Unified Frontend and Backend Industrie 4.0 Roadmap for Semiconductor Manufacturing

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ABSTRACT

Industrie 4.0 or digitalization of manufacturing currently create uncertainty and unrest in the manufacturing industry as many players do not know when, how or whether a disruptive change in industry will happen. Many published high-level strategies stay vague and leave practitioners unsure what to expect. Breaking Industrie 4.0 down into tangible pieces and steps is necessary for transporting the vision into reality. In this paper we develop an assessment and roadmap for Industrie 4.0 in semiconductor manufacturing - the FINCA model. The model covers semiconductor frontend and backend manufacturing. It was successfully applied and tested at one of Europe's largest semiconductor manufacturers, the Infineon Technologies AG. Results from the assessment are presented in this paper.

CCS CONCEPTS

• **Applied computing** → **Reference models**; *Enterprise information systems*; • **General and reference**; • **Computer systems organization** → *Embedded and cyber-physical systems*;

KEYWORDS

Industrie 4.0, Digitalization, Automation, Roadmap, Semiconductor Manufacturing

1 INTRODUCTION

Industrie 4.0, digitalization or digital transformation create a spirit of optimism but also a high uncertainty in the manufacturing industry. On a general level the three terms have the same meaning: The introduction of digital technology into manufacturing. Many consultancies and research institutions expect a high impact on manufacturing by the so-called fourth industrial revolution. Fraunhofer IPA estimates an average cost reduction potential of about 30% [3].

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Industrie 4.0 is a set of contemporary automation and data science technologies, as well as organizational paradigms for manufacturing in the 21st century. The core of Industrie 4.0 are Cyber-Physical-Systems (CPS), which connect the physical and the virtual world [5]. McKinsey & Company clusters the disruptive technologies which enable this concept under four headlines [2]:

- Data, computational power and connectivity,
- Analytics and intelligence,
- Human-machine interaction,
- Digital-to-physical conversion.

The high number of different technologies associated with Industrie 4.0 leads to the question of prioritization of different approaches at companies. In a fast moving field, with standardization still ongoing, companies are reluctant to make investments in new technologies. High-level strategies offer little orientation as they do not get specific enough to derive concrete recommendations. The fear of investing into the wrong technology slows down innovation tremendously. Strategies need to be broken down into smaller parts to provide tangible steps towards the implementation of an Industrie 4.0 vision.

There are several assessments and roadmaps for Industrie 4.0 and digitalization available (section 3). Still, no framework can directly be applied to semiconductor manufacturing. Most assessments are general and not industry-specific which leaves room for interpretation and leads to subjective results of the assessment. Additionally, no framework is currently available which can be applied to semiconductor frontend and backend to compare the level of digitalization in these manufacturing steps.

In this paper, we present a framework for Industrie 4.0 in semiconductor manufacturing. The framework can be applied to frontend and backend production. It can be used as assessment and roadmap for further development of the manufacturing site. The purpose of the framework is

- to foster a common understanding between Industrial Engineering, IT and Business on the existing capabilities,
- to create a vision for further development in semiconductor manufacturing,
- to identify gaps at manufacturing sites,

- to support benchmarking between semiconductor manufacturing companies, and
- to enable a fast assessment of acquired sites within integration projects.

In the section 2, we will describe the semiconductor manufacturing process and the difference between frontend and backend. In section 3, existing frameworks, assessments and roadmaps for Industrie 4.0 will be presented. We also highlight some existing roadmaps for the semiconductor industry. None of the existing frameworks offers a detailed semiconductor specific assessment and roadmap which can be used for frontend and backend manufacturing. Therefore, we developed the FINCA Model which will be presented in section 4. In section 5, the model is applied to frontend and backend sites of the Infineon Technologies AG and results are discussed. In the conclusion (section 6), further research directions and applications are presented.

2 SEMICONDUCTOR MANUFACTURING PROCESS

The semiconductor manufacturing process starts in the frontend. Structures in the sub-μm range are processed on raw wafers, which are thin slices of crystalline silicon. The manufacturing process requires a cleanroom as dust or other particles can destroy the sub-μm structures during the fabrication process. From a manufacturing point of view, frontends are complex job shops (for a detailled description see [18]). This production type is usually used for custom-made items but semiconductor manufacturing is a mass production with a strong economy of scale. Industrial mass production is mostly done in assembly lines but this concept is not suitable for semiconductor manufacturing due the nature of the physical processes on the wafer.

Semiconductor frontends are considered high-tech with complex processes and high levels of automation and digitalization. They are very capital intensive and mostly located in advanced economies.

After the frontend the wafers are brought into an intermediate storage facility, the so-called die bank. From the die bank the wafers are taken to the backend, the second and final manufacturing step. At the backend, the wafers are cut into separate dies. The dies are bonded to a leadframe, which connects the chip to electrical contacts on the outside of the package. After the bonding, the chips are packaged and sealed in order to make them robust against environmental impacts. The final product is now ready for sale.

In contrast to the frontend, the backend is traditionally a more mechanical and labor-intensive process rather located in low-cost countries. Latest backend technologies which comprises of assembly and final test became more sophisticated and more complex.

3 RELATED WORK: INDUSTRIE 4.0 ASSESSMENTS, FRAMEWORKS, BENCHMARKS AND ROADMAPS FOR THE SEMICONDUCTOR INDUSTRY

The Platform Industrie 4.0 released the Reference Architecture Model Industrie 4.0 (RAMI 4.0) [17]. RAMI 4.0 focuses on interfaces and standardization. The model has a broad scope. It is suitable for comparison of standards and identification of gaps in standardization. RAMI 4.0 has successfully been applied to semiconductor manufacturing [19].

There are several Industrie 4.0 assessments and roadmaps available [1, 4, 6, 16]. Still, all of them are on a general level and cannot be directly applied to semiconductor manufacturing. Our model is guided by the methodology of the VDMA Maturity model [1].

For technology development and the continuous shrinking of semiconductor devices (Moore's law) the International Technology Roadmap for Semiconductors (IRTS [20] and ITRS 2.0 [7]) played a crucial role. ITRS has a section on Factory Integration (FI, Manufacturing IT) which provides guidance. However, ITRS is not updated any more and is not linked to recent developments such as Industrie 4.0. The successor of the ITRS, the International Roadmap for Devices and Systems (IDRS [13]) which is part of the IEEE rebooting computing Initiative [15], is currently more focused on semiconductor technology. However, IDRS has not yet published influential material on digitalization in semiconductor manufacturing.

The increase in wafer size has always lead to substantial changes in manufacturing engineering at semiconductor plants. However, the switch to 450mm wafer-size has been delayed and is not expected within the next 2-3 years [12].

Current initiatives mostly focus on the application of specific technologies in semiconductor manufacturing without providing a full picture. Here, the focus is on intelligent algorithms [8, 10] and big data [14]. For specific areas in semicondcutor manufacturing detailed roadmaps exist, e.g. for dispatching [18].

All in all, the existing frameworks lack scope, are too general in their recommendations or do not focus on digitalization.

4 THE FINCA MODEL

The FINCA model is an Industrie 4.0 assessment and roadmap for the semiconductor industry for both frontend and backend manufacturing. It was developed at Infineon Technologies AG. The main properties are already encoded in the abbreviation FI-N-C-A:

- **Factory Integration (FI):**
  FI refers to all IT services necessary to run a semiconductor production. In some companies the responsible organization is called "Manufacturing IT" and can be under IT or a different central function, local factories or cluster management. Among different tasks, FI's mission is to ensure standardization within the company. At Infineon Technologies AG, FI is under the corporate supply chain function and has the mission to standardize across regions and manufacturing levels while maintaining and even increasing capabilities of the manufacturing system landscape.
- **Normalized:**
  Capabilities are, wherever possible, independent from region, manufacturing levels (frontend, backend) and products. Ideally any frontend site can be compared to any backend site using the normalized capabilities. There are five levels for each category going from zero (no capability or no system to support paper/manual process) to four (capability implemented in professional IT system and used to the fullest extend in regards of industry standards). Each category can be split into several sub-categories that need to be assessed

Industrie 4.0 Level

7 Dimensions of Automation

	Level 0	Level 1	Level 2	Level 3	Level 4
Workflow Automation	**Process rule**s are defined	Changes are **documented** [paper]	Standalone system with **Semi Auto** decision proposal	Standalone system with **Auto** decision proposal	Integrated system with **Auto decision making**
WIP Flow Management	**Partially** simulation [Lot Start] & **manual** scheduling, dispatching & recoding	Partially simulation [whole process] & manual scheduling, **Snap-Shot** dispatching & **system** recoding	**Snap Shot** simulation [whole process] & **Real Time** scheduling, dispatching & system recoding	Snap Shot simulation [whole process] & Real Time scheduling, dispatching & system recoding	**Real Time** simulation [whole process] & **Real Time** scheduling, dispatching & system recoding
Process Control Automation	**Paper** document, **No recording**, **Manual** control with **No** processing of data	**Paperless** document, **Manual** recording, manual control with **Storage of data** for documentation	**Paperless** document, Manual recording,**Semi auto** control with **Analyzing data** for **process monitoring**	**Paperless** document, Manual recording, **Online** control with **Evaluation for process planning /control**	**Paperless** document, **Auto** recording, **Online** control with **Automatic process planning / control**
Manufacturing Data Management	**Limited** [<50%] Data Availability / Accuracy, with **Manual** data provision from Product/Planning To MES System.	**Limited** [<70%] Data Availability / Accuracy, with **Semi Auto** data provision from Product/Planning To MES System.	**Limited** [<90%] Data Availability / Accuracy, with **Automatic** data provision from Product/Planning To MES System.	**Limited** [<100%] Data Availability / Accuracy, with Automatic data provision from Product/Planning To MES System.	**FULL** Data Availability / Accuracy, with Automatic & **Real time** data provision from Product/Planning To MES System.
Material Handling	**Manua**l storage & retrival with **Manual** transport delivery & Loading system	**Manua**l storage & retrival with **Automated** transport delivery with **Semi auto** Loading system	**Manua**l storage & retrival with **Automated** transport delivery with **Automated** Loading system	**Automated** storage & retrival with **Automated** transport delivery with **Automated** Loading system	Automated storage & retrival with Automated transport delivery with Automated Loading system [**Linked up**]
Material Identification & Tracking	**Manual** Identification, validation & traceability.	**Auto** Identification of Product [Lot Level], **Auto** Validation of employee qualification .	Auto Identification of Mounted Material**, Auto** Validation of employee qualification .	**Auto** Identification, validation & traceability [**Strip Level**].	**Auto** Identification, validation & traceability [Single Device].
Equipment Automation	**No communication**, **Manual** triggering for Setup / Change over	SEC/GEM **Connection** or Other EQ Connection (Eg : iTec/Tec), Machine Alarm retrieval, **Semi Auto** Identification of setup/change over	**Automated Retrieval of data from machine, Auto** Triggering for Setup / Change over	**Automated transfer of Logistic data, Automated Release**, **Flexible** schedule of Maint base on production situation.	**Load & Go** indetification od Setup, **Predictive** Maintenance.

Figure 1: Overview of the different dimensions and their maturity levels in the FINCA model.

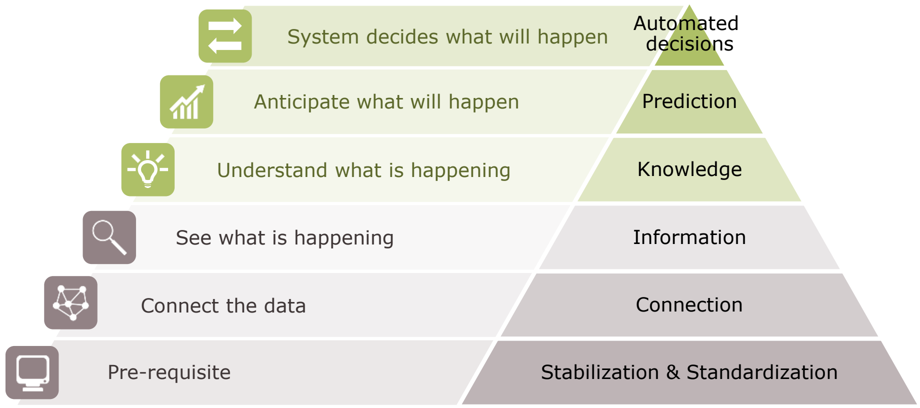

Figure 2: A general model of different Industrie 4.0 maturity levels used at Infineon Technologies AG.

individually and aggregated using a simple numerical average (no weighting).

- **Capability:**
  Focusing entirely on capabilities and availability (rollout %) of those capabilities in one location/sub location (whatever makes sense in terms of an existing homogeneous capability landscape). Out of scope are architecture, technology stack, service levels, application names, source of the applications (build vs. buy) and infrastructure. Applications are only used in an abstract way like application classes e.g. "Manufacturing Execution System (MES)". Application roadmaps, stability and architecture changes are only considered if they add/remove capabilities.
- **Assessment:**
  The FINCA model has to be assessed and filled by the business owner of a site or sub-site, usually supported by business domain experts, FI domain experts and FI business analysts. Business process experts and FI business analysts are in charge to keep the normalization of all dimensions (the grid) up to date, so the comparison independent of manufacturing levels or region is always possible.

The FINCA Model consists of seven dimensions and several sub categories. Each dimension can achieve a value from level zero (low capability) to level four (maximum in terms of desired capability). An overview of the dimensions is given in Fig. 1. Every dimension is described more precisely with the number of sub categories that are to be rated during the assessment. While all levels are separately defined, they follow a general guideline with different maturity levels. The different levels are depicted as a knowledge pyramid in Fig. 2. The foundation of the pyramid is "Stabilization & Standardization" and goes up to "Automated decisions":

- **Stabilization & Standardization:** Process is according to standard and running stable. First, local data collection is in place.
- **Connection:** Data sources are connected, standardized and can be accessed globally.
- **Information:** From data to visualized information, e.g. KPIs and cockpits. System processes data to gain information and to create transparency.
- **Knowledge:** Classification of events based on information that may lead to triggered actions or automatic generation of proposals for action.
- **Prediction:** Predict future events by simulation, machine learning or complex mathematical/statistical models.
- **Automated decisions:** Autonomous systems base their decisions on anticipated events and an awareness for their environment.

To score a sub category, certain criteria have to be taken into consideration. They are called differentiators. Those differentiators are specific features and their existence (or their extend) in a factory can be used to rate a capability.

For example, the differentiator "tool connectivity" can be used to rate the APC/FDC (Advanced Process Control / Fault Control and Classification) capability of a site. The tool connectivity determines to a great deal the amount of data that is available in the first place to allow for process control and monitoring.

As some factories do not have a consistent level e.g. some lines have more automation capabilities than other lines in the same factory, the level of a sub category can be broken down into multiple rollout scenarios. As some machines in a factory have a better connectivity than others a coverage/distribution/rollout percentage factor has to be applied. For example, if 80% of a factory's machine park has an availability of 50% of the critical parameters covered in APC/FDC (equals level four) and 20% is connected but has a coverage below 50% (equals level three), the overall rating for this sub category is $(80 \cdot 4 + 20 \cdot 3)/100 = 3.8$.

Not always all five levels are available, in that case only existing levels as per description have to be used.

Once each sub category has a calculated value based on the differentiators and the distribution of coverage across the levels, the overall dimension level is to be calculated as the average (non weighted) of its sub categories levels.

In the following, the capability categories and their sub-categories are presented. An overview of the capability categories is given in Fig. 1.

4.1 Workflow Automation

Workflow automation has seven sub-categories

- Deviation Management System
- WIP Routing (Workflow, Lot Route, ...)
- Exception Management (Workflow)
- Subcon [External] / Inter Site [Internal] Management
- Small Lot Size Mastering [Lot Size 1]
- High Automation Load & Go
- Experiment Management System for Sample and Engineering Lots

The definition of the levels is given in table 1.

4.2 WIP Flow Management

WIP flow management has five sub-categories

- Forecasting for Volume
- Dispatching
- Scheduling
- Work Area Control
- Capacity Planning

The definition of the levels is given in table 2.

4.3 Process Control Automation

Process control automation has eleven sub-categories

- Documentation & Documents
- Dynamic Parameters
- Check Sheets
- Work-In-Progress Data
- Sampling & Buyoff
- Recipe Handling
- Process Time Window / N2 Cabinet
- Statistical Process Control (SPC)
- Statistical Bin Analysis/ Automatic Lot Release
- Advanced Process Control/ Fault Detection and Classification
- Metrology

The definition of the levels is given in table 3 and 4.

4.4 Manufacturing Data Management

Manufacturing data management has eight sub-categories

- Master Data Systems Availability
- Master Data Systems Change/ Release
- Master Data Static Systems Accuracy
- Master Data Dynamic Systems Accuracy
- Operational Production Reporting
- Aggregated Reporting
- Data Analysis
- Lot Release

The definition of the levels is given in table 5, 6, 7 and 8.

4.5 Material Handling

Material handling has three sub-categories

- Storage & Retrieval System
- Transport & Delivery System
- Loading System [Robotics]

The definition of the levels is given in table 9.

4.6 Material Identification and Tracking

Material identification and tracking has nine sub-categories

- Product (WIP)/ Device (Lot, Strip, Chip) Identification, Validation & Traceability
- Production Material & Wafer Material Identification, Validation & Traceability
- Tool Identification, Validation & Traceability
- Carrier / Container Identification, Validation & Traceability
- Equipment Identification & Validation
- Operator Identification & Validation
- Non-Productive Products / materials / tools [durables] / Equipment
- Unified Material Mapping
- Split & Merge

The definition of the levels is given in table 10 and 11.

4.7 Equipment Automation

Equipment automation has six sub-categories

- Equipment Interface
- Equipment Data
- Automated Setup/Change Over
- Equipment Health Monitoring
- Maintenance
- Input loading/ Output loading

The definition of the levels is given in table 12 and 13.

5 APPLICATION OF FINCA TO SEMICONDUCTOR FRONTEND AND BACKEND MANUFACTURING SITES

The FINCA model has been tested by semiconductor production experts of the Infineon Technologies AG. The model has successfully been applied as internal benchmark. The results were used to identify best practices and lead factories in certain areas. Next steps for development of the sites could be identified.

As an example for the application of the model the aggregated results of one frontend and one backend site the Infineon Technologies AG are discussed. The aggregated outcomes are shown in Fig. 3. The axis have been rescaled, but still allow for a relative comparison and discussion.

The semiconductor frontend is relatively advanced in terms of Industrie 4.0. Frontends of the Infineon Technologies AG have a very high degree of automation. The Infineon site in Dresden is the 200mm-wafer-size frontend with the highest degree of automation [11]. Traditionally, backends have a lower degree of automation which can also be seen in this example. Still, backends are catching up as rising wages and energy prices in low cost manufacturing locations put semiconductor manufacturers under pressure [9].

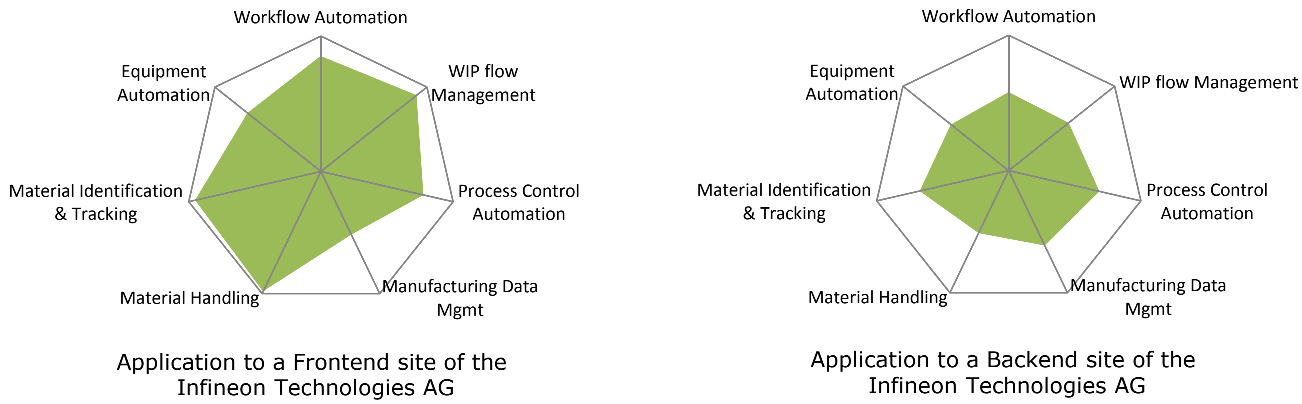

Figure 3: The FINCA model applied to a frontend manufacturing site and a backend manufacturing site. The axis are uniformly rescaled and do not show the absolute results of the model. A relative comparison is still valid.

According to a McKinsey & Company analysis Industrie 4.0 offers just the right tools for these productivity gains in backend [9].

Digitalization in capital-intensive frontends has started in the early 1980s. The early introduction of Manufacturing Execution Systems (MES) has lead to legacy systems in production. The learning from the frontend MES could be applied to the backend where introduction started significantly later. This difference can be seen in the FINCA dimension Manufacturing Data Management: The frontend site scores relatively low, while this is a strong dimension for the backend. This reflects the effort at the backend sites in the recent years to introduce a solid foundation for digitalization.

The assessment has provided useful insights for the next steps at both sites. Best practices or tools at different sites could be identified and transferred to other manufacturing locations.

6 CONCLUSION

In this paper we presented an assessment and roadmap for Industrie 4.0 for both frontends and backends. The FINCA model has been successfully applied at Infineon Technologies AG. It has proven itself to be a useful tool at evaluation and roadmapping for future improvements.

With this publication the authors want to foster the exchange with science as well as other semiconductor companies. In science, the FINCA model can be used as guideline how semiconductor manufacturers envision manufacturing in the future. The FINCA model assists researchers to find open challenges and problems. New technologies and approaches from science can help semiconductor manufacturers to reach new levels of productivity and quality.

The authors want to use the FINCA model to exchange with other semiconductor companies on their vision of Industrie 4.0 for semiconductor manufacturing. Furthermore, the assessment can be used for manufacturing benchmarks with other semiconductor companies.

FINCA was developed for semiconductor manufacturing. Still, we think the general model is also valid for other manufacturing industries. It is especially suitable for job shop production systems with large amounts of standardized products. The authors invite other industries to apply and test the model in their scope and welcome the exchange of experiences with FINCA.

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A APPENDIX

Level 0	Level 1	Level 2	Level 3	Level 4
Deviation Management System **Differentiators:** Detection [Auto / Manual], Containment [Auto / Manual], Release [Auto / Manual]				
Process to handle deviation is defined, paper recording of deviation, no deviation system in place	Manual detection with auto hold, auto detection with manual hold (standalone), manual detection with manual hold	Auto detection with defined action / containment for quality and yield areas (auto hold)	Following harmonized containment action through standardized deviation flow at FE / BE	Auto detection with auto hold for non quality related areas, integration of FE-BE deviation systems (BE: List down three Lots before and after if problem detected)
WIP Routing (Workflow, Lot Route, . . .) **Differentiators:** Decision [Auto / Semi Auto / Manual], # of Criteria [Single, Multiple]				
Rule defined	Manual decision by line personnel	Manual decision by engineers	Automated proposal by system but decision by human (Eg: Subcon selection based on load)	Automated proposal by system and decision by system (Eg: Path selector)
Exception Management (Workflow) **Differentiators:** Decision [Auto / Semi Auto / Manual], # of Criteria [Single, Multiple], Complexity [simple, complex models], Traceability				
Rule defined, no traceability of decision making	Manual decision, simple models	Manual Decision, simple models, traceability of decision making	Automated proposal by system but decision by human (Eg : Subcon selection based on load), complex models, traceability of decision making	Automated proposal by system and decision/execution by system (Eg: Path Selector), complex models, traceability of decision making
Subcon [External] / Inter Site [Internal] Management **Differentiators:** Data Transfer [paper, File Transfer], Visibility [Black Box, Sub Operation, Sub Step], Data availability				
Data exchange through paper	Data exchange through file transfer (in & out info)	Data exchange through file transfer for sub step info (Eg: Subcon operation points)	Data exchange through file transfer for sub step, process & equipment info	Subcon MES is fully integrated to company MES (including reporting), real time view of lot status, real time deviation control
Small Lot Size Mastering [Lot Size 1] **Differentiators:** Data Transfer [paper, File Transfer], Visibility [Black Box, Sub Operation, Sub Step], Data availability				
FE: Full wafer cassette processing, BE: Standard lot size (e.g. 25 Wafer) process for all processes	FE: No full wafer cassette processing, BE: Standard lot size (e.g. 25 Wafer) process for certain processes	FE: Compound Lot, BE: Sub Standard Lot size (e.g. Magazine)	FE: - , BE: Lead frame lot size process	Die level lot size process.
High Automation Load & Go **Differentiators:** Loading [Auto / Semi auto / Manual]				
Manual loading	Manual loading linked with MES	Semi auto loading linked with MES	Auto loading [with manual robot feeding], linked with MES	Auto loading [Full automation], linked with MES

Table 1: Workflow Automation

Level 0	Level 1	Level 2	Level 3	Level 4
Experiment Management System for Sample and Engineering Lots **Differentiators:** Number of capabilities (auto split/merge lot, recipe name and parameter overwriting, APC overwriting, . . .), Existence of an experiment management system				
Manual creation & release, manual maintenance, fixed/static alternate item (Route, Bill of Material, Tool plan...) upon release, no experiment management system	Fixed Route upon release, existing experiment management system, basic capabilities (routing, equipment/equipment-setup/tools)	Fixed route upon release some capabilities		Flexible route editing after release all capabilities
Forecasting for Volume **Differentiators:** Data Feed [Manual / Auto], Frequency, Scope [work center / line / factory], Method [Simulation / Mathematic Formula] **FE:** Simulation & mathematical optimization, **BE:** Mathematical optimization				
Manual data feed, weekly forecasting, work center forecasting manual reporting	Manual data feed, daily forecasting, work center forecasting, manual reporting	Semi-automatic data feed, 6hrs - 8hrs forecasting, line forecasting, manual Reporting	Semi-automatic data feed, 6hrs - 8hrs forecasting, whole factory, auto reporting	Automatic data feed, 4hrs - 6hrs forecasting, whole factory, auto reporting
Dispatching **Differentiators:** Integrated line control [one system apply to whole supply chain], Compliance [work center / line / factory], Flexibility [rules definition by Equipment / Work center/ line], Timeliness				
<50% Compliance	>50% Compliance	>80% Compliance	>90% Compliance	100% Compliance [Fully Automated], real time, integrated line control, full flexibility
Scheduling **Differentiators:** Integrated line control [one system applied to whole supply chain], Compliance [work center / line / factory], Flexibility [rules definition by Equipment / Work center/ line], Timeliness, Data integrity, Scope [lot start / whole line]				
Paper recording of creation/update schedule (fixed time, volume based)	System recording of creation/update schedule (fixed time, volume based), system warning of maintenance due	System warning of creation/update due, system stop of maintenance due (integrated to MES)	Automated predictive creation/update	Automated creation/update schedule based on capacity optimization (integrated to resource, tools, spare parts demand, WIP)
Work Area Control [Radar] **Differentiators:** Users [Operator / Supervisor / Engineers], Scope [work center, Line, Equipment], Information [4M - Man, Machine, Method, Material], Timeliness, View consolidation [One View, Multiple, easy access, mobility]				
View of critical line control information at the equipment	Snap-shot dashboard (multiple views) of critical line control information (all systems)	Snap-shot dashboard(1 view) of critical line control information (all Systems)	Real-time dashboard (multiple views) of critical line control information (all systems)	Real-time Dashboard (1 view) of critical line control information (all systems)
Capacity Planning				
Manual	Single Work Center only (Bottle Neck), manual	Multiple Work Center & Line, manual	Complete factory level, manual and partial auto	Complete factory level, auto

Table 2: WIP Flow Management

Level 0	Level 1	Level 2	Level 3	Level 4
Documents **Differentiators:** Paper / paperless, Search for correct Doc, Revision management				
Paper documents on equipment, manual search for the correct document (standalone), manual control to display the latest revision	Paperless documents on equipment, manual search for the correct document (standalone), manual control to display the latest revision	Paperless documents on equipment, semi automated search for the correct document (non integrated/standalone), manual/automated control to display the latest revision	Paperless document on equipment, automated search for the correct document (integrated - one transaction), manual control to display the latest revision	Paperless document in system, automated search for the correct document (integrated - one transaction), automated control to display the latest revision
Dynamic Parameters **Differentiators:** Paper / paperless, Search for correct Document, Revision management				
Paper documents on equipment, manual search for the correct info (standalone), manual control to display the latest revision	paperless documents on equipment, manual search for the correct info (standalone), manual control to display the latest revision	Paperless documents on equipment, semi automated search for the correct info (non integrated/standalone), manual/automated control to display the latest revision	Paperless info on equipment, automated search for the correct info (integrated - one transaction), manual control to display the latest revision	Paperless info in system, automated search the correct info (integrated - one transaction), automated control to display the latest revision
Check Sheet (Reminder to check tasks, anti-mix, Setup Yield, Test Program) **Differentiators:** Paper / Paperless / Online control, Validation				
paper check sheet with no validation	paper check sheet with validation, four eyes validation	paperless check sheet with validation, four eyes validation, defined ranges	paperless check sheet with validation, four eyes validation, defined ranges, warning/hold if out of range	online control
WIP Data (Equipment Data Collection, Lot Info) **Differentiators:** Paper / paperless /online control, Validation				
paper WIP data collection	paperless WIP data collection	paperless WIP data collection with validation, defined ranges	paperless WIP data collection with validation, warning/hold if out of range	online control [auto collection of WIP data]
Sampling & Buyoff (Products) **Differentiators:** Paper / paperless / nothing, Triggering, Sampling Type [Static / Dynamic]				
paper based, manual triggering, static sampling, 100% sampling rate, execution [manual]	paperless, manual triggering, static sampling, fix sampling rate, execution [manual]	paperless, automated triggering, static sampling, fix sampling rate, execution [manual]	paperless, automated triggering, static sampling, fix sampling rate, execution [automated]	paperless, automated triggering, dynamic sampling, execution [automated]
Recipe Handling (Tester recipe, Handler recipe, Assembly Recipe) **Differentiators:** Recipe Release, Recipe select / download, Recipe Validation [Body check]				
manual select from local m/c, manual adjustment after download	semi auto select from local m/c, manual adjustment after download	manual download of recipe from central storage, manual adjustment after download	semi automated download of recipe from central storage, manual adjustment after download	automated download of recipe from central storage (one transaction), no adjustment after download
Process Time Window / N2 Cabinet (Min / Max time control) **Differentiators:** Data Collection, Data Validation, Decision Making				
no recording	manual recording, manual validation	automated recording, manual validation	automated recording, automated validation [min max]	automated recording, automated validation [pre-warning before and during process], automated decision

Table 3: Process Control Automation, part 1

Level 0	Level 1	Level 2	Level 3	Level 4
Statistical Process Control (SPC) **Differentiators:** Data Collection, Data Validation, Decision Making (Lot Hold/ Tool Stop/ Trigger re-measurement)				
	manual data collection, manual validation, manual decision making	manual data collection, manual validation, automated decision making (lot hold)	manual data collection, automated validation, automated decision making (lot hold)	automated data collection, automated validation, automated decision making (lot hold, tool stop, trigger re-measurement)
Statistical Bin Analysis/ Automatic Lot Release (ALR) **Differentiators:** Data Collection, Analysis level, Validation, Decision Making)				
manual input, h-bin analysis only, manual Defect Density Management System trigger, manual validation	manual input, h-bin analysis only, auto Defect Density Management System trigger, manual validation	manual input, h-bin analysis only, auto Defect Density Management System trigger, automated validation (lot hold)	automated input (from test/handler summary), h-bin & s-bin analysis (offline ALR), manual Defect Density Management System trigger, automated validation (lot hold)	automated input (from test/handler summary), automated analysis of s-bin (ALR), automated Defect Density Management System trigger, automated validation (lot hold)
Advanced Process Control/ Fault Detection and Classification **Differentiators:** Tool Connectivity, Online Reaction, Out-of-Control Action Plan (OOCAP), Regular review process implemented				
tools not connected [no apc data flow]	tool connected [apc data flow], some limits defined, e-mail notification	1st online reaction [tool stop, lot hold, inhibit next lot] has been established with oocap.	50% critical parameters online reaction [tool stop, lot hold, inhibit next lot] has been established with oocap.	>90% critical parameters online reaction [tool stop, lot hold, inhibit next lot] has been established with oocap. Regular review process implemented.
Metrology **Differentiators:** Scope [all measurement], Virtual for level four				
SPC, physical measurement at define time interval	SPC, physical measurement at a control interval [event base]	SPC, physical measurement at a control interval, linked with MES	APC, linked with MES	virtual metrology

Table 4: Process Control Automation, part 2

Level 0	Level 1	Level 2	Level 3	Level 4
Master Data Systems Availability **Differentiators:** Standardization local, Data coverage (compared to overall site's master data content), Timeliness				
non harmonized, no use of global master data sets, only cascade from global to local on call	-	limited local change of global master data sets, 4M (Man, Machine, Method, Material) partially available in MES, batch/delayed cascade of global to local	-	high level of standardization global/local, no local change of global master data sets, 4M (Man, Machine, Method, Material) fully available in MES, global immediately cascade to local
Master Data Systems Change/ Release **Differentiators:** Maintenance [Manual / Auto], Release [Manual / Auto], Personal efficiency of the staff using the system, Capability of mass update automation, Workflow support (new workflow, workflow controlled data + performance management), Flexibility of data entry, Integrated effect analysis capability for change management, Analysis capability, Rollback capability				
manual maintenance/ synchronization/ enrichment, manual release, manual data changes from global planning/product to MES, not connected data structures between global and local (tedious sync), analysis capability not set up, rollbacks are not supported	semi-auto data changes from global planning/product to MES (non assisted)	auto maintenance/synchronization, manual release, mapped data structures between global and local with adaptions and aggregation, ability to do mass-change for global change for non dependency items, ability to do mass-release for global change for non dependency items low level of analysis capability implemented, some manual enrichment of master data locally	semi-auto data changes from global planning/product to MES (assisted), auto enrichment of master data locally high level of analysis capability implemented	auto maintenance/synchronization, auto release, auto data changes from global planning/product to MES, equivalent data structures between global and local (fast sync), ability to do mass-changes for items of dependency, ability to do mass-release for global changes for items of dependency, full rollback capability on mass and individual changes full object dependent level of analysis capability implemented, not required enrichment of master data locally
Master Data Static Systems Accuracy **Differentiators:** Integrity [accuracy / timely]				
low data integrity, no information on integrity available	-	high data integrity, select/pick lists assisted data entry for all available selections	high data integrity, select/pick lists assisted data entry for reduced selections (segment relevant)	high data integrity, information on integrity available (plausibility check) measurable
Master Data Dynamic Systems Accuracy **Differentiators:** Integrity [accuracy / timely]				
low data integrity, no information on integrity available, no aides (pick lists)	select/pick lists assisted data entry generated manual input	high data integrity, select/pick lists assisted data entry generated from static Master Data	-	high data integrity, information on integrity available (plausibility check) measurable, highly consistent with static Master Data

Table 5: Manufacturing Data Management, part 1

Level 0	Level 1	Level 2	Level 3	Level 4
Operational Production Reporting **Differentiators:** Standardization [Local, Global], Flexibility [Fix, flexible], Data Storage [Equipment, Local, Central], Integrity [accuracy / timely], Drill down functionality/capability, Automated report generation, Interlinking with mobile devices				
user generated reports by segment/site/user groups (Business Objects, excel), no standardization of reporting & manually generated, no link to mobile devices	central generated customized reports by segment/site/user groups, no standardization on cluster level - FE & BE, no link to mobile devices	mixture of cluster - wide (FE & BE) and customized reports by segment/site/user groups, no standardization between FE & BE, no link to mobile devices	1. regular report 2. cluster-wide harmonized reports a) same formula, data source b) same tool c) with different level of aggregation 3. no standardization between FE & BE 4. partially interlinking to mobile devices	1. on time 2. harmonized reports between FE & BE a) same formula, data source b) same tool c) with different level of aggregation 3. can be easily customized & automated reporting 4. drill down functionality is available & easy to use 5. interface to manufacturing reporting 6. able to fulfill all levels of reporting from management to engineering 7. fully interlinking to mobile devices
Aggregated Reporting **Differentiators:** Standardization [Local, Global], Flexibility [Fix, flexible], Data Storage [Equipment, Local, Central], Integrity [accuracy / timely], Drill down functionality/capability, Automated report generation, Interlinking with mobile devices.				
user generated reports by segment/site/user groups (bo, excel), no standardization of reporting & manually generated, no link to mobile devices	central generated customized reports by segment/site/user groups, no standardization on cluster level - FE & BE, no link to mobile devices	mixture of cluster - wide (FE & BE) and customized reports by segment/site/user groups, no standardization between FE & BE, no link to mobile devices	1. regular report 2. cluster-wide harmonized reports a) same formula, data source b) same tool c) with different level of aggregation 3. no standardization between FE & BE 4. partially interlinking to mobile devices	1. on time 2. harmonized reports between FE & BE a) same formula, data source b) same tool c) with different level of aggregation 3. can be easily customized & automated reporting 4. drill down functionality is available & easy to use 5. interface to manufacturing reporting 6. able to fulfill all levels of reporting from management to engineering 7. fully interlinking to mobile devices

Table 6: Manufacturing Data Management, part 2

Level 0	Level 1	Level 2	Level 3	Level 4
Data Analysis **Differentiators:** Correlation along the Supply Chain, Usages of multiple relevant data sources/capability, Data completeness & availability, Data accuracy, Data integrity, Access speed, On-line data access, Stability, Handling of high volume data, Robustness & performance capability, Fast & interactive analysis capability/functionality, Coverage in terms of statistical methods (existing/available), Flexible to interact between different software system, Automation capability				
Data correlation along the supply chain is not possible. Data availability for certain facilities along the supply chain. Data completeness & availability poor & not link to analysis system. Low data accuracy with no monitoring capability. No on-line access. Slow performance of data access & unstable software solution. Statistical methods are not state of the art and not standardize within software solution. Handling of high volume data is not possible. Offline analysis software is not aligned between FE & BE. Interaction to other solution system is not possible. No automation capability.	Data correlation within FE or BE supply chain is possible. Data availability for all facilities within FE or BE supply chain. Data completeness & availability moderate & partially linked to analysis system. Low data accuracy with manual monitoring effort. No on-line access. Moderate performance of data access & software solution fulfills for simple analysis tasks. Statistical methods are not state of the art and not standardize within software solution. Handling of high volume data is not possible. Offline analysis software is not aligned between FE & BE. Interaction to other solution system is not possible. No automation capability.	Data correlation within FE or BE supply chain is possible. Data availability for all facilities within FE or BE supply chain. Data completeness & availability good & linked to analysis system. Moderate data accuracy with manual monitoring effort. Low on-line access. Good performance of data access & software solution fulfills for most of the analysis tasks. Statistical methods are state of the art and available in existing non-harmonized software solution. Technology of software system is not state of the art. Handling of high volume data is not possible. Offline analysis software is partially aligned between FE & BE. Interaction to other solution system is partially possible. Low automation capability	Data correlation between FE & BE supply chain is possible. Data availability for all facilities within FE & BE supply chain. Data completeness & availability good & linked to analysis system. Good data accuracy with semi-automated monitoring. Partial on-line access. Good performance of data access & software solution fulfills for all of the analysis tasks. Statistical methods are state of the art and available in existing non-harmonized software solution. Technology of software system is partially state of the art. Handling of high volume data is partially possible. Offline analysis software is partially aligned between FE & BE. Interaction to other solution system is partially possible. Moderate automation capability.	Full Data correlation between FE & BE supply chain. Full Data availability for all facilities within FE & BE supply chain (including relevant data from Silicon Foundry/Outsourcing And Test (OSAT) with reference to contract). Excellence data completeness & availability & fully linked to analysis system. Full on-line access. Excellence data accuracy with fully automated monitoring & reaction to deviations. Excellence performance of data access & software solution fulfills for all of the analysis tasks. Statistical methods are state of the art and within harmonized software solution. Technology of software system is state of the art. Ability to handle high volume data according to requirement. Offline analysis software is fully aligned across FE & BE. Full interaction to other solution system. Full automation capability.

Table 7: Manufacturing Data Management, part 3

Level 0	Level 1	Level 2	Level 3	Level 4
Lot Release **Differentiators:** Data completeness, Data integrity/accuracy, Decision Making, Meet quality requirements, Linkage to other software system (eg. QMP/DDM, archive viewer, Esquare, analysis software …), Automated configuration & handling of different type of configuration, Storage capability, Process reporting & analysis capability, Speed/performance/stability, Inter-site/production capability				
data completeness & availability, poor & no linkage to software system, automated decision making not possible, software system not meeting quality requirement, linkage to other software system not possible, manual configuration & limited in terms of complexity, no storage capability, no process reporting & analysis capability, slow performance & unstable, no inter-site/production linkag, no FE & BE interlinked, no standard software system between FE or BE, no different levels of users administration	data completeness & availability, moderate & limited linkage to software system, automated decision making not possible, software system partially meeting quality requirement, linkage to other software system partially possible, manual configuration & limited in terms of complexity, no storage capability, no process reporting & analysis capability, slow performance & unstable, limited inter-site/production linkage, no FE & BE interlinked, no standard software system between FE or BE, no different levels of users administration	data completeness & availability, moderate & limited linkage to software system, automated decision making not possible, software system meeting quality requirement, linkage to other software system partially possible, semi-automated & handles partially complex configuration, limited storage capability, limited process reporting & analysis capability, moderate performance & stable, limited inter-site/production linkage, no FE & BE interlinked, partially harmonized software system for FE or BE, no different levels of users administration	data completeness & availability, good & full linkage to software system, automated decision making partially possible, software system meeting quality requirement, linkage to other software system available, semi-automated & handles partial complex configuration with limited FE & BE linkage, good storage capability, good process reporting & analysis capability, good performance & stable, partial inter-site/production linkage, partial FE & BE interlinked, harmonized software system for FE or BE, different levels of users administration partially available	data completeness & availability, excellence & full linkage to software system, fully automated decision making based on established rules, software system meeting quality requirement, linkage to other software system available, automated & handles fully complex configuration with FE & BE linkage. excellence storage capability excellence process reporting & analysis capability, excellence performance & stable, full inter-site/production linkage, fully interlinked FE & BE, harmonized software system across FE & BE. different levels of users administration fully available

Table 8: Manufacturing Data Management, part 4

Level 0	Level 1	Level 2	Level 3	Level 4
Storage & Retrieval System **Differentiators:** Manual/ Assisted / Auto, Manual record/ Standalone / Link to MES, Link to Transportation System				
			automated storage & retrieval system, linked to MES, no link to transport system, (FE: stocker)	automated storage & retrieval system, linked to MES, linked to transport system, (FE: stocker)
Transport & Delivery System **Differentiators:** Manual / Auto Transport System, Standalone / Link to Storage System, Link to Dispatching System, To Drop Point / Equipment, Link to Scheduling System				
			automated transport system (conveyer, AGV), linked to MES, linked to storage system, to drop point / Equipment	automated transport system, (conveyer, AGV, Automated Material Handling System), linked to MES, linked to storage system, to drop point / Equipment, linked to scheduling system
Loading System [Robotics] **Differentiators:** Manual / Auto Transport System, Standalone / Link to Storage System, Link to Dispatching System, To Drop Point / Equipment, Link to Scheduling System				
				auto link to MES [closed loop] & scheduling

Table 9: Material Handling

Level 0	Level 1	Level 2	Level 3	Level 4
Product (WIP)/ Device (Lot, Strip, Chip) Identification, Validation & Traceability **Differentiators:** Level [Lot/ Device / Wafer / Strip / Chip], Identify [Manual / Semi Auto / Auto], Validate [Type, ID, Shelf Life, Floor Life], Trace [Manual / Semi Auto / Auto], Equipment Internal wafer tracking				
manual identification on lot level, manual validation of in/out-quantity	automated identification on lot level , manual validation of in/out-quantity	automated identification on lot level, magazine, reel, FE: automated identification on wafer level, automated validation of in/out-quantity	Automated identification on strip level, FE: automated identification on wafer level, automated validation in/out - quantity, equipment internal wafer tracking	automated identification on strip level, automated identification on single device level after simulation, automated validation on strip and single device level, FE: chip level traceability [only applicable for some process steps]
Material consumption & Wafer Material Identification, Validation & Traceability **Differentiators:** Identify [Manual / Semi Auto / Auto], Validate [Type, ID, Shelf Life, Floor Life], Trace [Manual / Semi Auto / Auto]				
manual identification (sticker), manual recording (paper), manual validation (BOM, floor life, shelf life)	manual identification (sticker), manual recording (system), auto validation (BOM, floor life, shelf life)	semi auto identification (barcode), semi auto recording (barcode), auto validation (BOM, floor life, shelf life)	semi auto identification (barcode), automated recording (m/c reader), automated validation (Equipment : BOM, floor life, shelf life)	automated identification (Equipment : RFID/barcode), automated recording (m/c reader), automated validation (Equipment: BOM, floor life, shelf life, consumption)
Tool Identification, Validation & Traceability **Differentiators:** Identify [Manual / Semi Auto / Auto], Validate [Type, ID, Life span, Maintenance cycle], Trace [Manual / Semi Auto / Auto]				
manual identification (sticker), manual recording (paper), manual validation (group, ID)	manual identification (sticker), manual recording (system), automated validation (group, ID)	semi auto identification (barcode), semi auto recording (barcode), automated validation (group, ID)	semi auto identification (barcode), automated recording (m/c reader), automated validation (group, ID)	automated identification (EG : RFID/barcode), automated recording (m/c reader), automated validation (group, ID, lifespan)
Carrier / Container Identification, Validation & Traceability **Differentiators:** Identify [Manual / Semi Auto / Auto], Validate [Type, ID, Life span, Maintenance cycle], Trace [Manual / Semi Auto / Auto]				
same as above				
Equipment Identification & Validation **Differentiators:** Identify [Manual / Semi Auto / Auto], Validate [Type, ID, Life span, Maintenance cycle], Trace [Manual / Semi Auto / Auto]				
same as above				

Table 10: Material Identification and Tracking, part 1

Level 0	Level 1	Level 2	Level 3	Level 4
Operator Identification & Validation **Differentiators:** Identify [Manual / Semi Auto / Auto], Validate [qualify / not qualify], Trace [Manual / Semi Auto/ Auto]				
manual identification, manual recording (paper), manual validation (certification)	manual identification, manual recording (system), auto validation (certification)	semi auto identification (manual login + barcode), semi auto recording (barcode), auto validation (certification)	semi auto identification (single sign-on), automated recording, automated validation (certification)	automated identification (Equipment: RFID) automated recording (Equipment : M/C reader) automated validation (certification)
Non Productive Products / Materials / Tools [durables] / Equipments **Differentiators:** Identify [Manual / Semi Auto / Auto], Validate [Type, ID, Life span, Maintenance cycle, Floor life, Shelf Life], Trace [Manual / Semi Auto / Auto]				
manual identification (sticker), manual recording (paper), manual validation (BOM, floor life, shelf life)	manual identification (sticker), manual recording (system), auto validation (BOM, floor life, shelf life)	semi auto identification (barcode), semi auto recording (barcode), auto validation (BOM, floor life, shelf life)	semi auto identification (barcode), automated recording (M/C reader), automated validation (Equipment : BOM, floor life, shelf life)	automated identification (eg : RFID/barcode), automated recording (M/C reader), automated validation (Equipment : BOM, floor life, shelf life, consumption)
Unified Material Mapping **Differentiators:** Scope [Full / partial supply chain]				
no identification	standalone system, partial supply chain implementation, manual identification	standalone system, partial supply chain implementation, auto identification	linked with MES, partial supply chain implementation, auto identification	linked with mes, full supply chain implementation, auto identification
Split & Merge **Differentiators:** Compliance [Manual / Auto], Execution [Manual / Auto]				
no rules applied	rules in place, manual validation of rules by line personnel	auto validation by system	auto splitting by system	auto merging by system according to defined rules

Table 11: Material Identification and Tracking, part 2

Level 0	Level 1	Level 2	Level 3	Level 4
Equipment Interface **Differentiators:** No Connection / Serial / Ethernet, File Transfer/ SECS/GEM / Interface A				
no connection	serial / GPIB / USB, file transfer, legacy protocol	SECS/GEM - serial port, (min 9600 baud rate - low data bandwidth)	SECS/GEM - ethernet (HSMS - high speed SECS messaging services, high data rate - 10mb/sec) SECS/GEM, Interface A (extreme high data rate - > 100mb/sec)	
Equipment Data **Differentiators:** Status [Up/Down], Event [Alarms / Start / Stop], Parameter [Input / Output], Result [Pass / fail], Frequency [Real time for the smallest Unit]				
status - up/down (tower light), event - alarm (within equipment), result - complete cycle/stop, parameter - internal view only	status - signal from equipment to external, event - limited pre-set list (manual selection), result - complete cycle/stop, parameter - internal view only	status - SECS/GEM, event - unlimited alarm list from equipment, result - complete cycle/stop, parameter - RMS capable, tool start/stop	status - SECS/GEM, event - automated alarm list from equipment, result - complete cycle/stop, parameter - RMS & APC (input/output) capable, tool start/stop	
Automated Setup/Change Over **Differentiators:** Triggering [Auto / Manual], Identification [Auto / Manual], Change over [Auto / manual]				
mechanism - manual, tool - manual, lot management - no, recipe - no	mechanism - manual, tool - manual, lot management - manual key in lot ID, recipe - manual recipe selection	mechanism - auto change by recipe control, tool - manual, lot management - scan ID, lot ID, recipe - RMS manual download	mechanism - auto change, tool - auto change, lot management - by host control, recipe - RMS auto download	mechanism - auto change, tool - auto change, lot management - by host control, recipe - RMS auto download, automated release [inline buy off], automated calibration, automated parameter adjust
Equipment Health Monitoring **Differentiators:** # of critical parameters to be monitored, Availability				
no monitoring, indicator / counter only	monitoring [snap shot], only equipment status, simple health monitoring on machine (eg: timeout: servo motor and communication within the equipment)	monitoring [snap shot], equipment status & critical alarm, equipment with intelligent sensor to provide local heath monitoring - equipment related	monitoring [snap shot], equipment status, critical alarm & critical parameter, real time APC, health data from machine used to have intelligent process control - offline and not real-time (end of a day)	monitoring [real time], equipment status, critical alarm & critical parameter, linked with lot ID, real time APC, health data from machine used to have intelligent process control - offline and real-time (every lot)

Table 12: Equipment Automation, part 1

Level 0	Level 1	Level 2	Level 3	Level 4
Maintenance **Differentiators:** Reactive, Proactive, Preventive, Predictive, Assisted Maintenance, Close Loop, Maintenance Monitoring				
run to fail [break down]	time & volume based maintenance, fixed schedule / volume	time & volume based maintenance, fixed schedule / volume, integrated to SAP, equipment with intelligent sensor to provide local heath monitoring - equipment related, advice what needs to be changed before critical failure	time & volume based maintenance, integrated to SAP & MES	predictive modeling, automated scheduling based on production situation e.g. loading, integrated to SAP & MES
Input loading/Output loading (only backend) **Differentiators:** Batch size, Validation Capability				
single input / single output loading, manual validation	batch loading at input & output manual validation		batch loading at input & output, auto validation, support automated loading/unloading (Automated Material Handling System, AGV, overhead track	robotic handling)

Table 13: Equipment Automation, part 2