

A Review of Failure Mode and Effects Analysis (FMEA) for sustainable manufacturing and improvement in electrostatic chuck manufacture and operation

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Abstract. Failure modes and effect analysis (FMEA) is widely used in industry to quantify, mitigate, and eliminate risk for products and processes. It has the potential to be an important technique in supporting sustainable manufacturing by reducing the risks associated with transitioning to more sustainable processes. Whilst traditional FMEA does quantify risk by calculating a risk priority number (RPN), there are limitations to the usefulness of this due to the lack of objectiveness inherent in the method. In this paper improvements to the traditional FMEA approach are reviewed and their appropriateness in the specific case of the manufacture of electrostatic chucks (ESC) is considered.

Keywords: FMEA, Fuzzy FMEA, Electrostatic Chuck.

1 Introduction

Transitioning and changing existing manufacturing processes to more sustainable methods carries inherent risks. Badurdeen and Jawahir [1] argue that establishing a business case for sustainable manufacturing requires systems and procedures which facilitate sustainable manufacturing and create value for the organisation. Enyoghasi and Badurdeen [2] highlight opportunities for sustainable manufacturing through Industry 4.0 technologies. The potential for, and impact of, Failure Mode and Effect Analysis (FMEA) on enabling sustainable manufacturing is a developing area of research. Boral et al. [3] go as far as describing their novel approach to FMEA an essential requirement for sustainable manufacturing. Nguyen et al. [4] also proposed a novel method of FMEA with the intention of facilitating sustainable manufacturing. Malsch et al. [5] researched sustainable manufacturing of nanomaterials and the role of risk mitigation which is at the core of FMEA analysis.

This paper outlines part of the research undertaken during a collaborative project between 3 Universities in Wales (University of South Wales, Swansea University and Cardiff University) and SPTS Technologies, a division of KLA, based in Newport, South Wales. The SPTS Division of KLA provides advanced wafer processing solutions to the world's leading semiconductor and microelectronic device manufacturers and designs, manufactures, sells and supports semiconductor manufacturing

equipment. Their equipment provides advanced wafer processing technologies and solutions for the semiconductor and microelectronics industry.

The project aims to extend the understanding of electrostatic chuck (ESC) operation to improve wafer processing and to support the company's sustainable manufacturing goals. The project is divided into three parts, 1) The development of a computer model of the ESC to replicate its operation and simulate possible failure conditions, 2) Research into the use of FMEA as a technique to record, analyse and manage failure modes and 3) To explore the potential of industrial Internet of Things (IIoT) devices linked with the equipment for real time data analytics. This paper covers the work carried out in part 2 above, which is to review the wide range of FMEA hybrid approaches developed and to consider their applicability for failure identification within both the ESC and its manufacturing process.

The paper is structured as follows: Section 2 provides a description of an ESC, Section 3.1 provides a brief introduction to FMEA and explores the drawbacks of the standard FMEA approach. In Section 3.2 a critical review of FMEA literature is carried out with a focus on research articles describing enhancements to the traditional approach. Section 4 is the conclusion and future work.

2 Electrostatic Chuck

The Electrostatic Chuck (ESC) is a key component in semi-conductor manufacturing and is used in the etch and deposition process. It is subject to a number of complex interactions during use, often in extreme conditions such as low or high temperatures, vacuum environments, gas plasma, high voltage, and RF power. By applying a bipolar voltage to its internal electrodes, a directional electric field is created, and positive and negative charges drift within the material to match the polarity of the ESC's internal electrode. This attracting force between the ESC and the material allows it to be used to clamp or pick up silicon wafers as substrate materials [6].

Its manufacture is typically a fixed assembly of a bonded aluminum or titanium body with sealed internal cavities, RTV (room-temperature-vulcanizing) silicone, conductive epoxies, sputters metal layer and alumina ceramic. The final assembly is tested for its surface flatness, parallelism, roughness and internal bonds all of which are critical to quality.

Due to the complex nature of ESCs, and with limited access to internal components and layers, once assembled, failure modes and causes of failures are difficult to identify. A better understanding of the failures can lead to improved and more efficient production methods and provide opportunities for improved working practices and employee well-being. ESCs contain some components that cannot be reclaimed or recycled – principally the RTV silicone and ceramic (Alumina). Improved sustainability can be achieved through more reliable ESCs thus reducing failures and scrap rates. Greater reliability in

the product can lead to more efficient semiconductor processing helping to relieve impact on the global semiconductor market where shortages are on the increase.

The next section explores the use of FMEA as a technique to identify, understand and manage the risk of failures.

3 FMEA background and critical evaluation

3.1 Failure Mode and Effect Analysis: Background

FMEA is a systematic procedure for analysing the risks of a system to potential failure modes, their causes and effects on system performance. FMEA has been used as a technique in manufacturing since the late 1960s and was popularised in the automotive industry in the 1970s. Its origins go back further to the end of the 1940s where it was used by the US military to assess aircraft safety [7]. Today, whilst its use is commonplace in manufacturing industries, it has not endured the popularity of other quality methods promoted by lean and six sigma approaches. However, risk management is becoming increasingly important with an increased focus on sustainable manufacturing within an Industry 4.0 environment.

FMEA is based on conducting an analysis based on know-how and engineering decisions to generate occurrence, severity, and detection values. An RPN (Risk Priority Number) is calculated by multiplying $O \times S \times D$, where:

- Occurrence (O) is the probability of occurrence of the defect,
- Severity (S) is the significance of the defect/undesirable state,
- Detection (D) is the possibility of detection of the defect.

Each parameter is typically assigned a numerical value from 1 to 10 [8] or can be assigned a linguistic value (see Table 1).

Occurrence (O)		Severity (S)		Detection (D)	
1	Negligible	1	Meaningless	1	Very High
2-3	Occasional	2-3	Low	2-3	High
4-6	Moderate	4-6	Moderate	4-6	Moderate
7-8	High	7-8	High	7-8	Low
9-10	Very High	9-10	Very High	9-10	Accidental

Table 1: Typical numerical and linguistic values assigned to O, S and D parameters.

The risk level (indicated by the value of RPN) can have a value up to a maximum of 1000. In practice, the upper limits of this index which can be defined as the level of acceptability of risk, is arbitrary assigned. It is often assumed that an RPN less than 120 means an acceptable level of risk [10], [11].

FMEAs can be used at different stages of a project to achieve different outcomes.

- Design FMEA - used for the purpose of identification and prevention of failure modes of products, which are related to their design, in order to validate the established design parameters for a specific functional performance level, at system, subsystem or component level,
- Process FMEA - This type of FMEA focuses on potential failure modes of the process that are caused by manufacturing or assembly process deficiencies,
- Concept FMEA - The concept FMEA is used to analyse concept in the early stages before hardware is defined (most often at system and subsystem level).

Whilst the application of a traditional FMEA is well established with many templates and software tools available to support the process, it does have its limitations and relies heavily on the existing knowledge and data and it is not easy for engineers to express their evaluation of the risk factors in numerical terms [9]. Linguistic categories can be used to overcome this where three or five level can be used (See Table 1 for a 5-level example). Another limitation is that the RPN calculation overlooks relative importance amongst risk factors where O, S and D values are assumed to be of the same significance [8], [10], [11]. Also, in this case, different combinations of O, S and D values can provide the same RPN value, but in reality their risk priorities may differ [8]. Although this suggest that O, S and D values should be weighted relative to each other, assigning weights is not straightforward. [12] in their comprehensive literature review of FMEA also include interdependencies amongst failure modes and the limitation of only considering 3 risk factors (O,S,D) as further shortcomings which are not taken account in the traditional RPN calculation.

To overcome these limitations many researchers have explored alternative methods for implementing and evaluating FMEA RPN values to provide a more reliable risk ranking. The next section explores and evaluates alternatives to the standard FMEA approach.

3.2 Critical review of FMEA

A classification of evaluation methods to improves or enhance the standard FMEA approach is provided in [12]. The most popular category is AI, accounting for 40% of the papers reviewed. This category is dominated by a Fuzzy systems approach. Integrated approaches account for 11.25% of papers which also include a number of integrated Fuzzy methods. The Multi Criteria Decision Methods (MCDM) account for 22.5% of papers and include Analytical Hierarchy Process (AHP), Analytic Network Process (ANP), The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Grey, decision making trial and evaluation laboratory (DEMATEL) and Multicriteria Optimization and Compromise Solution (VIKOR - from Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje). Also included in the MCDM category are Fuzzy variant of the above (For a detailed review of MCDM methods and their applications see [13]).

In adding to the review by [12], papers post 2012 in Table 2 also show a dominance of Fuzzy and MCDM approaches. For Fuzzy approaches see [10] and [14], for combinations of Fuzzy and other approaches (integrated approaches) see [8], [11], [15], [16], [17], [18] and for MCDM techniques see [7], [11].

Other techniques have been explored including combining FMEA with other Quality tools such as QFD for supporting the decision-making process [19], [20], and the Taguchi method to explore combinations of decision criteria to minimise risk values [21].

Table 2 lists some of the FMEA hybrid analysis techniques developed in recent years with an indication of their application area.

Table 2. FMEA Hybrid methods and their application areas.

FMEA Hybrid Technique(s)	Application Area	Reference
Fuzzy	Sterilization unit in a large hospital	[10]
Fuzzy	Supercritical water gasification system	[14]
Fuzzy, TOPSIS, AHP	Hypothetical case of a Manufacturing facility in the automotive industry	[8]
Fuzzy, TOPSIS, AHP	Development of a new street cleaning vehicle with a telediagnosis system	[16]
Fuzzy IT2 (interval type 2) integrated model	Furniture manufacturing company	[15]
Complex Proportional Assessment (COPRAS), Analytic Network Process (ANP), Interval-valued intuitionistic Fuzzy Sets (IVIFS)	Hospital service setting	[22]
IVIF, MABAC - Results compare with Fuzzy-VIKOR and Intuitionistic	Radiation therapy process at cancer treatment centres	[11]

fuzzy TOPSIS (IF-TOPSIS)

Fuzzy, AHP, MULTIMOORA	Occupational accidents at a steel factory	[17]
Fuzzy, Possibility theory	EOT crane for material handling	[18]
Fuzzy QFD	Shoe Manufacturing	[23]
Process Activity Mapping (PAM)	Low volume, high integrity manufacturing	[24]
AHP, Composition of Probabilistic Preferences (CPP)	Oil and gas sector services	[7]
VIKOR	Customer-oriented: 1. Ticket issuing service at a travel agent; 2. Movie theatre service	[25]
Action Research based approach	New Product Development (NPD) in the hydro-sanitary industry: manufacture of flush toilets – flush control board	[26]
FTA	Additive manufacturing system for metal printing	[27]
QFD	Steel manufacturing: Blast furnace operation	[19]
QFD-System Dynamics (SD) -Causal Loop Diagram (CLD)	Steel manufacturing: Roller transmission system	[20]
Process-Aware (PA) using Delphi, AHP, BPM life cycle	White goods manufacturing: end of assembly line	[28]

Expectation Interval, Taguchi, MOORA and Geometric Mean (GM)	Fuel oil system of a marine diesel engine [21]
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In Table 2, focusing specifically on Fuzzy approaches, [10] and [14] use a Fuzzy rule based method to rank the PRN numbers and compare the Fuzzy results with the classical calculations. Differences in rankings of failure modes were observed between classical and Fuzzy FMEA and the authors claim improvements in using the Fuzzy approach due to overcoming drawback of equal weighting of the O, S and D values in the traditional approach although there was no objective measure of this improvement. In both classical and Fuzzy approaches the failure modes were determined using expert opinion. In [8], instead of using a fuzzy rule based approach, use a Fuzzy MCDM approach based on Fuzzy TOPSIS and Fuzzy AHP, where experts use linguistic variables to determine O,S, D values. This approach also overcomes drawback of assigning equal importance to O,S and D values.

A Fuzzy TOPSIS AHP approach was also adopted in [16], with the addition of 2 alternative evaluation criteria to the traditional S and D criteria and instead use two criteria related to maintenance management along with the traditional O. Sensitivity analysis was performed to test the influence of criteria weights.

Expert evaluation was also used by [15] to calculate the RPN values by applying a novel integration model based on an interval type-2 Fuzzy (IT2F) inference approach. This approach was designed specifically for group decision making where the main advantage of this approach in that it enables evaluations from different area of expertise to be assessed and combined. The authors claim the approach to be an improvement on a traditional FMEA in that it overcomes the limitation of different O,S,D values giving the same RPN score thus missing a potential of a high value in one of the measures influencing the RPN value.

Whilst Fuzzy approaches remain the most popular approach to enhance FMEA analysis, its drawback is that it is characterized by only membership functions and initial information may be lost in the process [22]. In order to address this shortcoming, the authors have developed the Interval-valued Intuition fuzzy sets (IVIF) approach to deal with uncertainty and incompleteness of information along with COPRAS and ANP (an extension of AHP) to address the MCDM aspects. This approach was applied to a case study in a hospital department setting. In this case, O, S and D values were further sub divided into 2 or 3 sub factors. IVIF was used to construct pair-wise comparison matrices between risk factors and sub-risk factors. The method was evaluated by comparing the results with both a traditional FMEA and a GRA-based FMEA. Distinct differences were reported between the traditional FMEA and the new model. The new model is able to distinguish and assign different priority levels to Failure modes that score the same RPN using the traditional method. Uncertainty is handled by IVIF-ANP and

ranking handled by IVIF-COPRAS. However the approach still relies on expert knowledge and experience to develop the weighting of risk factors.

IVIF were also used by [11], where an integrated IVIF and Multi Criteria Broader Approximation area Comparison (MABAC - a new form of Multi Criteria Decision Analysis (MCDA)) method was developed. This approach has merits in that it recognises that information about risk factor weights is often only partially known or understood.

A Fuzzy based approach to determine weights of O, S and D parameters using an extended Fuzzy AHP and Fuzzy Multiple multi-objective optimization by ratio analysis (MULTIMOORA) for MCDM evaluations was adopted by [17]. In this case the criteria of Cost, time and profit are used to calculate the weights of each failure mode.

All the above methods have combined or integrated Fuzzy approaches with other methods, mainly MCDM, using information drawn from experts. Whilst this can be a positive aspect where there is a lot of inherent knowledge in existence, the disadvantage is when the existing knowledge on a product or process is unknown or poorly understood.

4 Conclusion and Future Work

The adoption of FMEA as a risk mitigation tool in industry is now widespread and it is an expectation of many regulated industries that the procedures are followed. Whilst some consideration of risk is better than no consideration of risk, the limitations of traditional process and design FMEAs are repeatedly shown in the literature. The regulatory requirement to have an FMEA document often results in a box-ticking exercise of little value. The reliance on opinions and subjective scoring results in unquantifiable risks which cannot be compared across processes. FMEAs, particularly concept FMEAs, can support the development of sustainable manufacturing processes by evaluating risk before implementation, however traditional FMEAs have many shortcomings due to the subjectiveness of the process.

Alternative FMEA methodologies are becoming more frequently applied in industry, as seen in this literature review. Novel hybrid FMEA methodologies are numerous and the literature shows that, in practice, they are more effective in quantifying risks than the standard FMEA approach. This will provide industry with more confidence in taking on risk when developing new products or processes.

In general techniques utilizing a Fuzzy approach are the most widely used methods as it provides a mechanism to translate crisp values for O,S, D measures into linguistic valuables for the Fuzzy approach to analyse. In the short term, a standard FMEA has its merits and provides a good starting point for developing more in-depth knowledge of a complex product such as ESC [29]. However more work is needed to evaluate the effectiveness of applying Fuzzy FMEA or other hybrid approaches to a complex

product such as an ESC where access to internal structures is limited making it difficult to assess causes of failures.

There is a lot of existing knowledge and understanding of ESC operation in the literature and within the company which makes many of the approaches reviewed in this paper suitable where expert knowledge is needed for the FMEA development. The IVIF approaches developed by [22] and [11] are potentially suitable for this application where uncertainty and incomplete information can be accommodated. Also the approach by [15] has merits in that it is applicable for group work where knowledge from experts from different areas of expertise can be combined. This can be of advantage to the company where data from customers using their products can be gathered and integrated into the model.

The outcome of this literature review will be utilized in an ongoing research project to improve the manufacturing process and design of an electrostatic chuck, with the intention of improving the overall sustainability of the operations.

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