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Self-assessment of an 5S Audit in Semiconductor Manufacturing

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Abstract: The 5S audit is known as troublesome as it evaluates how the 5S practice is implemented on the shopfloor with respect to thousands of continuous improvements. This study applies a novel sustainable benchmarking framework that assists practitioners in understanding their current position and to make continuous improvements with priority on the self-assessment of a 5S audit for a semiconductor fabrication plant (fab). This study applies the novel 5S-Failure Modes and Effects Analysis (5S-FMEA) framework to categorize findings in the 5S audit and subsequently justify the 5S-Risk Priority Number (5S-RPN) for a fab. The self-assessment result for a 5S audit can be transformed from qualitative statement into a quantitative evaluation to examine and prioritize all descriptive failure modes (findings) on a 5S audit. Practitioners can stepwise apply the proposed 5S-FMEA and 5S-RPN to their self-assessment of a 5S audit in a closed-loop Plan-Do-Check-Act (PDCA) cycle. This is the first attempt to evaluate (check) and prioritize (act) descriptive failure modes (findings) of 5S-FMEA using the quantitative approach of the 5S-RPN for semiconductor manufacturing. A case study demonstrates the feasibility and robustness of the proposed model.

Key words: Self-assessment, semiconductor fabrication, 5S audit, failure modes and effects analysis, risk priority number

INTRODUCTION

Semiconductor fabrication plants (fabs) have the most complex manufacturing system, capital-intensive assets and processing technology in the electrical industry. The cleanroom of a 300 mm fab is roughly 750,000 square feet-the equivalent to 13 football fields-with a capacity of 130 K wafers per month. As contamination, hazards, and hazardous situations must be avoided due to the demanding yield and complex equipment in state-of- the-art facilities, fabs must merge strategic safety, health and the environment (SHE) into Total Quality Management (TQM) for loss prevention. The practice of Structurize, Systematize, Sanitize, Standardize and Self-discipline (5S) is a straightforward and effective tool for managing workplaces (Ho, 1998). Moreover, the 5S practice is aimed at housekeeping and SHE (O'hEocha, 2000; Gapp *et al*., 2008; Kobayashi *et al*., 2008). The Plan-Do-Check-Act (PDCA) cycle is a conceptual framework for developing and creating improvements. However, two important problems are usually neglected by practitioners when the 5S practice is implemented in a fab: findings in a 5S audit are usually presented in descriptive statement (check) and all audit findings are equally severe with the same occurrence (act). Previous studies of the 5S practice focused the "plan" and "do" components of 5S activities (e.g., commitment from top management and the 5S campaign and audit) (Ho, 1998; Ahmed and Mohiuddin, 2005; Gapp *et al*., 2008; Korkut *et al*., 2009). Based on Deming's PDCA cycle, this study reveals the missing parts in 5S practice as "check" and "act" which are filled by the proposed 5S-Failure Modes and Effects Analysis (5S-FMEA) and 5S-Risk Priority Number (5S-RPN) that are applied to successfully implement the 5S practice (Fig. 1). In current industrial practices, action items for the 5S practice (e.g., top-management commitment, self-inspection of the current position and training workshops) have focused on "plan" and "do," which is a drawback for a robust 5S practice. Hence, the proposed 5S-FMEA and 5S-RPN were initially constructed based on shop floor observations of industrial practices to add "check" and "act" in Deming's PDCA cycle to our study.

One problem is "check", in that action items of the 5S practice can number in the thousands; in contrast, findings in a 5S audit are vital and few, usually presented in descriptive statements. The FMEA has long been an established and reliable engineering application for design, safety, testability and related functions (Eti *et al*., 2007; Kutlu and Ekmekcioglu, 2012). The FMEA bridges the gap between design characteristics and the

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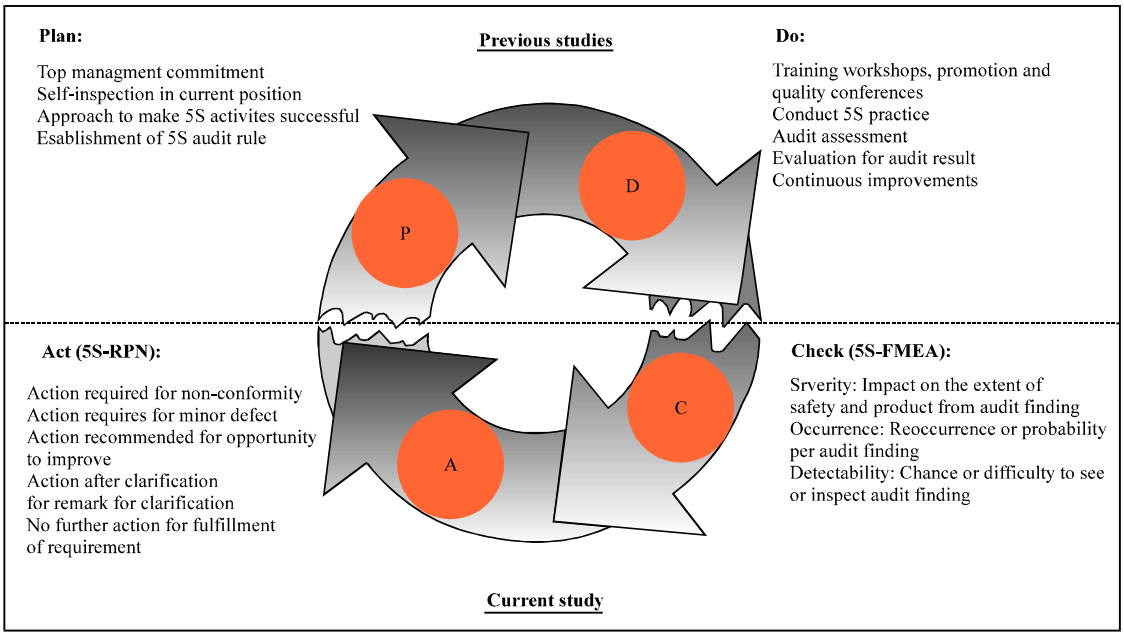


Fig. 1: Enhancement of PDCA closed-loop for 5S practice

planned manufacturing process to meet both requirements and expectations (Yadav *et al*., 2006; Karim *et al*., 2008; Zhang and Chu, 2010). Thus, the novel 5S-FMEA uses the concept on "check." For instance, failure mode of "pipeline leak" from 5S audit findings lacks specific criteria because "leak" is an adjectival statement to describe 5S finding from one auditor to another. The baseline of failure modes (findings) is not measurable and not objectively aligned for comparison with multiple quality attributes. The proposed 5S-FMEA systematically identifies and differentiates critical failure modes (resulting in quality dissatisfaction) into defined categories based on specific criteria for required remedial actions.

The other problem is "act." The 5S audit evaluates potential failure modes (findings) of the 5S practice and the response to 5S findings is based on the assumption that all audit findings are equally severe with the same occurrence. Moreover, remedial efforts for audit findings are not financially and practically equal. Hence, practitioners should take appropriate corrective actions to reduce potential for occurrence by using occurrence (O) and detectability (D) in line with severity (S) criteria from the Risk Priority Number (RPN) that ranks corrective actions when failure modes (findings) are identified (Su and Chou, 2008; Chuang, 2010). The RPN is a structural measure used when assessing risk to help identify critical failure modes associated with a design or process (Prasad, 1991). Hence, the proposed 5S-RPN approach based on the algorithm of the generic RPN is used to translate 5S findings (usually descriptive statements) into quantified and prioritized corrective actions. That findings can be fixed with prioritized corrective action is practical and realistic. Otherwise, actions to correct non-prioritized findings could be endless. By this proposed model, for example, the computed score by the 5S-RPN of "poor coating"-photoresist bubbles dispensed on a wafer-is tentatively 64 based on its severity score of 2. Thus, the wafer theoretically requires rework with an occurrence score of 4 (assumed probability of 0.001) and a detectability score of 8 (usually caught in After Develop Inspection (ADI)). This case of "poor coating" requires a specific corrective action (e.g., software upgrade or specification revision).

This study focuses on the scope of "check" and "act" in 5S-FMEA to evaluate (check) the findings of a 5S audit and subsequently apply the 5S-RPN to quantify (act) descriptive failure modes (findings) for a fab. Hence, this study uses "check" and "act" to effectively implement the prioritized 5S practice in a closed-loop PDCA cycle, such that practitioners can stepwise apply the 5S-FMEA and 5S-RPN to their self-assessment of a 5S audit. As action requests for the 5S practice are associated with resource constraints (e.g., due date and available manpower/budgets), taking corrective actions can be prioritized by 5S-FMEA and the 5S-RPN.

LITERATURE REVIEW

Manufacturing Integrated Circuits (IC) on silicon wafers is a complex production process. Roughly 200-500 different types of equipment are required to produce a complex circuit. Typically, a 0.15 μm wafer processed by a fab goes through approximately 750 steps (workstations) among the over 1,000 pieces of equipment in the fab. Figure 2 presents the partial layout of a semiconductor fabrication line (Kim *et al*., 2007). Investments in equipment in a fab are higher than those in most other industries; a set of equipment can cost up to -25 million. Because of increases in manufacturing complexity, controlling systems in the case of fault detection is important (Johnzen *et al*., 2007). The 5S practice is part of the foundation of a lean manufacturing. In Janke's study of a Qimonda 300 mm fab, ongoing lean transformation, including the 5S practice, resulted in a 40% cycle time reduction with shorter development cycles and faster delivery of new products to customers (Janke and Kuschereitz, 2009). Hence, the 5S practice is essential to lean manufacturing and the 5S audit can monitor and control fault detection.

Auditing plays a critical role in quality and risk assessment (Dereli *et al*., 2007; Hernandez, 2010; Alic and Rusjan, 2011). The scope of an audit covers all business processes such as management responsibilities, product performance management, process/equipment control and production line management (Chrysler, 1998; ISO/TS 16949:2002, 2002; Hernandez, 2010). The major purpose of an audit is to further ensure that auditees can offer products with no "surprises" (e.g., timely delivery) and to identify the continuous improvements undertaken. An organization typically strives for commitment in quality recognition and safety standards by a series of quality assessments and improvements with quality confirmed by its customers (Hersey, 1998; Hernandez, 2010). Practically, a series of internal audits is conducted by internal auditors in an organization prior to an external audit from a second party, i.e., customer or third party such as the International Organization for Standardization (Chrysler, 1998; Pheng, 2001).

The 5S audit is a key item in production line management during the process of auditing quality and safety. For instance, ISO/TS16949 sections 6.4, 7.1, 7.5, 8.1 and 8.3 clearly state that production line management is in the scope of ISO/TS16949 (ISO/TS 16949:2002, 2002). Consequently, a fab can claim conformity to this quality standard and section requirements. Quality certification is then granted. Customers often expect that their products (wafers) are produced by a "clean," "lean" and even

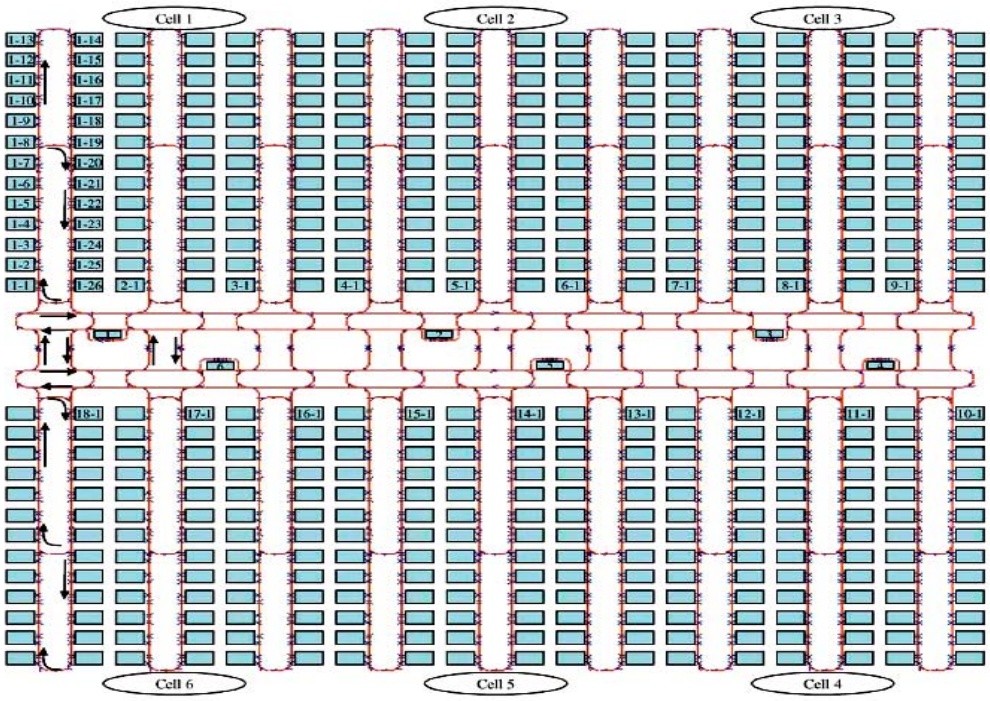


Fig. 2: A sample fab line (Kim *et al*., 2007)

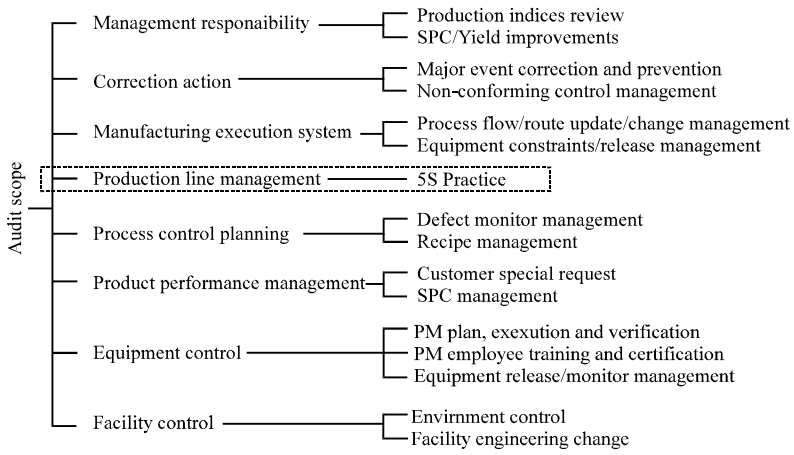


Fig. 3: Scope of audit

Fig. 4: Procedures of 5S audit

"green" manufacturing process in a hazard-free environment. For example, a typical 28 nm process (also called the 28 nanometer half-node) has over 1,500 manufacturing processes (workstations/machines) and tens of chemicals in the cleanroom of a fab. Cleanroom condition (i.e., Class 100) is necessary for this extra-pure manufacturing process to ensure that the wafer and its mask (customer's property) are not contaminated with process media, usually resulting from explosive, toxic and inflammable chemicals. A class 100 cleanroom is designed such that no more than 100 particles (0.5 microns or larger) exist per cubic foot of air. Hence, a line audit is extremely broad in a customer audit (Fig. 3) and the 5S audit is a comprehensive assessment of loss prevention, safety, and quality.

To successfully pass a 5S production-line audit, an official steering team is needed and the audit will use the following procedures (Fig. 4). Usually, a notice of the 5S audit will be first issued by the auditor (internal quality assurance department or external customer) and preparation time will be given to the auditee. After a production line is 5S audited, the auditor issues a 5S audit report to the auditee. The auditee reviews the audit and follows up with corrective actions. Finally, the 5S audit report is retained for continuous improvements. When auditors assess the shopfloor in a cleanroom, they have their own 5S checklist or a blank piece of paper to record their audit. For example, they look to see whether 5S campaigns or posters are present; whether the auditee's fab has implemented the 5S practice, including goals and planned actions; whether the 5S training program is frequently promoted and whether a Polyvinyl chloride (PVC) curtain is used to prevent particle contamination when equipment is installed. They also check the cleanness of equipment, labelling on gauges, tools and wafer and mask handling. Hence, the 5S audit, a random behavior that checks or detects very few findings from thousands of 5S action items, depends on auditors' experiences, preferences, attention, or concerns.

PROPOSED METHOD

As stated in the previous section, the 5S practice is not easily managed. Compared with the thousands of 5S action items for a fab, findings in a 5S audit are few. When auditors analyze a production line, they assume thousands of 5S action items have been done without excuse. A typical large-scale fab has over 1,500 machines with over 5,000 accessory facilities in a cleanroom of 750,000 square feet. Thus, the 5S practice is difficult to implement. To identify and evaluate findings, the 5S-RPN approach for self-assessment by 5S-FMEA is proposed for a 5S audit. First, 5S-FMEA is adopted from FMEA. Then, the 5S-RPN is used as an analytical technique that facilitates the identification of potential failures (findings) in the workplace by examining the effects of audit findings by 5S-FMEA. To prioritize each failure mode finding, the 5S-RPN is computed with assigned values for S, O and D

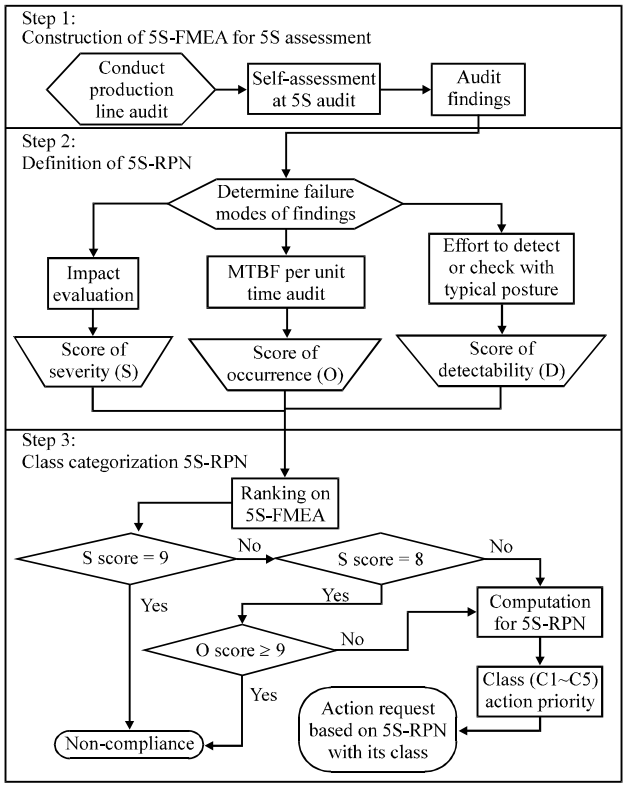


Fig. 5: Decision flowchart for 5S-RPN on 5S-FMEA

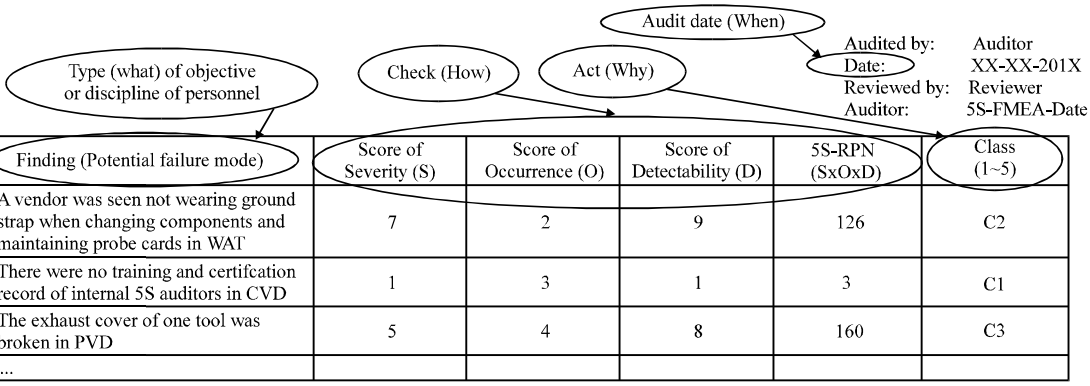
Audited by: Auditor
Date (When): XX-XX-201X
Reviewed by: Reviewer
Auditor no: 5S-FMEA-Date

Type (What) or Personnel (Who)	Location (Where)	Score (1~5; minor~unacceptable)
A vendor was seen not wearing ground strap when changing components and maintaining probe cards	In Wafer acceptance test (WAT) area	5
There were no training and certification record of the 6S auditors	In Chemical vapor deposition (CVD) area	2
The exhaust cover of one tool was broken	In Physical vapor deposition (PVD) area	3
...		

Fig. 6: Typical worksheet of self-assessment for 5S audit

in the 5S-FMEA. Last, this study quantifies failure modes (findings) using quantitative criteria by ranking of 5S audit findings into correspondent classes. Figure 5 shows the decision flowchart for applying the 5S-RPN approach to the self-assessment by 5S-FMEA of the 5S audit.

Step 1: Construction of 5S-FMEA for 5S assessment: Auditors conventionally use an audit table listing the type (what), personnel (who), location (where) and date (when) of findings to record non-conformance using scores ranging from 1 (minor) to 5 (unacceptable). Figure 6 presents an audit table with typical examples. However, this table simply lists findings and it may cause bias in overestimating or underestimating the effort required for a remedial action under resource constraints. For example, one finding (e.g., floor stain) does not mean that it is not server without action request. The finding should be further examined by occurrence and detectability to give a practitioner a correct priority from measurable criteria. Hence, 5S-FMEA is integrated with "how" and "why" based on the who-when-where-why-what-how (5W1H) method to eliminate ambiguity in the statement of findings. "How" means how severe, frequent, or detectable a finding is per audit. "Why" is



Finding (Potential failure mode)	Score of Severity (S)	Score of Occurrence (O)	Score of Detectability (D)	5S-RPN (SxOxD)	Class (1~5)
A vendor was seen not wearing ground strap when changing components and maintaining probe cards in WAT	7	2	9	126	C2
There were no training and certifcation record of internal 5S auditors in CVD	1	3	1	3	C1
The exhaust cover of one tool was broken in PVD	5	4	8	160	C3
...					

Fig. 7: 5S-FMEA worksheet of self-assessment for 5S audit

why a finding occurred. With the disclosure of "how" and "why", the reasons underlying a finding can be traced and practitioners can prioritize their decision for action items. Since findings range from trivial (e.g., a stain on equipment) to vital (e.g., a blocked fire door), all findings must be differentiated based on their severity. Thus, 5S-FMEA worksheet of self-assessment for the 5S audit is created as a platform (Fig. 7) and "check" in PDCA from 5S-FMEA can transform vague findings into promising directions for action requests. This 5S-FMEA worksheet contains audit findings (potential failure modes) and the possible effect(s) of failure(s) with respect to S, O and D as well as the 5S-RPN associated with their defined class. The worksheet provides a comprehensive summary of prioritized 5S action items based on the 5S-RPN and classes. From the 5S-RPN of each finding, the "how" and "why" in 5S-FMEA can be identified and controlled.

Step 2: Definition of 5S-RPN: One can further evaluate all findings checked or detected by the 5S-FMEA with respect to S, O and D. As findings are descriptive and sometimes vague statements, qualitative findings must be quantified based on specific rules with certain performance metrics to prioritize action requests. In this step, the 5S-RPN is applied to generate a weighted value for each finding on 5S-FMEA, such that "act" in PDCA can be prioritized relative to resource constraints. In the proposed method, the 5S-RPN is determined as the product of weights from S, O and D. Thus, the rule of evaluation for weights and criteria of S, O and D is defined with typical examples and it is explained in the next subsections. Some numbers cannot be a 5S-RPN from 1 to 1,000. For example, 17 cannot be a 5S-RPN because it is a prime number that is larger than 10 and it cannot be multiplied using three numbers from 1 to 10. Long stretches of numbers cannot be 5S-RPNs. For example, no number in the range of 901-999 is a 5S-RPN. The detailed definition of S, O and D is as follows.

Definition of severity (S): The S score is evaluated first. In terms of the 5S audit, the severity of safety or product performance is the key indicator to judge the severity of a finding. A finding is viewed as extremely severe as a result of findings related to SHE or a customer property for a wafer or mask. In other words, dominant descriptions of high severity levels are hygiene problems related to SHE issues or these wafers/masks are scrapped. As the description for severity is as linguistic statement containing subjective or adjectival wordings, the linguistic statement of a finding is transformed into a number on a numerical scale based on severity of safety or product performance. Additionally, all linguistic statements and their effects are differentiated based on a numerical evaluation into 10 categories of severity (Table 1) because severity is a subjective estimate of how severe an auditor will perceive the effect of a finding (failure). For example, the word "terrible" is derived from a safety issue or non-compliance with government regulations and is assigned a weight of 9 or 10; the S score is the severity of a finding. The S score is an integer between 1 and 10; the most severe is 10.

Definition of Occurrence (O): The second input is the O score. Occurrence, sometimes called probability, is an objective estimate of likelihood. Once a cause is identified, it produces a failure mode and its particular effect. The O score is based on the frequency with which a cause (or failure finding) will occur. In the computation of evaluating O score, the O score is the numerical frequency with which potential defect(s) or risk(s) will occur in an audit. The O score is rated against the probability that the effect occurs as a result of a failure mode. The O score is

Table 1: Evaluation rule for weights and criteria of Severity (S)

Weight of Severity	Linguistic level	Criteria of evaluation (Impact on safety, quality and reliability)	Severity of effect on safety/product	Typical example
10	Terrible	Heavy contamination, safety / hazardous issue or noncompliance with government regulation due to dangerous environment	Affect safety and product operation or involve noncompliance with government regulation without warning	Wafer/probe card exposed to contamination OR blocked fire door/chemicals improperly stored & without labeled
9			Affect safety and product operation or involve noncompliance with government regulation with warning	
8	Critical	Significant disruption or minor injury to personnel due to non-fnnctionality of system	Result in total loss of final product function or minor injury to personnel	Measurement instruments/devices not sorted, arranged, stored and labeled OR anything too close to fire extinguisher
7			Partially meet product specification but some dies may fail product application or minor injury to personnel	
6	Serious	Noticeable impact to quality due to deterioration of system performance or inappropriate layout	Result in subsystem or partial malfunction of the product (e.g. product outliner) or minor injury to personnel.	Supplying pipes/ belts greasy, dirty or cracked OR floor with any drops, cracks or variation in level
5			Affect partial yield but can be reworked or re-screened on wafer(s) or cause minor injury to personnel	
4			Minor product performance loss or cause minor injury to personnel yet able to be eliminated with modifications of process	
3	Minor	Little impact to product quality or no injury to personnel due to minor system damage of system performance or nndesired equipment appearance	Result in minor performance loss and can be reworked on wafer(s) usually without scrap or cause injury to personnel	Shelves or storage areas marked without location indicators and sponsors OR tools/parts being stored incorrectly
2			Treat as a minimal and able to be corrected without impacts on product performance or cause no injury to personnel	
1	Negligible	No impact to product quality or safety concern	No discernible effect at all on wafer(s) or safety	Annoying noise, vibrations and heat/cold

on a linear scoring scale (accumulated number of failure counts) for the occurrence of failure modes associated with the frequency of an occurrence per audit. The quantified evaluation is straightforward for the O score (Table 2). Total counts of occurrence for the same finding in an audit period is the major factor for the O score in any audit. For example, the weight of occurrence is 9 or 10 based on total counts of occurrence in the case that repetitive findings have been found = 5 times within 1 h or the same number of occurrences are found in longer than a 1 h audit per audit. In another example, the O score is 9 when the same finding occurs = 5 times within a 1 h audit; the Mean Time Between Failure (MTBF) of the same incident (failure mode) is <12 min. An O score is an integer between 1 and 10; the highest score is 10.

Definition of Detectability (D): The last input is the D score. In the auditing process, detectability is the certainty with which a finding (failure) will be detected or checked. The D score is rated as the ability to detect or check the effect of a finding or the ability to detect or check the finding itself. Evaluation criteria of a finding are associated with the effort needed to detect or check a finding with a typical posture (Table 3). For example, an auditor will assess whether a First-In-First-Out (FIFO) inventory system for a Photoresist (PR), a chemical coated with a thin film on a wafer, is implemented. Based on the detectability from an auditor's viewpoint, the auditor assesses that detectability is moderately low. The reason is that the FIFO mechanism will be detected unless the door of the PR cabinet is intentionally opened using a key, as in the criteria of "What you GAZE or CLOSELY LISTEN TO is what you get." Detectability requires an auditor to expend effort to detect or check a finding (find a key to open the door and inspect the FIFO mechanism). Other typical postures for detecting or checking are raising the head, bending down, or lying on the ground. The D score is an integer between 1 and 10; the easiest finding to detect or check is 10.

Computation for 5S-RPN: The 5S-RPN is the product of the three individual component weights for S, O and D,

Table 2: Evaluation rule for weights and criteria of Occurrence (O)

Weight of Occurrence	Description of Probability	Criteria of evaluation (Findings per unit time audit)	Probability of the same finding	MTBF of the same finding	Quantified rule
10	Frequent	5 times or above of occurrence within 1 hour audit	>1/2	Less than 12 min	Persistent failures of the same have been noted in several relevant findings within one hour shopfloor audit
9		5 times or above of occurrence per more than one hour audit	1/2	Span between 12 and 15 min	Five times or above occurrences of the same failure have been noted in several relevant findings per more than one hour shopfloor audit
8	Probable	4 times of occurrence within 1 hour audit	1/10	Less than 15 min	Repetitive 4 occurrences of the same failure have been noted in several relevant findings within one hour shopfloor audit
7		4 times of occurrence per more than one hour audit	1/20	Span between 15 and 20 min	Repetitive 4 occurrences of the same failure have been noted in several relevant findings in more than 1 h shopfloor audit
6	Occasional	3 times of occurrence within 1 hour audit	1/40	Less than 20 min	Occasional failures have been noted in several relevant findings within one hour shopfloor audit. If procedures are followed, the finding of potential failure is relatively minimal
5		3 times of occurrence per 1~2 hours audit	1/80	Span between 20 and 30 min	Occasional failures have been noted in several relevant findings per 1~2 hours shopfloor audit. If procedures are followed, the finding of potential failure is minimal
4		3 times of occurrence per more than 2 hours audit	1/400	Span between 20 and 30 min	Occasional failures have been noted in several relevant findings per more than 2 h shopfloor audit. If procedures are followed, the finding of potential failure is very minimal
3	Remote	Twice of occurrence per audit	1/1000	Less than 30 min	Relatively few failures of the same finding have been noted twice per shopfloor audit
2		Once of occurrence per audit	1/4000	Less than 60 min	Relatively few failures of the same finding have been noted once per shopfloor audit
1	Improbable	None of occurrence per audit	<1/4000	Not applicable	The same failure has never been noted in any relevant findings, yet theoretically possible happening

Table 3: Evaluation rule for weights and criteria of Detectability (D)

Weight of Detectability	Detectability on finding	Criteria of evaluation for the finding	Description of effort to detect or check the finding with typical posture	Typical example
10	Completely certain	What you SEE, HEAR, or TOUCH is what you get.	Auditor does it without thinking to find the fault by an inactive effort to sense with eyes, ears or hands. (i.e. immediately see the fault, hear the noise, or touch the defect without too much effort once stepping on the workplace)	Easily to see any tools, spare parts, materials left on the floor at anywhere
9			Auditor easily sees or hears the fault when just walking around	Walking around to see persounel not dressed appropriately and prepared
8	Almost certain	What you LOOK AT or CLOSELY HEAR is what you get	Auditor does it within a shorter time to examine the fault or must raise or lower head usually in standing position	An active effort to look at designated walkways / stairs not free of dirt, oil, grease and dust
7			Auditor does it within a short time to examine the fault or must raise or lower head usually in standing position	An active effort to look at labels and signs not clean, current and broken
6	Moderate	What you WATCH or LISTEN TO is what you get	Auditor must want to do it but it is for a long period of time or must bend down to find the fault	Bend knees to watch needed items without convenient location or without visually designated homes for tools
5			Auditor must want to do it but it is for a longer period of time or must bend knees	Watch cleaning materials and tools not easily accessible
4	Low		Auditor makes an active effort in the sense of "to intentionally watch" usually lying on the ground	Lying on the ground to watch underneath equipment and work stations not kept clean and free of oil, grease and debris
3		What you GAZE or CLOSELY LISTEN TO is what you get.	Auditor looks steadily for a long time or needs to use tools to observe inside the equipment or to uses keys to check inside the cabinet	Uncover a lid to closely check connections (e.g. wires, hoses, belts, covers, lids) inside the equipment not in place and tight
2			Auditor must critically notice or carefully listen to the finding if the fault exists	Listen to vibration buzzing inside the equipment
1	Completely undetected	What you OBSERVE or READ is what you get.	Auditor is hardly able to detect or check the fault. Or questionable fault must go through an experiment or measurement to clarify the dispute	Observe unidentified purpose of liquid in the bottle used by a technician, which needs further confirmation . Or read suspicious Standard Operation Procedure (SOP) instructing staudard working guideline, which triggers further clarification

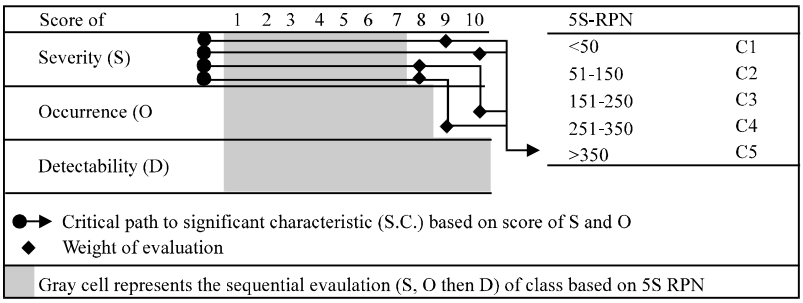


Fig. 8: Quick reference to determine significant characteristics

Table 4: Class of 5S-RPN and corresponding action request

5S-RPN (S×O×D)	Class (Action priority)	Characteristic	Action request
<50	C1	Fulfilment of requirement	No further action
51~150	C2	Remark for clarification	Action after clarification
151~250	C3	Opportunity to improve	Action recommended
251~350	C4	Minor defect	Action required
>350	C5	Non-conformity	Action required

and provides a priority for taking action-as the 5S-RPN increases, the importance of addressing a defect (failure) increases. For instance, the 5S-RPN is 60 (i.e., 6×5×2) when, say, S = 6, O = 5 and D = 2. The 5S-RPN is not a measure of risk, but of risk priority. The 5S-RPN is used by a practitioner to direct limited resources to the most important problem. A high 5S-RPN means that an action request is high priority-with exceptions explained in the next section; therefore, the practitioner should work on a fault with a 5S-RPN of 600 before allocating resources to fix a problem with a 5S-RPN of 60.

Step 3: Class categorization of 5S-RPN: Once all 5S-RPN scores are assigned to findings (failure modes) on the 5S-FMEA worksheet, they can be further categorized into five classes with corresponding actions (Table 4). Based on the categorized classes, subsequent prioritized actions can be identified and triggered. The 5S-FMEA of an audit report will be provided to allocate findings into five classes: Non-conformity; Minor Defect; Opportunity to Improve; Remark for Clarification; and Fulfilment of Requirement. Non-conformity is a non-compliance issue with safety or government regulations. A Minor Defect has an adverse impact on quality, but can be eliminated by continuous improvement. Opportunity to Improve is any opportunity for continuous improvement to a quality system. Remark for Clarification requires further clarification of a single event and is reported to the auditor. Fulfilment of Requirement exists within requirement specifications. The thresholds to differentiate between classes should be periodically revisited and realigned to ensure that the range of 5S-RPNs fits the classes of desired characteristics with their action request.

Since very high scores for S and O and a very low score for D will generate very low 5S-RPNs, 5S-RPN thresholds between classes should not be used as the primary trigger for definition of recommended actions. For example, a score of 72 (i.e., S = 9, O = 8 and D = 1) will be classified as a Remark for Clarification with Action after Clarification. However, this result will mislead a practitioner and bias the action request. Hence, this study designed two exception rules that surpass the generic rule when evaluating 5S-RPNs (Fig. 5). The two exception rules are regarded as Significant Characteristic (SC) which is exempt from the evaluation of the 5S-RPN. The two exception rules (SC) are treated directly as Non-conformity with "action required" after findings have been filled in the 5S-FMEA worksheet. In our extensive experience, S and O are the two dominant factors when determining the SC. For one exception rule, the S score of 9 or 10 means heavy contamination and safety/hazardous issues or non-compliance with government regulations. Thus if and only if the S score is 9 or 10, this finding is viewed as catastrophic and Non-conformity and is given the highest priority for immediate remedial actions. For the other exception rule, O at = 5 times for the same finding per audit is exceptionally high (MTBF is about 12 min). Thus, if and only if S = 8 and O = 9 or 10, the finding is also Non-conformity with "action required." Figure 8 shows a quick reference to determine the SC. The critical paths to the SC are only based on S and O scores. The grey area without the SC represents the sequential evaluation (S, O, then D) of class based on the 5S-RPN. Therefore, practitioners can justify their prioritized action request simply based on S and O.

CASE STUDY

Here, the integrated framework of 5S-FMEA and the 5S-RPN was applied to a real case of a new 300 mm fab in Taiwan. This company has hundreds of customers, ranging from Integrated Device Manufacturers (IDMs) to fabless design companies. It operates many foundries worldwide and has been certified by ISO 9001, ISO 14001, OHSAS 18001 and other management systems. The company is committed to maintaining excellence in safety and quality and has dedicated itself to sustaining a culture of continuous ensure customer satisfaction as well as workplace safety. Top managers of this company give their full support to all of its fabs to make the 5S practice successful.

As 5S-FMEA and the 5S-RPN were constructed with their algorithm, how to successfully implement them in a practical manner can be determined. The following excerpts are from an actual self-assessment for an 5S audit of this fab (Fig. 9). Each excerpt demonstrates the review procedure of the 5S-RPN and action priority based on the 5S-FMEA worksheet for self-assessment, such that practitioners can mimic the procedure and stepwise apply it from the 5S self-assessment.

Example A: Some dirty wipers used by cleaners were left in a can in the cleanroom and this could affect wafer quality:

- **Severity analysis:** The linguistic statement was "serious" and this finding might generate customer complaints since it may adversely affect quality; however, such a defect could be recovered by continuous improvement. The S score is 6 since this finding directly impacted the product (wafer) with respect to wipers potentially re-used by the cleaner
- **Occurrence analysis:** The occurrence for this finding was 3 times in this 1.5 h audit; the approximate MTBF for same finding was 20-30 min. The finding was "occasional" and its O score was 5
- **Detectability analysis:** Since an auditor had to bend down to detect this finding, the D score was 6. This finding followed the criteria of "What you WATCH or LISTEN TO is what you get," required to auditor to watch closely for this finding

The 5S-RPN for Example A was 180 (6×5×6) with a class of C3 that was characterized as Opportunity to Improve. The action request was "action recommended" to prevent any source of particles in the short term and provide a "double-check" box for wiper usage in the Standard Operating Procedure (SOP), such that a cleaner avoids possible re-usage of dirty wipers in the long term.

Example B: The vacuum pump control panel was installed close to the floor near an operator terminal in the Gate-oxidation Area, increasing the risk of accidental damage or inappropriate settings:

- **Severity analysis:** The linguistic statement was "terrible" since this finding was non-compliance with government regulations and endangered operators without warning; the S score was 9
- **Occurrence analysis:** The occurrence of this finding was 1 in this 1 h audit. It was considered a "remote" occurrence; the O score was 2

Audit finding (Potential failure mode)	Score of severity (S)	Score of occurrence (O)	Score of detectability (D)	S-RPN (SxOxD)	Class (1~5)
Some dirty wipers used by cleaners were left in a can in the cleanroom and this could affect wafer quality	6	5	6	180	C3
The vacuum pump control panel was installed close to the floor near an operator erminal in the Gate-oxidation area, increasing the risk of accidental damage or inappropriate settings	9	N/A	N/A	S.C.	C5
In the wafer testing area, the floor had a protective layers that appeared to be too dirty for carts. Also, these carts had small pieces of debris on top of the carts when some probe cards were temporarily stored on the carts	8	9	N/A	S.C.	C5
...					

Fig. 9: 5S-RPN on 5S-FMEA for the audit report

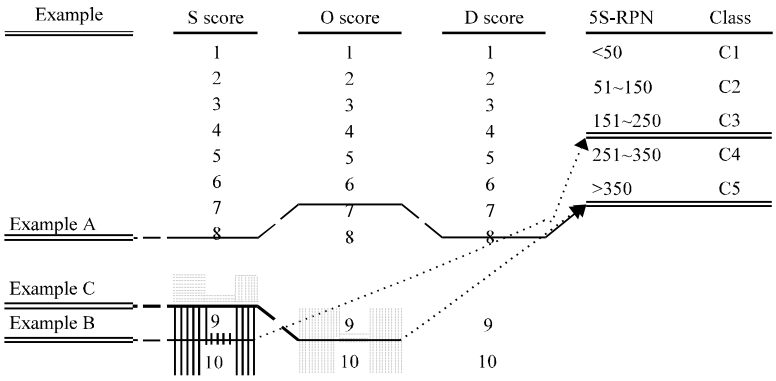


Fig. 10: A decision tree for three examples associated with their classes

- **Detectability analysis:** The D score was 2 because an auditor had to notice this finding by examining the vacuum pump control panel

Without consideration of the SC, the class of Example B would be C1 from the 5S-RPN of 36 (9×2×2). However, the class of the 5S-RPN should be revised to C5. According to the quick reference to determine the SC (Fig. 8), this case has an S score of 9 or 10 for non-compliance with government regulations. It was treated directly as Non-conformity with "action required" regardless of its 5S-RPN score. To avoid misoperation, the panel was temporarily covered inside a protection box before all panels were completely replaced with new panels. The action request was "action required."

Example C: In the Wafer Testing Area, the floor had a protective layer that appeared to be too dirty for carts. Also, these carts had small pieces of debris on top of the carts when some probe cards were temporarily stored on the carts.

- **Severity analysis:** The linguistic statement was "critical" since it would result in the loss of the primary function of wafers (customer's product). The S would be scored 8 because debris adversely affected wafers. Moreover, particles were dropped onto the surface of the wafer and probe card (i.e., an integrated circuit wafer testing device incorporated into probing equipment to test finished wafers). This finding would result in total loss of final product function and adversely affect final product reliability or yield
- **Occurrence analysis:** The occurrence of this finding was 6. It was "frequent" and the O score was 9. This high number was due to annual Preventative Maintenance (PM) without good operational skills and discipline of technicians
- **Detectability analysis:** Since this finding required the auditor to lie on the ground, the D score was 4

Although the class for Example C would be classified as C4 from the 5S-RPN score of 288 (8×9×4), the class was re-examined while considering the SC. The combination of the *S* score of 8 and O score of 9 exactly followed the critical path to SC (Fig. 8) (i.e., any *S* score of 8 with an O score of 9 or 10 is directly treated as Non-conformity with "action required"). Hence, it was re-characterized as class C5, Non-conformity, from C4. The action request was "action required" for C5 by giving a standard PM workbook to prevent technicians from failing to clean and assigning each workplace to dedicated staff to clean places most people fail to notice.

Based on the decision tree (Fig. 10), a structural decision for examples A, B and C was obtained. A decision tree was made for these three examples. Each tree was associated with their classes to understand how the 5S-RPN can be used to make an action request.

DISCUSSION

Deming's PDCA cycle is a conceptual and managerial framework for improvement and development. Based on the PDCA cycle, the motivation to solve the problem of prioritizing 5S action items first revealed that the missing parts of "check" and "act" were integrated into the proposed 5S-FMEA and 5S-RPN. Many studies have focused on the management and benefits of the 5S practice and implementation plans. However, few studies have examined how to quantify and prioritize 5S action items from audit results to technically implement the 5S practice. Traditional self-assessment of a 5S audit is conducted in linguistic mode to record and evaluate 5S findings. The action requests per audit result are difficult

to determine technically or objectively and to subsequently manage due to inconsistent and non-compliant viewpoints among auditors. The proposed method, 5S-FMEA and the 5S-RPN, with three examples shows that prioritizing 5S action items can technically follow reliable and practical rules for wafer manufacturing.

When implementing 5S-FMEA, the S, O and D must be carefully addressed with respect to technical descriptions. First, the S score associated with safety should be high during a ramp-up stage as many chemicals are used in semiconductor manufacturing, and most are dangerous (i.e., toxic, poisonous, corrosive and volatile. Any accident can cause a catastrophic result such as human injury, death, or ecological disaster. By the time a fab's management standards become mature (e.g., meeting ISO 9001, ISO 14001 and OHSAS 18001), findings concerned with wafer yield are regarded as decisive because wafers are the only product and the fab's baseline, especially with respect to safety, is already above international standards. This implies that the criteria for S depend on the status of the 5S practice and must be technically reviewed and periodically justified to retain their flexibility and robustness. The criteria associated with S scores are set by each fab.

Second, the O score is solely determined by the MTBF of the same finding (Table 2). Although the MTBF is a number with a time unit (minutes), the duration of the MTBF is proportionally justified according to quantity of auditors per audit. In a normal 5S audit, a fab is audited by more than one auditor. For example, the MTBF duration will be <6 min for two auditors, not <12 min for one auditor, with the same weight, 10, for the same finding. Thus, as the number of auditors increases, the MTBF proportionally decreases. Last, in industrial practice the criteria of D do not differ from one fab to another as fabs have similar layouts and equipment clusters (i.e., array assembly process). Hence, arguments for the evaluation of S and O scores imply that a fab should technically and dynamically adjust the criteria for S and O.

RECOMMENDATIONS

The problem of prioritization in a self-assessment of the 5S audit was solved by 5S-FMEA and 5S-RPN for semiconductor manufacturing. Thus, a practitioner can allocate resources to the right pace. However, future work can address two major challenges. One is the industrial scope by this proposed model and the other is prioritization of multiple findings in each class. For the former, the current study only targeted a fab and the criteria for S, O and D may not be the same in other high-tech industries (e.g., computer assembly line, chemicals manufacturers and pharmaceutical firms) and should be technically based on layouts, infrastructures, or manufacturing processes. Therefore, empirical analysis of other industries will complete research findings. For the latter, the action request in each class can be determined. However, two or more 5S-RPNs that can yield the same value still need to be technically differentiated for ranking. Bowles (2004) pointed out that the conventional RPN, though well documented and easy to apply, is seriously flawed from a technical perspective. Problems with methodology include the presence of holes making up a large portion of the RPN measurement scale, duplicate RPN values and varying sensitivity to small changes. Thus, investigations of the 5S-RPN, especially ranking associated with the same score, can be make the proposed model more complete.

CONCLUSIONS

Readiness for a 5S shopfloor audit plays an important role in the audit process. To fulfil the completeness of the PDCA cycle for the 5S practice, this study applied the novel 5S-RPN approach to the self-assessment of 5S-FMEA with three examples for evaluating (check/how) and prioritizing (act/why) each finding (failure mode) in a 5S audit under limited resources. The 5S-FMEA worksheet for a 5S audit, S, O and D criteria and the 5S-RPN approach show that prioritizing 5S action items from different auditors with identical experiences, preferences, attentions, or concerns can follow reliable and practical rules to sustain continuous improvements under resource constraints on a 5S audit for a wafer manufacturer.

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