INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS

2011 EDITION

FACTORY INTEGRATION

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FACTORY INTEGRATION

1 INTRODUCTION

The Factor Integration (FI)[1] chapter of the ITRS focuses on integrating all the factory components needed to produce the required products efficiently in the right volumes on schedule while meeting cost targets. 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 that can fully integrate all other factory components. Preserving the decades-long trend of 30% per year reduction in cost per function also requires capturing all possible cost reduction opportunities.

The success and market growth of semiconductors have been driven largely by continuous improvement to cost per function. Many factors have led to these productivity gains including process technology shrinks, wafer size changes, yield improvements, and manufacturing productivity improvement or waste reduction. The era of non-incremental technology introductions (high-κ gate dielectric, metal gates, Cu/low-κ interconnect, etc.), complex product designs and large-scale transistor integration, and process complexity (such as System on a Chip (SoC) and System in a Package (SiP)) is making the pace of productivity improvements harder to sustain when compared with historical norms. Fab investment costs continue to increase driven both by the cost of technology as well as the desire to build larger factories to get economies of scale.

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

1. *Complex business models with complex factories*—Rapid changes in semiconductor technologies, business requirements, and the need for faster product delivery, high mix, and volatile market conditions are making 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 and software applications to meet complex market objectives and customer requirements. High mix and low-volume product runs are making mask cost, fabrication, and factory integration extremely difficult in a market where average selling prices are declining.
2. *High potential of waste generation and inclusion in factory operations and resources due to the high operation complexity*—Continuously improve factory productivity with more comprehensive visualization of wastes and systematic improvement so as to achieve the growth 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.
4. *Continuing 300 mm factory challenges*—We have addressed several 300 mm challenges but it is still necessary to continue to focus on improving 300 mm efficiency 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.

[1] *Factory integration is the combination of factory operations, production equipment, facilities, material handling, factory information and control systems, and probe/test manufacturing working in a synchronized way to produce complex products profitably for a time-sensitive market.*

5. *Supplier and manufacturer readiness for the next wafer generation* (450mm 450mm Integrated Device Manufacturer (IDM) and Foundry pilots by 2013-14 and volume manufacturing by 2015-16]. These targets, set by manufacturers in 2008 and used by the ITRS in subsequent additions, continue to hold but are aggressive and require R&D investment by both suppliers, manufacturers, and consortia.
6. *Post Bulk CMOS*—the conversion to novel devices will represent key inflection points for semiconductor manufacturing. Novel devices beyond bulk CMOS and their potential impacts to equipment and manufacturing are not well defined, but are expected to be significant.
7. *Significant productivity improvement either by next wafer size manufacturing paradigm or through 300mm manufacturing technology improvement*—the industry needs to review the productivity losses in 300mm and improve prior to the next wafer size transition so to make this transition more consistent.
8. The movement from a reactive to predictive paradigm of operation for waste minimization and productivity and quality improvement.

2 SCOPE

Semiconductor manufacturing extends across several manufacturing domains. Factory Integration's scope is wafer manufacturing or fabrication in FEOL and BEOL as shown in the Figure FAC1.

In order to clearly understand the integrated factory requirements and at the same time define measurable and actionable metrics, the factory integration is divided into five thrusts, or functional areas, that are required to perform semiconductor manufacturing. They are Factory Operations (FO), Production Equipment (PE), Material Handling (MHS), Factory Information & Control Systems (FICS), and, Factory Facilities (Facilities).

Overall, these five thrusts are used to clarify how difficult challenges translate into technology requirements and potential solutions. In addition to these five thrust areas, the Factory Integration chapter also addresses the cross-cut issues and key focus areas that cut across all these five thrusts.

- FO provides many of the key drivers of requirements and actions for the other four thrusts with associated factory business models. FO has most of the original requirements that are deduced required factory service provision viewpoints driven by the business needs.
- PE covers process and metrology equipment and their interfaces to other factory elements. It also focuses on addressing equipment related productivity losses.
- MHS covers transport, storage, identification, tracking, and control of direct and indirect materials. MHS covers requirements for the automated MHS hardware and control systems.
- FICS includes computer hardware and software, manufacturing execution and decision support systems, factory scheduling, control and diagnostics associated with control of equipment and material handling systems, and process control. FICS also covers decision making support systems for the productivity waste visualization and reduction.
- Facilities include the infrastructure of buildings, utilities, and monitoring systems.

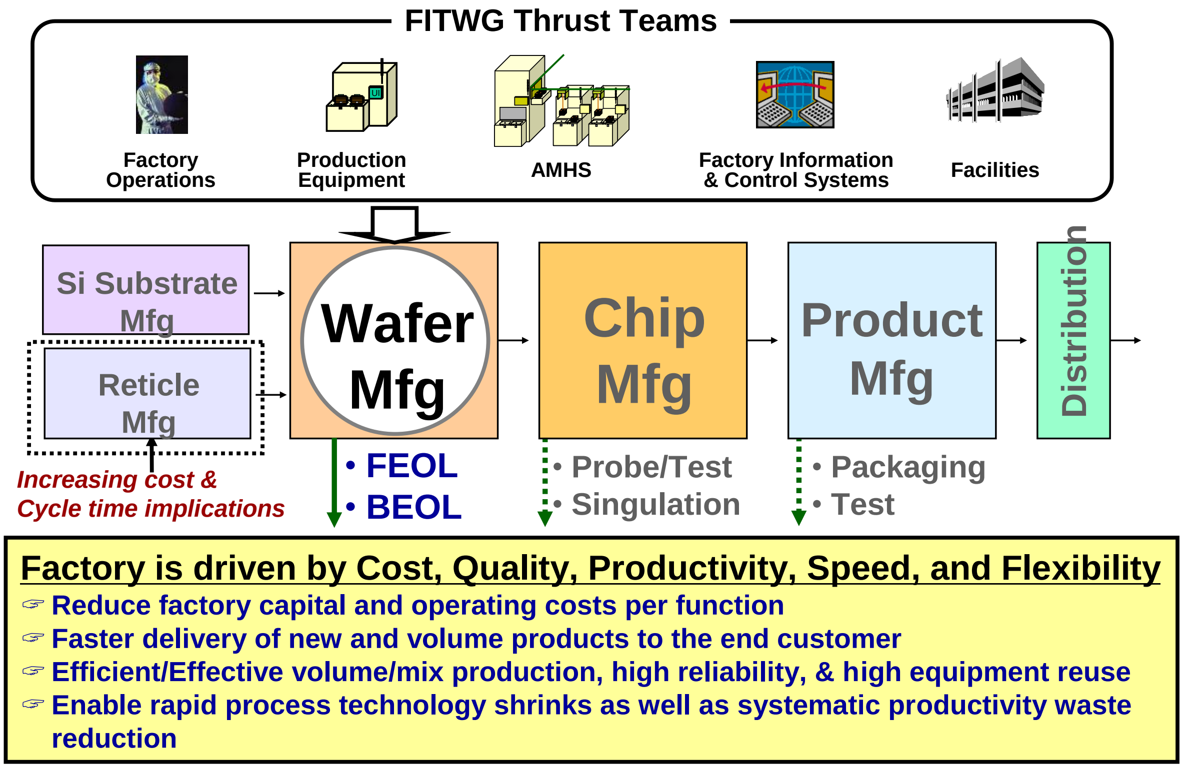

Figure FAC1 Factory Integration Scope

3 DIFFICULT CHALLENGES

Difficult challenges associated with factory integration span multiple technology generations and cut across the five factory thrust areas. Near-term difficult challenges for the factory integration include business, technical, and productivity issues that must be addressed.

Table FAC1 Factory Integration Difficult Challenges

Difficult Challenges through 2019	*Summary Of Issues*
1. Responding to rapidly changing, complex business requirements	• Increased expectations by customers for faster delivery of new and volume products (design → prototype and pilot → volume production) • Rapid and frequent factory plan changes driven by changing business needs • Ability to load the fab within manageable range under changeable market demand, e.g., predicting planning and scheduling in real-time • Enhancement in customer visibility for quality assurance of high reliability products; tie-in of supply chain and customer to FICS operations
2. Managing ever increasing factory complexity	• Quickly and effectively integrating rapid changes in process technologies • Increased requirements for high mix factories. Examples are (1) significantly short life cycle time 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 • Manufacturing knowledge and control information need to be shared as required among factory operation steps and disparate factories • Need to concurrently manage new and legacy FICS software and systems with increasingly high interdependencies • Ability to model factory performance to optimize output and improve cycle time for high mix factories • Need to manage clean room environment for more environment susceptible processes, materials, and, process and metrology tools • Addressing need to minimize energy resource usage and waste; e.g., need to integrate fab management and control with facilities management and control • Comprehending increased purity requirements for process and materials Providing a capability for more rapid adaptation, re-use and reconfiguration of the factory to support capabilities such as rapid new process introduction and ramp-up. This includes a challenge of supporting evolution of a FI communication infrastructure to support emerging capabilities beyond interface A. • Supporting adoption and migration of equipment communication protocol standards to meet ITRS challenges and be in sync with emerging technologies in systems communication and management such as XML and cloud computing. • Meeting equipment design 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 • Addressing AMC challenges through possibly changing factory operation approach (e.g, maintaining vacuum in specific areas), as well as providing necessary interfaces, information and technologies (e.g., virtual metrology and APC). • Maintaining equipment availability and productivity while managing increase in senors and systems within and outside the equipment, coordinated to support new paradigms (e.g., management of energy expended by the equipment and the fab in general, movement from reactive to fully predictive) • Linking yield and throughput prediction into factory operation optimization • Real-time simulation in lock-step with production for operations prediction

3. Achieving growth targets while margins are declining	• Ability to visualize cost and cycle time for systematic waste reduction from all aspects. • Reducing complexity and waste across the supply chain; reducing white space in cycle times • Minimize the cost of new product ramp up against the high cost of mask sets and product piloting
4. Meeting factory and equipment reliability, capability and productivity requirements per the Roadmap	• Increased impacts that single points of failure have on a highly integrated and complex factory • More equipment reliability, capability and productivity visualization that can be used bidirectionally between equipment suppliers and users for more efficient task sharing • Design-in of equipment capability visualization in production equipment; design-in of APC (R2R control, FD , FC and SPC) to meet quality requirements • Equipment supplier roadmap for equipment quality visualization and improvement, and, reduction of Equipment Output Waste. • Reduction of equipment driven NPW (non-product wafers) operations that compete for resources with production wafers and Dandori operations[1] • Meeting wait-time waste factory level management targets; developing wait-time waste reporting for tools; supporting standardized fab-wide equipment state information management. • Moving from reactive to predictive paradigm for scheduling, maintenance and yield management
5. Emerging factory paradigm and next wafer size change	• Addressing issues in movement from lot-based to single-wafer processing and control • Uncertainty about 450 mm conversion timing and ability of 300 mm wafer factories to meet historic 30% cost effectiveness. 450mm era: Effecting architectual and other changes as necessary at an affordable cost to maintain or improve wafer-throughput-to-footprint levels in migration to 450mm
Difficult Challenges Beyond 2019	*Summary of Issues*
1. Meeting the flexibility, extendibility, and scalability needs of a cost-effective, leading-edge factory	• Ability to utilize task sharing opportunities to keep the manufacturing profitable such as manufacturing outsourcing • Enhanced customer visibility for quality assurance of high reliability products including manufacturing outsourcing business models • Scalability implications to meet large 450 mm factory needs • Cost and task sharing scheme on industry standardization activity for industry infrastructure development
2. Managing ever increasing factory complexity	• Higher resolution and more complications in process control due to smaller process windows and tighter process targets in many modules • Complexity of integrating next generation lithography equipment into the factory • More comprehensive traceability of individual wafers to identify problems to specific process areas • 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
3. Increasing global restrictions on environmental issues	• Need to meet regulations in different geographical areas • Need to meet technology restrictions in some countries while still meeting business needs • Comprehending tighter ESH/Code requirements • Lead free and other chemical and materials restrictions • New material introduction
4. Post-conventional CMOS 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

Notes for Table FAC1

[1] Dandori operations: Peripheral equipment related operations that are in parallel or in-line and prior to or following to the main thread PE operations. So-called in-situ chamber cleaning is another good example than NPW operations.

4 TECHNOLOGY REQUIREMENTS

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

Table FAC2 provides a summary of key focus areas and issues for each of the factory integration functional areas beyond 2011.

Table FAC2 Key Focus Areas and Issues for FI Functional Areas Beyond 2011

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) Interdisciplinary factory productivity improvement method such as systematic factory waste visualization of manufacturing cycle times and factory output opportunity losses 3) Extendable and reconfigurable factory service structure
Production Equipment (PE)	1) 450mm production tool development 2) Hierarchical service structure for functional process execution and process control 3) Realization approach to reliable and predictable equipment availability and process performance variability loss reduction by EEQA (enhanced equipment quality assurance) and subsequent systematic and comprehensive equipment health monitoring endorsed by bidirectional equipment functional visibility 3) Run rate (throughput) improvement and reduction of equipment output waste that comes from NPW and other Dandori operations
Automated Material Handling Systems (AMHS)	1) Reduction in average delivery times, 2) More interactive control with FICS and PE for accurate scheduled delivery, 3) Less wait time waste realization by such as near-tool buffering
Factory Information and Control Systems (FICS)	1) Increased reliability, 2) Increased FICS performance for more complex factory control 3) Enhanced system extendibility
Facilities	1) Enhanced extendibility 2) AMC management, electric static control on masks, wafers, and, facility surfaces 3) Facility cost reduction 4) 450mm unknown requirements

5 FACTORY OPERATIONS

5.1 FO Challenges

5.1.1 SYSTEMATIC FAB PRODUCTIVITY IMPROVEMENT

One of the most important FI's missions is to assist fab productivity improvement effort by providing productivity information to those who are responsible at each of the hierarchical operation responsibility layers and providing means to evaluate the improvement before and after its implementation. There should be methodologies to identify the room for improvement as Continuous Improvement Program (CIP) and the strategic improvement planning. For these methodologies to be effective the factory activity information is to be designed to have rationalized structures to facilitate high data utilization for decision makings. It is also imperative to define commonly usable productivity metrics so that the productivity improvement activities can cooperate among many. The FI ITWG has concluded that such metrics are expressed as productivity waste. Factory Integration 2011 adopts Waste Reduction as one of the focus area topics. Readers are to refer to the Focus Areas section for more detail.

5.1.2 AGILITY AND FLEXIBILITY IN FACTORY SERVICES

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

5.1.3 HIGH GRANULARITY AND PROACTIVE SERVICES

Finer material handling operation is required due to strong demand on cycle time reduction. More real-time control of production equipment (PE) is required to meet elaborated process control such as wafer-to-wafer and within wafer APC. Frequent confirmation of production equipment healthiness 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.

5.1.4 HIERARCHICAL OPERATION STRUCTURE

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. Such structure of FO needs to be designed so to enable the comprehensive optimization of FO for the required productivity. A good example is the *hierarchical quality assurance* in which the wafer fabrication execution control and process outcome control are hierarchically delineated with aid of increased visibility of the individual hierarchical layers. The challenge is appropriate design of the services and their interfaces, and appropriate enhanced bidirectional visibility across the services and business boundaries.

5.2 What is New with the 2011 Edition

5.2.1 FOCUS ON PREDICTION

A major addition to the 2011 edition is an emphasis on the movement from a reactive to predictive mode of operations. Solutions such as predictive maintenance, predictive scheduling and planning, virtual metrology and yield prediction are all part of this paradigm shift. It is expected that all of these technologies will begin to play a significant role in productivity improvement and waste reduction over the next seven years, with the roadmap indicating a migration towards an integrated predictive extension of all systems.

5.2.2 Advanced Process Control as an Equipment and Fab Design Requirement

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

5.2.3 Integration of Facilities Requirements into Factory Operations

The increasing pressure of achieving environment goals will require that factory and facilities operations be coordinated. This will require increased attention to facility objectives in factory objective functions.

5.2.4 Significant Productivity Improvement

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

This waste reduction is to meet 30% 300mm wafer cost reduction and 50% cycle time reduction to keep up with Moore's Law trend. The implementation of such significant improvement will be somewhat delayed to 2014 from 2012 due to the current economic situation.

The introduction of waste reduction thread into the roadmap as a future manufacturing requirement is the most important topic of 2011 edition. Readers are to refer to Focus Areas section for additional detail.

5.2.5 Future Manufacturing Requirements

Large scale productivity improvement scheme has been sought for at least for four years in the industry. It is known as 300mm Prime technology. The FI ITWG also comprehended the 300mm Prime requirement input investigated by other partners; JEITA 300mm Prime Guidelines[2] in which the requirements were deduced from factory operation services provision viewpoint and ISMI's 19 Points Detractor List.

A future manufacturing requirement is significant productivity improvement scheme by means of systematic waste reduction activity based on an infrastructure that enables hierarchical FO service provision with aid of enhanced mutual operation visibility.

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

Waste reduction is believed to be able to drive comprehensive productivity optimization together with localized optimization of individual technology areas. These waste metrics are to be measurable and potent to provide useful information to increase factory-level productivity.

5.2.6 Waste Reduction Metrics

The 2011 FI ITWG decided to introduce two waste reduction metrics; Wait Time Waste (WTW) and Equipment Output Waste (EOW), into the FO TR Table with intent of aligning the significant productivity improvement scheme to be implemented by 2014. It is beyond FI ITWG's task to capture all of the waste types existing in the fab into the roadmap. It is important to introduce the more comprehensive waste metrics for ITRS FI so as to address the direction of overall productivity optimization of highly complicated manufacturing system. These need to be

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[2] *http://www.jeita-smtj.com/pdf/300P_GLv2.pdf*

comprehensive and measurable factory-level waste metrics. This addressing will further promote newer manufacturing concept, manufacturing control models and algorithms.

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

5.2.7 CYCLE TIME METRICS

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

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

5.2.8 WASTE METRICS FOR CYCLE TIME

Factory WTW is defined as a total sum of wait time for a wafer to go through the manufacturing process divided by number of the masks. Since the factory cycle time for Super Hot Lots (SHLs) can represent the least WTW for a fab the equation can be rewritten using cycle time values in the FO TR Table as the difference between the factory cycle time of production lots (of 25 wafers) and the super hot lot cycle time. Readers are to refer to the explanation text in the FO TR Table. It is noteworthy that WTW can be measured or calculated from daily fab operation.

5.2.9 WASTE METRICS FOR EQUIPMENT OUTPUT WASTE

EOW is defined as normalized difference between instantaneous throughput and averaged throughput over a period of time that contains a normal production equipment usage cycle in which, for an example, maintenance procedure (i.e., 1 week to 1 month period) is included. The instantaneous throughput is what is observed during continuous runs without any process changes. Factory EOW is defined as a total EOW sum over all the production tools used for that product divided by the # of total tools [%]. The FI ITWG conducted a preliminary survey on limited production tools. Factory EOW may be refined as more factory EOW data become available.

5.2.10 DATA USAGES AND BIDIRECTIONAL VISUALIZATION

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

The 2011 FO TR Table has introduced a new requirement "Equipment bidirectional visibility." The history of equipment data usage through SECS protocol has been such that device makers (equipment users) are the primary user and the equipment data was designed to monitor process parameters. Furthermore the equipment data usage was believed to be device maker proprietary information in the premature stage of FDC and APC, and this tradition is still impeding the data usage by the equipment suppliers.

Enhanced Equipment Quality Assurance (EEQA)[3] is a scheme in which equipment suppliers validate and adjust equipment performances using the equipment data for quality assurance enhancement and that equipment performance validation procedure will be succeeded by the equipment user using the same data set during

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[3] *"Requirement on Enhanced Equipment Quality Assurance upon Equipment Installation" http://www.jeita-smtj.com/pdf/Request%20on%20EEQA%20English%20Translation%20V1.0.pdf*

production. The equipment data design for bidirectional visualization should include the information relevant to waste reduction. Dandori operations (Peripheral equipment operations other than product processing such as process condition change preparation operation) are to be visualized for more opportunity of waste reduction. ITRS Factory Integration addresses this bidirectional equipment visualization since the equipment data design is still in premature stage.

5.2.11 450MM RELATED METRICS

450mm specific requirement has been discussed in order to seek any FO TR Table items. Although the factory services requirements specific to 450mm manufacturing have not been identified in the 2011 edition, 300mm factory services are expected to be applicable to 450mm and so do the FO requirements captured. There are apparent different requirements in 450mm for the FO. The distinct example is cycle time requirement. The longer factory cycle time requirements are expected since the beam production equipment such as litho exposure tools and inspection tools inevitably have a longer cycle times compared to the similar 300mm tools (since the process time is proportional to the area of treatment (beamscan).

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

5.2.12 SINGLE WAFER MANUFACTURING SYSTEM

The FI ITWG decided to specify a year for onset of single wafer manufacturing. Investigation of the implication of this extreme manufacturing method helped, and will continue to help the ITWG induce roadmap consensus.

Single wafer manufacturing method intends to reduce all the waste due to lot based manufacturing control such as long waiting time waste and high equipment output opportunity losses.

Single wafer manufacturing system needs highly elaborated technologies in production equipment, its physical interface, equipment control factory system, and AMHS control. MHS control is a good example; it calls for precise process execution scheduling of individual wafers. Individual wafers are scheduled for its delivery timing to the tools with least WTW and EOW. The dispatch and process execution schedules are to be re-scheduled immediately if there are any unexpected tool downs. Predictive maintenance and predictive scheduling will become important to maximizing throughput. Wafer-based run-to-run is already now available and not only related to single wafer manufacturing. Some level of time synchronization may be required to facilitate wafer-level run-to-run control.

5.3 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 Dandori operations or 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, and resource scheduling policies are required to reduce WIP, improve on-time-delivery, and improve capacity utilization.

Table FAC3 Factory Operations Technology Requirements

Explanation of Items for Factory Operations Requirements

Item	*Explanation*
Wafer diameter	All the values are for 300mm wafer. Values beyond 2014 will be amended as more 450mm requirements become available. Factory cycle time, for an example, is thought to become considerably longer than 300mm due to longer process time of beam equipment (litho, ion implantation, inspection, etc.) for 450mm
Factory cycle time per mask layer (days) 25 wafer lot Factory cycle time per mask layer (days) 12 wafer lot	A key metric of time to money and measure of total time to process is a lot cycle time per mask layer. For example, if a process has 30 masking layers, and cycle time per mask layer is 1.5, then total factory (fabrication) cycle time based on 25 wafers per lot is: 30 × 1.5 = 45 days. Cycle time for a 12 wafer lot would be calculated accordingly.
Super hot-lot (average top 1% of lots) factory cycle time per mask layer	Assume ~ 5 wafers per lot. Factories typically prioritize these lots over any other lots, tools downstream are reserved for the super hot lot. As a result, the cycle time for super hot lots is considered as the fastest speed of that fab line and for that product.
Wait Time Waste (days): 25 wafers in a carrier	Factory Wait Time Waste can be expressed as follows; WTW (average) = Σ (wait time)/ N [day/mask layer], Where N: # of total masks. Since the factory cycle time for SHL can represent the least Wait Time Waste cycle time, the equation can be rewritten with using cycle time values in FO TR Table as the difference between the factory cycle time of production lots (of 25 wafers) and the super hot lot cycle time. $= \Sigma (CT_{25}-CT_{SHL})$ [days/mask layer] where; CT : Cycle Time for production lots [days/mask layer] CT_{SHL} : Cycle Time for super hot lots/mask [days/mask layer] The subtraction needs to be compensated with the number of wafers between production lots and super hot lots. Waite Time Waste indicator is adapted for more direct visualization of waste or room to improvement in terms of factory cycle time.
Wait Time Waste (days): 12 wafers in a carrier	Waite Time Waste for 12 wafer lot would be calculated accordingly as description above.
X factor	X-factor is the total cycle time (queue time + hold time + raw process time + travel time) divided by the Raw Process Time (RPT). Raw process time for a lot at a tool is the time it takes to process a lot on the tool. Generally this time will be from when the tool starts to process the lot (and thus cannot be moved to another tool for processing) until the lot is finished and can be moved to the next operation. X-factor is shown for continuous improvement. Actual X-Factor values will depend heavily on WIP and raw process time for a given process technology or generation. X factor deteriorates if raw process time is shorten. X factor improves with lower WIP.
Equipment Output waste (%): 25 wafers in a carrier, high mix production	Equipment Output Waste is defined as normalized difference between instantaneous throughput and throughput averaged over a period that contains a usual production equipment usage cycle that includes maintenance procedure (such as 1 week to 1 month period). The instantaneous throughput (TH_0) is such that observed during continuous runs of wafers without process changes before and after. EOW for a single equipment can be defined as; $EOW = (TH_{25}-TH_0)/TH_0 \times 100$ [%] Where TH_{25} is averaged throughput in a 25 wafers per a carrier manufacturing environment. Factory EOW is defined as a total sum over all the production tools used for that product divided by N the # of total tools [%]. Factory $EOW = \Sigma((TH_{25}-TH_0)/ TH_0) / N \times 100$ [%] FI ITWG conducted a preliminary survey on limited production tools. Factory EOW may be refined as more EOW data become available. The values are for 25 wafers in a carrier, high mix production.
High mix operation	High mix is defined as the followings: • Running more than three technology generations concurrently in the same Fab • Running more than ten process flows within the same technology generation • Running more than 50 products concurrently through the Fab • Many of small lots of 1–10 wafers in size • Running an average of less than 50 wafers between reticle changes for each lithography expose equipment • Lot starts are based on customer orders. There is a daily variation in the number of lots you start with different products and process flows • At least five large volume products (product flows) with no one product having >50% of production volume
Bottle neck equipment utilization and availability	A bottleneck tool usually refers to a lithography tool. Availability is defined in SEMI E10 as “the probability that the equipment will be in a condition to perform its intended function when required.”

	Utilization is defined in SEMI E10 as "the percentage of time the equipment is performing its intended function during a specified time period." Availability includes setup, idle and processing time, utilization is considered as time directly adding value of constraint equipment (usually lithography tools) measured in % without sacrificing cycle time. Constraint equipment utilization (normally lithography) is the pulse of the Fab and usually determines the output capacity.
Average delivery time (minutes)	The time begins at the request for carrier movement from the factory system and ends when the carrier arrives at the load port of the receiving equipment.
Overall NPW activities versus production wafers activities	Total equipment-driven non-production wafers processed on equipment divided by total production wafers processed on equipment, for the same time period, assuming that equipment is running at designed availability and planned utilization rates. Typical non-production wafers include test wafers, monitor wafers, calibration wafers. The requirement as shown is for all production (non-metrology) equipment.
Bidirectional equipment functional visualization	Equipment functional performance should be bi-directionally visible to validate equipment capability performance at the time of equipment delivery to both the equipment supplier and the user, and it should be visible to the user during that equipment is being used for production. Bidirectional visibility ensures equipment performance quality traceability and efficient technical information exchange between relevant equipment users and suppliers. Such bi-directionality is assured by standardized equipment data models and quality. Partial implementation means such as the equipment data available through SECS where equipment capability behaviors are usually not intended to be visualized. So-called second equipment data port is expected to provide such visibility.
Single wafer manufacturing system	Wafer manufacturing system that utilizes carriers with extremely small wafer capacities, or, in some cases, handles individual wafers is thought to be an enabler for the least WIP manufacturing method. 2009 Factory Integration roadmap captures such manufacturing method to become feasible due to the strong demand on very short product cycle time for 2009 implementation. The factory cycle time is expected to be reduced significantly although more future study is needed to represent appropriate cycle time requirements that meet the cost criteria.

6 PRODUCTION EQUIPMENT

6.1 Scope

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

6.2 BIDIRECTIONAL DATA VISUALIZATION (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 visualization 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 an equipment; this validation will be performed by an equipment supplier prior to delivery with respect to equipment functionality.

Tool data visualization must address the following important use case. To achieve good device yields, the process tools used to create the device must be in statistical control. That is key process settings must be in control during a run as deviations will impact the final product yield. To help IDMs accomplish this parameter control, tool manufacturers should provide a reference set of parameters and values for a properly operating tool. The tool manufacturers can then test that tools perform to these values prior to shipment, and IDMs can then check basic tool health by monitoring these parameters over time. If there is a performance discrepancy, the IDM and tool manufacturer can use the reference parameter values compared to target values as a starting point for problem diagnosis This equipment functional validation process shared between the tool manufacturer and the IDM is sometimes referred to as EEQA[4], and a representation of the state of equipment or equipment component at a particular point or range in time is often called and equipment fingerprint.

6.3 Waste Reduction

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

The industry’s growth rate will not be sustainable in the future if increasing capitalization cost trends continue without significant improvement in productivity. The PE TR Table is also responsible to the intended significant productivity improvement preceding 450mm insertion. Although the FO TR Table owns the EOW requirement EOW metrics may be broken down to EOW for the PE section to address waste reduction in 2011 and after. The waste due to Dandori operations and the frequent recipe changes can be the killer of EOW especially in high product mix operations. The information of Dandori operations needs to be made visible. These include time counter and/or consumption counter information need to be made available per bidirectional visualization.

6.4 Productivity Requirements

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

The process control in the equipment is controlled by event driven method. 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

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[4] *EEQA: EEQA (Enhanced Equipment Quality Assurance) addresses the effort to validate equipment functionality performance. For example, process gas pressure generation capability is to be validated to be in accordance with the setting values and stable as designed. EEQA calls for visibility of equipment capability performance via data made available routinely so that EEQA can be performed when the tool is tuned and validated at OEM, during ramp up period, and also during production. EEQA is sometimes called fingerprinting if performed during manufacturing at device maker. EEQA/fingerprinting is to be differentiated from process health monitoring since the monitoring content is different.*

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 happenings. .

Sustaining productivity improvements will necessitate the tighter coupling of software capabilities, such as APC, maintenance, and scheduling/dispatch, with the PE. As such, some of these capabilities, such as APC, may be designed into the equipment (e.g., to facilitate more elaborate and fast or adaptive control implementation), or the equipment may be designed to require functionality with external APC systems. Further, PE will be required to produce the necessary data in a timely fashion and accept the appropriate actuation to enable the tight coupling with these software systems. These requirements will be become even stronger as the industry moves towards a predictive (rather than reactive) mode of operation. Such predictive and self-running PE are the prerequisites for the single wafer manufacturing system that will take place in 2019 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 FAC4 Context Data Importance for Good Equipment Visibility

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

6.5 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 Dandori operations. More discussion is required to understand the requirement of such control and implementation methodology.

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

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

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

6.6 Energy Savings and Factory Environment

More energy-efficient equipment designs 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 area of opportunity for reducing utilities consumption is the concept of a ”smart idle” or “sleep mode” operational model for equipment.

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

Table FAC5 Production Equipment Technology Requirements

Explanation of Items for Production Equipment Requirements

Item	Explanation
Process equipment availability (A80)	Availability is defined as 100% minus (scheduled downtime% + unscheduled downtime %). The metric in the table is the requirement for an 80% confidence (i.e., equipment is at or above this value 80% of the time) for each individual process (non-metrology) equipment, over a period of one week of 7 × 24 operations. Scheduled and unscheduled downtimes are defined in SEMI E10. Note: The value shown in the process equipment table is the minimum A80 value for all equipment - please refer to the Factory Operations requirements table for availability requirements specific to factory bottleneck equipment.
Metrology availability (A80)	Availability is defined as 100% minus (scheduled downtime% + unscheduled downtime%). The metric in the table is the requirement for an 80% confidence (i.e., equipment is at or above this value 80% of the time) for each individual metrology equipment, over a period of one week of 7 × 24 operations. Scheduled and unscheduled downtimes are defined in SEMI E10
Maximum allowed electrostatic field on wafer and mask surfaces (V/m) for ESD (Electric static discharge) prevention	Refer SEMI standards E78 and E43 for measurement methods. This guidance does not apply to EFM prevention. (SEMI E78: Electrostatic Compatibility – Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment. SEMI E43: Guide for Measuring Static Charge on Objects and Surfaces.)
Maximum recommended electrostatic field at chrome mask surfaces (V/m) for EFM	Field induced migration of chrome degrades reticle CD and the damage is cumulative, being dependent on the duration of field exposure as well as field intensity. 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. Reduction of field levels to this extent may require adoption of special handling methods referred to as "EES Compatible" (see SEMI Standard Guide for Handling of Extremely Electrostatic Sensitive Items, draft document 4783, in preparation) NB: Permanently reducing the humidity of a reticle is believed to reduce the rate of reticle degradation by EFM and also other continuously operating mechanisms (i.e. 193nm haze formation and the "Sun Effect").
Pervasiveness of predictive technologies such as virtual metrology PdM, PHM, yield prediction and predictive scheduling in certain equipment components (e.g., vacuum, abatement, gas supply systems) feeding into overall equipment predictive solution, to support improvements such as reduction in unscheduled downtime and improved yield.	Pervasiveness is defined as a percentage of tools and tool components that will benefit from the application that have been outfitted with all of these technologies or are providing data to support all of these technologies. Minimal is defined as less than 25%. Partial is defined as 25-75% and All is defined as greater than 75%.
Pervasiveness of Prognostics Health Management (PHM)	Pervasiveness is defined as a percentage of tools that will benefit from the application that have been outfitted with this technology or are providing data to support this technology Minimal is defined as less than 25%. Partial is defined as 25-75% and All is defined as greater than 75%.
PdM: requirement for tool data and control support for PdM, both in-tool and in conjunction with external systems	Pervasiveness is defined as a percentage of tools that will benefit from the application that have been outfitted with this technology or are providing data to support this technology Minimal is defined as less than 25%. Partial is defined as 25-75% and All is defined as greater than 75%.

7 Material Handling Systems

7.1 Overall

Ergonomic and safety issues coupled with the need for efficient and rapid material transport are the major drivers in defining material handling systems for the 300 mm wafer generation and beyond. Automated Material Handling Systems (AMHS) must have acceptable Return on Investment (ROI) and must interface directly with all inline (i.e., used in normal process flow) production and metrology equipment. Throughput must be increased substantially and achieved with reduced delivery time. Furthermore, the material handling system needs to be designed so that it can accommodate the extendibility, flexibility, and scalability demands on the factory.

The technology requirements table is based on the premise that as demands on the material handling system continues to increase that drives toward combining interbay and intrabay transport functions into one integrated service, or direct transportation. This does not imply overall one system or even one system from one supplier. The system 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 and 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 to reduce WTW and EOW. 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 are on a tool are finished.

The potential impact of high mix operations and smaller lot sizes must be investigated, and the tradeoff between lot size and MPH increase 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.

7.2 450mm

Investigation and evaluation of the 450 mm physical interface and carriers (PIC) have been underway. 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.

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

Table FAC6 Material Handling Systems Technology Requirements

Explanation of Items for Material Handling Systems Requirements

Item	*Explanation*
Transport E-MTTR (min per SEMI E10)	Mean time to repair equipment-related failures (AMHS Transport); the average time to correct an equipment-related failure and return the equipment to a condition where it can perform its intended function; the sum of all equipment-related failure time (elapsed time, not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not maintenance delay downtime), divided by the number of equipment-related failures during that period. Notes: Refers to unscheduled, supplier dependent failures. Includes interbay and intrabay transport systems. Offline repair of components is not included in this time. Includes embedded software control systems (transport controllers). Does not include storage AMHS equipment or errors induced by the storage equipment. Does not include load port, FOUP carrier, or MES level software issues. Does not include reticle system.
Storage E-MTTR (min per SEMI E10)	Mean time to repair equipment-related failures (AMHS Storage); the average time to correct an equipment-related failure and return the equipment to a condition where it can perform its intended function; the sum of all equipment-related failure time (elapsed time, not necessarily total man hours) incurred during a specified time period (including equipment and process test time, but not maintenance delay downtime), divided by the number of equipment-related failures during that period. Notes: Refers to unscheduled, supplier dependent failures. Includes storage equipment load ports and embedded software. Does not include interbay or intrabay transport or incidents induced by these errors. Does not include FOUP carrier or MES level software issues. Does not include reticle system.
Transport MMBF (mean moves between failure)	Average number cycles (delivery from point A to point B) made by AMHS interbay or intrabay transport equipment before a person has to intervene to fix a failure. Number of transport moves / Number of supplier dependent unscheduled failures. Reference transport MPH definition for details on move.

Item	*Explanation*
Storage MCBF (mean cycles between failure)	Average number cycles (delivery from point A to point B) made by AMHS storage equipment before a person has to intervene to fix a failure. Number of storage cycles / Number of supplier dependent unscheduled failures per quarter. Reference cycle time definition for details on stocker cycle.
Stocker cycle time (seconds) (100 bin capacity)	Stocker cycle time is defined as the time (in seconds) from when the Host(MCS) issues the move command to the time the stocker signals completion with the move complete command to the host. The physical motion is the stocker internal robot moving to a carrier at a port or storage bin, picking up the carrier, and delivering it to another port or storage bin within the same stocker. Stocker cycle time shall be determined as the average of several different types of moves over a period of time. The moves should include all ports and all shelf locations. Each move needs to alternate between different carriers. The maximum MCS communication time is assumed to be 1 second.
Peak delivery time (minutes)	Peak delivery time is considered the peak performance capability defined as the average delivery time plus two standard deviations.
Downtime to extend system capacity when previously planned (minutes)	Impact to material handling system in terms of downtime, in minutes, of the material handling system, required for making connections to system track extensions or a new storage when previsions for this expansion were incorporated in the original design.
Time required to integrate process tools to AMHS (minutes per LP)	The downtime to the transport system when a process tool is integrated to the AMHS. Addition of tool occurs on a track with existing vehicle traffic (no bypass units around tools). Assume tool is placed correctly and physical tool move in does not impact the AMHS. System not stopped for PIO install (tool side). Time includes: hardware install on track, teaching LP, software updates, and delivery testing. Scope ends when all vehicles have capability to deliver to new LP.

8 FACTORY INFORMATION AND CONTROL SYSTEMS

8.1 Scope

The scope of Factory Information and Control Systems (FICS) includes computer hardware and software, manufacturing execution, decision support systems, factory scheduling, control of equipment and material handling systems, and process control. FICS serves as an essential infrastructure and technology enabler to a number of critical functional areas addressed by the ITRS; including Yield, Factory Operations, Production Equipment, and Material Handling control and management.

8.2 Improve Factory Effectiveness

Factories must be able to adjust schedules and dispatching schemes rapidly to quickly respond to unexpected equipment downs or product scrap to maximize productivity and maintain target production rates and production times of high priority (hot) lots as well as the production lots. This calls for optimization and prediction models that include predicting impacts of operational or configuration changes to other FICS applications. The objective is to make the best choice of what to process looking beyond the boundaries of a single tool or cluster tool. With a global view of factory activity the scheduling component can make decisions beyond a small area in the factory. The effect will be greater factory utilization, higher throughput, and reduced cycle time variability. Integration of FICS applications with business-level software systems provides accurate factory floor data for supply management, and improved product tracking. Potential solutions will require the standardization of technologies (e.g., SOAP[5] / XML[6] and web services)) that enable this level of integration.

8.3 Improve Factory Yield and Minimize Waste

Yield improvement and waste minimization will rely heavily on FICS solutions. Process Control Systems (PCS) which utilize Advanced Process Control (APC) technologies including Run-to-run (R2R) control, Fault Detection (FD), Fault Classification (FC), Fault Prediction (FP) and Statistical Process Control (SPC) will become more

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

[6] *XML: Extensible Markup Language*

pervasive and an integral part of FICS solutions. 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 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, and the automated material handling system (AMHS). This level of system integration is required to ensure delivery of the right material, lot, and wafers at the right time at the right locations maximizing equipment utilization and will be enabled by event-driven, reconfigurable supervisory control capabilities at the heart of the FICS, common data warehouse and data models, adoption of Interface 'B' and associated standards for application integration, proliferation of networks for control diagnostics and safety signals across the fab.

8.4 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.

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

8.5 Highly Reliable, High Performance Systems

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

Cyber security continues to remain a high priority from the factory operations perspective. Cyber security guidelines were first published by ISMI in March 2005 documenting available methods for cyber security. With cyber security posing less of a threat to semiconductor manufacturing, the focus is turning to protecting intellectual property (IP) within the equipment. Semiconductor equipment is now well integrated into the FICS infrastructure with engineers and technicians. Ensuring IP protection is critical to overall financial success in an environment where there is a significant amount of operations-level overlap.

Table FAC7 Factory Information and Control Systems Technology Requirements

Explanation of Items for Factory Information and Control Systems Requirements

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

9 FACILITIES

9.1 Scope and facility mission

Facilities include the overall physical buildings, cleanroom and facility infrastructure systems, up to and surrounding the production equipment directly associated with semiconductor manufacturing operations (does not include adjacent general office spaces and corporate functional areas). Requirements due to production equipment, manufacturing goals, management philosophies, environmental, safety, and health (ESH) goals, building codes and standards, defect-reduction and wafer cost reduction targets will affect the facility and supporting facility infrastructure systems with respect to their complexity and costs.

The industry continues to demand facilities that are increasingly flexible, environmentally benign, extendable and reliable, that come on-line more quickly, and are more cost-effective. However, production equipment requirements, ESH compliance and factory operational flexibility continue to drive increased facility capital and operating costs. Production and support equipment are becoming more complex, larger, and heavier, thereby driving the need for a continuous increase in factory size and tool packing density. New and different process steps are increasing the growth of the cleanroom's size faster than the increases in factory production output. A focus on environmental issues such as carbon footprint reduction place 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 production equipment operation, maintenance, environmental requirements, facility infrastructure system design, installed utility capacities, and facility spaces/volumes are necessary to achieve these goals, improve system and space utilization, and control facility capital and operating costs.

Facility complexity and costs are also rising due to impacts from many other areas including the greater variety of gases/chemicals, more stringent ESH regulations, more stringent electrostatic discharge (ESD) and electromagnetic interference (EMI) controls, and acoustic controls. 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.

Despite the continuous increase of process shrinkage and complexity in process technology according to Moore's Law, the drive towards the reduction in manufacturing cost will result in the introduction of larger wafer sizes, such as the pending use of 450mm wafers. Such a change will also have implications on the design and construction of a wafer manufacturing facility due to increases in overall size, height, and weight of process equipment, their utility consumption, and other process- driven facility requirements such as AMC, EMI, ESD and acoustic controls. With more PE support equipment being placed in the subfab, a utility subfab may be required to house the additional equipment. For example, the addition of local purification systems at the support equipment will require more subfab area. These challenges will continue to drive the need for further facility technology development in such areas as structural design, AMHS facility integration, chemical delivery facility integration, Ultra-pure Water (UPW) delivery, energy efficiency, Airborne Molecular Contamination (AMC) control, and EMI/ESD controls to name a few. Such considerations must also be evaluated in the case of a planned conversion of an existing wafer manufacturing facility to the next wafer size.

9.2 Yield considerations

The rise of Airborne Molecular Contamination (AMC: see SEMI Std F21 for definition) will require revisiting contamination control procedures with new methods and materials, which can also affect the facility components selected and even the building materials used during construction. Facility operations will also require coordination with production equipment vendors to ensure proper AMC control.

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

9.3 Resource Conservation Considerations

The need to reduce resource consumption is an area of that requires greater attention. This will necessitate the need of 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. This would have a ripple effect on the exhaust and the make-up air systems, which would lead to reduction in power consumption. Process equipment idle modes can also reduce energy consumption during non-processing times. Heat recovery systems can reuse heat otherwise dissipated to the atmosphere. Utilizing 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 that require 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 be more explicitly defined.

9.4 Industry collaboration for facilities

In order to meet the demand to reduce time from groundbreaking to first full loop wafer out while fabrication process and the production equipment increase complexity, factory operations seek more flexibility, and global codes, standards, and regulations increase in variability, a paradigm shift in the way facilities are designed and constructed will be required. 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, EHS 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 for a minimum of three (3) generations. 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:

- 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 far 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, relaxing cleanroom cleanliness requirements through the use of mini-environments and isolation technologies (such as FOUPs), and implementing operational visualization through real time monitoring and control of utility utilization.

However, care must be exercised that facility and production equipment operational requirements are not compromised. For example, reductions in cleanroom airborne particle cleanliness and the associated airflow may cause temperature, humidity, cleanliness and production equipment maintenance concerns. As an example, as the general fab cleanliness is relaxed to ISO Class 7, production equipment maintenance needs should be built into the equipment utilizing solutions such as portable vertical flow hoods. Another consideration before the recirculating air volume in the fab can be reduced is the heat dissipation from the cleanroom. Currently, heat removal is the major driver for the recirculating air flow volume and thereby the energy consumption of the cleanroom. The challenge for process equipment designers is not only to reduce overall power consumption/heat dissipation, but also to maximize the proportion of heat transferred to the process cooling water system.

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.

9.5 450mm Considerations

Any significant change in the production equipment, both for post-CMOS or for the next generation wafer size, such as new chemistries, the wafer environment or handling requirements (nitrogen or vacuum atmospheres, single wafer processing etc.), will have an impact on future factory requirements.

Table FAC8 Facilities Technology Requirements

Explanation of Items for Facilities requirements:

Item	*Explanation*
Manufacturing (cleanroom) area (m^2)	Manufacturing (cleanroom) area is defined as the gross space in square meters containing the process and metrology equipment used for direct manufacturing processes such as photolithograph, diffusion, etch, thin films, CMP, excluding subfab spaces containing support equipment and facility infrastructure systems. Special back-end process areas such as C4 technology are excluded from this value. Foreseeable technologies that will impact cleanroom size are factors such as additional metal layers, single wafer processing and double exposure for litho.
Wafer starts per month (WSPM)	Wafer starts per month is defined as the number of new 300 mm wafers introduced into production for processing during a given 30 day period.
# of mask layers (low mix only)	This refers to number of mask layers of DRAM.
Sub-Fab to Fab ratio	Sub-Fab to Fab ratio is defined as the footprint of the production equipment support plan area to the manufacturing area above. The 25% reduction in floor space allows for columns and safety equipment in the subfab that is required by the facility. Relates to and extends factory operations "floor space effectiveness."
Facility service life (in three-year nodes)	Facility service (system) life is the number of nodes (process changes) that the system is available before major renovation is required to meet process requirements.
Facility cleanliness class (ISO 14644)	Cleanliness classification of wafer factory manufacturing (cleanroom) area as defined by ISO 14644-1[7].
Facility critical vibration areas (litho, metro, other) (micrometers per second)	“Vibration critical” is defined as area of the primary manufacturing floor in which a significant portion of the equipment is highly sensitive to floor vibration, the mitigation was not provided at the tool itself, and excessive vibrations can have serious deleterious effects on product. Extensive measures may be required in the facility’s structural and mechanical equipment design based upon the needs of this space category. Vibration criteria are limits on vibration amplitudes at the floor or other support of a tool, given as VC-x, where x is a letter designation from A through E, each corresponding to a specific vibration amplitude spectrum. Refer to IEST-RP-CC0012.2[8]
Facility non-critical vibration areas (micrometers per second)	“Vibration non-critical” is defined as area of the primary manufacturing floor in which all or some of the equipment is only moderately vibration sensitive, and the structural system performance can be reduced. Vibration criteria are limits on vibration amplitudes at the floor

[7] *ISO 14644-1.: Cleanrooms and controlled environments, Part 1: Classification of air cleanliness*

[8] *IEST-RP-CC012.2: Considerations in Cleanroom Design.*

	or other support of a tool, given as VC-x, where x is a letter designation from A through E, each corresponding to a specific vibration amplitude spectrum. Refer to IEST-RP-CC0012.2.
Maximum allowable electrostatic field on facility surfaces (V/m) for ESD prevention.	Facility surface electric field limits apply to all factory materials-construction materials, furniture, people, equipment, and carriers Refer to SEMI standards E129[9], E78,[10] and E43[11] for measurement methods. This guidance may not apply to EFM prevention. See Crosscut Issues section.
Ratio of tool idle versus processing energy consumption (kW/kW)	Ratio of energy consumption of process tool and support equipment when not processing wafers over energy consumption while tool is processing wafers per SEMI S23 application guide.

10 POTENTIAL SOLUTIONS

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

Potential solutions are shown as "*Research required*," "*Development underway*," and "*Qualification/pre-production*." The purpose is to provide guidance to researchers, suppliers, and IC makers on the timing required to successfully implementing solutions into factories.

Research Required

Development Underway

Qualification/Pre-Production

Continous Improvement

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[9] *SEMI E129: Guide to Assess and Control Electrostatic Charge in A Semiconductor Manufacturing Facility.*

[10] *SEMI E78: Electrostatic Compatibility – Guide to Assess and Control Electrostatic Discharge (ESD) and Electrostatic Attraction (ESA) for Equipment.*

[11] *SEMI E43: Guide for Measuring Static Charge on Objects and Surfaces.*

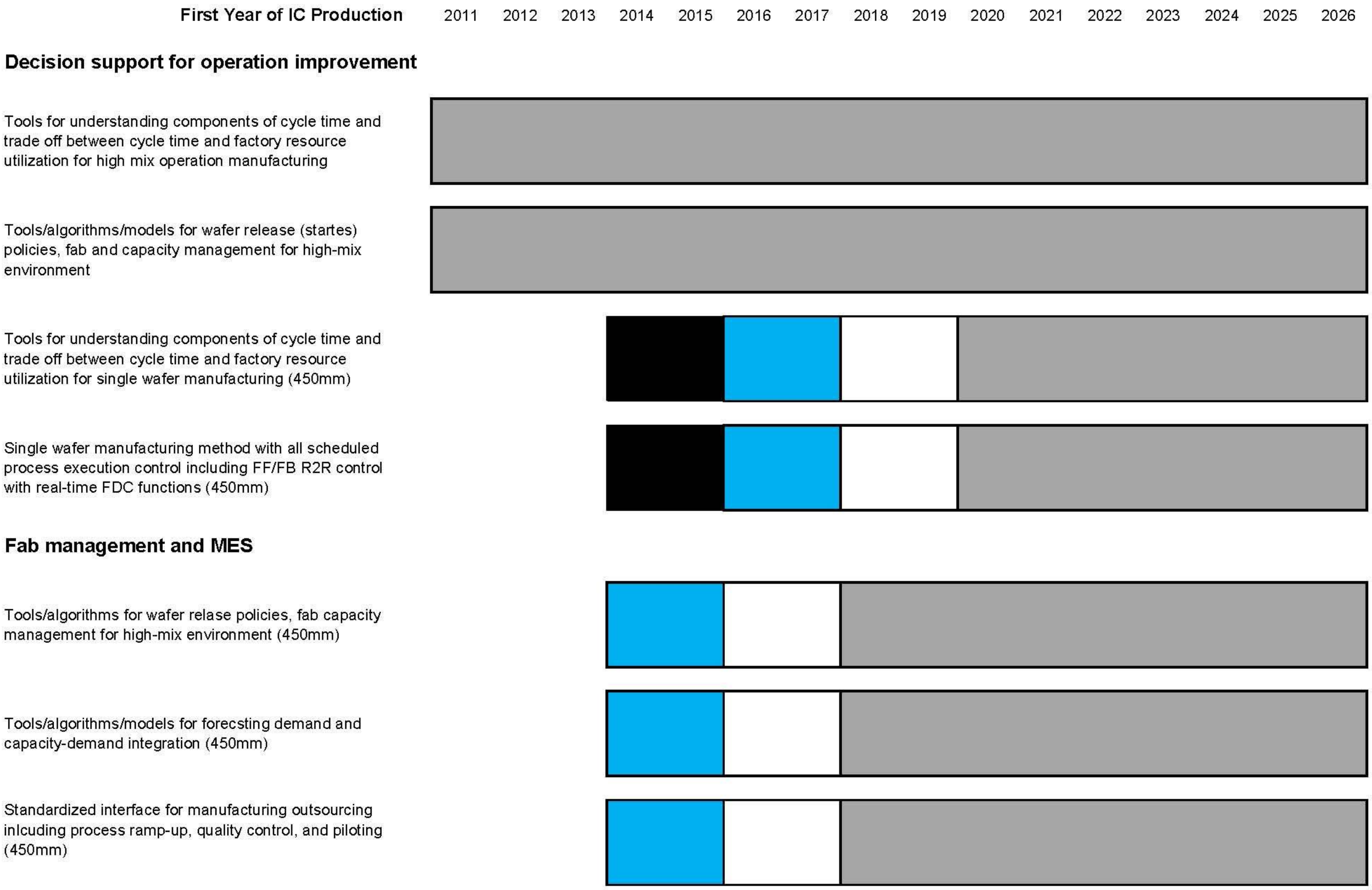


Figure FAC2 Factory Operations Potential Solutions

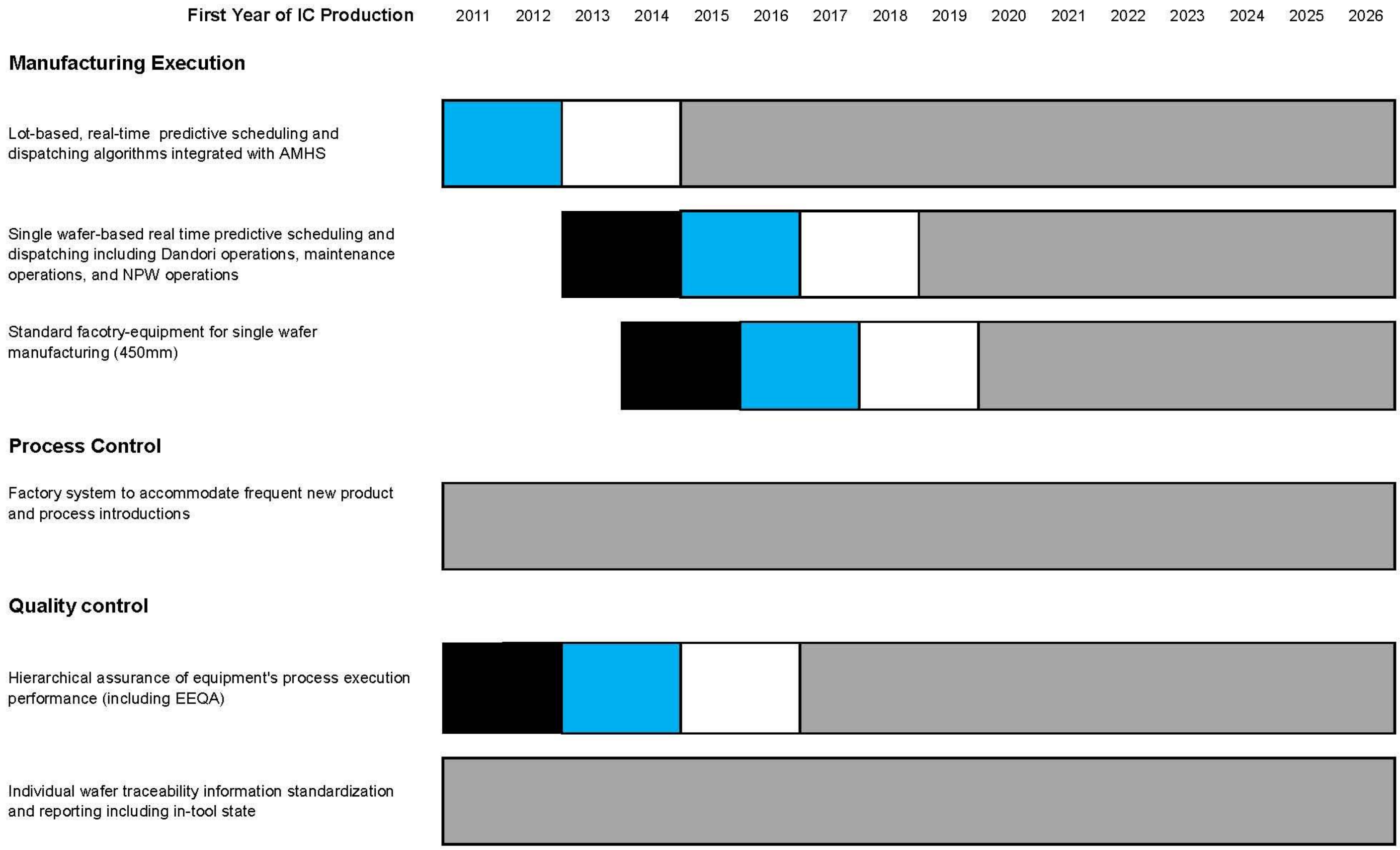
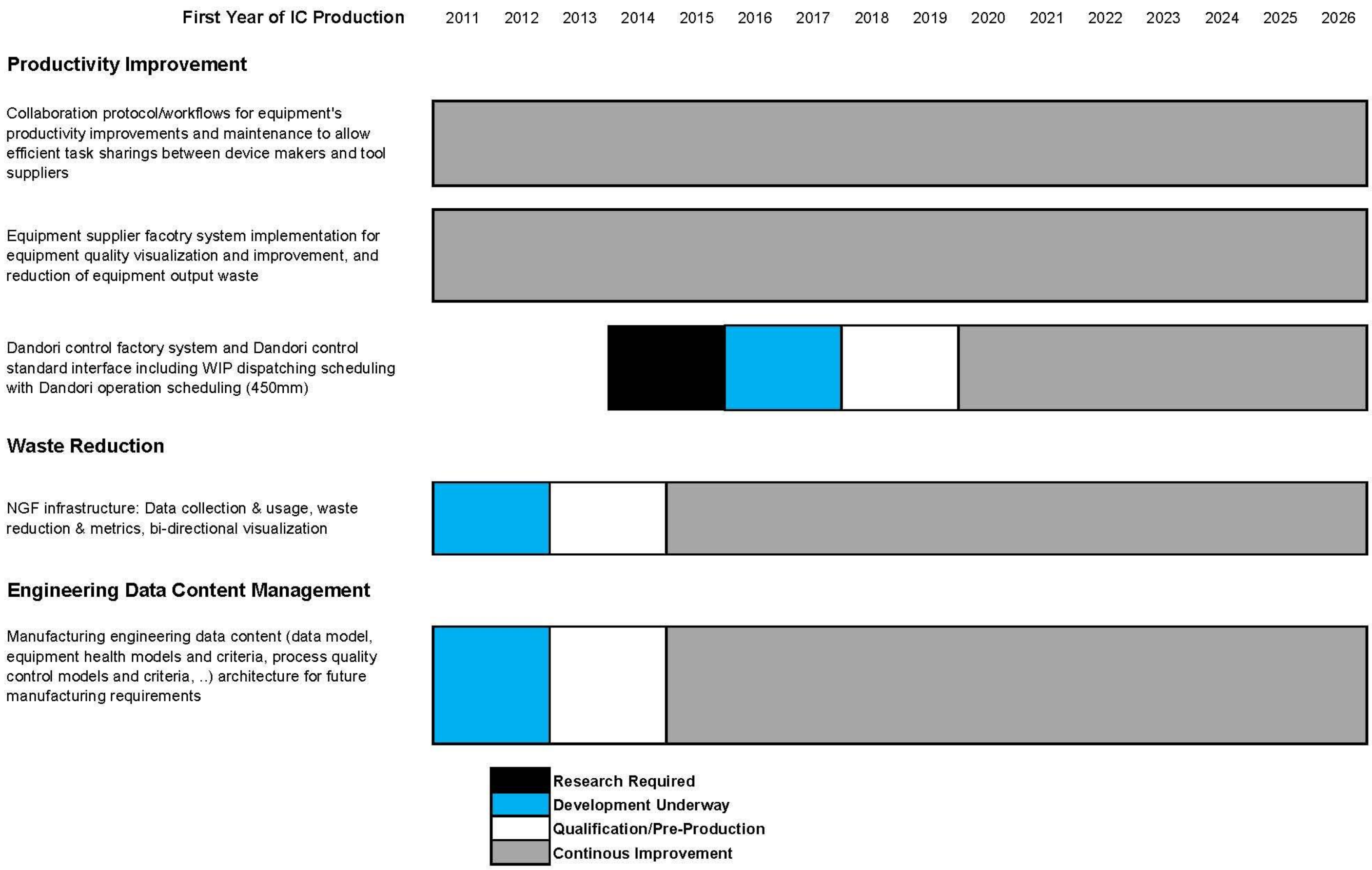


Figure FAC2 Factory Operations Potential Solutions (continued)



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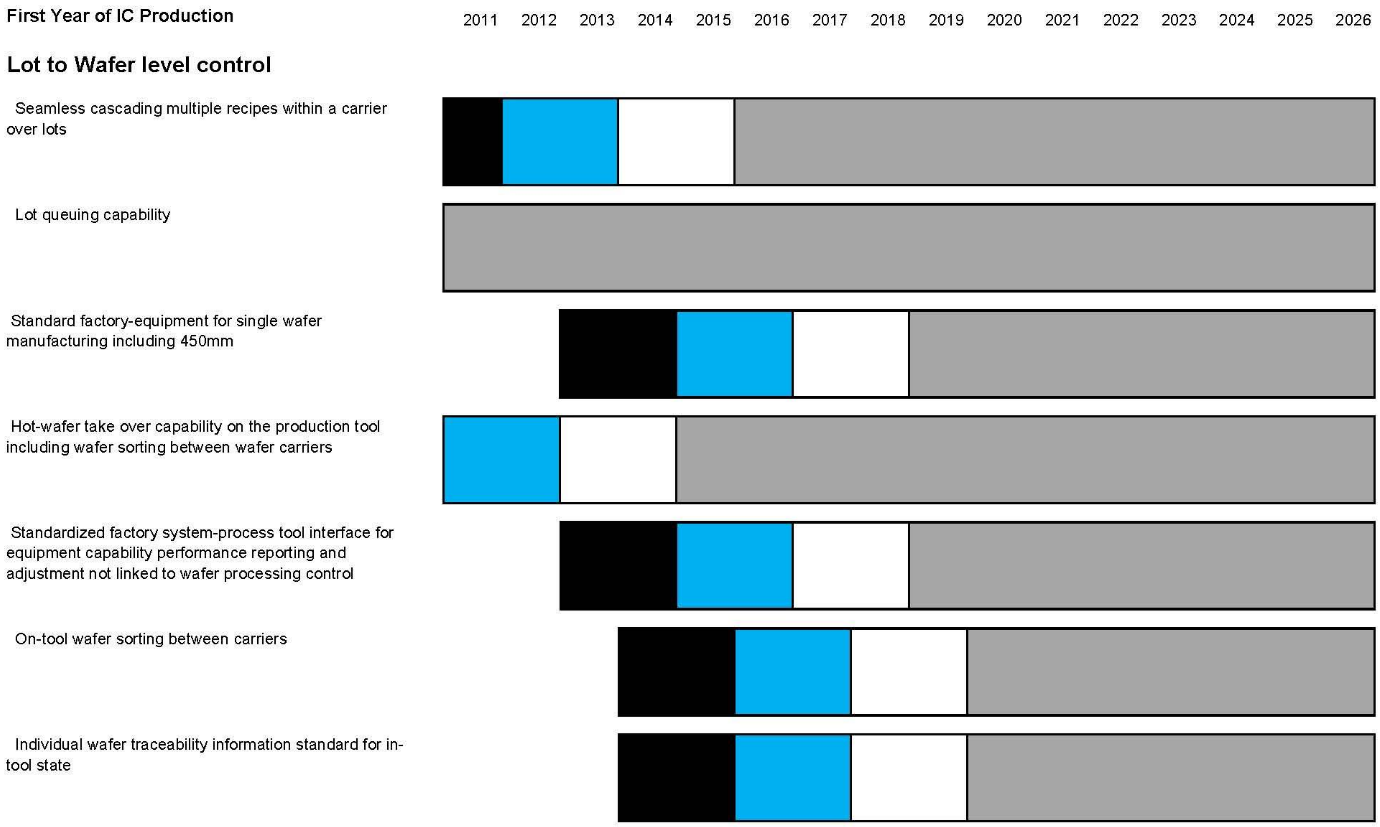


Figure FAC3 Production Equipment Potential Solutions

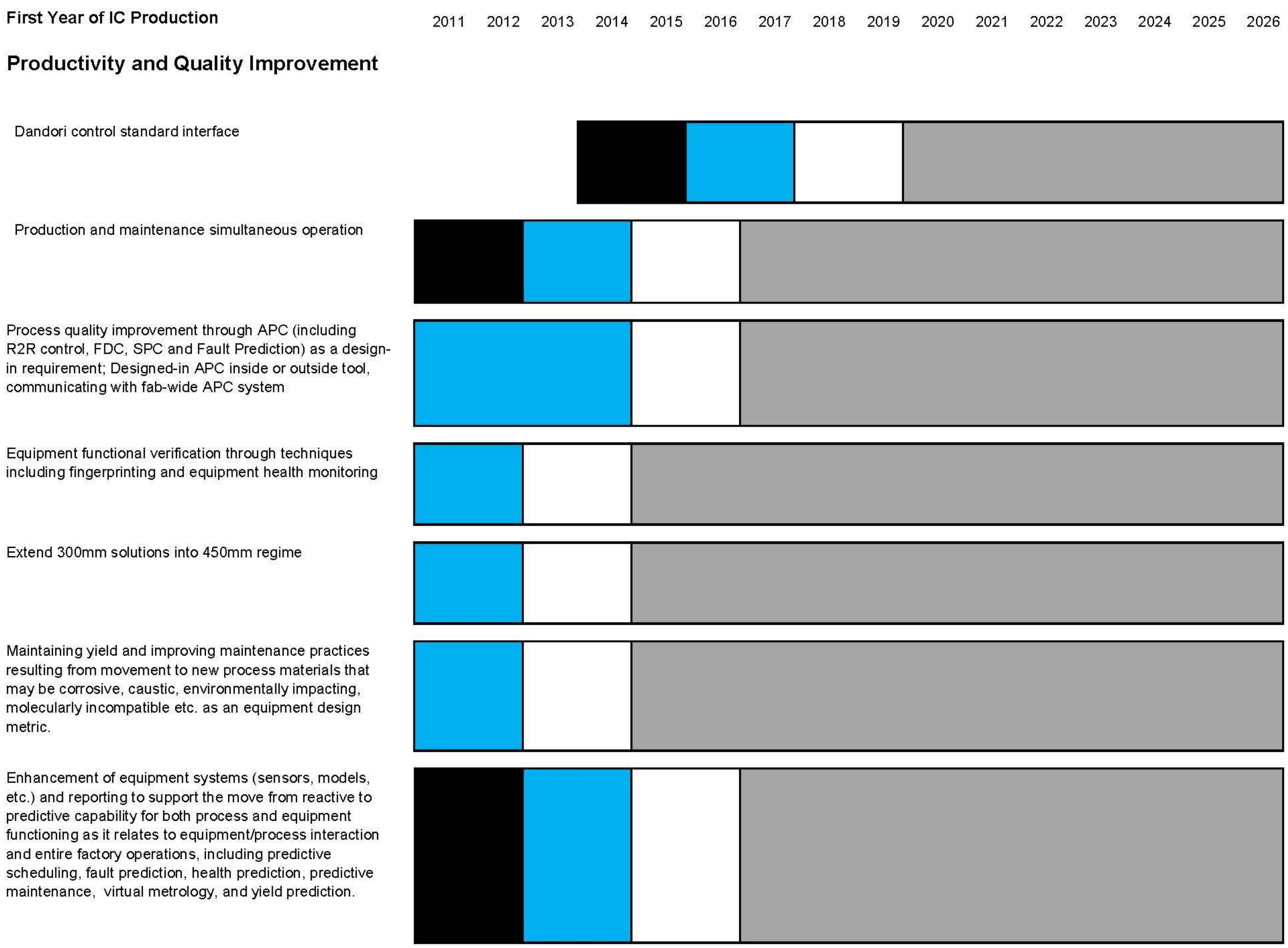
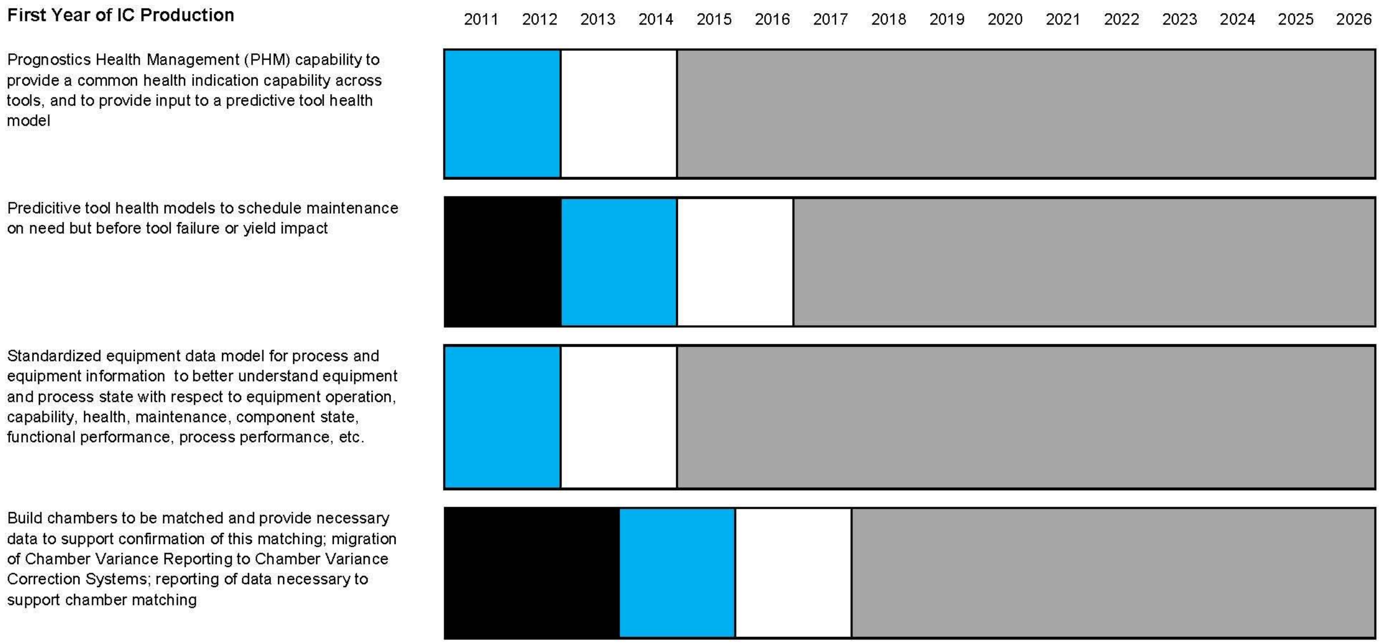


Figure FAC3 Production Equipment Potential Solutions (continued)



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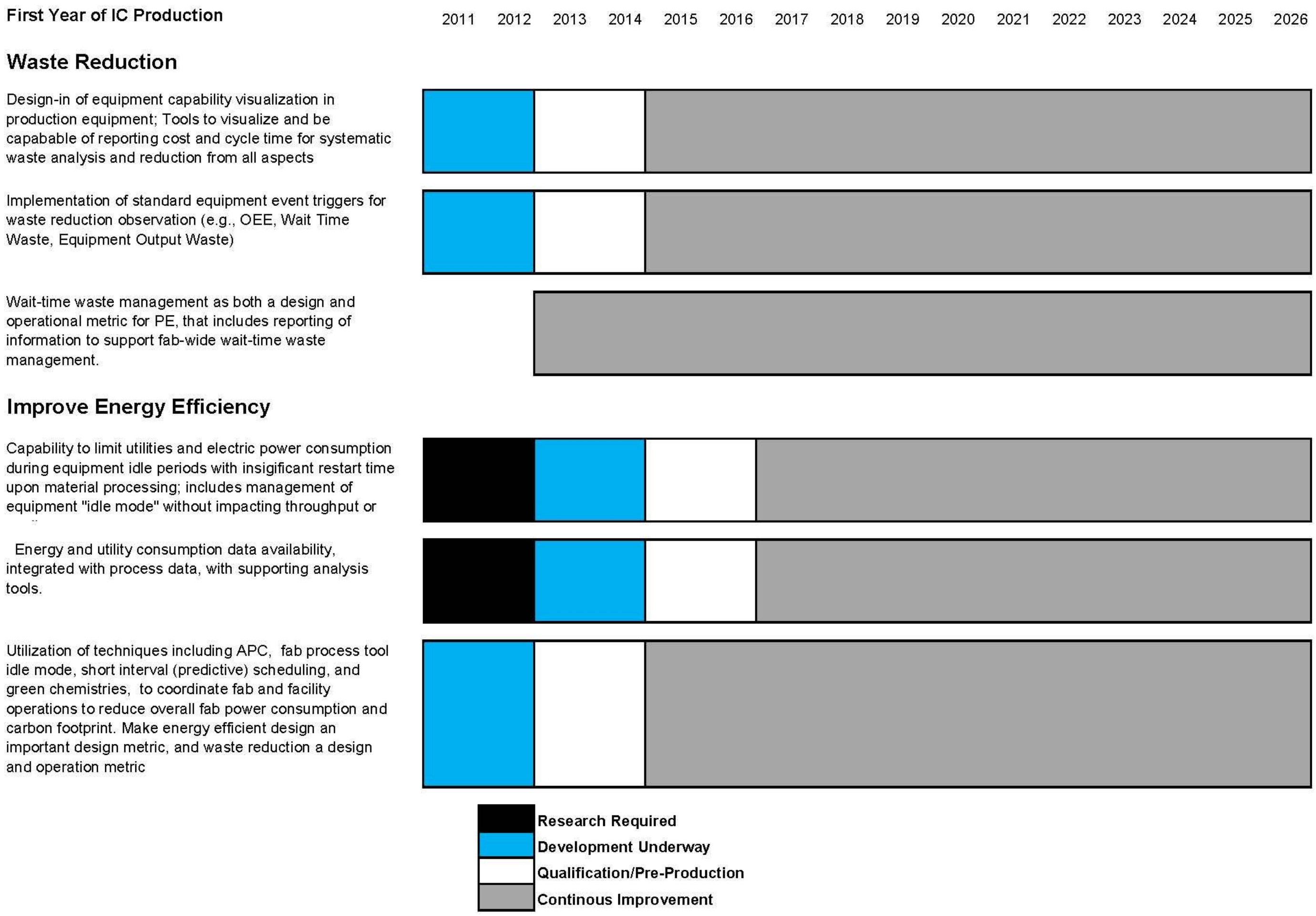

Figure FAC3 Production Equipment Potential Solutions (continued)

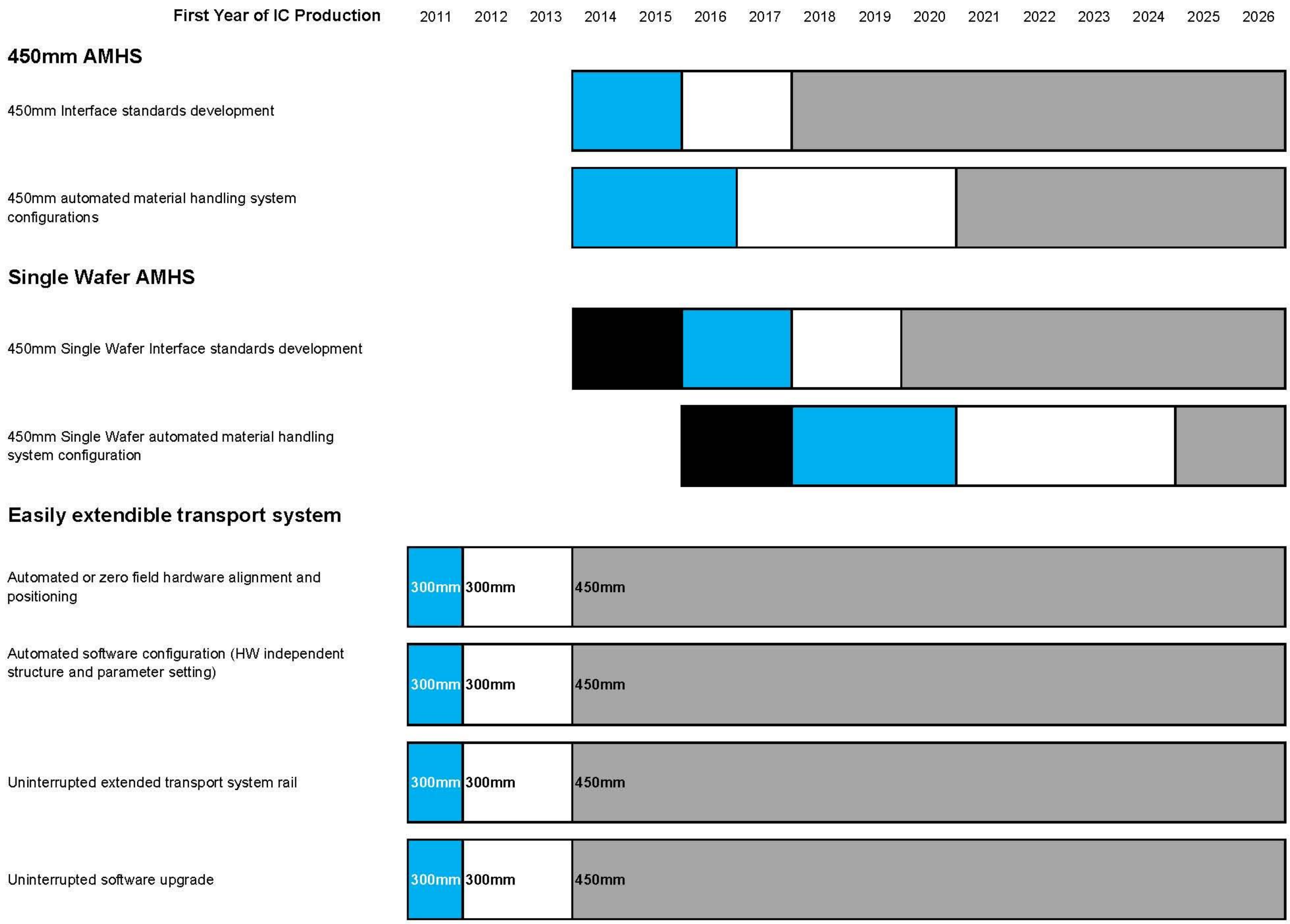

Figure FAC4 Material Handling Potential Solutions

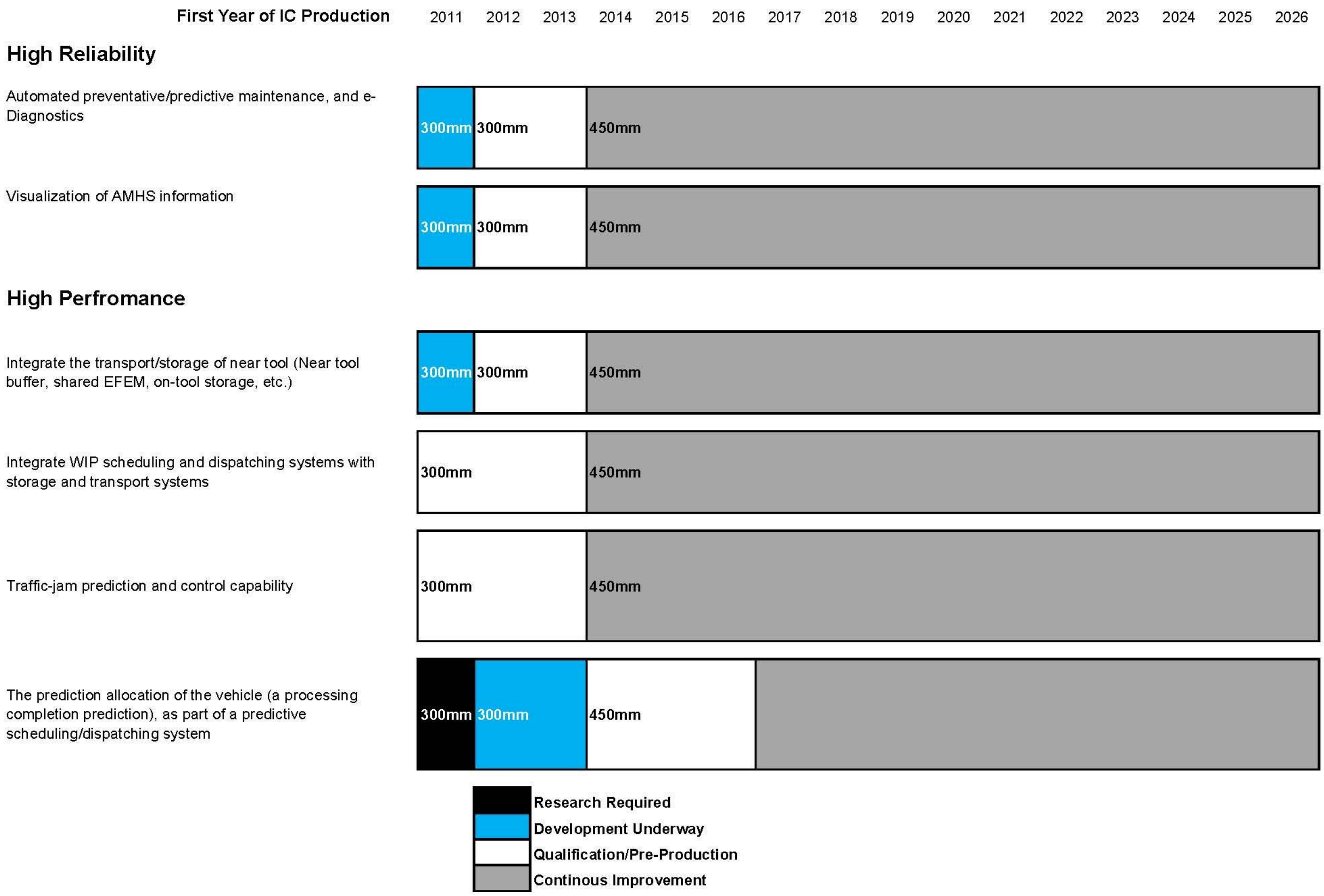

Figure FAC4 Material Handling Potential Solutions (continued)

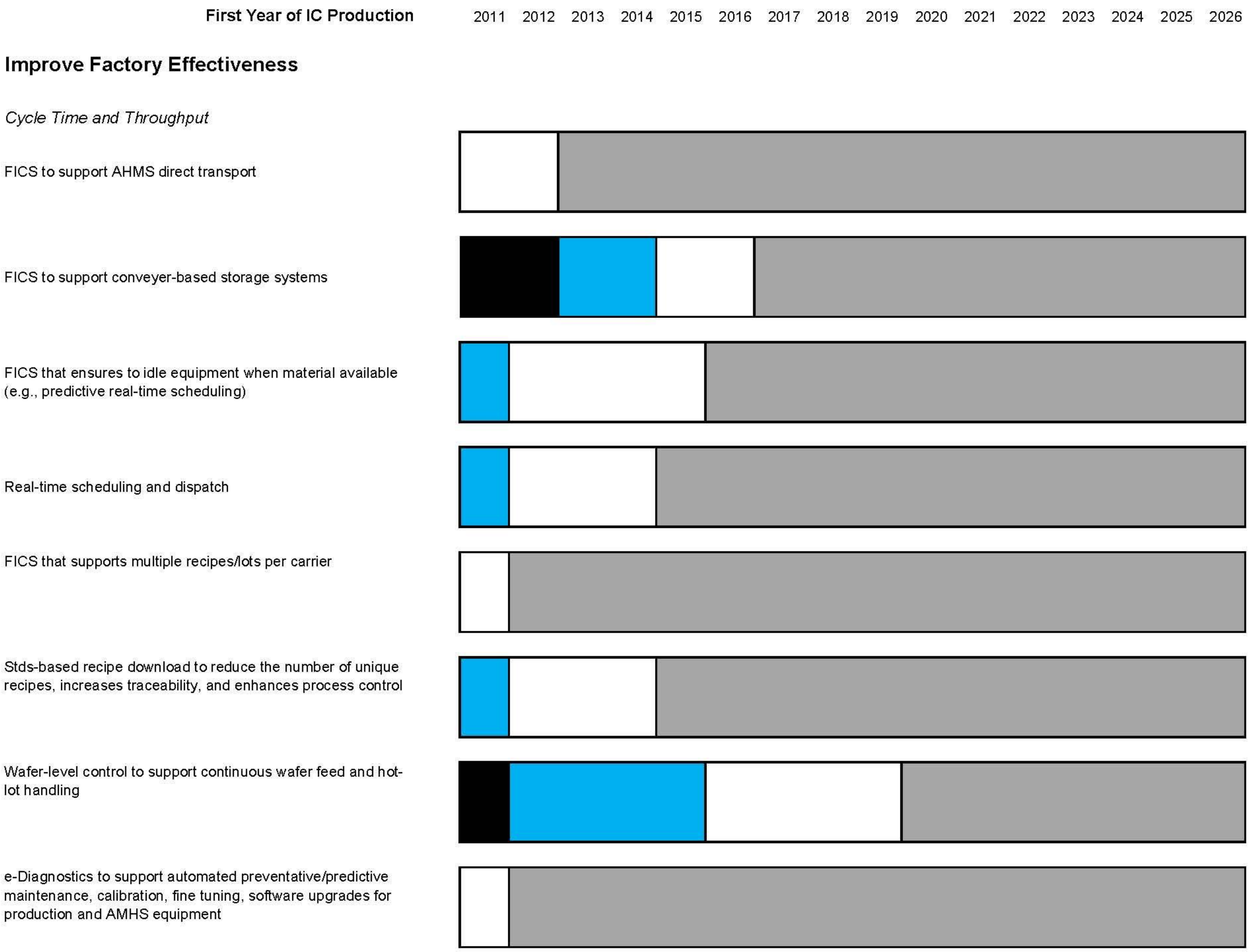

Figure FAC5 Factory Information and Control Systems Potential Solutions

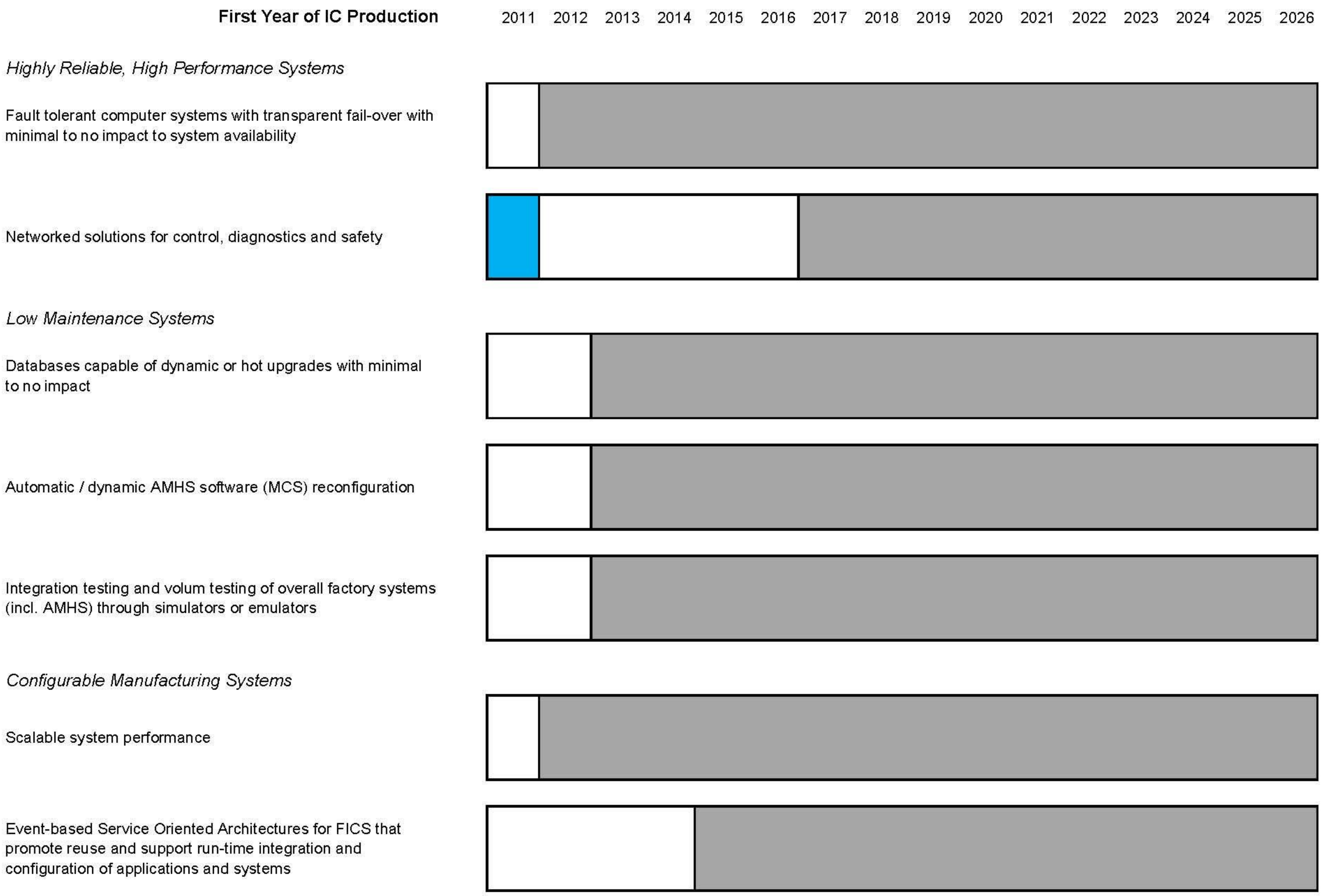

Figure FAC5 Factory Information and Control Systems Potential Solutions (continued)

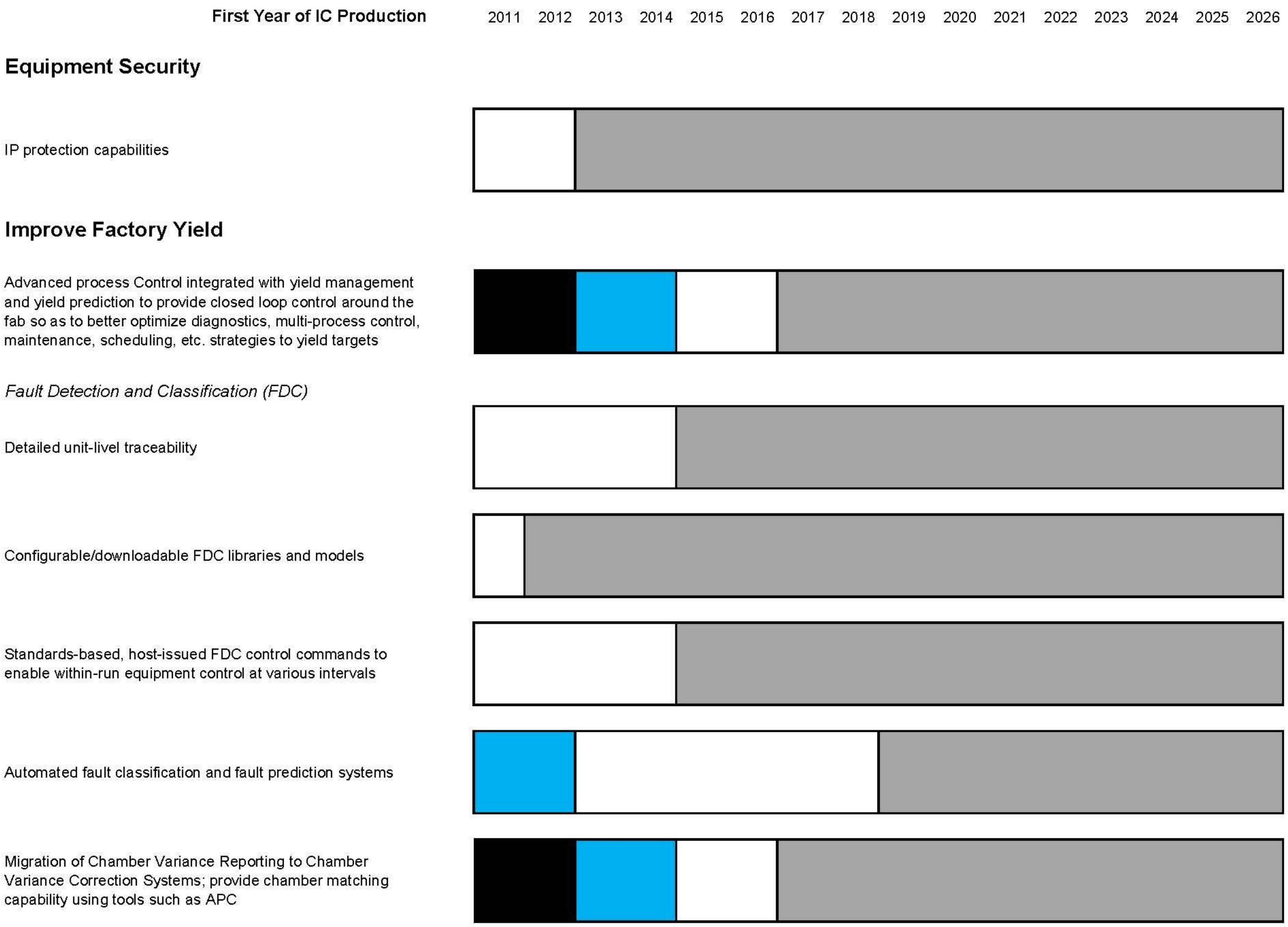

Figure FAC5 Factory Information and Control Systems Potential Solutions (continued)

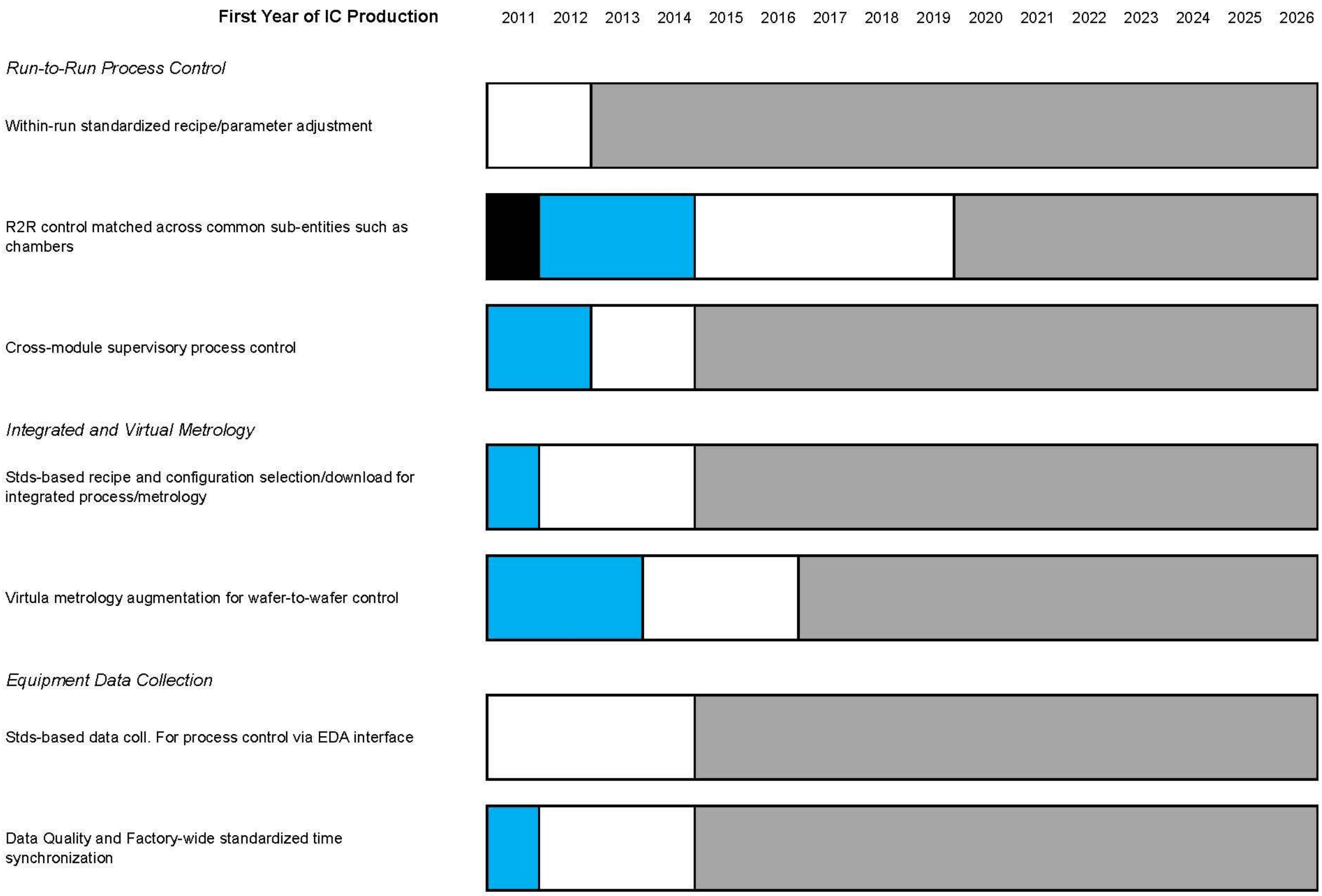

Figure FAC5 Factory Information and Control Systems Potential Solutions (continued)

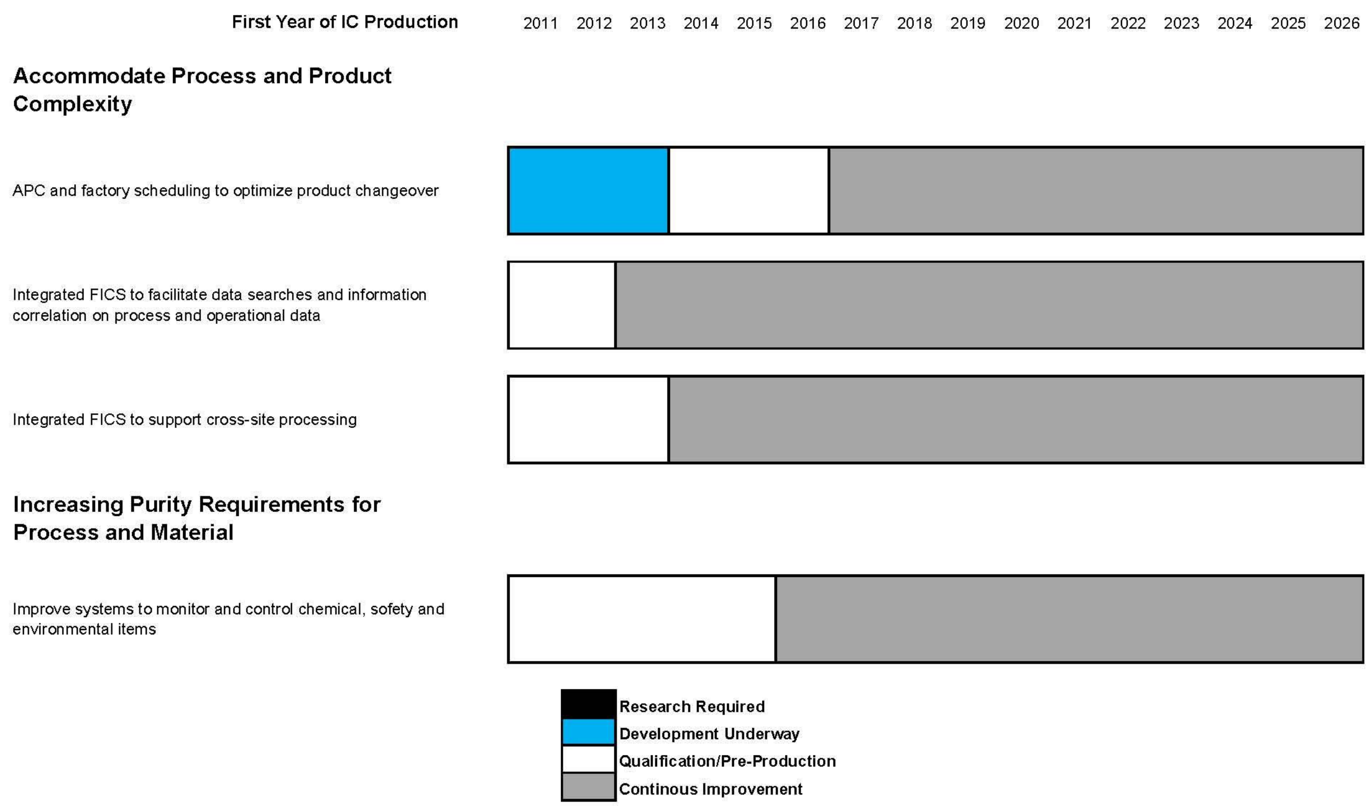

Figure FAC5 Factory Information and Control Systems Potential Solutions (continued)

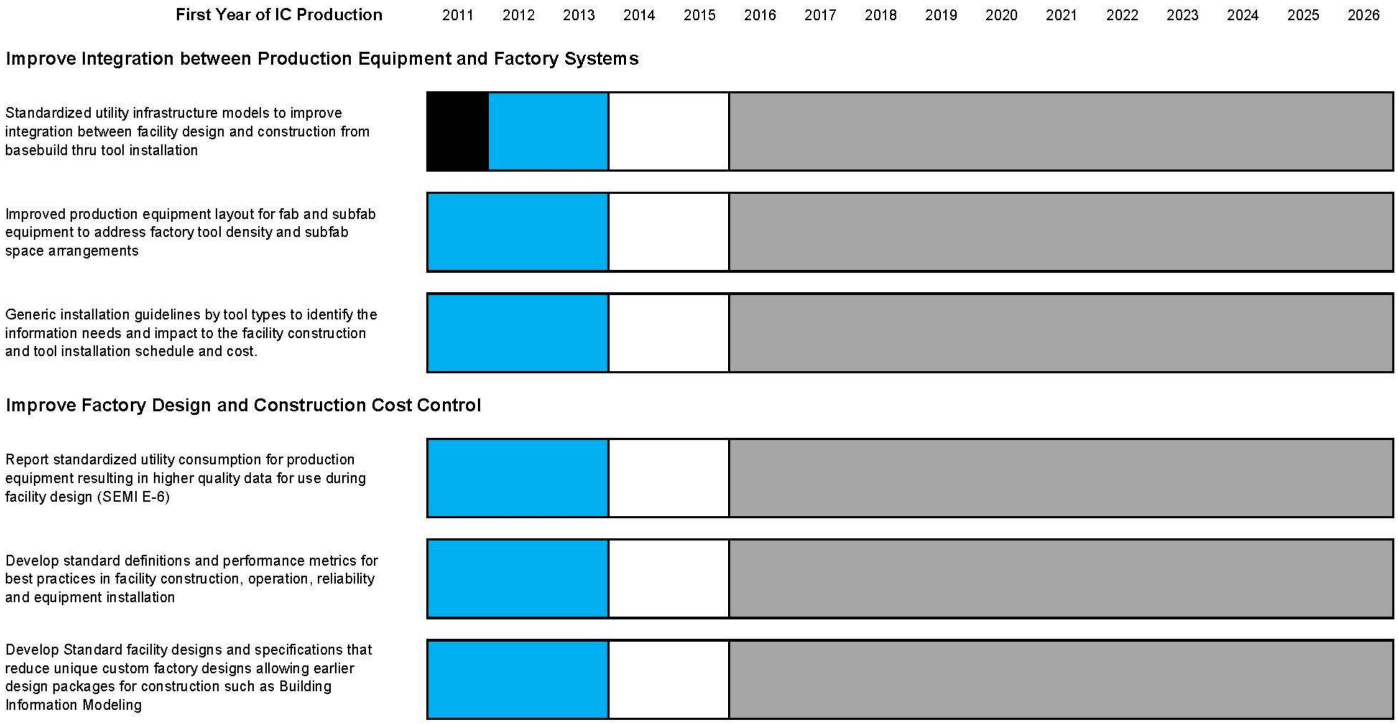

Figure FAC6 Facilities Potential Solutions

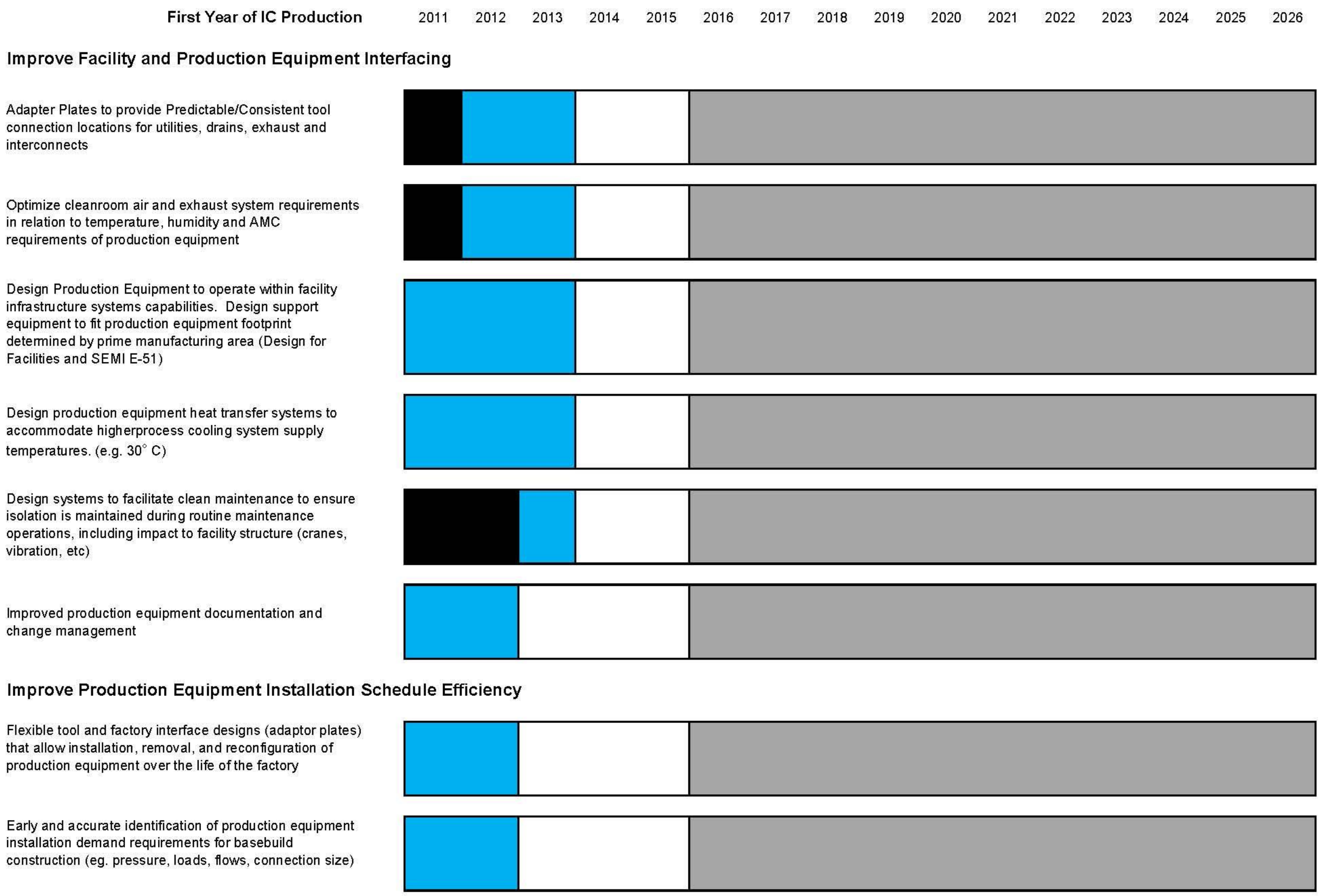

Figure FAC6 Facilities Potential Solutions (continued)

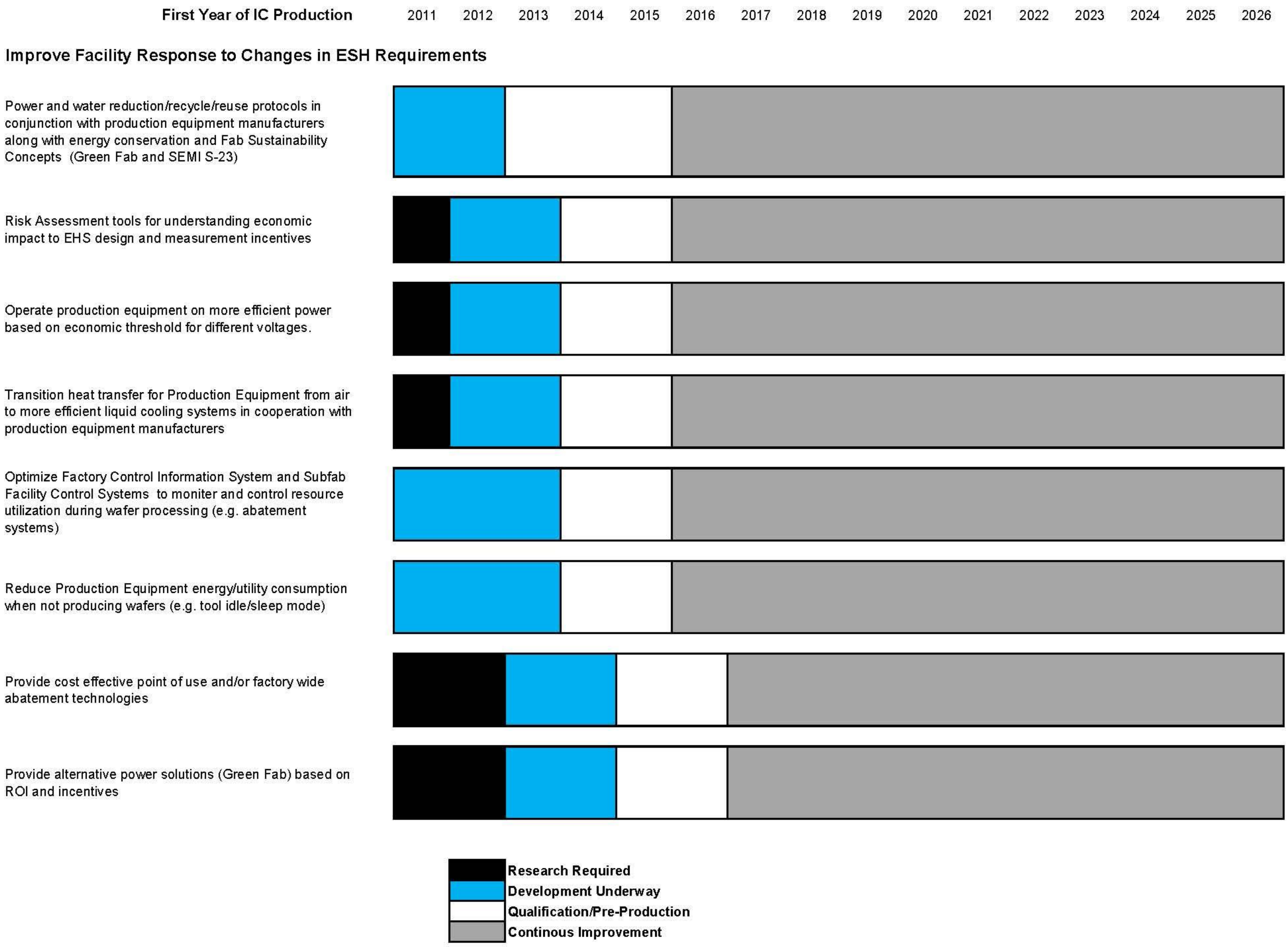

Figure FAC6 Facilities Potential Solutions (continued)

11 CROSSCUT ISSUES

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

Table FAC9 Crosscut Issues Relating to Factory Integration

Crosscut Area	*Factory integration related key challenges*
Front end Process (FEP)	Factory and FEP teams will continue to work on AMC requirements. FEP and Factory Integration will work on 450 mm challenges. Energy conservation effort: such as equipment sleep mode for energy conservation and the 1.5 mm wafer edge exclusion for long term challenge to starting material and SOI.
Lithography	Continuing to understand EUVL (power, consumables) requirements from the FI perspective; completely different factory design is expected. Fast reticle change; reticle storage issues and reticle buffering due to small lots; AMC relative to the reticle and tighter process control needs. Lithography DFM needs. EFM may be added as it is confirmed as mask quality detractor.
ESH	Primary focus on energy and resource conservation; Production tools to be designed for LCA from ESH viewpoints; AMC and particulate levels to be maintained; Advance resource management programs needed;
Metrology	Comprehensive metrology roadmap to be jointly defined. AMC, temperature, and humidity control remain crosscut issues
Yield Enhancement	Maintain temperature control at the lithography and metrology areas. Surface electric fields requirement on mask and wafer to be separated; FI ITWG to work with the Yield ITWG on specifying particle and AMC targets for equipment, AMHS, and FOUP. Yield changes with the 450mm and change in wafer handling.

11.1 Lithography

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

11.2 Environmental, Safety and Health (ESH)

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

A plan for continuous improvement of safety in future factories must be established. A thorough understanding of safety risks associated with automated equipment will lead to standards that assure safe working conditions for both people and product. These standards must be directed at the integrity of automated systems, the tools with which they interface, and the interfaces as well.

Our industry faces increasing environmental limitations. The availability of adequate water supply already places restrictions on the size and location of factories. The goal is to build factories that minimize resource consumption and maximize resource reclamation. Effluents of environmentally toxic materials need to be reduced to near zero—perhaps to zero levels.

Conservation of energy is very critical. The constraint to this is the size of the factory, which then puts a very large potential pollution burden on the energy provider and the wafer fabrication plant. While much of the responsibility for ESH programs rests with the equipment suppliers, application of advanced resource management system services will have a significant impact. International ESH standardization and design programs can be greatly enhanced through training programs established for and by the industry. One key thrust is the integration of facility systems and system goals with factory operation objectives. Consideration of ESH standards in equipment design, maintenance, de-commissioning, and final disposition will reap substantial rewards in ESH performance as well as cost. Refer to *Environment, Safety, and Health chapter* for comprehensive information.

11.3 Yield Management

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

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

Yield management systems (YMS) must be developed that can access and correlate information from multiple data sources. YMS should also work with measurement/metrology equipment from multiple suppliers using pre-competitive standards based data models and structures. Refer to the *Yield Enhancement chapter* for a more comprehensive discussion on YMS.

11.4 Airborne Molecular Contamination

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

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

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

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

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

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

11.5 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 and process technology shrinks. Virtual metrology will become an important solution to augment existing metrology for improving quality without negatively impacting cost in terms of capital and lost throughput. In factories, review and classification tools may eventually appear in clusters or integrated clusters to create a more efficient factory interface. Some process equipment will include integrated measurement (IM) capabilities to reduce cycle time and wafer-to-wafer process variance. The FI and Metrology ITWGs will continue to work on the Virtual Metrology (VM) and IM requirements. Refer to the *Metrology chapter* for overall metrology topics.

11.6 Static Charge and Electromagnetic Interference Control

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

1. Electrostatic attracted (ESA) contamination increases as particle size decreases. ESA of particles to masks will become a more serious problem if future lithography methods eliminate the pellicle used to keep particles away from the mask focal plane.
2. Electrostatic discharge (ESD) causes damage to both devices and photo-masks. Shrinking device feature size means less energy is required in an ESD event to cause device or mask damage. Increased device operating speed has limited the effectiveness of on-chip ESD protection structures.

Recent research has indicated that progressive reticle pattern feature degradation can start at electric fields that are induced by the voltage values weaker than the ESD prevention voltage values recommended in the PE TR Table. This phenomenon is called EFM (Electric Field Induced Migration).

Electromagnetic interference (EMI) (see the standard SEMI E33 for definition)[12] causes variety of problems for semiconductor manufacturing, including, but not limited to, equipment lockup, and malfunction, sensor misreading, metrology errors and others. The impacts described above are likely to become more pronounced, particularly for metrology equipment. Currently EMI is not well understood by PE users and thus it leads to misdiagnosis and misapplication of EMI mitigation/remedies.

12 Factory Integration Focus Areas

In addition to working on the five factory integration sub-sections and cross-ITWG challenges, the FI ITWG also evaluated key technology focus areas that impact the factory integration near-term and long-term needs and also

[12] *SEMI E33-94: Specification for Semiconductor Manufacturing Facility Electromagnetic Compatibility.*

cuts across all the FI thrusts in 2011. This section provides details on the four key focus areas of 1) Waste Reduction and Proactive Visualization, 2) 450 mm Transition Challenges, , 3) Energy Conservation and 4) Migration from Reactive to Predictive Operations.

12.1 Waste Reduction and Proactive Visualization

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

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

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

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

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

More study is needed to prepare for the general waste reduction approaches. Such approach should include systematic measurement and visualization methods of wastes. The systematic knowledge on waste is used as guidance to the effectiveness and reliability of equipment design and operation practices in addition to the conventional CIP effort.

Such approaches are effective for WTW (Waite Time Waste) and EOW (Equipment Output Waste) visualization and reduction. Industry needs to have standardized measurement methods, data model, and structure for Dandori operations. Although the on-line data collection history has been that the most focus is on the parametric data during processing, it should be emphasized that the scope expansion for the data collection and usages is extremely important and needs to be designed appropriately. Dandori operations are expected to be designed as parallel operation, or non-constraining operations to the main thread operation.

WTW for a wafer can be measured by simply summing up all the wait time for that wafer. Such measured data is not necessarily used for the improvement planning. There are numerous interactions between wait times and the other factors such as resource availability and other wafers' waiting for the production tools. To visualize the causes of waits calls for more study on the principal interactions.

EOW can be characterized relatively simply for a single piece of equipment. The factory level EOW can be measured likewise, but EOW proactive visualization for EOW improvement planning is significantly difficult due to the interactions between tools and localized Work in Progress (WIP) status. Factory simulator needs to be hooked up with the visualization tool for the planning and evaluation after improvement implementation.

Industry needs to work on the standardization of triggers for state transitions of factory resources and products. Especially production equipment should provide reasonable granularity to facilitate waste reduction in the equipment.

12.2 Future manufacturing Requirements and 450mm Transition Challenges

In keeping up with the Moore's law the semiconductor industry looks at increasing the wafer size as one viable option in addition to device innovations for 30% improvement in cost/cm^2 (primary goal) and 50% cycle time reduction. The last wafer size transition from 200 mm to 300 mm occurred 10 years ago and it is showing clear indication of ~30% cost improvement. As 300 mm wafer production enters its 4^{th} major technology generation (45 nm), the industry will work on transitioning to 450 mm, in a seamless manner from the current 300 mm technology. The Next Generation Fab activity is expected to address the seamless improvement usable both to 300mm significant improvement and 450mm. Discussions on the 450 mm wafer transition within the FI ITWG and also with the other ITWG uncovered several technical as well as business challenges. More factory services specific to 450mm are expected to be systematically studied and captured in the roadmap in 2010 and after.

12.3 Energy Conservation

The primary goal of energy conservation is to reduce facility operation cost by enabling facility demand based utilization model in which energy conservation plays a pivotal role. Factory Integration team worked on several initiatives within the facilities and production equipment sub-team to define energy conservation related challenges and the outcome of this work is reflected as a metric (tool idle versus processing energy consumption) in the Facilities technology requirements table. Equipment sleep mode means that the equipment support units such as pumps will be shut down when no wafers are processed (i.e., when the tool is idle). The FI ITWG needs to work on energy conservation more intensively from 2012 and beyond based on the waste reduction and proactive visualization schemes.

12.4 Migration from Reactive to Predictive Operations

All of the previous focus areas will benefit significantly from a movement of factory operations from a reactive mode to a predictive mode. Reactive practices such as fault detection, preventative and unscheduled maintenance, and real-time scheduling and dispatch have been used and optimized in the past to achieve quality and productivity objectives. Unfortunately these techniques cannot ultimately eliminate waste (product, downtime, cycle time, etc.) because they wait for the problem to occur before addressing it, or, as in the practice of preventative maintenance, employ conservative and potentially wasteful practices in order to avoid an unexpected event. With the move to predictive, systems will be modeled and problems will be predicted before they occur. This means that (1) fault detection should migrate to fault prediction, eliminating scrap on fault occurrence, (2) predictive maintenance can reduce unscheduled downs and allow for relaxing of conservative (and wasteful) maintenance practices, (3) predictive scheduling shall minimize wait time and cycle time waste, (4) virtual metrology shall provide metrology values for all wafers, and (5) yield prediction should be used to control processes and systems to quality and productivity targets directly. A key challenge in the migration from reactive to predictive is the ability to establish accurate, robust, reconfigurable, real-time updateable and understandable models that are the basis for prediction. A key focus for prediction will be techniques for improving prediction accuracy and for utilizing prediction accuracy information (along with the prediction itself) to optimize prediction systems.

13 SUMMARY

The Factory Integration chapter of the ITRS focuses on integrating all the factory components needed to efficiently produce the required products in the right volumes on schedule while meeting cost targets. The Factory Integration chapter provides the technical requirements by the five sub-groups 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 2011 Factory Integration chapter has three highlights;

1) Future manufacturing requirements technology requirements inclusion prior to 450mm introduction

2) Waste reduction metrics introduction for the first time in order to address necessity of an additional drive axis to Si scaling.

3) A focus on the move from a reactive to predictive mode of factory operations which includes the development of capabilities such as predictive scheduling, predictive maintenance, virtual metrology and yield prediction.

The ITRS needs to extensively study how to incorporate waste reduction as a new common driver axis for the roadmap in a similar fashion to the historic Si scaling.

The FI ITWG should continue to work towards the goal of supporting cost per unit area requirements of silicon and increasing factory flexibility to changing technology and business needs and the FI ITWG should identify the needed factory services and technologies along with the corresponding potential solutions in 2010 and after.

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