improved hardware and software capabilities as well as more rapid reliable deployment of these capabilities. Examples include process characterization involving nascent device materials, chemicals, gases, and consumables; where the wafer process environments are far better protected to prevent productivity degradation.
9. *Security*— Information security will be associated with significant issues in addressing almost all difficult challenges in the near term and to a certain extent in the long-term as shown in Table FAC3. It will be made more challenging with the increase of data shared across the factory integration space. For example, the concept of the "connected fab," which is one of central concepts of Industry 4.0/Smart Manufacturing, even indicates potential direct data exchanges beyond the factory integration space. While data must be made available to promote fault detection and classification (FDC), predictive maintenance (PdM), advanced process control (APC), etc. at more granular levels (e.g., lot based to single wafer oriented for maximizing productivity), protection of data and intellectual property (IP) within data will become more complicated and sometimes contradictive to needs of data availability. Typical issues are listed below: (Note that some of these issues are addressed in SEMI E169-0616: Guide for Equipment Information and System Security, however this is a guide and thus does not contain any specific standards requirements.)
    a. Protection of crucial production parameter data (e.g. recipe, equipment parameters) from unauthorized viewing or changing within the factory including between factory, original equipment manufacturers (OEMs) and 3rd party suppliers [1]
    b. Managing access authentication mechanisms for both human and non-human entities (e.g., software program)
    c. Managing user class read-write privileges to support user capabilities while preventing access that would result in breach of IP security or factory operation issues
    d. Achieving balance between data availability (e.g., log-data for improved equipment performance) and protection of device manufacturer's manufacturing IPs and equipment suppliers' proprietary information (e.g., equipment design and control)
    e. Maintaining software security levels when interacting with 3rd parties on the factory floor
    f. Maintaining software and communication performance in the face of security measures such as antivirus software operations or compartmentation firewalls.
    g. Protecting quality and integrity of big data and application of big data analytics to identifying security issues
    h. Protection of the facility's instrumentation and control systems from attack
    i. Protecting fab and equipment operation control systems from unauthorized operation or alteration from both inside fab and outside.
10. *The move to Smart Manufacturing (SM)*—Smart manufacturing (SM) is a term "generally applied to a movement in manufacturing practices towards integration up and down the supply chain, integration of physical and cyber capabilities, and taking advantage of advanced information for increased flexibility and adaptability"[1]. It is often equated with "Industry 4.0" (I4.0), a term that originated from a project in the German government that promotes a 4th generation of manufacturing that uses concepts such as cyber-physical systems, virtual copies of real equipment and processes, and decentralized decision making to create a smarter factory. The industry needs to embrace the movement to SM that incorporates advances in big data, augmenting reactive with Predictive and Prescriptive, advanced analytics and applications, digital twin, industrial internet of things and the cloud, integrated supply chain, and reliance on a knowledge network.
11. *Challenges and issues associated with increased integration of FI with Yield and ESH/S solutions*—As noted above FI challenges and solutions directly impact aspects of ESH/S and Yield roadmaps and these roadmaps in turn place requirements and provide direction for FI. This is exemplified in areas such as yield prediction and energy savings.

1.2. DRIVERS AND TECHNOLOGY TARGETS

Societal driving forces and trends such as mobile devices and the internet of things (IoT) are impacting all areas of the IRDS, however, as shown in Figure FAC1, these factors impact the evolution of FI from two perspectives, namely:

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[1] *Wikipedia: Smart Manufacturing. Available online: https://en.wikipedia.org/wiki/Smart_manufacturing. Accessed September 2018*

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 FAC1, and then determining how the FI roadmap addresses the related tighter process requirements. With respect to perspective 2), the following is an example of how some of these drivers directly impact FI:

- *The Cloud:* The advent of the cloud and cloud-based technologies provides tremendous opportunities in terms of analytics, addressing data volumes, coordination, enterprise-wide sharing and commonality and leveraging capabilities across industries. However, it also presents challenges in terms of security from attack, security for IP protection, and performance.
- *Big Data:* The data explosion in manufacturing provides both challenges and opportunities for FI; a section of the FI chapter was created in the ITRS 2013 Edition and enhanced in the ITRS 2.0 2015 Edition, as well as in the IRDS 2017 whitepaper that describes these in detail.
- *Mobility:* Mobile devices have and will continue to enhance the capabilities of FI systems in terms of accessibility, ergonomics and human-machine interaction, flexibility, portability, etc., but also can present many security challenges as well as performance challenges.
- *Green Technology:* The movement towards greener technologies and subsequent requirements for reduction in energy costs and "carbon footprint" significantly impact FI. First and foremost, they require that facilities objectives such as energy consumption and ESH/S objectives such as contamination waste reduction be an integral part of FI factory operation objectives.
- *IoT:* The definition of IoT varies in detail however the definition from Wikipedia is applicable in the context of this report: "The internet of things is the network of physical devices, vehicles, home appliances, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to connect and exchange data." [2]. IIoT (industrial internet of things) technologies provide opportunities in terms of flexible connectivity and interoperability strategies for dissimilar system across the FI infrastructure. This connectivity could be used for non-time-critical and human-in-the-loop activities when the communication is the internet, however issues of security and response time variability must be considered. The connectivity could be used for more time critical applications such as control with intranet connectivity.
- *Supply Chain:* An important trend in FI is tighter integration up and down the supply chain for improved quality, traceability, efficiency, etc. This is discussed in further detail in sections 5.8.8 and 8.2.

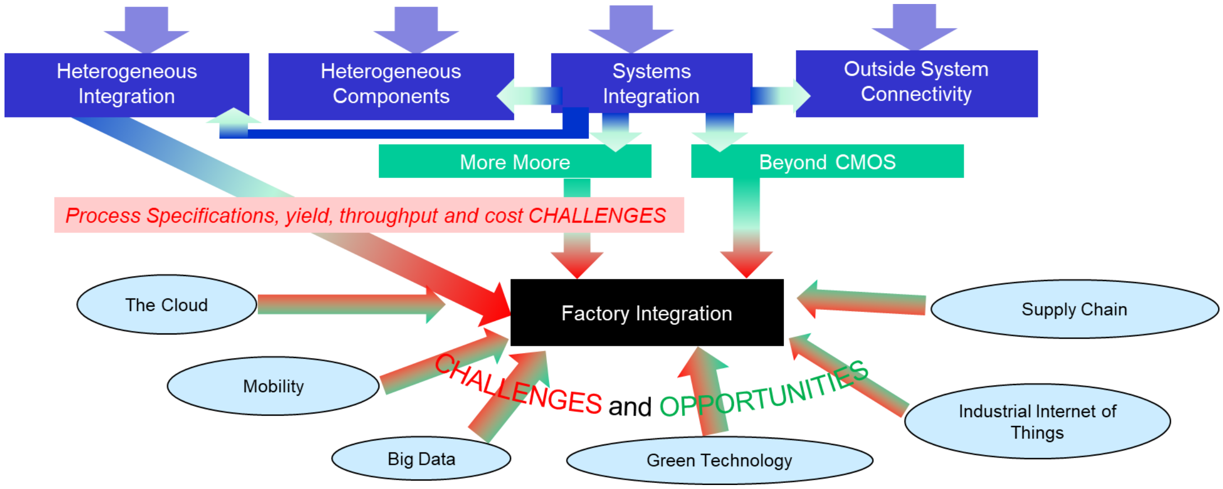

Figure FAC1 Societal Forces Impacting Challenges and Opportunities in FI

1.3. VISION OF FUTURE TECHNOLOGY

The future of microelectronics manufacturing FI is imbued in large part in the tenets of "Smart manufacturing" (SM) and Industry 4.0 (I4.0). "Smart Manufacturing" is a term "generally applied to a movement in manufacturing practices towards integration up and down the supply chain, integration of physical and cyber capabilities, and taking advantage of advanced information for increased flexibility and adaptability" [3–5]. It is often equated with "Industry 4.0", a term that originated from a project in the German government that promotes a 4th generation of manufacturing that uses concepts such as cyber-physical systems, virtual copies of real equipment and processes, and decentralized decision making to create a smarter factory [6,7]. Key tenets of this migration include leveraging big data infrastructures, integrating with the supply chain network, leveraging advanced analytics, improving use of cyber-physical systems (CPS), improving the use of real-time simulation through realizing the "digital twin," and reliance on a knowledge network for using subject matter expertise (SME) in an increasingly collaborative environment. These terms are expounded upon through this document, with detail provided in Section 5.8. This migration is associated with a number of challenges ranging from moving from reactive to predictive/prognostic mode of operation to addressing security associated with data sharing.

1.4. BACKGROUND INFORMATION

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

1.4.1. ACRONYMS

The following acronyms are used in this report:

Table FAC1 Acronyms Used in This Report

Acronym	*Meaning*	*Acronym*	*Meaning*
ACSEC	Advisory Committee (AC) on Information Security and Data Privacy	ITRS	International Technology Roadmap for Semiconductors
AMC	Airborne Molecular Contamination	JIT	Just-In-Time
AMHS	Automated Material Handling System	LEED	Leadership in Energy and Environmental Design
APC	Advanced Process Control	LP	Low Power
ARAMS	Automated Reliability, Availability, and Maintainability Standard	MES	Manufacturing Execution System
ARPP	Augmenting Reactive with Predictive and Prescriptive	MFL	Maximum Foreseeable Loss
BD	Big Data	MHS	Material Handling System
BEP	Back End Process	NGOs	Non-Government Organizations
BKMs	Best Known Methods	NIST	National Institute of Standards and Technology
CIP	Continuous Improvement Program	NPW	Non-Product Wafer
CPS	Cyber-Physical System(s)	NTP	Networked Time Protocol
CPU	Central Processing Unit	OEE	Overall Equipment Efficiency
CSA	Control Systems Architectures	OEM	Original Equipment Manufacturer
CVD	Chemical Vapor Deposition	PCL	Predictive Carrier Logistics
DFM	Design for Manufacturing	PCS	Process Control Systems
DM	Data Mining	PdM	Predictive Maintenance
DOT	Deliver-On-Time	PE	Production Equipment
DS	Decision Support	PFC	Perfluorocarbon
DT	Digital Twin	PIC	Physical Interface and Carriers
EES	Extremely Electrostatic Sensitive	PM	Preventative Maintenance
EESM	Equipment Energy Saving Mode	POC	Point of Connection
EFEM	Equipment Front-End Module	POD	Point of Delivery
EFM	Electric Field Induced Migration	POE	Point of Entry
EHM	Equipment Health Monitor	POP	Point of Process
EMI	ElectroMagnetic Interference	POS	Point of Supply

Acronym	*Meaning*	*Acronym*	*Meaning*
EOS	Electrical Overstress	POU	Point of Use
EOW	Equipment Output Cycle Time Waste	PPM	Predictive and Preventative Maintenance
EPT	Equipment Performance Tracking	PTP	Precision Time Protocol
ESA	Electrostatic Attracted, Electrostatic Attraction	R&D	Research and Development
ESD	Electrostatic Discharge	R2R	Run-to-Run (control)
ESH/S	Environmental, Safety, Health, and Sustainability	RAM	Reliability, Availability, and Maintainability
EUV	Extreme Ultraviolet	RM	Real Metrology
EUVL	Extreme Ultraviolet Lithography	ROI	Return on Investment
ExD	Excursion Detection (VM capability)	RUL	Remaining Useful Life
FC	Fault Classification	SCOR	Supply Chain Operations Reference
FD	Fault Detection	SECS	SEMI Equipment Communication Standard
FDC	Fault Detection and Classification	SEM/TEM	Scanning Electron Microscopy/Transmission Electron Microscopy
FEP	Front end Process	SESMC	Subsystem Energy Saving Mode Communication
F-GHG	fluorinated greenhouse gases	SFORMS	Secured Foundation of Recipe Management Systems
FI	Factory Integration	SHL	Super Hot Lots
FICS	Factory Information and Control System	SM	Smart Manufacturing
FO	Factory Operations	SMet	Smart Metrology (e.g., a VM capability)
FOUP	Front Opening Unified Pod	SMC	Surface Molecular Contamination
FP	Fault Prediction	SME	Subject Matter Expertise, or Subject Matter Expert
GEM	Generic Equipment Model	SOAP	Simple Object Access Protocol
HSMS	High-Speed SECS Message Services	SOS	Software as a Service
HVM	High Volume Manufacturing	SPC	Statistical Process Control
I/O	Input/Output	STS	need to define
I4.0	Industry 4.0	TH	Throughput
IC	Integrated Circuit	TR	Technical Requirements
ID	Identity	UF	Ultra-Filtration
IDM	Integrated Device Manufacturer	UPW	Ultra-Pure Water
IFT	International Focus Team	VM	Virtual Metrology
IGPT	Insulated-Gate Bipolar Transistor	W2W	Wafer-to-Wafer (control)
IM	Integrated Measurement	WIP	Work in Process
iNEMI	International Electronics Manufacturing Initiative	WIW	Within Wafer (control)
IoT	Internet of Things	WTW	Wait Time Waste
IIoT	Industrial Internet of Things	XML	eXtensible Markup Language
IP	Intellectual Property	YEx	Yield Excursion
IRDS	International Roadmap for Devices and Systems	YMS	Yield Management System
ISMI	International SEMATECH Manufacturing Initiative	YP	Yield Prediction
ISO	International Standards Organization		
IT	Information Technology		

1.4.2. STANDARDS

A number of standards fall within the scope of the FI report and are important to the realization of the FI roadmap, as shown in Table FAC2. These standards are listed here. Note that this list is not meant to be comprehensive; for a complete listing of SEMI standards, refer to https://www.semi.org/en/products-services/standards.

Table FAC2 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 E5	SEMI Equipment Communications Standard 2 Message Content (SECS-II)
SEMI E6	Guide for Semiconductor Equipment installation Documentation
SEMI E10	Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM) and Utilization
SEMI E30	Specification for the Generic Model for communications and Control of Manufacturing Equipment (GEM)
SEMI E33	Specification for Semiconductor Manufacturing Facility Electromagnetic Compatibility
SEMI E37	High-Speed SECS Message Services (HSMS) Generic Services
SEMI E43	Guide for Measuring Static Charge on Objects and Surfaces.
SEMI 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 E78	Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment
SEMI E87	Specification for Carrier Management (CMS)
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 E148	Specification for Time Synchronization and Definition of the TS-Clock Object
SEMI E151	Guide for Understanding Data quality
SEMI E160	Specification for Communication of Data Quality
SEMI E163	Guide for the Handling of Reticles and Other Extremely Electrostatic Sensitive (EES) Items Within Specially Designated Areas
SEMI E164	Specification for EDA Common Metadata
SEMI E167	Specification for Equipment Energy Saving Mode Communications (EESM)
SEMI E169	Guide for Equipment Information System Security
SEMI E170	Specification for Secured Foundation of Recipe Management Systems (SFORMS)
SEMI E171	Specification for Predictive Carrier Logistics (PCL)
SEMI E175	Specification for Subsystem Energy Saving Mode Communication (SESMC)
SEMI E176	Guide to Assess and Minimize Electromagnetic Interference (EMI) in a Semiconductor Manufacturing Environment
SEMI S2	Environmental, Health, and Safety Guideline for Semiconductor Manufacturing Equipment
SEMI S23	Guide for Energy, Utilities, and Materials Use Efficiency of Semiconductor Manufacturing Equipment

1.4.3. EDUCATIONAL TABLES

Some of the technical challenges that had been identified in previous roadmap efforts have become more routine technical requirements. Although their challenging natures are somewhat diminished, they still need close observation and continuous improvement. Such items are summarized in the Educational FI Metrics Table FAC5.

Similarly, some of the potential solutions that were considered to address the technical challenges that had been identified in previous roadmap efforts have been adopted but they are still in need of continuous improvement. Such former "potential" solutions are summarized in the Educational Solutions Table FAC21.

2. SCOPE OF REPORT

2.1. INTRODUCTION

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

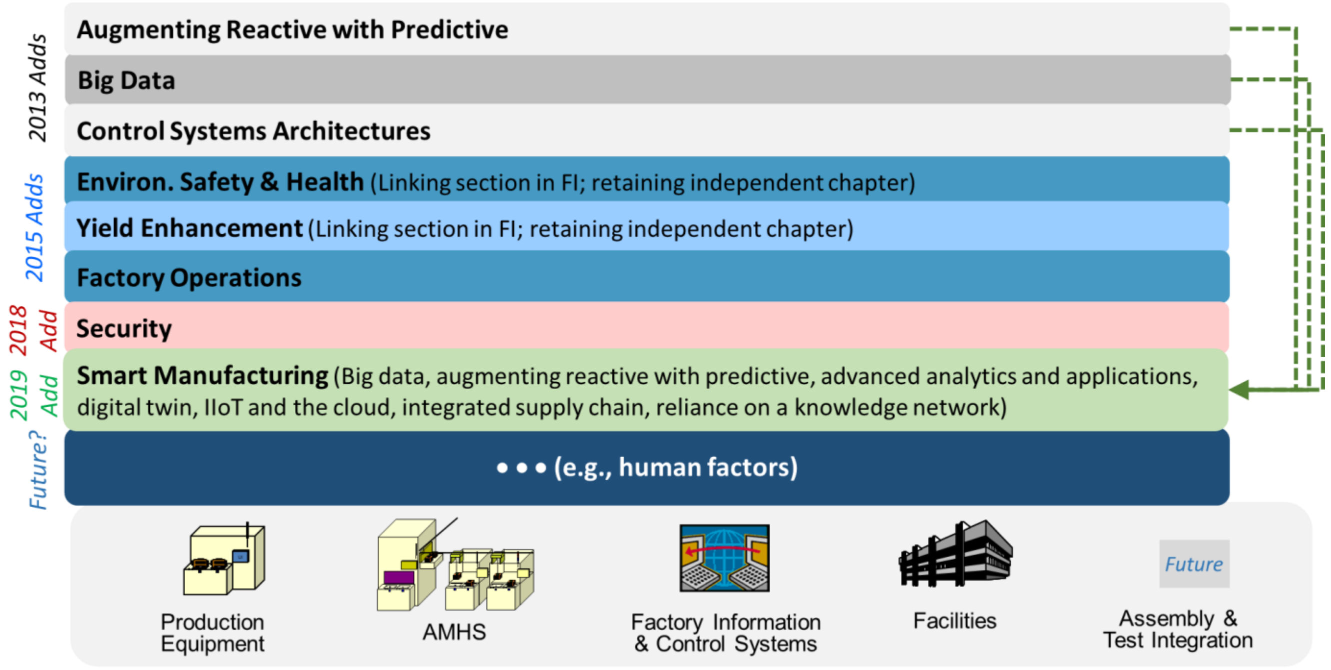

Figure FAC2 Factory Integration Scope

2.1.1. FACTORS CONTRIBUTING TO DEFINING FACTORY INTEGRATION SCOPE

The following are key factors impacting the scope of FI

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

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

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

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

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

3. SUMMARY AND KEY POINTS

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

Security subchapter summarizes basic security challenges and solution areas, such as data partitioning and IP security, though security related technology requirements remain in each applicable section that needs security considerations. Future roadmap versions will seek to better define an evolving FI security roadmap by providing consolidated technology requirements in the security section.

3.1. WHAT IS NEW IN THE 2021 EDITION?

3.1.1. SECURITY UPDATE

Security has been addressed in the FI beginning with ITRS 2.0 2015. In 2018 update of the IRDS, the security topics are consolidated and upgraded as a new subchapter that summarizes basic security challenges and solution areas, such as data partitioning and IP security because security permeates across different functional areas, and there are significant levels of commonalities in potential solutions to address security issues in these functional areas identified in the FI chapter. Significant updates are made in 2020, followed by inclusion of the technology requirement table in 2021

3.1.2. SMART MANUFACTURING SUBCHAPTER UPDATE

Smart Manufacturing was added as a new sub-chapter of the Factory Integration chapter in 2020 IRDS. In the 2020 version of the IRDS, sections on each of the smart manufacturing tenets were provided, each with narrative, technology requirements tables and potential solutions tables. Some updates including expansion of ARP to ARPP and refinement of technology requirements roadmap are made in this edition. The narrative and tables will be expanded in future years as more information becomes available to support improvement in the roadmap.

4. CHALLENGES

Difficult challenges associated with factory integration span multiple technology generations and often cut across the factory functional areas. Near-term difficult challenges for the factory integration include business, technical, and productivity issues that must be addressed, as shown in Table FAC3.

Table FAC3 Factory Integration Difficult Challenges

Difficult Challenges through 2025	*Description*
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)
	• Developing metrics on performance of factory integration systems and understanding how these metrics translate to factory financial information
	• 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 address security gaps (e.g., data ownership, access authentication and authorization systems) that have prevented microelectronics industry's migration to Cloud based Big Data Analytics
	• 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.
	• To allow data sharing with appropriate level of IP protection across systems and parties to realize Smart Manufacturing tenets.
	Address complexity and requirements associated with demands coming from the move to an integrated supply chain in smart manufacturing (e.g., high reliability end-consumers requirements, and trust in sharing between partners across the supply chain to support traceability and data mining). Determine mechanisms to achieve higher productivity per square foot (meter) of space without incurring higher COO of equipment.
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 • Need to protect fab and equipment operation control systems as well as facility's instrumentation and control systems from unauthorized operation or alteration from both inside fab and outside in consideration with - Synchronizing/harmonizing security measures for various level of control systems (e.g., equipment, SCADA, MES) in the Fab. - Continuously supporting all updates for all systems critical for factory operation (extremely challenging for legacy systems) without compromising their functionality, performance, and security • Ability to model factory performance as part of an integrated supply chain to optimize output and improve cycle time. • 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 • 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. • Communication protocols developed for semiconductor manufacturing are not aligned with trends in information technology communication such as web services.

Difficult Challenges through 2025	*Description*
	• 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 Airborne Molecular Contamination (AMC) challenges through possibly changing factory operation approach (e.g., maintaining vacuum in specific areas), as well as providing necessary interfaces, information and technologies (e.g., virtual metrology and APC). • Minimizing and isolating sources of particulate contaminants that impact yield (e.g., defining mechanisms to detect and measure, and analysis methods such as virtual metrology to isolate and predict). • 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. • 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 • Addressing shifting focus from line width pitch shrinks, to 3D and emerging disruptive technologies
3. 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 need the system to have multiple cross checks and software that can be adversarial to learn and improve the outcomes when one or more failures occur. • 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) in multiple levels (modules, production equipment, cells, floor, etc.) to meet quality requirements • Equipment data, analytics and visualization to support equipment health monitoring (EHM) • Address structured incorporation of subject matter expertise (SME) into the lifecycle of analytical solutions (from planning through development, deployment and maintenance) • Address security issues that hinders data sharing between equipment users and suppliers, and up and down across the supply chain, which is needed to support advanced capability, reliability, and productivity solutions. • Establish cost/benefit analysis templates for balancing IP/security risk against expected return, where parties seek to collaborate through the exchange of specific data sets, so that parties can agree when to share data and when not. • Standardize legal and commercial guidelines for value-sharing, where solutions for advanced capability, reliability or productivity are developed through the collaboration of parties (each providing their own background data and SME effort), so that data-derived IP resulting from collaborative efforts can benefit all parties appropriately. • 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

Difficult Challenges through 2025	*Description*
	• 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. • Methods to provide more comprehensive traceability of individual wafers to identify problems to specific process areas • Availability of published Standards for supply chain traceability of critical components and parts ~~spares~~, e.g., for better understanding of lifetime, suitability, or robustness of them • 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 • EOS is suspected of causing latent yield issues (traditional countermeasures against ESD could worsen the EOS). To quantify EOS contribution, research is needed.
4. Cross leveraging factory integration technologies across boundaries such as 300 mm and 450 mm to achieve economy of scale	• Addressing the potential data explosion and other big data issues associated with crossing a technology boundary • Ensuring the advantage of the technology change to implement the appropriate factory integration enhancements such as control system paradigm shift. • Understanding the software roadmap for moving across these technology boundaries. 450 mm era: Effecting architectural and other changes as necessary at an affordable cost to maintain or improve wafer-throughput-to-footprint levels in migration to 450 mm
5. Addressing the migration to smart manufacturing	• Achieving a state of integration of analytics and knowledge network integration to the point where no knowledge is left behind • Achieving compatibility of existing systems that are largely reactive with emerging predictive paradigms of operation, such as Predict Maintenance and yield prediction • Achieving a state of prediction in facilities 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. • Full integration of facilities with a digital twin network for prediction of all performance metrics. • Integration of production with up and downstream supply chain to support optimization of production with respect to final customer experience. • IIoT infrastructures including cloud-based solutions that are optimized fully to performance metrics (and not hindered by limitations in infrastructure, security, etc., that imping on the optimization of the infrastructure).

Difficult Challenges Beyond 2025	***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 • Adoption and adaptation of newer data security technologies (e.g. quantum cryptography, blockchain) to facilitate information exchange in the supply chain and support traceability for products (e.g., identities of equipment used for production, production conditions, lot's test data). • 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.

Difficult Challenges Beyond 2025	***Summary of Issues***
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

5. TECHNOLOGY REQUIREMENTS

5.1. SUMMARY

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

Table FAC4 provides a summary of key focus areas and issues for each of the factory integration functional areas beyond 2020. It also includes a discussion of synergistic issues with ESH/S and Yield IFTs as well as issues that may be the topic of future focus areas.

Table FAC4 Key Focus Areas and Issues for FI Functional Areas Beyond 2020

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) 450 mm production tool development
	2) for integration into the factory information system; supporting bridge capabilities to 450 mm
	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) 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

Functional Area	*Key technology focus and issues*
	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) 450 mm 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 450 mm 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.
	7) Facility utility reduction
Information Security	1) The roadmap continues defining the current challenges and potential solutions for information security including secure data partitioning and IP separation. The roadmap begins to define technology requirements. Initial focus on itemizing technology requirements.
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.
Smart Manufacturing	1)The roadmap will continue to provide increased focus on smart manufacturing tenets providing narrative, technical requirements and potential solutions for each tenet. These tenets (listed below) are big data, augmenting reactive with predictive, advanced analytics and applications, digital twin, IIoT and the cloud, integrated supply chain, and reliance on a knowledge network.

Functional Area	*Key technology focus and issues*
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 / decompression, 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
Augmenting Reactive with Predictive and Prescriptive (ARPP)	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
Advanced Analytics and Applications (AAA)	1) Defining analytics for the enhancement of existing applications as well as for the realizing of new applications.
	2) Understanding the impact on an opportunities for analytics and applications in big data environments.
Digital Twin (DT)	1) provide a vision for a DT framework of DT classes existing at all levels of the ISA-95 infrastructure
	2) Outlining technical requirements for DT classes of run-to-run (R2R) control, Predictive Maintenance (PdM) and Virtual Metrology (VM) that leverage existing capabilities.
	3) Addressing evolutionary aspects of control system and control system architectures such as granularity, speed, quality, and capability.
	4) 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
	5) Addressing the framework to integrate monitoring and closed loop control tied to all semiconductor manufacturing key performance indices – including engineering and manufacturing control levels.
Industrial Internet of Things (IIoT) and the Cloud	1) Defining IIoT and cloud drivers and the distribution of intelligence between the cloud and edge devices.
	2) Understanding the impact of issues such as performance, data sharing and security on cloud support decision-making
Integrated Supply Chain (ISC)	1) Addressing the capability to integrate with supply-chain framework for value chain control.
	2) Exploring issues such as latency, confidentiality and data integrity and their impact on solutions that use and integrated supply chain.
Reliance on a Knowledge Network (KN)	1) Emphasizing the importance of SME throughout project workflows and across SM tenets.
	2) Defining mechanisms for incorporating subject-matter-expertise (SME) into to analytics solutions with a goal of "no knowledge left behind"

5.1.1. STABILIZED FACTORY INTEGRATION METRICS AND RECOMMENDED VALUES

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

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

Functionality Area	**Metric/ Requirement**	**Recommended value/level**	**Year of Stabilization**	**Justification**
Factory Operations (FO)	N/A			
Production Equipment (PE)	Maximum recommended electrostatic field at chrome mask surfaces (V/m) for EFM	0	2017	No amount of electric field exposure can be regarded as safe for a chrome reticle. The recommended field value should reduce the risk of degradation to an acceptable level over the normal production lifetime of a reticle.
Automated Material Handling Systems(AMHS)	Time required to integrate process tools to AMHS (minutes per LP) (300 mm)	5	2014	The value is important to keep disruption to production minimum, but it does not need roadmap as it already reaches practical limit with currently adopted interface between PE and AMHS
Factory Information & Control Systems (FICS)	Wafer-level (within-lot) recipe / parameter adjustment, e.g., for W2W control	YES	2015	This metric indicates FICS capability to facilitate wafer-to-wafer recipe and parameter adjustment and supports the ability to have multiple lots per carrier, which have been widely realized.
Facilities	Facility cleanliness level (ISO 14644-1)	Class 6	2013	Wide adoption of minienvironment for the critical areas/systems eased Facility cleanliness level requirement
	Design Criteria for Facility critical vibration areas (lithography, metrology, other) (mm/sec)	6.25 (VC D)	circa 2011	Observing the value is critical for area of the primary manufacturing floor in which a significant portion of the equipment is highly sensitive to floor vibration. But required measures are known and have been implemented.
	Design Criteria for Facility non-critical vibration areas (mm/sec)	50 (VC A)	circa 2011	The metric is for the area where all or some of the equipment is only moderately vibration sensitive. No need for special consideration to realize the value.
Security	N/A			Metrics for security will be provided in future versions of the roadmap.
Smart Manufacturing (SM)	N/A			Metrics for SM tenets will be provided in future versions of the roadmap.

5.2. FACTORY OPERATIONS NEEDS

5.2.1. SYSTEMATIC FAB PRODUCTIVITY IMPROVEMENT

One of the most important missions of FI is to assist fab productivity improvement effort by providing productivity information to those who are responsible at each of the hierarchical operation responsibility layers and providing means to evaluate the improvement before and after implementation. There should be methodologies to identify the room for improvement as a 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 making. It is also imperative to define commonly usable productivity metrics so that the productivity improvement activities can cooperate among many. The FI IFT has concluded that such metrics are expressed as productivity waste.

5.2.2. AGILITY AND FLEXIBILITY IN FACTORY SERVICES

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

5.2.3. HIGH GRANULARITY AND PROACTIVE SERVICES

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

5.2.4. HIERARCHICAL OPERATION STRUCTURE AND MANUFACTURING CONTROL OPERATION

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

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

5.2.5. INTEGRATION OF FACILITIES REQUIREMENTS INTO FACTORY OPERATIONS

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

5.2.6. SIGNIFICANT PRODUCTIVITY IMPROVEMENT

A focus of the FO Technology Requirements Table FAC6 is challenges associated with significant productivity improvement of the current technology preceding the 450 mm insertion.

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

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

5.2.7. FUTURE MANUFACTURING REQUIREMENTS

The industry can focus on common technology development for 300 mm and 450 mm. 450 mm factories would benefit by adaption of improved technology validated for 300 mm. FO metrics were reviewed and modified to reflect the future manufacturing, including 450 mm needs. Industry should study the implication of the FO Technology Requirements Table FAC6 and other FI technology requirements tables.

5.2.8. WASTE REDUCTION METRICS

Equipment Output Waste (EOW) is in the FO Technology Requirements Table FAC6 with intent of aligning the significant productivity improvement scheme. It is beyond the FI’s task to capture all of the waste types in the roadmap. It is important to introduce more comprehensive waste metrics for FI so as to address the direction of overall productivity optimization of highly complicated manufacturing system. These need to be comprehensive and measurable factory-level waste metrics. Addressing the issue of waste reduction metrics will promote new manufacturing concepts, manufacturing control models, and algorithms.

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

5.2.9. DATA USAGES

The stringent engineering requirement is driving need for more data that would result in so-called data explosion. This is explored in detail in the FI “Big Data Needs” section of the Smart Manufacturing subchapter. 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 with these models with usages for high data utilization efficiencies.

5.2.10. 450 MM RELATED METRICS

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

Readers are encouraged to read the FO Technology Requirements Table FAC6 with wafer size dependency in mind, but should not read all the same fab operation characteristic values as 300 mm being required for 450 mm. From the waste reduction view point, there should be much similarity between 300 mm and 450 mm requirements, but more study is needed for WTW as discussed earlier. As 450 mm factory services requirements and physical ones become available IRDS FI will capture 450 mm specific items into respective FI technology requirements tables.

5.2.11. OPERATIONAL PARADIGMS RELATED TO LOT SIZE

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

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

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

5.2.12. ASSEMBLY TEST INTEGRATION

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

Table FAC6 Factory Operations Technology Requirements

5.3. PRODUCTION EQUIPMENT NEEDS

5.3.1. SCOPE

The original scope of the production equipment section includes all factory integration requirements relevant to the process and metrology equipment. Also included are tool embedded controllers, front-end module (EFEM) and load ports, carrier, and wafer handling, software and firmware interfaces to host systems, and all facilities interfaces of the equipment. The most of PE and factory interfaces have been standardized as the result of 300 mm transition standardization. Further the factory operation driven metrics have been moved to the FO Technology Requirements Table FAC6 for clarity. The PE Technology Requirements Table FAC8 has metrics only on availability for process tools and metrology tools together with electrostatic field requirements.

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

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

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

5.3.3. WASTE REDUCTION

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

The industry’s growth rate will not be sustainable in the future if increasing capitalization cost trends continue without significant improvement in productivity. The PE Technology Requirements Table FAC8 is also responsible to the intended significant productivity improvement preceding 450 mm insertion. Although the FO Technology Requirements Table FAC6 owns the equipment output cycle time waste (EOW) requirement EOW metrics may be broken down to EOW for the PE section to address waste reduction. The waste due to NPW operations and the frequent recipe changes can significantly increase EOW especially in high product mix operations. The information of NPW operations needs to be made visible.

5.3.4. PRODUCTIVITY REQUIREMENTS

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

The process control in the equipment is controlled by event-driven method. 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 faster 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 FAC7 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* ■ *Wafer ID*	Inter factory-level (Factory wide)
Tool-to-facility combination activity	■ *Tool name* ■ *Chamber index / STS* ■ *Eq status* (e.g., maintenance state) ■ *Processing index* ■ *ID to indicate interactive control events*	Inter-Tool-level External sensors need their own time stamps
Additional sensor data utilization		
Within-tool activity data utilization	■ *Task ID* ■ *Processing index / Wafer locations* ■ *Internal control events*	Intra-Tool-level +/- equipment heart beat frequency

5.3.5. ENERGY SAVINGS AND FACTORY ENVIRONMENT

In order to minimize consumption rate of energy and other utilities of production equipment when it is not needed to perform its intended function (i.e., processing wafers), production equipment needs to have 'Smart' energy-saving modes capabilities, which enable automatic energy and other utilities shutoff or reduction control while maintaining quick startup for returning to production readiness, with the goal of no added productivity penalties at equipment re-start. The potential savings depend on the scenario, with greater potential savings during fab start-up/ramp and research and development (R&D) environments compared to high-volume manufacturing (HVM) because it is likely that the wafer processing tools are to spend more time in a non-wafer-processing state. Even at HVM, not all equipment types are utilized to their full capacity due to bottleneck and other reasons, thus 'Smart' energy-saving modes are expected to be effective 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 FAC3. 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) is not utilized, 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, 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 saving is also achieved through energy-efficient equipment designs, which are achieved through the use of higher efficiency power distribution systems within the tool, more efficient tool-heat-load removal methods, and optimized recycling and reuse of water.

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

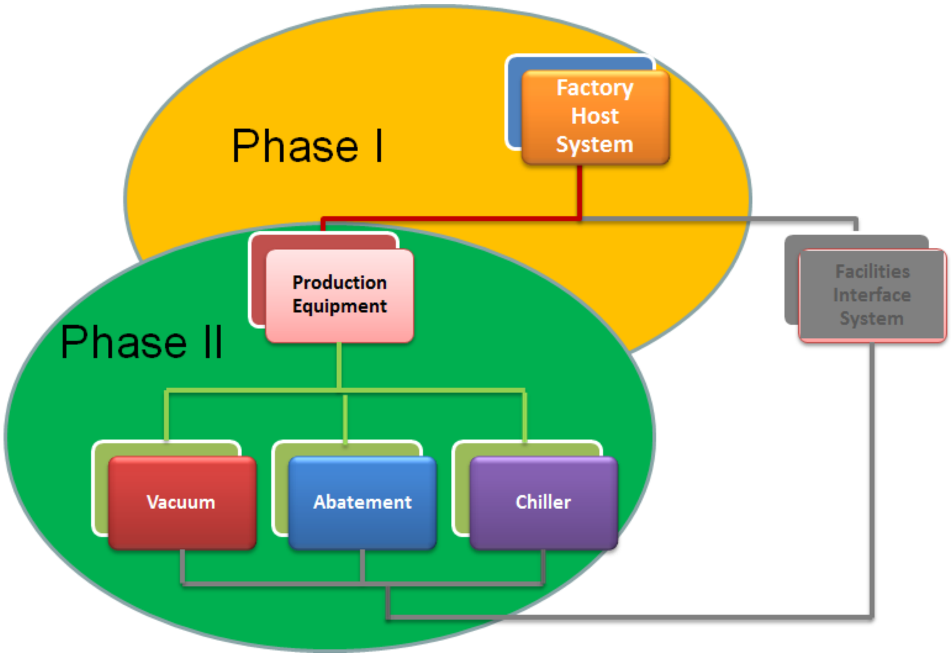

Figure FAC3 Phased Scope of SEMI Standards Work to Support PE Energy Savings

5.3.6. DATA INTEGRATION IN PRODUCTION EQUIPMENT

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

5.3.7. PREDICTION CAPABILITIES IN PRODUCTION EQUIPMENT

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

New specifications and standards on aspects of equipment prediction will be developed. As an example, SEMI E171 addressed "Specification for Predictive Carrier Logistics (PCL)"; the purpose of the standard is "…to provide a communication scheme for exchanges of carrier logistics related information, especially predictive information, between equipment and the factory system in order to support seamless cascading of carriers for continuous processing of equipment in microelectronics fabrication systems or similar ones".

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

Table FAC8 Production Equipment Technology Requirements

5.4. MATERIAL HANDLING SYSTEMS NEEDS

5.4.1. OVERALL

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

The AMHS Technology Requirements Table FAC9 is based on the premise that as demands on the material handling system continue to increase while supporting fab operations with decreased down time and reduced lot wait-time waste on bottleneck equipment. In order to achieve the requirements, AMHS may be composed of interoperable sub-systems from multiple (best of breed) suppliers.

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

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

5.4.2. 450 MM

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

Table FAC9 Material Handling Systems Technology Requirements

5.5. FACTORY INFORMATION AND CONTROL SYSTEMS NEEDS

5.5.1. SCOPE

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

5.5.2. IMPROVE FACTORY EFFECTIVENESS

Factories must be able to adjust schedules and dispatching schemes rapidly to quickly respond to unexpected equipment downs or product scrap to maximize productivity and maintain target production rates and production times of high priority (hot) lots as well as the production lots. This calls for optimization and prediction models that include predicting impacts of operational or configuration changes to other FICS applications. The objective is to make the best choice of what to process looking beyond the boundaries of a single tool or cluster tool. With a global view of factory activity, the scheduling component can make decisions beyond a small area in the factory. The effect will be greater factory utilization, higher throughput, and reduced cycle time variability. Integration of FICS applications with business-level software systems provides accurate factory floor data for supply management, and improved product tracking. Potential solutions will require the standardization of technologies (e.g., Simple Object Access Protocol, Service Oriented Architecture Protocol (SOAP) and Extensible Markup Language (XML) and web services) that enable this level of integration.

5.5.3. IMPROVE FACTORY YIELD AND MINIMIZE WASTE

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

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

The FICS will provide collaborative integration between APC, manufacturing execution system (MES), equipment performance tracking (EPT), factory scheduler/dispatcher, maintenance management, AMHS and supply chain elements. This level of system integration is required to ensure delivery of the right material, lot, and wafers at the right time at the right locations maximizing equipment utilization. It will be enabled by event-driven, reconfigurable supervisory control capabilities at the heart of the FICS; common data warehouse and data models; adoption of Interface 'B' and associated standards for application integration; proliferation of networks for control diagnostics, and safety signals across the fab and supply chain elements (see also Section 5.8.8).

5.5.4. DATA UTILIZATION

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

Achieving these FICS requirements will necessitate alignment to industry standards for data acquisition, data interchange, and recipe management. This will include alignment with standards from verticals in the supply chain in order to support data interchange for integrated supply chain objectives as described in Section 5.8.8. Specific tool, supplier, or manufacturing-defined proprietary interfaces will increase implementation time and cost to both the IC manufacturer and the FICS supplier. Time to develop these new standards must be decreased, through collaboration between IC makers, equipment suppliers, and FICS suppliers. Ultimately the standards-compliant applications will reduce time and cost of integration, allowing IC makers and suppliers to focus on improved capabilities rather than customized integration. This will decrease the risk of new applications integration into an existing factory system.

5.5.5. HIGHLY RELIABLE, HIGH PERFORMANCE SYSTEMS

The increasing reliance of the factory on the FICS infrastructure will continue to drive increased factory system complexity. There will be increased attention to maintaining the gains to overall factory system availability and to further decreasing the occurrence of full fab downtime incidents caused by a failure of a single, mission critical application as shown in the FICS Technology Requirements Table FAC10. Mission-critical FICS components, both software and hardware, must provide fault tolerant solutions that eliminate unscheduled factory system failures as well as scheduled downtime to install or upgrade. Potential solutions include software applications and databases that are capable of dynamic upgrades; software applications that can monitor health of factory systems and that can induce load-balancing, and fault tolerant computer systems with transparent hardware switching for failovers.

Cyber security continues to remain a high priority from the factory operations perspective. Cyber security guidelines were first published by ISMI in March 2005 documenting available methods for cyber security. The security focus is also on protecting IP within the equipment. Microelectronics equipment is now well integrated into the FICS infrastructure with engineers and technicians. Ensuring IP protection is critical to overall financial success in an environment where there is a significant amount of operations-level overlap. This topic is discussed further in Section 5.7.

Table FAC10 Factory Information and Control Systems Technology Requirements

5.6. FACILITIES NEEDS

5.6.1. SCOPE AND FACILITY MISSION

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

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

5.6.2. DEMAND ON FACILITIES SERVICES INCREASES

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

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

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

5.6.3. COMPLEXITY AND COSTS OF FACILITIES SERVICES RISING

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

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

acoustic controls

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

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

5.6.3.2. MEETING AMC REQUIREMENTS

An increasing impact on the AMC levels in the fabs is observed for the local scrubbers due to fugitive emissions during maintenance, e.g. for dopants, besides the impact of removal efficiency and the resulting reintroduction of exhaust gases back into the make-up air. The total AMC concept is illustrated in Figure FAC4.

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.

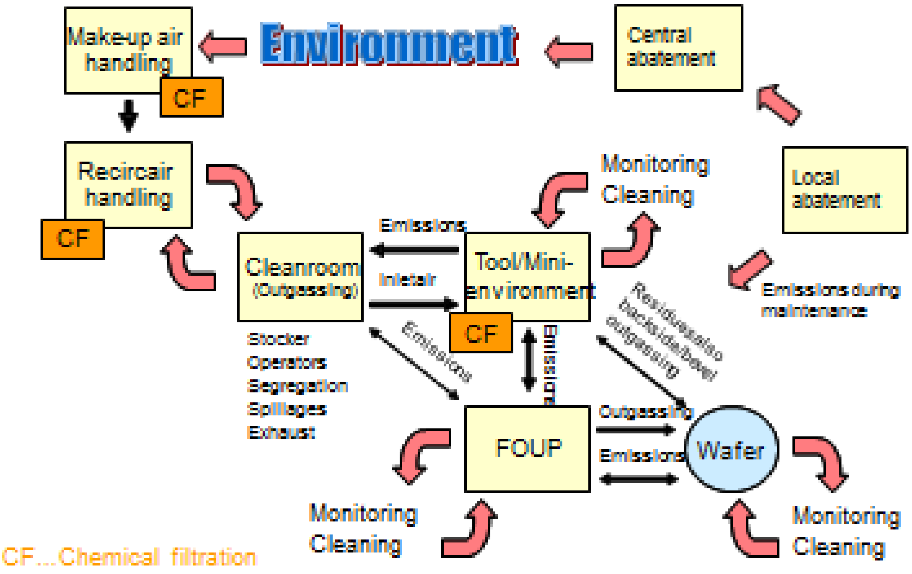

Figure FAC4 Total AMC concept

5.6.3.3. MEETING STATIC CHARGE REQUIREMENTS

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

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

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

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

5.6.3.4. GUIDANCE ON RETICLE ELECTROSTATIC PROTECTION

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

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

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

5.6.3.5. MEETING ELECTROMAGNETIC INTERFERENCE CONTROL REQUIREMENTS

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

In the past these influences were limited to applications in research. Now, due to ongoing shrinking of structures and the explosive increase of applications using wireless communication techniques, the influence of EMI effects in microelectronics manufacturing fabs becomes more pronounced, particularly in areas where uncontrolled electromagnetic fields are a very sensitive concern as in SEM/TEM, e-beam and metrology tools to perform its intended functions. Therefore, understanding EMI phenomena, its impacts, and how to mitigate it in a cost-effective fashion become more important as process technology progresses into the future. Currently EMI is not well understood by the end user and thus leads to misdiagnosed problems and misapplied EMI mitigation/controls. This needs to be addressed at a global level to prepare for what is expected to be more electromagnetic-related impacts in the future. Recently released SEMI E176-1017 “Guide to Assess and Minimize Electromagnetic Interference (EMI) in a Semiconductor Manufacturing Environment” offers comprehensive guidance for managing and mitigating EMI in semiconductor manufacturing and related industries. It includes EMI basics, guidance to EMI measurements in real-life installations, EMI mitigation recommendations and, recommended maximum EMI levels that are fully harmonized with the IRDS.

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

5.6.4. MICROELECTRONICS INDUSTRY FUTURE CHANGES AND REQUIREMENTS

Despite the continuous device feature size shrinkage and increase of process complexity in process technology according to Moore’s Law, the drive towards the reduction in manufacturing cost will result in the introduction of larger wafer sizes, such as 450 mm wafers. Such a change will also have implications on the design and construction of a wafer manufacturing facility due to increases in overall size, height, and weight of process equipment, their utility consumption, and other process-driven facility requirements such as AMC, EMI, electrostatic protection (including but not limited to ESD protection), and acoustic controls. 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 and other electrostatic control measures
- microelectronics materials ESH/S management

- Energetics Materials ESH/S management and facility consideration

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

5.6.5. RESOURCE CONSERVATION CONSIDERATIONS

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

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

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

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

The infrastructure itself will be a serious limiting factor for many locations both with regard to water and power availability, quality and cost. It will 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 increase parameters in the site outfall posing the risk of environmental compliance
    a. Chemical consumption has dramatically increased in latest technology generations. Unless the chemical consumption is reduced dramatically, or the chemical waste segregation is not improved, increased water recycling excursions in waste water concentration and issues environmental compliance and external water reuse will be the result.
4. Process requirements such as lithography needs (EUV or multiple patterning) as well as the need to reduce F-GHG and N_2O emissions will drive power consumption even further. Increased energy consumption adds cooling load, which results in higher water evaporation in the cooling towers. The effect is similar to recycling, increasing concentrations of the contaminants in the site effluent.

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

5.6.6. INDUSTRY COLLABORATION FOR FACILITIES

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

- the fabrication process and the production equipment will increase in complexity
- factory operations will seek more flexibility

global codes, standards, and regulations will increase in variability

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

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

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

Production equipment installation costs and time continue to be driven higher by increasing gas, chemical and utility connections, energy conservation methodologies, and process-driven facility and ESH/S compliance requirements. Earlier awareness of new production equipment designs, standardization of production equipment connections, and the materials of construction, and the availability of measured utility consumption flow data in a standardized database system would allow for appropriate construction of the base build with an emphasis on "Design for Facilities".

Construction costs can be substantially reduced by lowering exhaust /make-up air requirements, raising non-critical process equipment's cooling water inlet temperatures to a level where no central chiller plant is required for this equipment and using higher voltage power for production equipment as much as feasible.

Operating costs can be reduced by innovative reuse and recycling concepts for Ultra-Pure Water (UPW), implementing equipment "sleep" mode during idle periods, raising process cooling water temperatures.

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

5.6.7. 450 MM CONSIDERATIONS

Any significant change in the production equipment, both for post-CMOS or for the next generation wafer size, such as new chemistries, the wafer environment or handling requirements (nitrogen or vacuum atmospheres, transition of an equipment type from batch processing to single wafer manufacturing, etc.), will have an impact on future factory requirements. The high cost of a 450 mm fab will increase the capital investment risk and drive more focus on loss prevention mitigation such as increased fire protection, more robust building materials and MFL (maximum foreseeable loss) separation walls within the fab.

The table below outlines facilities technology requirements.

Table FAC11 Facilities Technology Requirements

5.7. SECURITY NEEDS

5.7.1. INTRODUCTION

Advancement of the "connected fab," which is one of central concepts of "Industry4.0/Smart Manufacturing," requires a growing number of direct data exchanges within and beyond the factory integration space. As an example, these data exchanges could be used to support distributed systems for specialized services including remote diagnosis and predictive analytics provided through a data network that may extend beyond the fab intranet. While it is unknown to what extent the "connected fab" concept prevails in microelectronics manufacturing space, it is certain information security will become more challenging with the increase of data shared across the factory integration space.

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

Currently in manufacturing, IT security issues are usually 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 often fails to deliver a reliable solution to the relevant problem. Consequently, it is necessary to take a comprehensive approach to security in factory integration; this approach would be a process that would include implementation of security threat identification and risk analysis, and mitigation cycles on security challenges.

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

Significant change will be associated with the transition from vertical silos of data within an organization, to a future based upon distributed data being shared between many data owners and consumers. This will require a different trust model and corresponding security approaches.

5.7.2. SECURITY OBJECTIVES

The primary objective of security in the FI data space is 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) of information, while providing the necessary availability of that information (a means of measuring a system's ability to perform a function in a particular time).

5.7.3. SCOPE

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

Physical security, such as protecting essential fab facilities and systems from physical attacks (e.g., destruction/breach of fences or locked gates around fab physical perimeter to sabotage basic fab infrastructures (e.g., hazardous chemical supply systems), is considered outside the scope of this chapter

5.7.4. SECURITY FOR DATA SHARING

Achieving business targets in the FI focus area requires that data be shared across the factory integration space. For example, the concept of the "connected fab," which is one of central concepts of Industry 4.0/Smart Manufacturing, even indicates potential direct data exchanges beyond the factory integration space. While data must be made available to promote fault detection and classification (FDC), predictive maintenance (PdM), advanced process control (APC), etc., at more granular levels (e.g., lot-based to single-wafer-oriented for maximizing productivity), protection of data and intellectual property (IP) within data will become more complicated and sometimes contradictive to needs of data availability).

5.7.5. SECURITY FOR EQUIPMENT OPERATION BY THE FICS

IP protection capabilities of equipment needs to be adaptable to conform with a fab's security policies while achieving balance between data availability and IP protection. In addition, equipment control systems must be able to maintain critical functionalities and performance (e.g., safety control functions) when security measures are implemented through FICS, or in the event of security attacks.

5.7.6. SECURITY FOR BIG DATA AND LEVERAGING BIG DATA FOR SECURITY

Security must be ensured to allow the effective use of technology such as cloud computing in microelectronics manufacturing. At the same time application of big data analytics such as abnormality detection and automated countermeasures should be leveraged for improved security capabilities.

5.7.7. IP SECURITY FOR IIOT WITH REGARD TO DATA VOLUMES, ACCESS, AND ASSOCIATED DATA PARTITIONING

5.7.7.1. UNIQUE NEED OF IIOT

The next stage in the evolution of the industry is predicated upon the ability for each step in the manufacturing process to make active decisions based upon a rich picture of environmental and process conditions, variations and issues in previous steps and anticipated demands from future steps.

The creation and operation of independent smart process components that can collaborate as part of a distributed network in this manner is entirely dependent upon access to unprecedented amounts of data. This new requirement for data must be understood from two key contexts:

(1) The creation of any given smart process component is constrained by the ability to train a suitable machine learning model to fit the problem. Training an effective model that is able to detect previously undiscovered patterns in a process operation and facilitate significant optimization requires a very large aggregated dataset that contains typically hundreds of thousands to tens of millions of examples of large numbers of features that can potentially impact the efficacy of the process.

(2) Once created, the operation of this smart component depends upon the supply of up-to-date information about all relevant features previously identified at a cadence appropriate to the time-sensitivity of the process. In this context, that is likely to involve moving volumes of data concomitant with processing at atomic scale, with latency low enough to support real-time processes.

5.7.7.2. IIoT AND IP SECURITY CHALLENGE

Taken on its own, this is a hard, but not intractable problem. Many suitable approaches exist in other fields. In the context of Factory Integration, however, there are other factors that we must consider:

In a free market, we must assume that individual process stages in a factory may be carried out using equipment sourced from multiple different suppliers, where each piece of equipment encapsulates some form of intellectual property owned by the relevant supplier. Furthermore, the combination of processes and equipment across the factory represents part of the IP of the factory operator.

The fundamental nature of the data required to operate a distributed network of smart components is such that it potentially also reveals key elements of the IP inherent in various stages of the process. Thus, the core of the issue relating to implementing IIoT solutions across the fab is one of trust.

To understand the problem, we must recognize that there are multiple perspectives at play here. A factory operator may consider that they have purchased all the equipment and therefore have a right to own all the data being utilized within that instance. They may desire to openly share all the data across all the equipment they own in order to optimize their process, protecting their IP at the boundaries of the facility. Whilst technically possible, this may not sit well with individual equipment providers, who will be naturally concerned that intimate details of their process IP can leak to both the factory operator and to competitive suppliers via equipment downstream from theirs.

If viewed as a zero-sum game like this, individual suppliers are likely to be predisposed towards offering only integrated, end-to-end Smart Manufacturing solutions that encapsulate at-risk IP within their own eco-system and also increase vendor lock-in. History shows however that this direction is always bad for the industry as a whole.

If we are to be successful in delivering Smart Manufacturing as a forward enabler to More than Moore, it is essential that we do so in a way that enables collaborative, non-zero-sum outcomes through the continuation of the pre-collaborative behaviors that have served the industry so well in the past. It is critical that we encourage the adoption of mechanisms that continue to support working together to solve big problems.

Some of 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. Beyond this, however, we need to establish standards for federated networks of trust between suppliers and operators such that critically needed data can be provided where needed to enable SM capabilities whilst mitigating the threats that undermine collaborative environments. This could take the form of automated data sharing agreements managed by smart contracts or involve trusted escrow systems to protect the usage of data whilst still enabling the overarching benefits of synergies that arise spontaneously in a modular system. Only if we have the benefits of network effects within our IIoT strategy will we see the improvements necessary to unlock this forward enabler.

There is a scale problem inherent in addressing this issue. Looking to examples in other industries such as logistics, we see somewhat of a trust paradox. Only the largest vendors have existing trust relationships that have enabled them to implement data sharing technologies at a scale large enough to see the benefits of network effects, but the larger the player, the less likely it becomes that other players will align to their shared proprietary protocols for fear that this grants the owner a tool to enforce commercial dominance in the original market. Left to individual suppliers, zero-sum thinking dominates.

As we have seen many times in the past, if we are to continue to maximize the benefits for all, we should seek to encourage the creation of a collaborative and open mechanism for federated trust that is jointly supported and open to all.

To facilitate this, it is recommended that a SEMI standard be developed in the area of federated data sharing for IIoT solutions, taking into account the needs of data consumers, data owners and suppliers in the context of data sharing and revenue attribution.

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.

5.7.8. SECURITY CONSIDERATION FOR INTEGRATED SUPPLY CHAIN

The integrated supply chain can be seen as a network of smart nodes making production decisions based upon information sourced from further up and down the network. In other words, it is much the same pattern as seen in the section relating to IIoT, but at a different fractal scale. Whilst some of the content being shared may be somewhat different, we are able to see from this perspective that we face the same patterns of trust and collaboration detailed above.

The largest difference between the two scenarios is that whilst shared data resides within an IIoT network inside a factory, there is at least the illusion that one might be able to use conventional IT structures to retain control over the data. Once we consider data sharing across the supply chain however, it becomes much more obvious that there are limits to our ability to control who might gain access to elements of this data as it transits across the distributed network.

We consider the issues relating to the confidentiality and integrity of the data in the security sub-chapter so here we shall focus on the issues relating to facilitating the availability of the data.

It is suggested therefore that the needs of both IIoT and supply chain networks be taken into account when proposing standards for information sharing within the industry.

5.7.9. CROSS-CUTTING CONCERNS AND OPPORTUNITIES

There is a trend of increased data sharing activities up and down the supply chain for different purposes such as regulatory (e.g., EU RoHS) compliance information; transfer from the upstream manufacturer of parts/materials to the supplier of final product at the downstream, or transfer of process condition information to meets traceability demands of downstream of the supply chain. The patterns associated with this sharing and control of distributed data are also the same as those faced in the IoT/edge computing space. For maximal business value, such data sharing activities need to be amenable to a common, standard approach. It is suggested that regular cross-cuts between FI, ESH/S, SA and OSC IFTs are maintained to align thinking on this problem.

5.7.10. SECURITY TECHNOLOGY REQUIREMENTS AND POTENTIAL SOLUTIONS

Achievement of the security vision is associated with a number of technology requirements which have been presented in the previous section. Some of the security technology requirements are consolidated in Table FAC12 in this edition. More of security requirements will be further quantified in the table in future versions of this report.

Table FAC12 *Security Technology Requirements*

5.8. SMART MANUFACTURING NEEDS

5.8.1. INTRODUCTION: THE SMART MANUFACTURING VISION

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

While the literature base for SM and I4.0 is wide and varied, common themes or tenets of SM are present that help provide an understanding of the whole SM and I4.0 space, as well as structure for organization of SM roadmap elements [3]. A SM vision for the microelectronics industry is shown in Figure FAC5[3]. Note that, while the tenants of SM and I4.0 are not industry specific, each industry has its own unique challenges and opportunities, and industry-specific variations of the SM vision emerge.

Figure FAC5 A Smart Manufacturing vision for the microelectronics industry.

Microelectronics manufacturing is a very unique industry characterized by high process precision and dynamics, process and equipment complexity, high degrees of intellectual property (IP) in equipment, processes, and analytical solutions, and a business model that focuses on development and maintenance of fab-wide solutions [3]. These characteristics result in unique requirements (or at least reprioritization of requirements) and challenges in realizing smart microelectronics manufacturing.

5.8.2. SCOPE

Combining an understanding of the focus areas of SM with the unique needs of the microelectronics manufacturing ecosystem results in a set of common themes or tenets of SM for microelectronics that provide an understanding of the scope of the whole SM and I4.0 space in this domain, as well as structure for organization of SM roadmap elements [3]. Specifically, unless otherwise indicated, the FI chapter is dedicated to maintaining a roadmap for each of the following SM tenets:

- *Big Data:* Data management infrastructures are being enhanced to support improvement in capabilities associated with the “5 ‘Vs’”, namely volume, velocity (data collection and analysis rates), veracity (data quality), variety (data merging and consolidation), and value (data analytics) [8]. This enhancement is punctuated by the movement to big data architectures such as Hadoop that support (1) storage of data in a serial or sequential fashion, which is much more “analysis friendly” than traditional relational architectures; (2) parallel and scalable approaches for higher speed analysis of larger quantities of data; and (3) an open-architecture style environment for development of data management and analysis tools. A key challenge is the migration from existing data management infrastructures and understanding how the data infrastructures co-exist in a collaborative environment to support capabilities ranging from real-time on-line decision making to off-line high-fidelity model building [17].
- *Augmenting reactive operations and analysis with Predictive and Prescriptive*: A key aspect of the SM movement is moving from a more reactive mode of operations, where techniques (e.g., fault detection) focus in detecting and responding to an event *after* it has occurred, to moving towards a mode where events can be predicted *before* they occur (e.g., predictive maintenance) thereby avoiding any costs associated with the event. This trend also incorporates the concepts of prognostics which can be thought of as the discipline around the prediction capability, as well as prescriptive analytics which focuses on determining why an event has or will occur and how to mitigate

issues in the future. While the SM focus is moving from reactive to predictive and prescriptive solutions, not all events are predictable or avoidable, thus prediction and prescription will *augment* reactive capabilities.

- *Advanced analytics and applications:* The primary benefit of implementation of big data infrastructures and practices will be the enhancement of analytics to support improvement in the quality of existing capabilities such as fault detection and classification (FDC), but also in the realization of advanced predictive capabilities such as virtual metrology and predictive maintenance (PdM). These analytics will leverage increased data "volume" and "veracity" for more robust and maintainable models; "velocity" for more granular models; and "variety" for more causal and predictive models. From the "value" perspective, traditional analytics will become much more effective, leveraging the higher data volumes and data quality to build more robust models. New big data analytics such as deep learning will also emerge to complement more traditional analytics.[2] Additionally, the better integration of data systems will enable these analytics to span much larger domains, such as up and down the supply chain, and incorporate techniques such as "digital thread" for linking analyses to data chains to solve factory-wide or even supply-chain wide problems. While there is a strong literature base in the industry of specific analytics being applied successfully to point solutions, it often is not clear how and when specific analytic types should be employed. This often results in a focus on the elegance of the *analytic* (e.g., deep learning or purely statistical techniques) over the practicality, extensibility and robustness of the *solution*, and a lack of emphasis on incorporating SME. As a first step to address this issue, SM literature efforts have tried to define the analytics capabilities in terms of dimensions and apply these dimensions to the needs of particular applications, [3,18]. This helps provide an analytics roadmap
- *Digital Twin:* "A digital twin refers to a digital replica of physical assets, processes and systems that can be used for various purposes" [11]. The digital twin vision is further refined in Section 5.8.4.2 as "a state of fab operations where … real-time simulation of all fab operations occurs as an extension of an existing system with dynamic updating of simulation models." Digital twin can be used to support and improve operations, controls and forecasting throughout the manufacturing ecosystem. Many of the predictive applications being developed in the industry today will likely continue to evolve to more directly support this vision.
- *Industrial Internet of Things (IIoT) and the Cloud*: The Industrial Internet of Things (IIoT) and Cloud refers to the technical challenges and solutions associated with providing localized individual analysis and solution capabilities closer to the problem source, often referred to as an "edge" device, and providing a wide range of capabilities in a centralized, internet accessible data management and analysis location usually referred to a "cloud". Oftentimes edge and cloud solution work together to provide more comprehensive solutions.
- *Integrated supply chain*: Tighter vertical and horizontal integration of systems is a common tenant of SM and leverages the "variety" data merging and consolidation enhancement in data architectures. From the horizontal integration perspective, the factory will become an integral part of the upstream and downstream supply chain network with factory optimization a component of overall supply chain optimization. The tighter connectivity will allow for leaner operation, better inventory management, higher flexibility of operation, improved response to demand, and better traceability to address issues such as warranty recall investigation. An obvious requirement is the development of standards for supply chain data integration that are not industry specific.
- *Reliance on a knowledge network*: The movement in technology associated with SM and I4.0 requires a corresponding change in the business operation paradigm. As solutions become more complex and consolidate larger domains of data systems and applications, realizing and maintaining these solutions requires a higher degree of cooperation between users, OEMs and analytics solution providers in a structured knowledge network [11]. This cooperation enables the required incorporation of subject matter expertise (SME), e.g., process, equipment and product knowledge) into data-driven (statistical) models for improved model quality and robustness. Issues such as data sharing and partitioning, intellectual property security, and managing solutions in the cloud have all come to the forefront as part of the move to enhance support for this cooperative knowledge network [8]. The heightened importance of incorporating subject matter expertise in microelectronics SM solutions comes from the complexity, precision and dynamics associated with processes and equipment as noted above, but also because the production environment is associated with a large of number of context changes (e.g., product change, maintenance event, or different upstream product route). In a purely statistical analysis world, these complexities would result in a need to partition data streams in order to understand the impact of each context change, process drift, etc. This, in-turn, would result in changing the "big data" source into a large number of "small data" sets with

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[2] *Deep Learning is a technique that is very similar to structured artificial neural networks and leverages hierarchical abstraction for improved quality and speed of high-volume data analysis [13].*

insufficient precise data in each set to support good models. Incorporation of elements of process, equipment and product SME allows quality models to be developed, verified and especially, maintained with less data. It also allows for the intelligent merging of these small data sets when the relationships between the different context and dynamics situations are understood.

- *Maintaining data and IP security:* While the opportunities in SM are significant, this new paradigm of operation brings with it a risk of maintaining security in the face of higher levels of integration, data production and management, and information sharing for collaboration. While this is a challenge for SM in general, it is especially acute in microelectronics manufacturing where there is significant IP in process, equipment and analysis solutions. In fact, it is noted in Section 1.1 that information security is one of the primary challenges hindering the advancement of microelectronics industry smart manufacturing and I4.0 concepts [1]. Aspects of this issue vary widely ranging from concerns such as protection of IP in collaborative activities to introduction of malware through a USB hookup. One specific area where security is severely limiting SM evolution is data sharing environments such as "the cloud." These environments allow data from multiple sources (including potentially multiple companies) to be centrally located so that analytics can be applied in a scalable fashion. However, cloud-based data and IP partitioning risks and solutions are not well-defined, leading many manufacturers to completely avoid these solution tools, instead choosing to execute SM activities completely and exclusively within the fab. With the help of the IRDS, a roadmap to address the data and IP security issue will eventually be charted that first identifies the issues, a solution baseline, and standards needed for moving forward [8]. Until that time, security will likely be the main issue governing the progress of SM in the microelectronics industry. Note that the FI chapter maintains a security roadmap in Section 5.7. This roadmap governs aspects of maintaining data and IP security in SM environments, thus a security roadmap section is not provided with the SM roadmap.
- *Improving use of cyber-physical systems (CPS)*: CPS refers to the "tight conjoining of and coordination between computational and physical resources"[16]. This is not a new concept as systems that integrate computational and physical resources have been in existence for some time. However future SM systems will continue to improve from a CPS perspective in terms of "adaptability, autonomy, efficiency, functionality, reliability, safety, and usability." Because CPS is a very general term that applies to the overall evolution of manufacturing systems, the FI roadmap currently does not have a dedicated CPS roadmap section, but rather integrates CPS elements in other portions of the SM roadmap.

Smart Manufacturing and the FI Roadmap

A number of SM and I4.0 common themes are expected to immediately impact the FI roadmap. Other aspects of SM and I4.0 will be addressed in greater detail in future FI roadmap reports.

Beginning with the 2020 FI roadmap, SM is consolidated in this subchapter, which contains an overview section as well as sections dedicated to the following SM tenets:

- Big data
- Augmenting reactive with Predictive and Prescriptive
- Advanced analytics and applications
- Digital twin
- Industrial internet of things (IIoT) and the cloud
- Integrated supply chain
- Reliance on a knowledge network

The sections that are dedicated to individual SM tenets are structured as functional areas and thus contain (or will contain) roadmap narrative and tables corresponding to technology requirements and potential solutions.

Figure FAC6 provides an illustration of how the roadmap materials associated with the various SM tenets are organized in the FI roadmap. Note that additional tenets may be added in future versions of the roadmap as they become an important part of the FI roadmap.

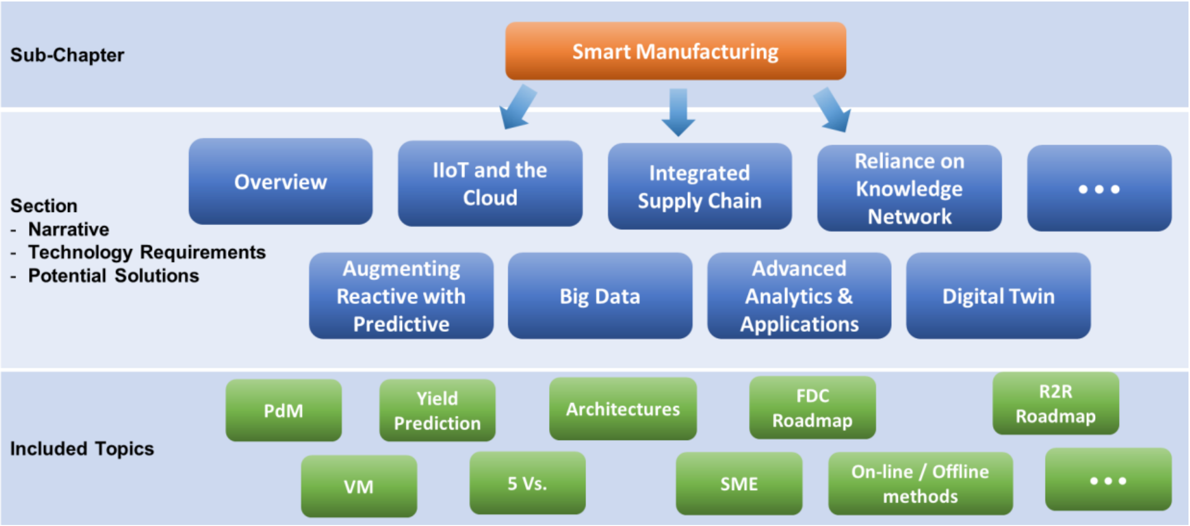

Figure FAC6 Illustration of how Smart Manufacturing (SM) tenets are organized in the FI roadmap

The various tenets related to SM, depicted as boxes in blue, have their own technology requirements and potential solutions roadmaps. Thus, each of these tenets will be given a sub-section in this SM section with narrative, challenges tables, and potential solutions tables. Example topical areas, shown in green, will be addressed in the appropriate tenet section.

5.8.3. BIG DATA NEEDS

5.8.3.1. INTRODUCTION

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

5.8.3.2. SCOPE

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

5.8.3.3. TECHNOLOGY REQUIREMENTS

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

Volume

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

Velocity

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

Variety

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

Veracity

Veracity refers to the accuracy or truthfulness of the data. For example, data store reduction can be accomplished by new and emerging techniques used to compress data without impacting the quality of the data and ensuring no loss of information. These tools or applications may not be sufficient or could be limited by the type of application used by the factory. Retrieving the compressed data by those applications may also impact the accessibility and quality of potential predictions from that big data.

Another common issue is using data timestamps from multiple sources to merge data. These timestamps are often unsynchronized resulting in low data quality of merged data, thus impacting the factory's ability to 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.

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 has not 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. Challenges and potential solutions related to these algorithms and analytics are presented in the Advanced Analytics and Applications section of this Smart Manufacturing subchapter. Big data environments will allow for the application of these algorithms more efficiently over much larger data sets. These environments will also encourage the development of more complex multivariate algorithmic approaches for data quality improvement, partitioning/ordering, clustering and analysis. Much of this development will be pioneered in other industries. The relatively rapid evolution in this area will require analysis solutions that are modular to support evolution, rapid prototyping and plug-n-play of analysis capabilities.

5.8.3.4. GENERAL BIG DATA AREAS OF CONCERN

Migration to 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-real-time[3] applications such as off-line data mining to support generation and maintenance of prediction models. In these areas, the move to big data-friendly solutions will be motivated by reduced cost of ownership with respect to data volumes, improved analysis processing speeds, and increased analysis capabilities resulting largely from the parallel processing capabilities of the ecosystem. Over the longer term some of these solutions will likely be used for on-line non-real-time applications; the development to support this capability will likely come from outside of the microelectronics industry. The level of real-time response capability of these systems over the longer term is unclear, however there will continue to be pressures from other industries to push big data system 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[4]). Often the big data-friendly ecosystems will represent a historical data warehousing extension of (near) real-time data management systems. For example, a transactional database component for an FD system might support housing control rules, report formats, etc., as well as a few days of trace data for analysis. Thus, it could support short term and small data size analysis queries. The corresponding big data-friendly ecosystem system would house all trace data and would support longer term, larger size data analysis, e.g., for development of prediction models. The data collection and analysis infrastructure would have to support populating and data mining across both infrastructures. The determination of the historical data size in the transactional component will be a function of a number of factors including a comparative analysis of transaction speeds.

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

Prediction capabilities will be one of the primary beneficiaries of the move to big data-friendly ecosystems, as many of the big data challenges associated with ARPP, such as Volume, Veracity (data quality), and Value (analytics) will be addressed in-part by the move to big data friendly 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.

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, see also section 5.7.

Data Retention

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

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[3] *"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.*

[4] *"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.*

Data Visualization

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

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

Production Tool Data

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

Network Issues

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

Table FAC13 Big Data (BD) Technology Requirements

5.8.4. AUGMENTING REACTIVE WITH PREDICTIVE AND PRESCRIPTIVE NEEDS

5.8.4.1. SCOPE

The scope of Augmenting Reactive with Predictive and Prescriptive (ARPP) 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 and Prescriptive technologies while retaining the reactive capabilities. These predictive technologies include, but are not limited to, Predictive Maintenance (PdM), Equipment Health Monitoring (EHM), Fault Prediction (FP), Virtual Metrology (VM), predictive scheduling, yield prediction and augmenting predictive capabilities of the factory through simulation and emulation. The following definitions are used for purposes of discussion in this document; these definitions should be replaced by standardized definitions as they become available in the industry.

- *Predictive Maintenance (PdM)* – Also referred to previously as Predictive and Preventative Maintenance (PPM) and Prognostic Health Management, PdM is the technology of utilizing process and equipment state information to predict when a tool or a particular component in a tool might need maintenance, and then utilizing this prediction as information to improve maintenance procedures. This could mean predicting and avoiding unplanned downtimes and/or relaxing un-planned downtime schedules by replacing schedules with predictions. PdM solutions as defined herein address the entire maintenance cycle, from predicting maintenance through addressing recovery from maintenance events towards returning to production. Note that PdM for equipment or a particular equipment component could be managed at the equipment level or fab level, while other PdM activities require fab level management.
- *Prescriptive Maintenance*—Specific preventive maintenance action(s) to perform that may include predefined procedures or predictive maintenance recommended by an advanced notice model. Depending on the complexity of the predefined procedures or the advanced notice model, the recommended preventive maintenance action(s) may change based on the specific set of conditions.
-

- *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 non-measurable) 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.

One common aspect of the SM vision is the movement from reactive to predictive to prescriptive operations in manufacturing application environments. Solutions such as digital twins will contribute to providing the indications, predictions, and prescriptions, respectively, in these environments. Thus, many solutions are expected to evolve from providing reactive type capabilities, such as anomaly detection, to providing more predictive capabilities, such as PdM, and eventually prescriptive contributions, such as recommendations for downtime avoidance. Note that while this general trend will be ongoing in SM, there will always be a need for reactive and predictive capabilities. For example, there will always be a need to detect anomalies that cannot be (accurately) predicted or avoided, and there will be a need for reactive systems to reduce false negatives of predictive systems.

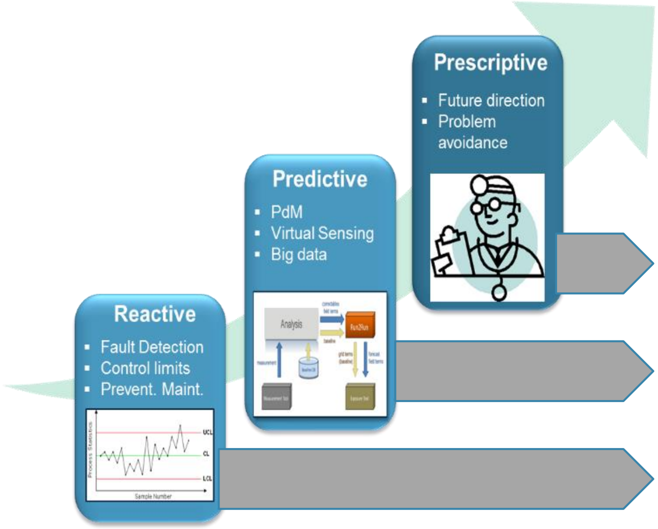

Figure FAC7 Illustration of the continuum of reactive, predictive and prescriptive technologies

5.8.4.2. PREDICTION VISION

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

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

1. Roadmaps for each of the predictive technologies must be structured to support their eventual merging in terms of sharing data and capabilities. This is because the prediction vision can only be achieved through the cost-effective collaboration of all prediction technologies.
2. Prediction technologies should be structured wherever possible to be net 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 (Section 5.3) 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 do not always have the necessary data quality to support cost-effective prediction capabilities. Examples include inaccurate human-entered and missing context data in maintenance management systems, and insufficient archiving of data necessary to realize robust predictive models. The data quality issue is especially true of maintenance management systems (e.g., with human data entry). A roadmap for improvement of data quality of these systems to make them “prediction ready” is needed. Data quality guidelines and standards such as SEMI E151 and E160 should be leveraged. See also the Big Data section of this Smart Manufacturing subchapter for additional information on data quality (i.e., “veracity”).
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 fewer “mistakes” (such as false positives or missed events) are available as feedback to update the predictor; for example, if the predictor results in zero unscheduled downtime, it may be due to high accuracy of the predictor or an overly conservative prediction.
7. Prediction solutions must provide predictions of required accuracy in a timely manner with respect to the application for which they are being used. This means that the prediction engine can be constrained by a maximum time for prediction (e.g., response time, or event occurrence), a required accuracy for prediction, or some combination of time and accuracy. Prediction solutions will have to be designed to support configuration to these constraints, depending on the application.
8. Human expertise (e.g., SME) plays an important role in the reactive-predictive-prescriptive continuum. For example, SME expertise can be a critical component of enhancing prescriptive capabilities.
9. The lifecycle of ARPP includes continuous improvement of the components to which the ARPP is being applied. For example equipment design improvements can results from ARPP solutions which in-turn results in an augmentation of those ARPP solutions.

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

5.8.4.3. TECHNOLOGY REQUIREMENTS

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

Table FAC14 Augmenting Reactive with Predictive and Prescriptive (ARPP) Technology Requirements

5.8.5. ADVANCED ANALYTICS AND APPLICATIONS NEEDS

The highly complex and precise production environment in microelectronics has resulted in a heavy focus on analytics to support enhancement of existing solutions such as FDC, and the realization of newer predictive solutions such as VM and PdM. This industry is somewhat unique when it comes to the application of analytics because 1) equipment and processes are highly complex, oftentimes with many interacting variables; 2) the cost of a false or missed positive (alarm) in applying analytics can oftentimes be very high; 3) processes are highly dynamic with continuous drift and frequent shifts; 4) processes environment changes are associated with a relatively large number of context variables such as product/recipe type and maintenance event type and time; 5) processes are often poorly visible with only a subset of the parameters necessary to fully quality the process being available, and 6) the industry favors factory-wide re-usable solution approaches versus point solutions. As a result, analytical techniques successfully applied in other non-microelectronics manufacturing domains may not be directly transferrable to widespread use in microelectronics manufacturing. Specifically, purely data driven or statistical techniques will continue to be less successful than techniques that incorporate SME in terms of process, equipment and component knowledge relative to the analysis (see also section 5.8.9). Big data-friendly techniques such as deep learning may have utility in highly complex environments such as wafer topography and defect mapping analysis [13,14]. The progress of algorithms applied to specific problem analysis should be tracked especially where approach-to-approach comparative analysis is provided. Algorithmic approach progressions in roadmaps should be assessed with respect to dimensions of capability, e.g., as shown in Figure FAC8 [3].

Big data environments (see section 5.8.3) 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.

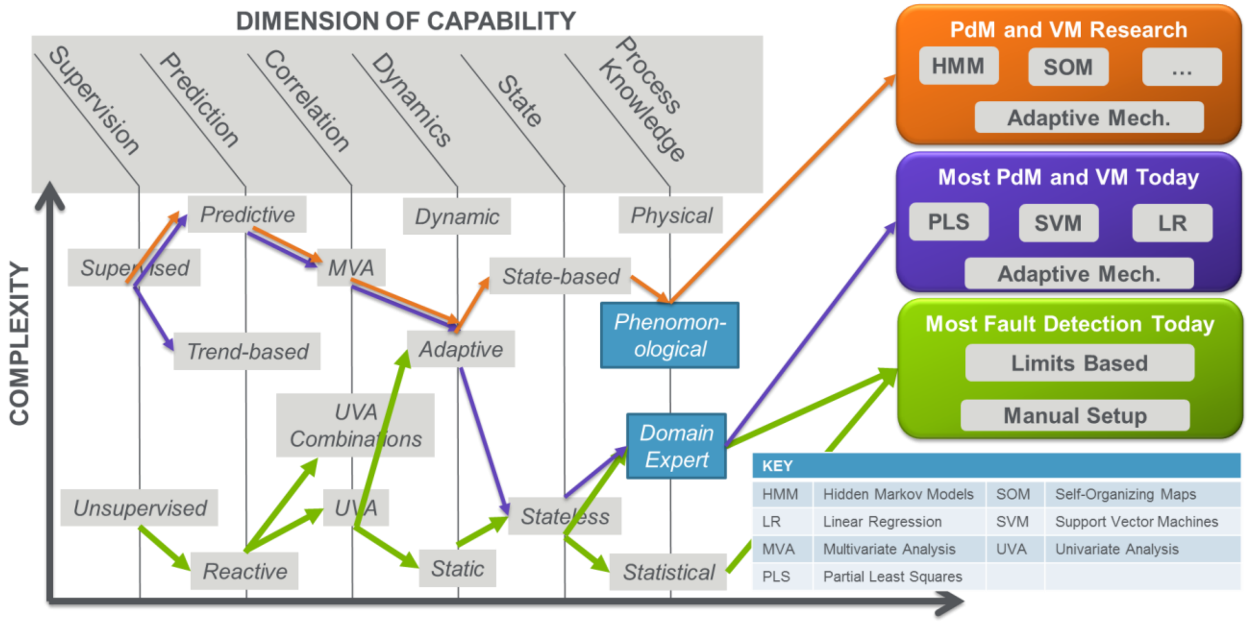

Figure FAC8 Example of Defining the Dimensions of Analytics Capabilities [3]

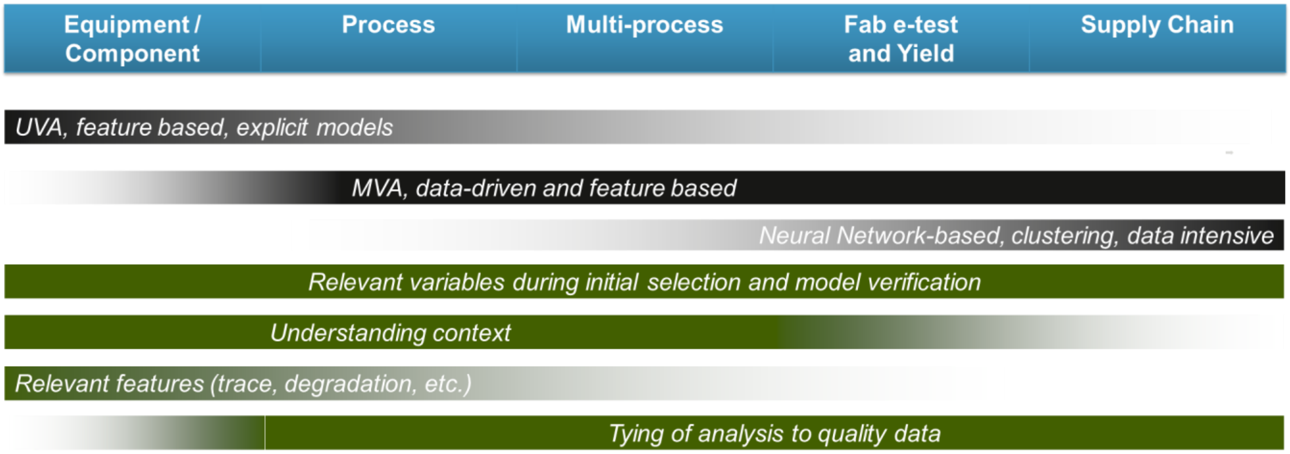

Figure FAC9 Illustration of Areas Where Algorithmic Approaches are Best Suited for Application [26].

5.8.5.1. TECHNOLOGY REQUIREMENTS

Achievement of the advanced analytics and applications vision places requirements in the individual analysis technologies as well as the comprehensive advanced analytics and applications strategy.

Table FAC15 Advanced Analytics and Applications (AAA) Technology Requirements

5.8.6. DIGITAL TWIN NEEDS

5.8.6.1. SCOPE

A generally accepted definition of DT can be found in Wikipedia, namely *"A digital twin refers to a digital replica of physical assets, processes and systems that can be used for various purposes"* [11]. If we break down this definition we see that the scope of DT is more than just replicas or models of things, but also models of processes and systems. For example, in addition to a duplication of the etch system configuration, a model of an etch application process, pump health profile, or product flow at a detailed, or even high level, in the fab is considered to be part of the DT family. Assuming this more complete definition of DT we can make the following statements on the state-of-the-art for DT in microelectronics manufacturing:

- The microelectronics manufacturing industry is already successfully employing DT components fab-wide. Examples include Run-to-Run (R2R) control, VM and PdM (described later in this subsection and in the ARPP subsection—Section 5.8.4).
- The extraordinary scale and precision required to repeatably create microelectronic devices make microelectronics manufacturing one of the most intricate and sophisticated manufacturing processes in the world, and we have had to develop DT technology to meet our manufacturing needs. As such, our industry is arguably a leader in driving aspects of DT technology advancement.
- The microelectronics manufacturing industry is beginning to explore and benefit from abstracting and combining these DT components [20].
- The IRDS must maintain a realistic vision and roadmap for DT technology that will provide for improvements in quality, throughput and reductions in variability and costs over the next 15 years.

5.8.6.2. DIGITAL TWIN STATE-OF-THE-ART AND VISION

Many fabs today are already at the forefront of the DT revolution, having pioneered many DT technologies and providing testament to DT success. As shown in Figure FAC10 existing pervasive technologies, such as run-to-run (R2R) control and real-time Scheduling and Dispatch (S/D), and emerging technologies such as Predictive Maintenance (PdM) and Virtual Metrology (VM) are key members of the DT family [19].

The vision for DT is a framework of DT classes existing at all levels in the ISA-95 infrastructure (see Figure FAC10) with benefits resulting from the utilization of DTs instances in isolation (e.g., R2R control of a process), but also in collaboration with other instances in the same class (e.g., coordinated R2R controllers across chambers for improved chamber matching [21]), with other classes (e.g., coordination of R2R control with scheduling/dispatch—S/D in order to incorporate yield objectives into S/D decisions), and within and with other SM components (e.g., coordination of PdM predictions with supply chain management). DTs can exist at any level, with much of the benefit from digital twins arising from the abstract of DTs to higher levels and integration with other DTs. [19] The various classes within the framework will be developed at different rates depending on need, level of technical challenge, influence from other industries, etc., and flexible DT framework that supports interchange and interoperability of DT instances and classes will be a longer-term technical challenge[22], [23], [24].

5.8.6.3. DIGITAL TWIN CLASS NEEDS

As noted above, the various DT classes (some of which are shown in Figure FAC10) will develop unevenly and largely independent of each other, with consolidation and interoperability concerns addressed as instances of consolidation and collaboration become more pervasive. As a result, the needs of the various DT classes are provided in this section in a topical fashion.

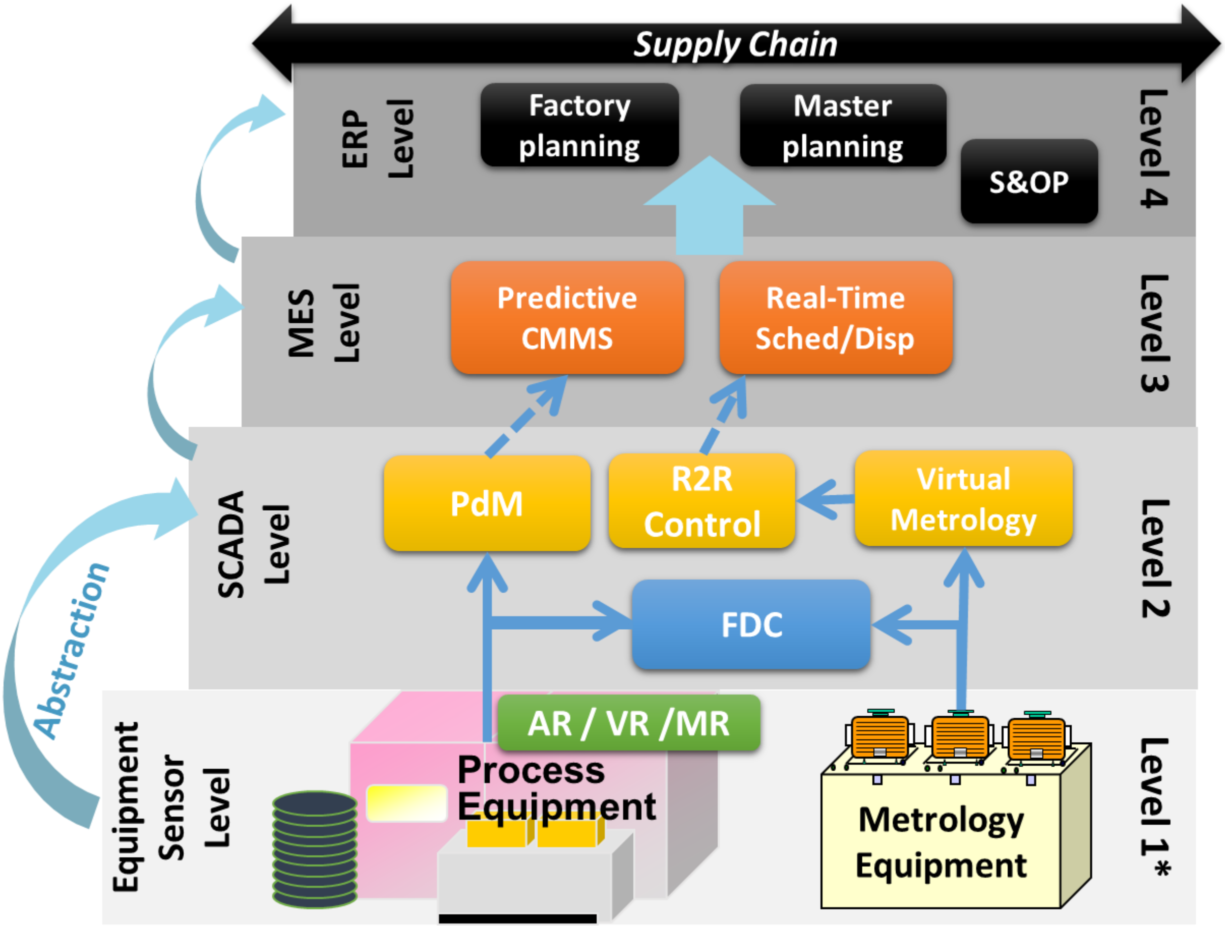

Figure FAC10 Digital Twin representation from the perspective of the International Society of Automation (ISA-95) Levels.*

5.8.6.3.1. MODEL-BASED PROCESS CONTROL OR "R2R CONTROL"

R2R control is defined in SEMI E133 as "the technique of modifying recipe parameters or the selection of control parameters between runs to improve processing performance. A 'run' can be a batch, lot, or an individual wafer." From the perspective of DT, R2R control determines the control parameters by maintaining a DT of one or more processes, with the model being updated on a "R2R" basis using pre and/or post metrology information.

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.

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[5], and the control capability utilizes this synchronization and time stamping of data. Another example is just-in-time style control systems decision making where the controller is given a time deadline for providing an advice and the controller determines the "best" advice given that deadline, thereby balancing speed and quality for a particular application.

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

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 microelectronics manufacturing will increasingly be leveraged.

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

A fourth dimension in which control capabilities will increase is through improved methods of machine learning and artificial intelligence: This paradigm in control systems architectures includes 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 AA&A section of this SM subchapter) might also be thought of as learning to some extent as predictive models are tuned. It is expected that more comprehensive learning techniques will be explored and applied to control systems architectures; these techniques and their application will likely be a trend observed across manufacturing in general with microelectronics manufacturing following this general manufacturing trend.

5.8.6.3.2. PREDICTIVE MAINTENANCE (PDM) AND VIRTUAL METROLOGY (VM)

PdM and VM are DTs respectively of a component or equipment's health, and a metrology system. As both of these DT classes utilize predictive technologies their technology needs are discussed in detail in the ARPP sub-section of this SM section.

5.8.6.4. TECHNOLOGY REQUIREMENTS

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

Table FAC16 Digital Twin (DT) Technology Requirements

5.8.7. INDUSTRIAL INTERNET OF THINGS AND THE CLOUD NEEDS

5.8.7.1. INTRODUCTION AND SCOPE:

The exponential reduction of cost per unit functionality inherent in Moore's Law has brought us to the point where it is now possible to heavily instrument industrial systems using very large numbers of sensors. These 'cyber-physical systems' are

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

capable of producing data at a scale and resolution that enable us to observe our processes in an entirely new way, opening up new opportunities to optimize for efficiency, productivity, performance, quality, innovation and compliance.

To benefit from this Industrial Internet of Things, we have to negotiate two significant challenges.

Firstly, we have to harness the new volume and velocity levels of data and capture its output over time to create a dataset large enough to reveal statistically valuable trends using highly scalable analytical processes combined with a knowledge network in the Cloud. This “cloud” could range from a secure set of internal servers to an off-site third-party maintained cloud service; the concept of consolidating the data in a location for improved data consolidation (variety) and centralized processing (value) is a trend that will increasingly be leveraged. Once we have identified patterns of interest, however, the sheer volume and rate of the data involved precludes us from leveraging it centrally due to inherent bandwidth and latency constraints. Additionally non-performance factors such as security or the simple fact that the solution does not require complex (breadth or depth) analysis may render a cloud solution a non-optimal approach.

Thus, our second challenge is to embed knowledge of these patterns within smart devices located close to the source of the data, at the so-called ‘edge’, such that they can enhance the operation of existing control systems at the appropriate pace.

In this section, we will consider the technology drivers for IIoT trends, and some of the technical challenges to realizing these trends.

5.8.7.1. IIOT AND CLOUD DRIVERS

There are at least two drivers for IIoT framework of a central “cloud” and edge devices:

1) the perceived need to collect more signals from a wide variety of sensors, and

2) a growing need to have more distributed computing and storage capabilities.

For the first driver the reality is that, despite the industry’s best efforts, traditionally available equipment and process parameters cannot explain all observed yield losses. The hope is that, by collecting this extra information, previously hidden correlations between wafer yield loss and tool or process parameters will become clear. Although local solutions and implementations exist across the industry, parameters and sensors that are currently not generally incorporated into equipment monitoring, process monitoring and data analytics platforms include vacuum gauges, mass flow controllers, valve position sensors, pressure transducers, thermocouples, residual gas analyzers, vibration measurements etc. The data quantity, quality and frequency these different sensors and analysis devices provide can vary enormously. Some only provide a few basic voltage levels as output, and both capture and translation are required. Others provide large data files in an industry standard format, ready to be communicated over existing networks. When required, edge devices can simultaneously offer a solution for capture, communication and integration. What is clear is that different types of edge devices will be needed to match to these different types of sensors.

The second driver, i.e. the growing need for distributed compute and data storage power, is mainly to share the load, rather than some intrinsic value of physical proximity. The latter is often driven by trivial connection requirements and challenges as much as other reasons. Irrespective of whether the IIoT will add many more devices, collecting data from the existing sensors may already provide a challenge. Depending on the parameters the required computing power can easily overwhelm a central system as well as the communication networks that connect both. Some sensors, such as thermocouples for instance, probably generate much less data than vibration measurements where analog vibration spectra and subsequent FFT analysis requires significant storage and compute capacity.

Although the fab traditionally is very unit process focused, integration of such edge devices sensor data (and indeed all data) across different tool makes or even processes may reveal more holistic underlying causes of yield issues of a fab as an interconnected system. This may require the development of industry standards to address issues of data exchange IP, user interface, look and feel etc.

5.8.7.2. IIOT AND CLOUD TECHNICAL CHALLENGES

5.8.7.2.1. DETERMINING THE DISTRIBUTION OF INTELLIGENCE BETWEEN THE CLOUD AND EDGE DEVICES

A key technical challenge in the IIoT and Cloud roadmap is determining and quantifying the metrics that drive the decision process of providing a solution component at the edge or in the cloud, and identifying potential collaborations of components at the edge and in the cloud that would facilitate more effective solutions.

Key metrics that currently drive this decision process are shown in Table FAC17. Technical challenges include quantifying these metrics and their interactions and evaluating solutions with respect to these metrics. Potential solutions include technology improvements, standards, best practices, etc., that will improve the metrics for both edge and cloud devices, but also improve the capability for seamless interaction to deliver improved collaborative solutions.

Table FAC17 Key metrics that currently drive the cloud versus edge-device decision process for placement of solution components

Item	Edge solutions	Cloud solutions
Data access	Generally limited to edge device location.	Very high levels of data access from multiple levels.
Performance	Generally high and oftentimes a motivational factor for choosing an edge solution.	Lower due to communication times to/from cloud, security levels, data management delays, etc. However significant resources are being applied across industries to improve response times
Algorithmic complexity	Edge devices tend towards lower complexity higher response time algorithmic environments.	Cloud solutions are capable of supporting highly complex and diverse algorithmic environments.
Security	Higher and oftentimes a motivational factor for choosing an edge solution. Solution components that contain a high level of IP are often motivated to be delivered as edge devices.	A technical challenge (see discussion below and in section 5.8). Considerable efforts are being made across industries to address this issue via standards and technical innovation . Solution components or solution application environments that have a high level of IP are oftentimes cloud-adverse.
Business model	Provided by suppliers with higher SME in the particular-application area, or for solutions that require a high level of SME integration. Solutions that require a hardware component (e.g., novel sensor) will also tend towards edge devices.	Generally focused on solutions that are more data intensive and require lower amounts of SME. Solutions or solution components that are repeatable and reusable also tend towards the cloud as well as solutions that are analytic with no directly associated hardware component.
Cost	Important cost factors are oftentimes hardware, hardware integration, power delivery, hardware invasiveness, etc.	Cost factors are often associated with security (data access, data partitioning, IP) and operational practices.
Summary: Technical challenge areas	Breadth of data access, hardware costs, analysis power.	Security, performance.
Summary: Potential solution areas	Integration standards, performance metrics, integration with cloud.	Security standards and solutions, performance metrics, integration with edge devices.

5.8.7.3. TECHNOLOGY REQUIREMENTS

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

Table FAC18 Industry Internet of Things (IIoT) and the Cloud Technology Requirements

5.8.8. INTEGRATED SUPPLY CHAIN NEEDS

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 FAC11)[6]. Besides continuous improvement of factory deviation control to improve manufacturing performance, there are other sources of deviation from the overall supply chain into factory that also require good control to reduce the deviation and improve the complexity management. There are several key parameters that should be considered in the control formulation; the inclusion of these parameters in the control does not necessarily mean that these factors are under control:

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

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

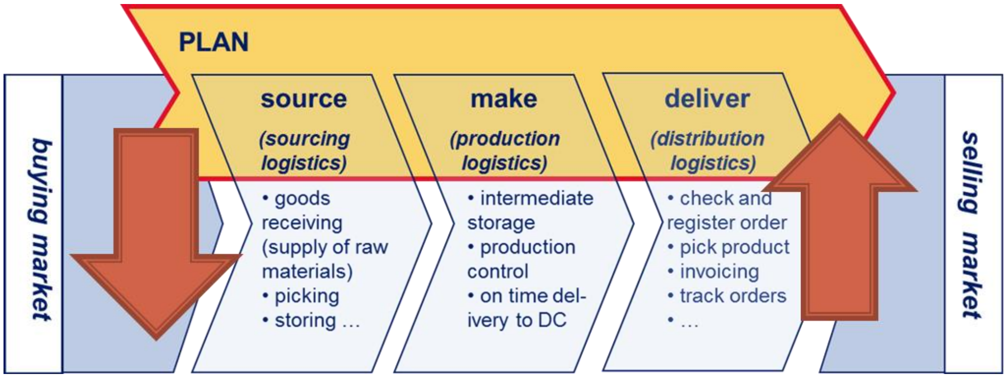


Figure FAC11 Supply Chain Model SCOR

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

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

objectives will be impacted by the supply chain in the future. The real-time integration of product yield data will also help improve the responsiveness of the supply chain.

5.8.8.1. TECHNOLOGY REQUIREMENTS

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

Table FAC19 Integrated Supply Chain (ISC)Technology Requirements

5.8.9. KNOWLEDGE NETWORK NEEDS

5.8.9.1. INTRODUCTION AND SCOPE

As we more fully embrace smart manufacturing (SM) strategies and environments, analytic solutions for the microelectronics manufacturing ecosystem are becoming more complex, precise, robust (from a control system definition perspective), granular, and more integrated, leveraging information from larger and more diverse data sources. These analytics, ranging from tool-level fault detection to end-of-line yield and supply chain analysis, are evolving in large part to support emerging prediction solutions such as predictive maintenance, but also to improve fundamental existing capabilities such as run-to-run control and fault detection, and to enable new capabilities such as supply chain optimization as well [2,3].

Given the complexity of environments and solutions there is an increasing trend to attempt to rely too heavily on the data and not enough on the available domain information. Increasing available, extensive, and higher performance open analytics platforms and the increased emphasis on data analyst expertise across industries. There is a corresponding bias to try to solve problems purely with analytics, i.e., without understanding the application environment, leveraging domain expertise.

This "data-only" approach to solutions generally does not work in the microelectronics manufacturing environment [25]. As detailed in [3], the microelectronics manufacturing ecosystem is characterized by highly complex equipment operating in a very dynamic environment with a large number of context shifts (e.g., recipe changes and PMs). As a result, as part of the analysis process, large stores of data often have to be broken into much smaller clusters that relate to particular situation and context environment. The "Big Data" benefit quickly disappears.

As shown in Figure FAC12, experts, each with subject-matter-expertise (SME) in a variety of areas including equipment, process and applications, can provide a knowledge network to augment analytics and provide more optimal, robust and usable solutions.

The scope of the Knowledge Network SM section is to provide a roadmap for a knowledge networks that will allow them to interact in a complementary way with analytics, with the ultimate goal being than no information is unavailable or unusable in solutions. This scope includes, but is not limited to:

- Identifying different types of SMEs and how they interact as well as challenges and potential solutions for securing and maintaining this knowledge network.
- Identifying points of interaction between analytics and SMEs
- Identify challenges and potential solutions towards a more automated and optimal scheme for interaction between analytics and the knowledge network.

5.8.9.2. HIGH LEVEL VISION

The key aspects of the knowledge network vision for SM are:

- SME is required in effective fab analytics;
- SME needs to be mapped into the project plan and/or workflow of events; and
- Analytics and SME must be incorporated so that "no knowledge is left behind".

Figure FAC12 provides an illustration of the latter points. Note that that there are different types of SME that must have to work together with analytics in an effective application, and that the interplay is structured and automated. Deep SME's have detailed knowledge about a particular facet of the project, such as the modes of failure of a component in a predictive maintenance (PdM) project, but it is important that these SMEs be coordinated across the project workflow by a broad coordinating SME that has (1) general knowledge of the entire project and (2) understands the nature of the expertise of the extreme SMEs that are (or need to be) on the team. The knowledge network vision includes seamless integration between human SME resources and cyber resources such as analytics and workflow systems. This integration includes bi-directional communication where each resource is capable of accepting and processing knowledge from another resource at any time, as well as knowing when information is needed from another resource and asking for that information. This vision will especially require addressing technical challenges in the analytics to SME structured collaboration space.

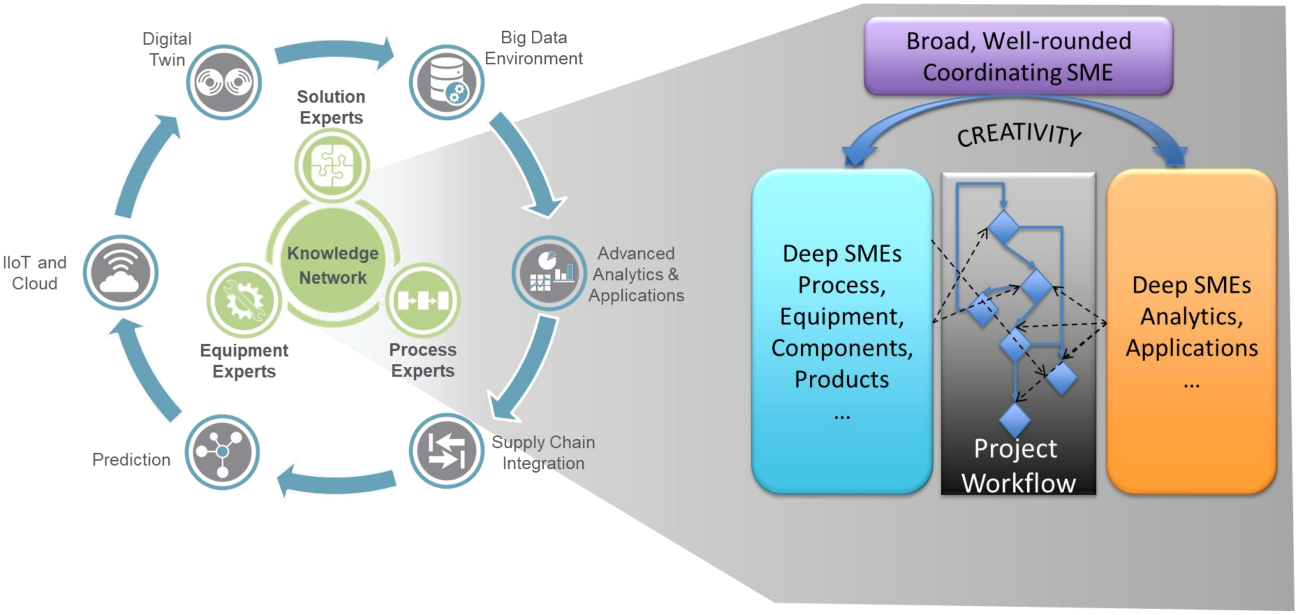


Figure FAC12 Illustration of how SME expertise is incorporated into the knowledge network. [23]

5.8.9.1. TECHNOLOGY REQUIREMENTS

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

Table FAC20 Knowledge Network Technology Requirements

6. POTENTIAL SOLUTIONS

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

Potential solutions are shown as "*Research required*," "*Development underway*," "*Qualification/pre-production*," or *"Continuous improvement",* coded in potential solutions tables as shown below. The purpose is to provide guidance to researchers, suppliers, and IC makers on the timing required to successfully implementing solutions into factories. In some cases, the IFT determined that there is insufficient information either in the IFT or in the industry in general to provide specifics on the timing of a potential solution; in these cases, the code "*To be determined*" is used.

⬛ Research Required
🟦 Development Underway
⬜ Qualification/Pre-Production
▨ Continous Improvement
🟨 To Be Determined (TBD)

As the industry develops potential solutions, they often reach a point of continuous improvement and capturing their progress in a potential solutions roadmap is not necessary. However, in many cases it is still important to describe these solutions from an educational perspective. These solutions are captured in Table FAC21 delineated by functional area.

Table FAC21 Stabilized FI Potential Solutions with Description

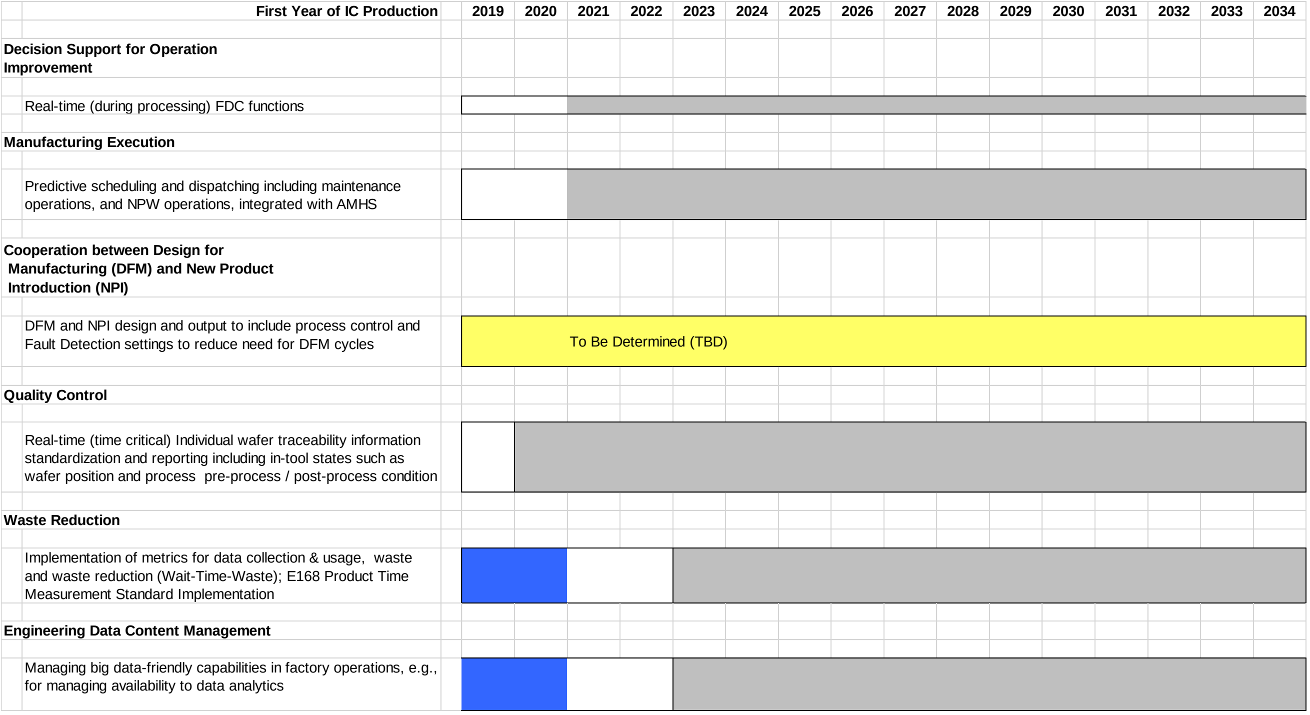
Functionality areas	**Solutions**	**Year of entering CIP**	**Justification to regard the item "educational"**
Factory Operations (FO)	To provide direct support for experiment design and management associated with NEW Product Introduction (NPI)	2019	The solutions are available though not standardized
	Factory system implementation for equipment performance visualization and tracking in order for productivity improvement	2019	The solutions are available though not standardized
Production Equipment (PE)	Seamless cascading multiple recipes within a carrier over lots	2016	Viable solution to improve utilization but cannot be called "potential" solution anymore.
	Hot-wafer take over capability on the production tool	2015	Important solution for keeping cycle time as short as possible for critical reasons (e.g., send ahead metrology, important sample) but cannot be called "potential" solution anymore
	On-tool wafer sorting between carriers in select tools	2017	Having been realized where it is necessary, or at least known as viable solution.
	Process quality improvement through APC (including R2R control, FDC, SPC and Fault Prediction) as a design-in requirement; the APC that is leveraged could be inside or outside of the equipment	2011	APC has been implemented for some time. There is a lot of room for improvement but it is not "potential" solution anymore.
	Equipment functional verification through techniques including fingerprinting and equipment health monitoring	2017	Dashboard function for equipment fingerprinting and health data becomes prevalent.
	Capability to limit utilities and electric power consumption during equipment idle periods; includes management of equipment "energy saving mode" without impacting throughput or quality	2017	Standards to support equipment sleep mode coordination with FICS became available.
	To make energy efficient design an important equipment design metric, and waste reduction equipment design and operation performance metrics	2015	There is a SEMI Standard that provides metrics for equipment energy efficiency. It can also be used to evaluate utility use efficiency.
Automated Material Handling Systems(AMHS)	450 mm Interface standards development	2016	Physical interface Standards Suite for AMHS and 450 Carriers/production equipment had completed and stabilized. It is expected, however, once 450mm systems implementation for quantitative production starts the Standards Suite may need some more revisions.
	Uninterrupted software upgrade	2017	This solution is not wafer diameter dependent and has already been available.
	Visualization of AMHS information	2017	This solution is not wafer diameter dependent and has already been available.

Functionality areas	**Solutions**	**Year of entering CIP**	**Justification to regard the item "educational"**
Factory Information & Control Systems (FICS)	Cross-module supervisory Run-to Run process control	2015	Have already been implemented for critical processes
	Stds-based equipment data collection for process monitoring and diagnostics via EDA interface	2015	Have already been implemented for critical equipment
	Data Quality and Factory-wide standardized time synchronization	2015	Standards are available
	Integrated FICS to facilitate data searches and information correlation on process and operational data	2015	Correlation is possible but speed can be improved
	Integrated FICS to support cross-site processing	2015	already been implemented
Facilities	Early and accurate identification of production equipment installation demand requirements for base build construction (e.g. pressure, loads, flows, connection size)	From 300 mm tools	SEMI E6 and other Standards are available to specify and communicate production equipment installation demand between supplier and user. Without quantifying how early or accurate these cannot be solutions.
Security	Establishment and Operation of Security Audit, Assessment and Incident Management Processes	2018	Fabs already implemented security management system but are in needs of CIP
SM-Big Data (BD)	*Volume--No Entries*		
	Velocity--Solutions to support peak equipment and peak factory data transfer rates for off-line data analysis	2019	Generally solved and in the CIP space. There are restrictions in the wireless space (Zigbee, etc.), 5G problems with line of site, etc.; IIoT funneling to the higher levels is an issue.
	Variety-- No Entries		
	Veracity-- No Entries		
	Value-- No Entries		
	Other-- Fab-wide big data ecosystem	2019	Capabilities exist and implementation is not a technology issue.
SM-Augmenting Reactive with Predictive (ARP)	Standards for virtual metrology capabilities and interfaces	2019	SEMI E133 addresses this at a basic level. Additional standards will likely be developed as part of CIP.
	Re-usable VM methods for excursion detection to support across- fab implementation	2019	VM capabilities for excursion detection will continue to improve as model accuracy and understanding of that accuracy improve, as VM is used for other purposes, and as VM standards continue to be developed and more widely implemented
	Standard to support Lot-based, real-time predictive scheduling and dispatching algorithms integrated with AMHS	2019	Revision to SEMI E87 and a new Standard, SEMI E171 support predictive scheduling

6.1. FACTORY OPERATIONS POTENTIAL SOLUTIONS

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

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



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Decision Support for Operation Improvement																
Real-time (during processing) FDC functions	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Manufacturing Execution																
Predictive scheduling and dispatching including maintenance operations, and NPW operations, integrated with AMHS	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Cooperation between Design for Manufacturing (DFM) and New Product Introduction (NPI)																
DFM and NPI design and output to include process control and Fault Detection settings to reduce need for DFM cycles	🟨 To Be Determined (TBD)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Quality Control																
Real-time (time critical) Individual wafer traceability information standardization and reporting including in-tool states such as wafer position and process pre-process / post-process condition	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Waste Reduction																
Implementation of metrics for data collection & usage, waste and waste reduction (Wait-Time-Waste); E168 Product Time Measurement Standard Implementation	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Engineering Data Content Management																
Managing big data-friendly capabilities in factory operations, e.g., for managing availability to data analytics	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure FAC13 Factory Operations Potential Solutions

6.2. PRODUCTION EQUIPMENT POTENTIAL SOLUTIONS

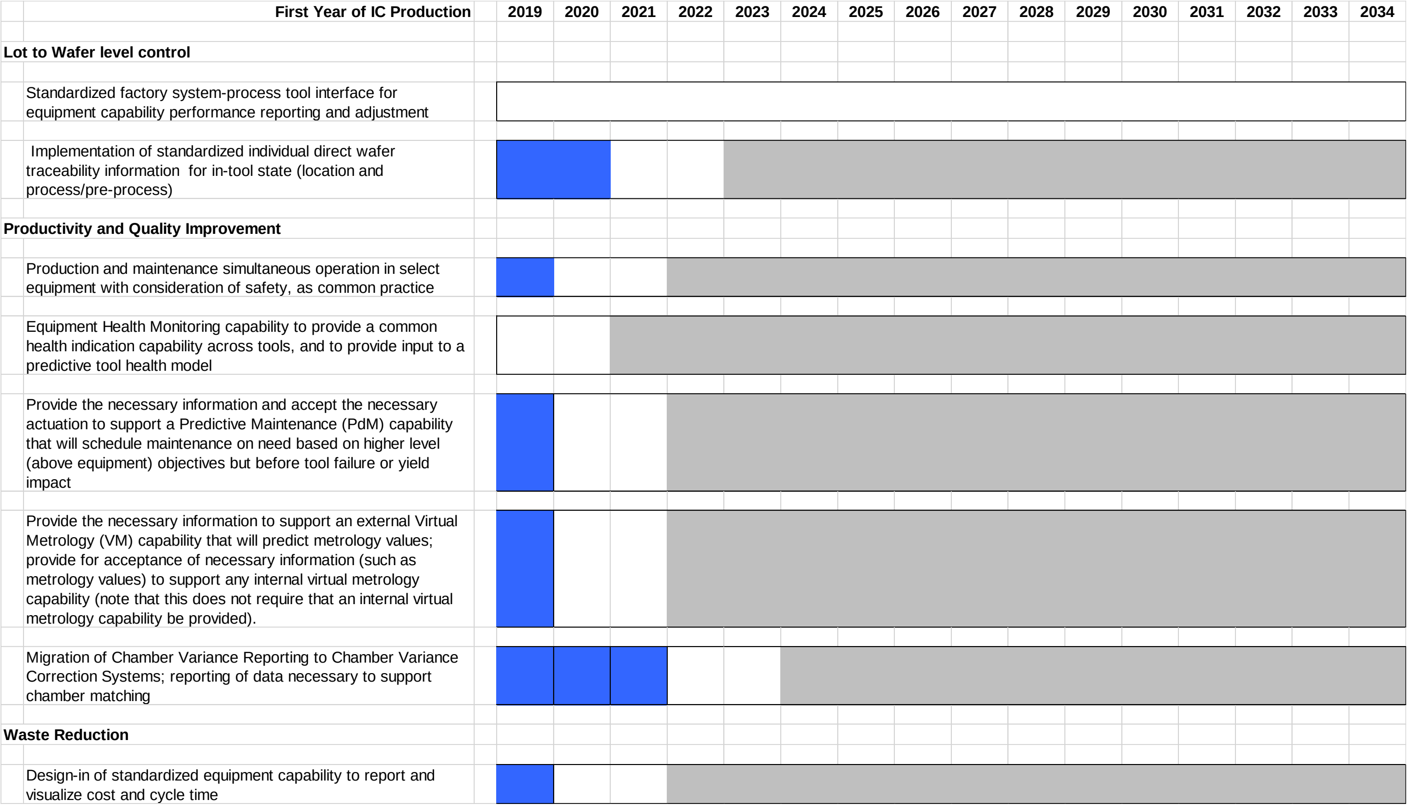
The PE interface with factory is expected to facilitate such factory operations such as Just-In-Time (JIT) or Deliver-On-Time (DOT) operation of carriers for seamless processing, coordination of APC capabilities such as Fault Detection and Run-to-run Process control both inside and outside of the tool,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

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

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

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

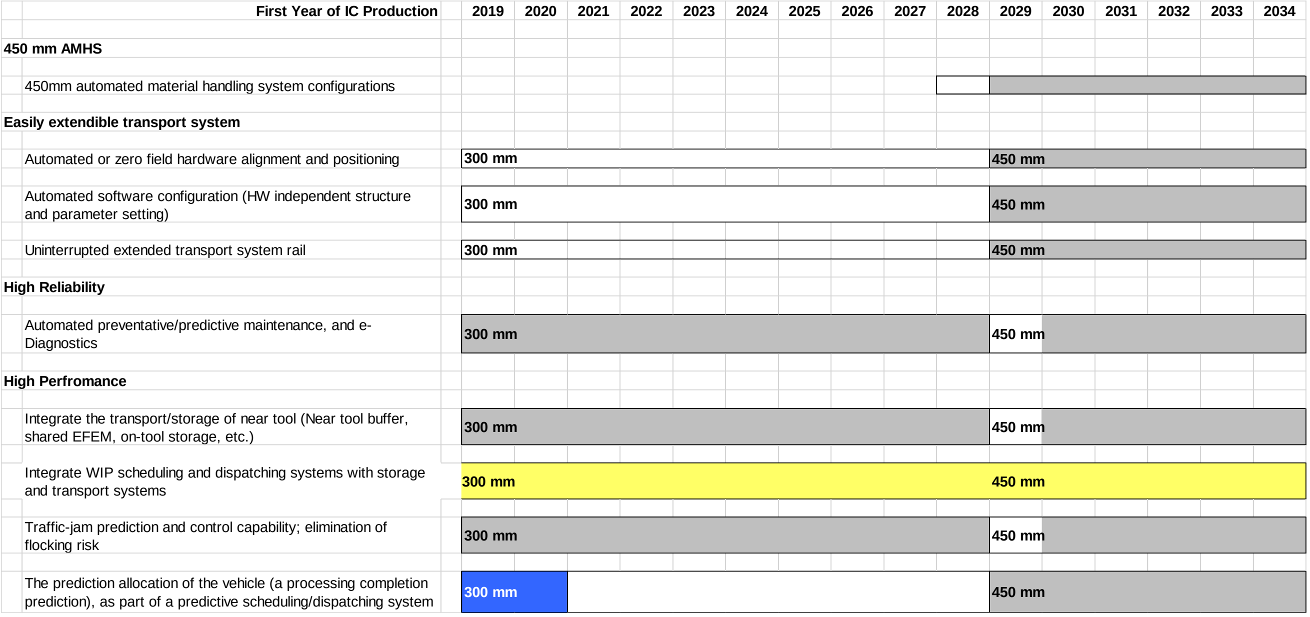
Just as with the fab in general, equipment operations will gradually evolve from reactive to reactive augmented with predictive and prescriptive operations. This is discussed in detail in the ARPP section. Corrective maintenance will be augmented with predictive and prescriptive maintenance. Fault detection 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.



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Lot to Wafer level control																
Standardized factory system-process tool interface for equipment capability performance reporting and adjustment	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Implementation of standardized individual direct wafer traceability information for in-tool state (location and process/pre-process)	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Productivity and Quality Improvement																
Production and maintenance simultaneous operation in select equipment with consideration of safety, as common practice	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Equipment Health Monitoring capability to provide a common health indication capability across tools, and to provide input to a predictive tool health model	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Provide the necessary information and accept the necessary actuation to support a Predictive Maintenance (PdM) capability that will schedule maintenance on need based on higher level (above equipment) objectives but before tool failure or yield impact	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Provide the necessary information to support an external Virtual Metrology (VM) capability that will predict metrology values; provide for acceptance of necessary information (such as metrology values) to support any internal virtual metrology capability (note that this does not require that an internal virtual metrology capability be provided).	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Migration of Chamber Variance Reporting to Chamber Variance Correction Systems; reporting of data necessary to support chamber matching	🟦	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Waste Reduction																
Design-in of standardized equipment capability to report and visualize cost and cycle time	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure FAC14 Production Equipment Potential Solutions

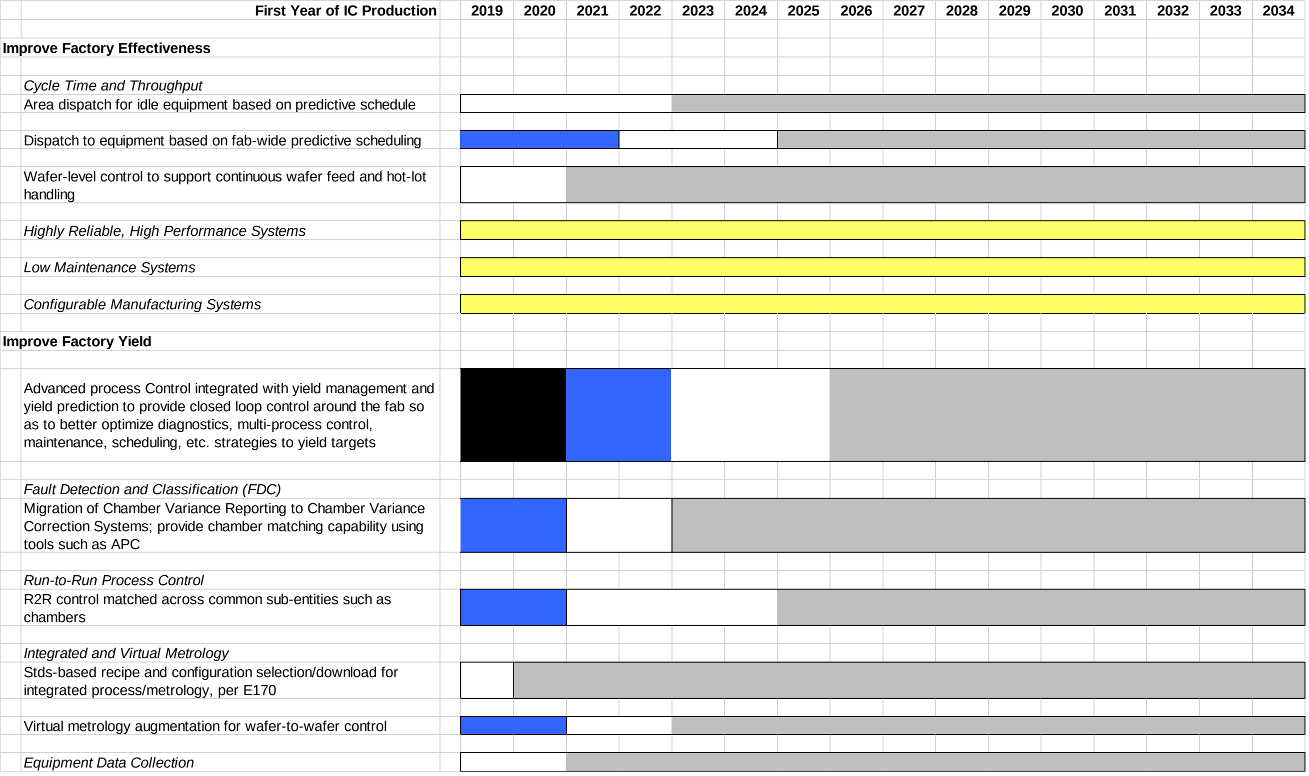
6.3. MATERIAL HANDLING SYSTEMS POTENTIAL SOLUTIONS



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
450 mm AMHS																
450mm automated material handling system configurations										⬜	▒	▒	▒	▒	▒	▒
Easily extendible transport system																
Automated or zero field hardware alignment and positioning	⬜ 300 mm	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	▒ 450 mm	▒	▒	▒	▒	▒
Automated software configuration (HW independent structure and parameter setting)	⬜ 300 mm	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	▒ 450 mm	▒	▒	▒	▒	▒
Uninterrupted extended transport system rail	⬜ 300 mm	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	▒ 450 mm	▒	▒	▒	▒	▒
High Reliability																
Automated preventative/predictive maintenance, and e-Diagnostics	▒ 300 mm	▒	▒	▒	▒	▒	▒	▒	▒	▒	⬜ 450 mm	▒	▒	▒	▒	▒
High Perfromance																
Integrate the transport/storage of near tool (Near tool buffer, shared EFEM, on-tool storage, etc.)	▒ 300 mm	▒	▒	▒	▒	▒	▒	▒	▒	▒	⬜ 450 mm	▒	▒	▒	▒	▒
Integrate WIP scheduling and dispatching systems with storage and transport systems	🟨 300 mm	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨 450 mm	🟨	🟨	🟨	🟨	🟨
Traffic-jam prediction and control capability; elimination of flocking risk	▒ 300 mm	▒	▒	▒	▒	▒	▒	▒	▒	▒	⬜ 450 mm	▒	▒	▒	▒	▒
The prediction allocation of the vehicle (a processing completion prediction), as part of a predictive scheduling/dispatching system	🟦 300 mm	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	▒ 450 mm	▒	▒	▒	▒	▒

Figure FAC15 Material Handling Systems Potential Solutions

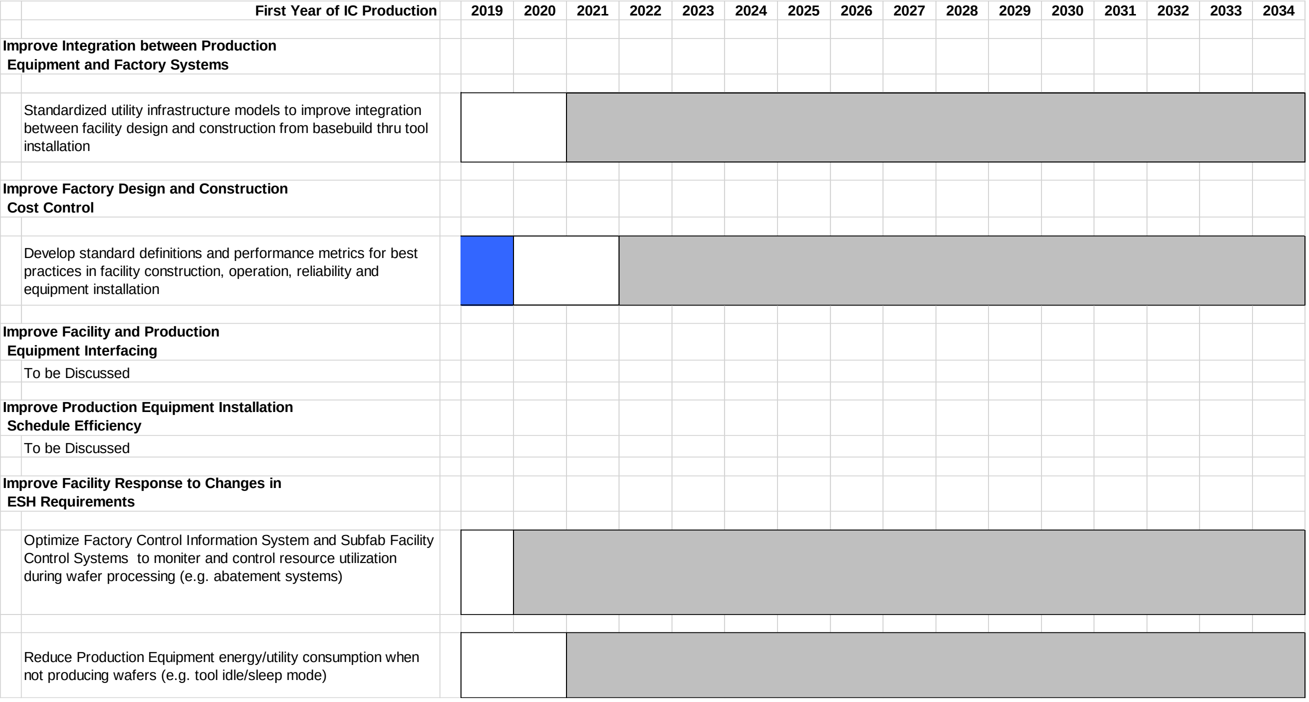
6.4. FACTORY INFORMATION AND CONTROL SYSTEMS POTENTIAL SOLUTIONS



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Improve Factory Effectiveness																
Cycle Time and Throughput Area dispatch for idle equipment based on predictive schedule	⬜	⬜	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Dispatch to equipment based on fab-wide predictive scheduling	🟦	🟦	🟦	⬜	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Wafer-level control to support continuous wafer feed and hot-lot handling	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Highly Reliable, High Performance Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Low Maintenance Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Configurable Manufacturing Systems	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Improve Factory Yield																
Advanced process Control integrated with yield management and yield prediction to provide closed loop control around the fab so as to better optimize diagnostics, multi-process control, maintenance, scheduling, etc. strategies to yield targets	⬛	⬛	🟦	🟦	⬜	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒
Fault Detection and Classification (FDC) Migration of Chamber Variance Reporting to Chamber Variance Correction Systems; provide chamber matching capability using tools such as APC	🟦	🟦	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Run-to-Run Process Control R2R control matched across common sub-entities such as chambers	🟦	🟦	⬜	⬜	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Integrated and Virtual Metrology Stds-based recipe and configuration selection/download for integrated process/metrology, per E170	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Virtual metrology augmentation for wafer-to-wafer control	🟦	🟦	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Equipment Data Collection	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒

Figure FAC16 Factory Information and Control Systems Potential Solutions

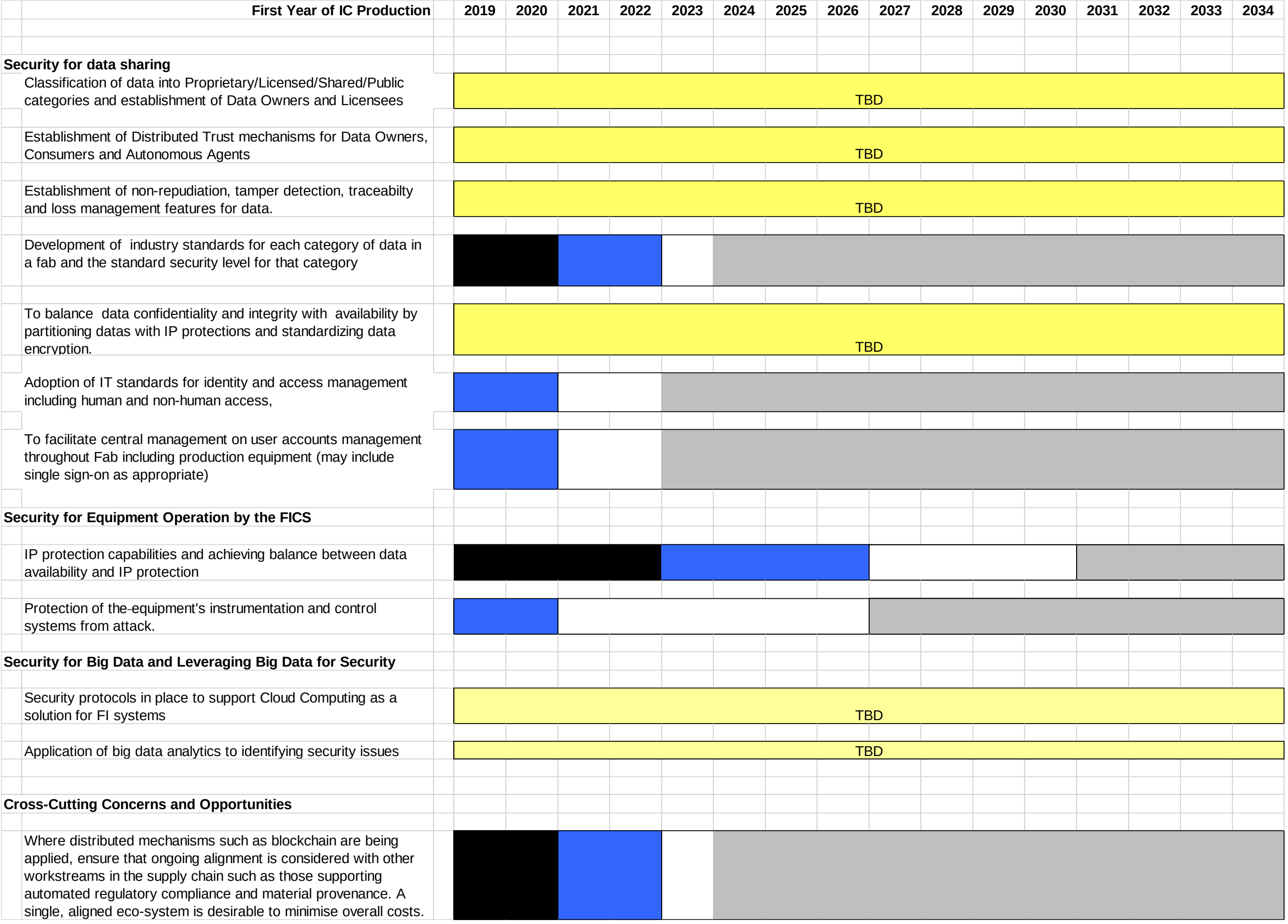
6.5. FACILITIES POTENTIAL SOLUTIONS



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Improve Integration between Production Equipment and Factory Systems																
Standardized utility infrastructure models to improve integration between facility design and construction from basebuild thru tool installation	☐	☐	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Improve Factory Design and Construction Cost Control																
Develop standard definitions and performance metrics for best practices in facility construction, operation, reliability and equipment installation	🟦	☐	☐	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Improve Facility and Production Equipment Interfacing																
To be Discussed																
Improve Production Equipment Installation Schedule Efficiency																
To be Discussed																
Improve Facility Response to Changes in ESH Requirements																
Optimize Factory Control Information System and Subfab Facility Control Systems to moniter and control resource utilization during wafer processing (e.g. abatement systems)	☐	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Reduce Production Equipment energy/utility consumption when not producing wafers (e.g. tool idle/sleep mode)	☐	☐	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure FAC17 Facilities Potential Solutions

6.6. SECURITY POTENTIAL SOLUTIONS



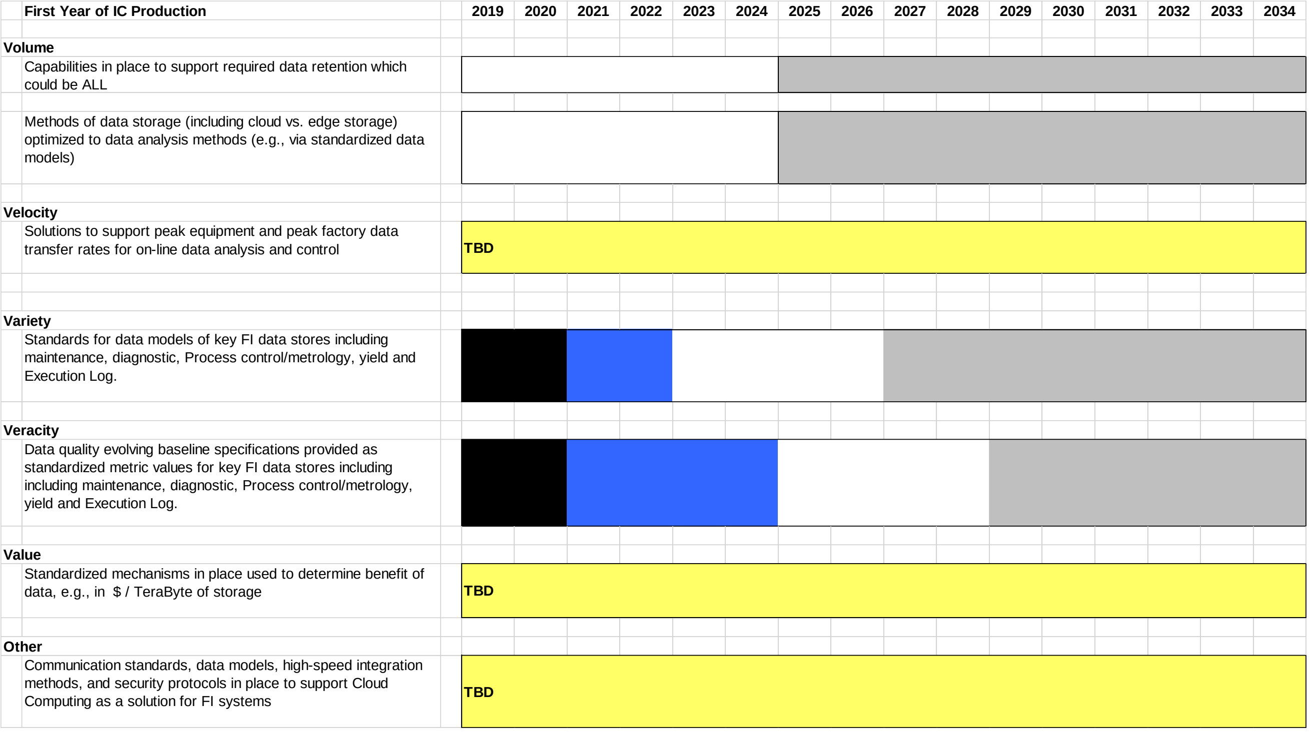
First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Security for data sharing																
Classification of data into Proprietary/Licensed/Shared/Public categories and establishment of Data Owners and Licensees	TBD															
Establishment of Distributed Trust mechanisms for Data Owners, Consumers and Autonomous Agents	TBD															
Establishment of non-repudiation, tamper detection, traceabilty and loss management features for data.	TBD															
Development of industry standards for each category of data in a fab and the standard security level for that category	⬛	⬛	🟦	🟦	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
To balance data confidentiality and integrity with availability by partitioning datas with IP protections and standardizing data encryption.	TBD															
Adoption of IT standards for identity and access management including human and non-human access,	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
To facilitate central management on user accounts management throughout Fab including production equipment (may include single sign-on as appropriate)	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Security for Equipment Operation by the FICS																
IP protection capabilities and achieving balance between data availability and IP protection	⬛	⬛	⬛	⬛	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	▨	▨	▨	▨
Protection of the-equipment's instrumentation and control systems from attack.	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨
Security for Big Data and Leveraging Big Data for Security																
Security protocols in place to support Cloud Computing as a solution for FI systems	TBD															
Application of big data analytics to identifying security issues	TBD															
Cross-Cutting Concerns and Opportunities																
Where distributed mechanisms such as blockchain are being applied, ensure that ongoing alignment is considered with other workstreams in the supply chain such as those supporting automated regulatory compliance and material provenance. A single, aligned eco-system is desirable to minimise overall costs.	⬛	⬛	🟦	🟦	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

Figure FAC18 Security Potential Solutions

6.7. Smart Manufacturing Potential Solutions

As noted in Section 5.8.2, the scope of smart manufacturing (SM) can be organized into a set of common themes or tenets. In this section the potential solutions are presented of each of the SM tenets described in Section 0.

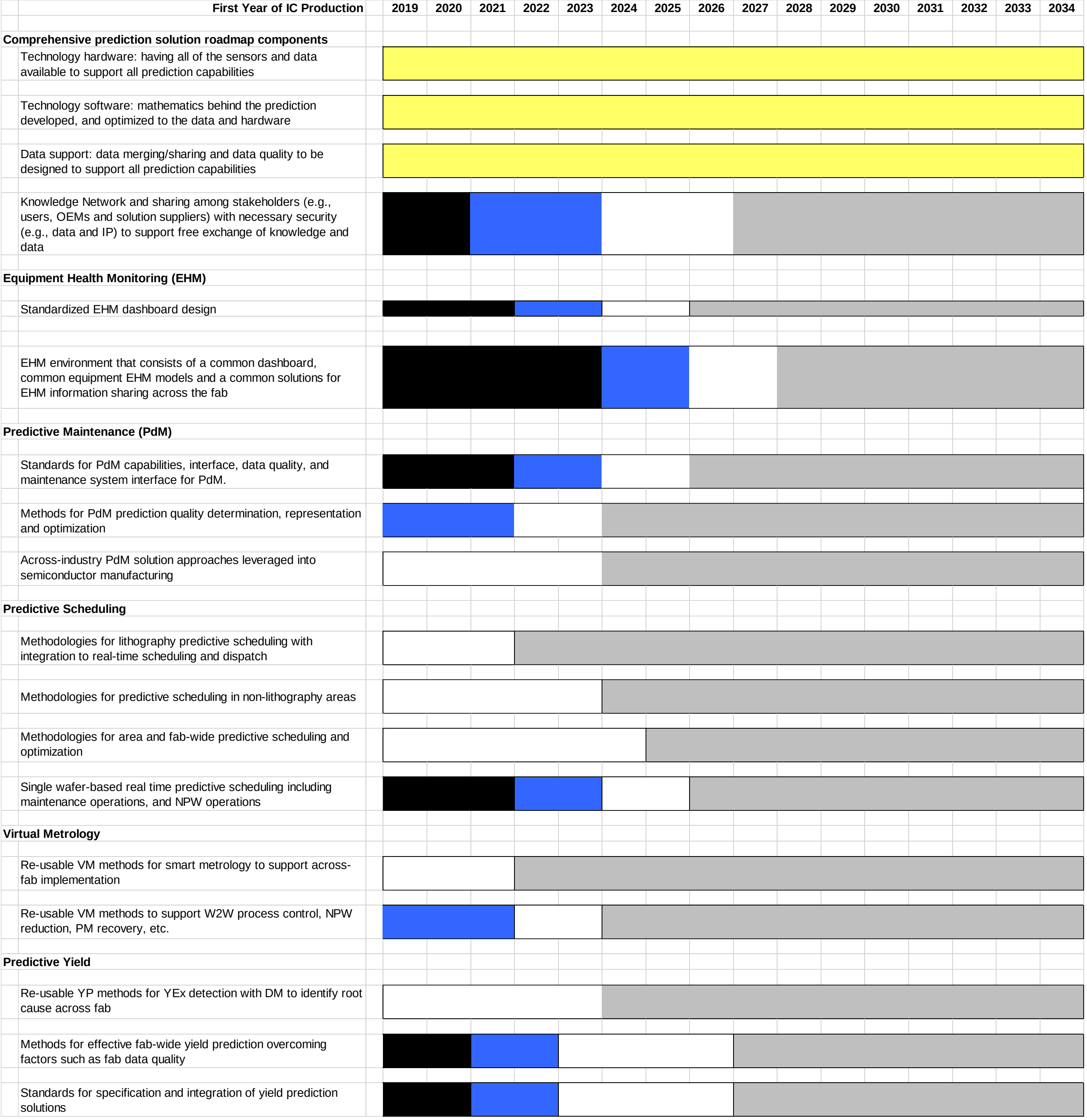
6.7.1. Big Data Potential Solutions



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Volume																
Capabilities in place to support required data retention which could be ALL	⬜	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Methods of data storage (including cloud vs. edge storage) optimized to data analysis methods (e.g., via standardized data models)	⬜	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Velocity																
Solutions to support peak equipment and peak factory data transfer rates for on-line data analysis and control	**TBD**	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Variety																
Standards for data models of key FI data stores including maintenance, diagnostic, Process control/metrology, yield and Execution Log.	⬛	⬛	🟦	🟦	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨
Veracity																
Data quality evolving 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	**TBD**	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Other																
Communication standards, data models, high-speed integration methods, and security protocols in place to support Cloud Computing as a solution for FI systems	**TBD**	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure FAC19 Big Data Potential Solutions

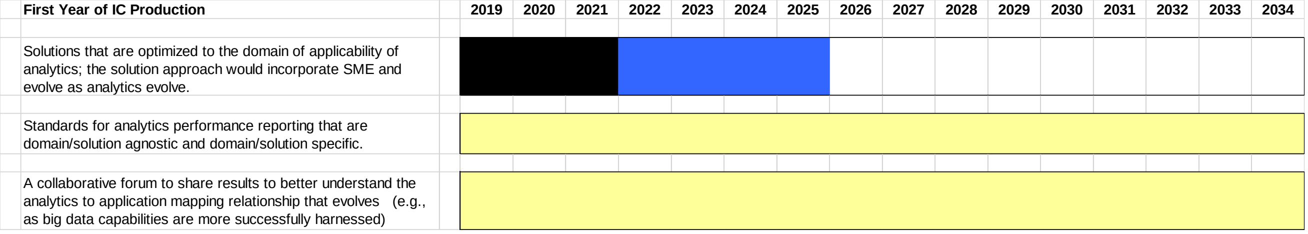
6.7.2. AUGMENTING REACTIVE WITH PREDICTIVE AND PRESCRIPTIVE POTENTIAL SOLUTIONS



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Comprehensive prediction solution roadmap components																
Technology hardware: having all of the sensors and data available to support all prediction capabilities	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Technology software: mathematics behind the prediction developed, and optimized to the data and hardware	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Data support: data merging/sharing and data quality to be designed to support all prediction capabilities	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Knowledge Network and sharing among stakeholders (e.g., users, OEMs and solution suppliers) with necessary security (e.g., data and IP) to support free exchange of knowledge and data	⬛	⬛	🟦	🟦	🟦	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨
Equipment Health Monitoring (EHM)																
Standardized EHM dashboard design	⬛	⬛	⬛	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨
EHM environment that consists of a common dashboard, common equipment EHM models and a common solutions for EHM information sharing across the fab	⬛	⬛	⬛	⬛	⬛	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨
Predictive Maintenance (PdM)																
Standards for PdM capabilities, interface, data quality, and maintenance system interface for PdM.	⬛	⬛	⬛	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨
Methods for PdM prediction quality determination, representation and optimization	🟦	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Across-industry PdM solution approaches leveraged into semiconductor manufacturing	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Predictive Scheduling																
Methodologies for lithography predictive scheduling with integration to real-time scheduling and dispatch	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Methodologies for predictive scheduling in non-lithography areas	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Methodologies for area and fab-wide predictive scheduling and optimization	⬜	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Single wafer-based real time predictive scheduling including maintenance operations, and NPW operations	⬛	⬛	⬛	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨
Virtual Metrology																
Re-usable VM methods for smart metrology to support across-fab implementation	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Re-usable VM methods to support W2W process control, NPW reduction, PM recovery, etc.	🟦	🟦	🟦	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Predictive Yield																
Re-usable YP methods for YEx detection with DM to identify root cause across fab	⬜	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Methods for effective fab-wide yield prediction overcoming factors such as fab data quality	⬛	⬛	🟦	🟦	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨
Standards for specification and integration of yield prediction solutions	⬛	⬛	🟦	🟦	⬜	⬜	⬜	⬜	▨	▨	▨	▨	▨	▨	▨	▨

Figure FAC20 ARPP Potential Solutions

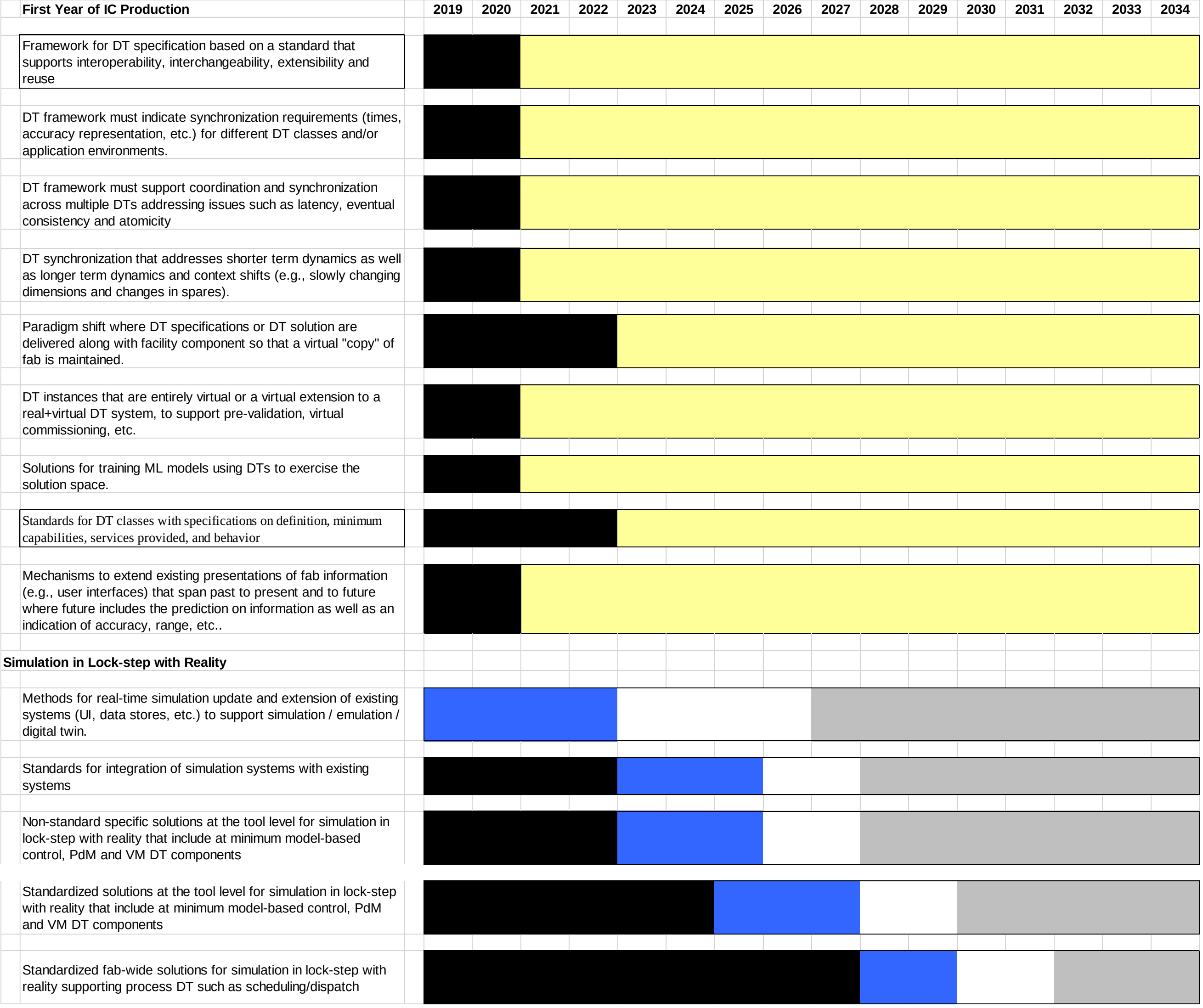
6.7.3. ADVANCED ANALYTICS AND APPLICATIONS POTENTIAL SOLUTIONS



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Solutions that are optimized to the domain of applicability of analytics; the solution approach would incorporate SME and evolve as analytics evolve.	⬛	⬛	⬛	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Standards for analytics performance reporting that are domain/solution agnostic and domain/solution specific.	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
A collaborative forum to share results to better understand the analytics to application mapping relationship that evolves (e.g., as big data capabilities are more successfully harnessed)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure FAC21 AAA Potential Solutions

6.7.4. DIGITAL TWIN POTENTIAL SOLUTIONS



First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Framework for DT specification based on a standard that supports interoperability, interchangeability, extensibility and reuse	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
DT framework must indicate synchronization requirements (times, accuracy representation, etc.) for different DT classes and/or application environments.	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
DT framework must support coordination and synchronization across multiple DTs addressing issues such as latency, eventual consistency and atomicity	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
DT synchronization that addresses shorter term dynamics as well as longer term dynamics and context shifts (e.g., slowly changing dimensions and changes in spares).	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Paradigm shift where DT specifications or DT solution are delivered along with facility component so that a virtual "copy" of fab is maintained.	⬛	⬛	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
DT instances that are entirely virtual or a virtual extension to a real+virtual DT system, to support pre-validation, virtual commissioning, etc.	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Solutions for training ML models using DTs to exercise the solution space.	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Standards for DT classes with specifications on definition, minimum capabilities, services provided, and behavior	⬛	⬛	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Mechanisms to extend existing presentations of fab information (e.g., user interfaces) that span past to present and to future where future includes the prediction on information as well as an indication of accuracy, range, etc..	⬛	⬛	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Simulation in Lock-step with Reality																
Methods for real-time simulation update and extension of existing systems (UI, data stores, etc.) to support simulation / emulation / digital twin.	🟦	🟦	🟦	🟦	⬜	⬜	⬜	⬜	▒	▒	▒	▒	▒	▒	▒	▒
Standards for integration of simulation systems with existing systems	⬛	⬛	⬛	⬛	🟦	🟦	🟦	⬜	⬜	▒	▒	▒	▒	▒	▒	▒
Non-standard specific solutions at the tool level for simulation in lock-step with reality that include at minimum model-based control, PdM and VM DT components	⬛	⬛	⬛	⬛	🟦	🟦	🟦	⬜	⬜	▒	▒	▒	▒	▒	▒	▒
Standardized solutions at the tool level for simulation in lock-step with reality that include at minimum model-based control, PdM and VM DT components	⬛	⬛	⬛	⬛	⬛	⬛	🟦	🟦	🟦	⬜	⬜	▒	▒	▒	▒	▒
Standardized fab-wide solutions for simulation in lock-step with reality supporting process DT such as scheduling/dispatch	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	🟦	🟦	⬜	⬜	▒	▒	▒

Figure FAC22 DT Potential Solutions

6.7.5. INDUSTRIAL INTERNET OF THINGS AND THE CLOUD POTENTIAL SOLUTIONS

First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Standards for heterogeneous edge device communication to intermediate or cloud data collection components	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Low power solutions for remote wireless edge devices	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure FAC23 IIoT and the Cloud Potential Solutions

6.7.6. INTEGRATED SUPPLY CHAIN POTENTIAL SOLUTIONS

First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Multi-industry standards to guarantee secure supply chain data transfer / sharing	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Standards for automated demand signaling, (e.g., for automatted inventory management of parts and alerting of delivery shortages)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure FAC24 ISC Potential Solutions

6.7.7. KNOWLEDGE NETWORK POTENTIAL SOLUTIONS

First Year of IC Production	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Open analytical platforms that support pre-defined access points for integration of subject-matter-exertise and have capabilities to request this expertise asynchronously	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Structured methods to capture and store subject-matter-expertise for re-use (e.g., language processing for interpretation of log files into a knowledge base that would be used by analytics)	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Quantification of analytics cost of ownership as a component of reduced cost in fab (by reducing cost directly or providing more value) in integrated supply chain, advanced packaging, reduced downtime, etc.	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Solutions that extend the KN to be integrated up and down the supply chain as part of a continuum	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Figure FAC25 KN Potential Solutions

7. CROSS TEAMS

FI technology requirements are often driven by other IFT requirements as shown in Figure FAC1. In order to understand the crosscut issues fully, the FI IFT interfaces with the other IFTs and puts together a list of key crosscut challenges and requirements as shown in Table FAC22, delineated by IFT area. This is followed by a discussion of interactions with specific IFTs or interactions around specific issues. FI will continue to address these key crosscut challenges and requirements.

Table FAC22 Crosscut Issues Relating to Factory Integration

Crosscut Topic	*Counterpart IFT(s)*	*Factory integration related key challenges*
Front end Process (FEP)	*More Moore Beyond CMOS Outside System Connectivity*	[Common across counterparts IFTs] Facility to support material (e.g., chemical distribution to abatement systems) and production environment (e.g., AMC, ESD) for novel device structure including materials used in them.
		FICS to support increased number of parameters, detailed controls with FB from metrology and other support tool and systems.
		ARP will impact all FE process in some way; coordinate roadmaps to make sure FEPs are moving toward "prediction ready", e.g., by providing necessary data
		Novel devices and their production processes may require more extensive data collection and its utilization for improvement of process performance. Getting to know FEP's BD data requirements (identification of 5V) is prerequisite for preparedness of BD system
Back end Process (BEP)	*More Moore Beyond CMOS Outside System Connectivity Packaging Integration*	[Common across counterparts IFTs] FICS for backend may need optimization including customization of supporting standards to allow full integration of data through processes (i.e., FEP-BEP integration)
		Tests needs (sampling rates and frequency) must be optimized by utilizing BD based analytics; BEP may impose higher data rate and bandwidth requirements in FICS
		Better integration between BEP and FEP will be required both to meet device design requirements and to achieve yield and productivity objectives
Lithography	*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 to support practical cycle time (especially for small lots operation)
		Facility to support production environment (e.g.., AMC, ESD) for reticle and tighter process control needs.
		Predictive scheduling is important to lithography as it is often the critical process to maintaining overall throughput of the Fab.
		Lithography DFM needs. EFM may be added as it is confirmed as mask quality detractor.
Sustainable Manufacturing Green Chemistry	*ESH*	ESH/S to identify required Fab/equipment capabilities to measure resource consumption and release/emission to environment.
		FI to provide necessary metrics/methodology/data systems/infrastructure to accommodate ESH objectives
	Metrology	Comprehensive metrology roadmap to be jointly defined.

Crosscut Topic	*Counterpart IFT(s)*	*Factory integration related key challenges*
Real and Virtual Metrology		Virtual Metrology is an emerging cross-cut issue. The role of VM in metrology will be increasing; VM may become an integral part of some metrology offerings. Metrology capabilities will become part of the prediction engine input (e.g., for throughput projections) and output (e.g., for VM tuning).
		Metrology requirements on ESD and EMI could impact Facility targets
Yield Enhancement	*Yield Enhancement*	Facility/PE needs to contemplate necessary capabilities for supporting YE related requirements at different interface points (i.e., POS, POD, POC, POE, POU, POP)
		Facility need to support AMC, temperature, humidity and other environment controls as required by YE
		FI and YE to discuss opportunities to optimize tests (frequencies, condition to do/skip test) by utilizing BD and predictions
		YE to benefit from yield excursion detection and analysis and ultimately yield prediction provided as part of FICS, ARP and BD capabilities.
Big Data	*All*	Big data and prediction requirements and solutions will impact and provide solutions for Test.
		Big data and associated enabling of prediction technologies and advanced analytics will allow for improvement of and innovation in YE techniques, metrology and real + VM metrology capabilities, and better integration of FEP and BEP.
		Big Data and its better enabling of prediction and other analytics will improve all aspects of FI allowing for realization of production capabilities to support emerging production requirements from IFTs such as More Moore and Beyond CMOS

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

7.1.1. SCOPE

The Environmental, Safety, Health, and Sustainability (ESH/S) activities, strategies and vision has an aim of projecting the principles of a successful, sustainable, long range, global, industry-wide ESH/S program. Execution remains largely independent of the specific technology thrust advances to which the principles are applied. Thus, many ESH/S Roadmap elements, such as the Difficult Challenges and the Technology Requirements, feed directly into the other IFTs in the IRDS, notably Factory Integration. The six basic and overarching ESH/S Roadmap strategies are:

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

To provide proactive engagement with stakeholder partners and customers and reset strategic focus on the roadmap goals.

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

ESH/S and Factory Integration Synergy

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

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

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

Continue focus on factory, and supply chain safety for employees and the environment

Sustainability

Manufacturers are increasingly taking a proactive approach to sustainability, working to minimize the effect of manufacturing operations on the environment. Drivers include:

- Employees increasingly want to work for companies that are good stewards of the environment.
- Customers want to buy product from environmentally friendly companies.
- Global regulatory limits and reporting requirements are likely to continue to tighten.

A good example is the IPCC GHG Emissions Guidelines; 2019 Refinement of 2006 Document. This document includes many emission factors changed since 2006, including Volume 3 Chapter 6, which refers to the semiconductor, FPD and PV industries : http://www.ipcc-nggip.iges.or.jp/home/2019refinement/sod.html.

An important aspect of sustainability is data collection, i.e., insuring that we have the right sensors, monitoring, tool trace data, SCADA, etc., and associated analytics to meet environmental reporting requirements, and drive informed decisions on environmental footprint-reduction opportunities. In the facilities area factory construction is increasingly incorporating environment new buildings seeking accreditation in LEED, Greenmark, etc.

7.2. YIELD ENHANCEMENT

7.2.1. SCOPE

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

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

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

YE and Factory Integration Synergy

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

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

- The road mapping focus will move from a technology orientation to a product/application orientation.
- Airborne molecular contamination (AMC), packaging, liquid chemicals and ultra-pure water were identified as main focus topics for the next period.

Electrical characterization methods, big data and modeling will become more and more important for yield learning and yield prediction.

7.2.2. AIRBORNE MOLECULAR CONTAMINATION

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

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

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

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

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

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

FOUP purging has been proven extremely difficult due to the dead-end type internal design of air spaces between the wafers as well as the limited possible flow rate. New methods such as vacuum/N_2 purge cycles can support faster cleaning times and overcoming the long dead legs. Nevertheless, further development is needed to establish suitable control limits of FOUP status and purging efficiency with on-line and off-line methods. Refer to *Yield Enhancement Chapter* for more information. Meeting AMC requirements is also addressed from a facilities perspective in the *Facilities* section of this chapter.

7.2.3. ULTRA-PURE WATER

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

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

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

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

7.2.4. ELECTRICAL CHARACTERIZATION METHODS AND VIRTUAL METROLOGY FOR YIELD CONTROL

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

Furthermore, virtual metrology becomes more and more essential for yield considerations. Virtual metrology is 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 and Prescriptive (ARPP) section of this chapter for more information.

7.2.5. THE MOVE TOWARDS YIELD PREDICTION

As noted in the *ARPP* section of this chapter, part of the prediction vision is a state of fab operations where “yield and throughput prediction are an integral part of factory operation optimization”. Yield prediction will also become an integral part of yield control and enhancement. Big data capabilities will be leveraged to develop and maintain yield prediction models. These models will provide indications of potential yield excursions as part of the process flow, so as to provide “real-time”[7] indications of issues to avoid quality issues associated with the delay between processing associated with the yield excursion and the end-of-line e-test and yield analysis (a delay that can often be days or even weeks). Analytics will identify culprits of yield excursions in terms of process and process parameters; analytics from other prediction technologies, notably virtual metrology, will be leveraged. Eventually control actions will be defined to allow the evolution from real-time yield excursion detection to real-time yield excursion control, and then real-time yield continuous optimization.

7.3. METROLOGY

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

7.4. LITHOGRAPHY

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

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

7.5. MULTI-IFT ISSUE: WAFER DEFECT METROLOGY

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

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

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

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

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

8. EMERGING CONCEPTS AND TECHNOLOGIES

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

8.1. BUSINESS PARADIGM CHANGE: MIGRATION TO COOPERATIVE SERVICES-BASED APPROACH TO FI

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

8.2. SUPPLY CHAIN MANAGEMENT

FI connectivity up and down the supply chain leveraging the accelerated IT technology trends will be necessary to support tightening of production methods (e.g., associated with lean manufacturing) and addressing business requirements (e.g., for warranty traceability, improved quality, improved productivity, and cost reduction). Supply chain integration and management is thus a necessary part of the FI roadmap. Developing this roadmap will require and understanding of both microelectronics supplier and consumer sectors. For example, with respect to suppliers it will require an understanding of methods for specifying, bidding and ordering to support lean manufacturing inventory management requirements. With respect to customer, it will require 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.. In the future Supply Chain Management may be one of the focus areas of the FI thrust.

8.3. 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:

- *Distributed control and autonomous control:* The advent of technologies such as web-based services and tablets has resulted in the enabling of a highly distributed control environment where disparate capabilities and suppliers can be brought together to achieve control objectives, moving away from the centralized control concept. This technology trend is already being harnessed in many FI domains (e.g., mobile computing units for maintenance management or process monitoring), however the level and timing of impact on the FI control approach as a whole is unclear. It is likely that movement to this control paradigm will be guided by trends across manufacturing in general rather than trends specific to microelectronics manufacturing.

9. CONCLUSIONS AND RECOMMENDATIONS

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

The 2020 Factory Integration report evolved from the 2017 Report, which succeeded ITRS 2.0 FI chapter [8,9]. The 2020 report has the following highlights:

1. Introduction of Smart Manufacturing (SM) subchapter and restructuring existing sections that are the tenets to the SM as sections under the subchapter
2. Added sections for Advanced Analytics and Applications (AAA), Digital Twin (DT), Industry Internet of Things (IIoT) and the Cloud, Integrated Supply Chain (ISC), and Reliance on a Knowledge Network (KN) that are tenets to the SM
3. An expanded discussion of security, identifying data partitioning and IP security as a key gating factory in moving forward in many of the SM and I4.0 tenants.
4. Continued emphasis on addressing the 5 "Vs" of big data and data management, recognizing that the big data revolution is occurring faster than previously envisioned. Determination that a potential exists for retention of ALL data in archival fashion with respect to particular data stores, and this may be desirable in future scenarios, e.g., to support predictive analytic model development.
5. An expanded discussion of the prediction vision especially with respect to specific capabilities of VM and yield prediction and how they will evolve over time.
6. A presentation of an algorithm analytics roadmap component defining the requirements that shape algorithm choices and explaining the requirement for incorporation of SME into most analytics solutions in microelectronics FI.
7. An identification of the reemergence of 200mm as an important component of the FI ecosystem moving forward.

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

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

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