Deployment of an FMEA-Integrated Framework to Improve Operational Performance in Semiconductor Manufacturing: A Case Study

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Abstract. The failure mode effect analysis (FMEA) aims to strengthen the operational performance of a process of a product. However, current FMEA practice does not quantify the achievement in operational performances. Risk priority number (RPN), the only success indicator of FMEA, is independent of operational performance monitoring. Thus, the capability of FMEA to strengthen operational performance may be ineffectual unless it demonstrates a quantifiable improvement in operational performance. This study offered guidelines for manufacturing industry to quantify the operational performance within the FMEA methodology by operational performance indicator (OPI). In tandem with RPN, the OPI in FMEA ascertains the priority set by RPN and defines more refined priority than RPN. Design for manufacturing and assembly (DFMA) and Poka-yoke provide systematic guidelines for developing corrective actions for eliminating or reducing the occurrence of failure while strengthening current control to prevent the delivery of any non-conformance to customers. Application of the new FMEA-based integrated framework in a semiconductor manufacturer in Malaysia demonstrated that 69.2% improved the overall equipment efficiency (OEE).

1. Introduction

Failure mode and effect analysis (FMEA) aims to improve operational performance (OP) of a product or process [1]. However, risk priority number (RPN), a product of severity (S), occurrence (O), and detection (D), is the only indicator of FMEA, has no relationship with operational performance (Puente et al., 2002). RPN can be improved by reducing S, O, or D due to three risk factors are weighed equally. For instance, RPN can be reduced by reducing D, which is a solution for containing failure [2]. However, the OP, such as defect rate or scrap cost, may not decrease. Thus, the capability of current FMEA practice to improve OP cannot be validated unless it demonstrates a quantifiable operational improvement [3].

Operational performance indicator (OPI), which is an accurate indicator to quantify the OP of a product or process, can be used to determine the success of FMEA in tandem with RPN [4]. The priority of goal of corrective action in FMEA is to eliminate the occurrence of failure and enhance current control [2] [5]. Both OPI and RPN can be improved concurrently by optimising the product design [2], which, in turn, is correlated with the occurrence of failure [3]. In reality, design modification is not always
feasible due to manufacturing constraints, cost concerns, or rigid customer requirements. Thus, an alternative approach is to develop a more effective error-proofing system for preventing delivery of non-conformance to customers [2] [6]. Design for manufacturing and assembly (DFMA) and Poka-yoke provide systematic guidelines for optimising design and developing a more robust error-proofing system.

DFMA is the amalgamation of design for manufacturing (DFM) and design for assembly (DFA) [7] to increase manufacturability and reduce assembly difficulty [7-8]. DFM streamlines and standardises the design and manufacturing activities of a product concerning the integration of function, form, or fabrication [9-10]. DFA simplifies the product and enhances assembly quality by minimising part count and integrating parts based on function [9]. Poka-yoke is an error-proofing method for preventing the occurrence of failure or facilitating error detection [6]. Poka-yoke has two approaches [10], which are: (1) preventive-based, a control method for stopping the process whenever the error that creates the failure is encountered; and (2) detection-based, a warning method for preventing non-conformance from flowing to the downstream process.

This paper presents a framework for improving FMEA by integrating the OPI, DFMA, Poka-yoke with FMEA. This paper is organised as follows. Section 2 presents the methodology of the proposed integrated framework. Section 3 presents the case study, which is used to validate the new integrated framework. Section 4 discusses the implementation results. Section 5 concludes the paper.

2. Methodology
A new integrated framework, namely FODP framework is constructed by integrating the methodology of FMEA, OPI, DFMA, and Poka-yoke. As shown in Figure 1, the proposed FODP framework consists of 10 steps. Details of each step are discussed below.

Step 1: Team formation – form a cross-functional team to work towards a common goal.
Step 2: Scope and function establishment – determine the scope to establish the boundaries of the initiative. Consequently, understand how the product or process functions within requirements.
Step 3: Process flowchart – provide a logical and visual depiction for better visualisation and comprehension of the entire assembly or manufacturing processes to be analysed.
3. Case Study

The FODP framework was validated in company S, a semiconductor manufacturer located in Ipoh, Malaysia. Product B, an integrated circuit (IC), was selected to demonstrate the FODP framework. Product B encountered low overall equipment efficiency (OEE), which is the product of yield, equipment availability, and equipment performance [11]. The application of FODP framework is intended to increase the OEE.

A multi-discipline team was formed. Consequently, process flow chart (Figure 2) was constructed for illustrating the process and its function in the testing department. Table 1 showed that for before improvement, the electrical testing process had the lowest yield, availability, and OEE. Further equipment downtime analysis before improvement (Table 2) showed that the significant downtime was relevant to the test contactor, which constituted the test probe and elastomer, as shown in Figure 3(a). FMEA analysis results were summarised in Table 3. The process of electrical testing, vision and tape and reel, and visual inspection had the same RPN. However, the electrical testing process had the highest priority for improvement due to it had the highest criticality in pre-OPI. The test probe connects the IC and printed circuit board. The elastomer disseminates the spring force to test probe to prevent the damage of IC and reducing the wear of test probe, which, in turn, leads to a longer lifespan. However, after specific insertions, the elasticity of elastomer started deteriorating, which eventually lead to the lower spring force. Test probe started deforming (Figure 3b) with lower spring force. Thus, the underperformed test contactor resulted in: (1) higher yield loss due to weak contact established between IC and the printed circuit board; and (2) higher equipment downtime for frequent test contactor maintenance.
The current underperformance test contactor was resulted by the inappropriate profile design and coating material. Two modifications were subsequently proposed to enhance current test contactor, which is: (1) modified the test probe profile for higher spring force and longer lifespan, as shown in Figure 3(c). The need of elastomer could be eliminated by the enhancing the spring force on the new test probe; and (2) coated a layer of durable alloy on test probe for reducing the cleaning frequency by minimising the solder migration. The new test contactor prolonged the cleaning and lifespan. However, routine maintenance, such as cleaning and replacement were still required due to the test contactor is a consumable part. Current manual control of manually monitoring the yield and tracking the insertion was automated by developing a system. When the yield and insertions hit the predefined limit, the system automatically stops the equipment for the operator to conduct the routine maintenance.

Table 1 and 2 (after improvement) show that the test contactor significantly improved the OEE and equipment downtime with a new profile and coating material. As shown in Table 3, by the same corrective actions reduced the RPN from 280 to 24. By comparing the OEE before and after improvement, the OEE of an electrical testing process was improved from 45.7% to 82.7%.

4. Discussion
The FODP framework successfully quantified the OPI before and after the improvement. Furthermore, by comparing the OPI before and after improvement, the success of FMEA initiative was qualitatively quantified in term of operational performance. The FODP framework ascertained the electrical testing process as the most critical process due to it has the highest criticality in RPN and OPI. Besides improving the RPN and OPI, the modification of test probe profile also simplified the test contactor design by eliminating the need of elastomer. However, routine maintenance, such as cleaning and replacement were still required due to the test contactor is a consumable part. Thus, a new system was developed to automate the manual yield monitoring and lifespan tracking process.

5. Conclusion
By applying the OPI in tandem with RPN in FODP framework, the applicability of FMEA is improved in few aspects: (1) the success of FMEA is quantified in operational performance by comparing the OPI before and after improvement; (2) besides RPN, the priority that is determined for improvement is also
critical in OPI; (3) the corrective actions are planned to improve the RPN and OPI by mitigating or reducing the occurrence of failure; (4) the effectiveness of corrective actions in OPI is assured before and after the implementation. The orientation toward OPI improvement and the conformance of results arising from the FODP framework are demonstrated through the case study.

Table 1. Average yield, availability, performance, and OEE for two consecutive weeks.

| OPI        | Before improvement | Simulation | After improvement |
|------------|--------------------|------------|-------------------|
|            | ET     | VTR | VI  | ET     | VTR | VI  | ET     | VTR | VI  |
| Y (%)      | 70.8   | 98.7 | 99.4 | 92.5   | 98.3 | 98.4 | 94.0   | 98.4 | 98.9 |
| A (%)      | 65.7   | 85.0 | 86.0 | 80.7   | 84.4 | 85.5 | 83.7   | 84.7 | 85.8 |
| P (%)      | 98.3   | 98.6 | 98.8 | 98.3   | 98.4 | 98.3 | 98.3   | 98.4 | 98.2 |
| OEE (%)    | 45.7   | 82.7 | 84.5 | 73.4   | 81.6 | 82.7 | 77.3   | 82.0 | 83.3 |

Y: yield; A: availability; P: performance; OEE: overall equipment efficiency; ET: electrical testing; VTR: vision inspection and tape and reel; VI: visual inspection

Table 2. Average equipment downtime for two consecutive weeks (hours).

| Downtime                        | Before improvement | Simulation | After improvement |
|---------------------------------|--------------------|------------|-------------------|
| Test contactor cleaning         | 25.8               | 2.8        | 2.5               |
| Test contactor replacement      | 8.6                | 0.8        | 0.5               |
| Handler jamming                 | 1.3                | 1.2        | 1.2               |
| Cover and carrier tape changeover| 0.9                | 1.5        | 1.3               |
| Total downtime                  | 36.5               | 6.3        | 5.4               |
| Process | Pre-OPI (OEE) | Potential failure mode | Potential effect(s) | Potential cause(s) | Current process control | Existing rating | Corrective action(s) | Post-OPI | New rating |
|---------|---------------|------------------------|--------------------|-------------------|------------------------|----------------|----------------------|----------|------------|
| ET      | 45.7%         | Low OEE in electrical testing process | Failing customer's delivery plan | Underperformed test contactor with improper profile design and coating material results in high yield loss and equipment downtime for regular test contactor maintenance | 1) Hourly yield monitoring and insertions tracking 2) Test contactor cleaning after every 5,000 insertions 3) Replace new test contactor after every 30,000 insertions | 8 7 5 280 | Change the test contactor profile and coating material | 77.3%   | 8 3 1 24     |
| VTR     | 82.7%         | Low OEE in vision and tape and reel process | Failing customer's delivery plan | High equipment downtime is resulted by: 1) Reteach the reference in vision system for detecting the IC marking defect 2) Incorrect carrier and cover tape are used 3) The cover tape is not sealed properly on the carrier tape | 1) Provide relevant training to technicians, who do the reference teaching 2) Specify the part number of the carrier and cover tape on traveller for reference 3) Visual inspection to check the condition of the sealing | 8 5 7 280 | Develop a system to automate the manual yield monitoring and insertion tracking process | 82.3%   |           |
| Process | Pre-OPI (OEE) | Potential failure mode | Potential effect(s) | Potential cause(s) | Current process control | Existing rating | Corrective action(s) | Post-OPI | New rating |
|---------|---------------|------------------------|--------------------|-------------------|------------------------|----------------|----------------------|----------|------------|
| VI      | 84.5%         | Low OEE in the visual inspection process | Failing customer’s delivery plan | High equipment downtime is resulted in 1) Re-teach the reference in vision system for detecting the IC marking and sealing defect 2) Not able to roll the carrier tape due to motor faulty | 1) Provide relevant training to technicians, who do the reference teaching 2) Provide relevant training to technicians, who maintain the roller 3) Preventive maintenance to check the roller module | 8 5 7 280 |                     | 83.6%    |            |
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