Engineering Failure Analysis 31 (2013) 211–224

Contents lists available at SciVerse ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Enhancing FMEA assessment by integrating grey relational analysis and the decision making trial and evaluation laboratory approach

Kuei-Hu Chang [a,*], Yung-Chia Chang [b], I-Tien Tsai [b]

[a] Department of Management Sciences, R.O.C. Military Academy, Kaohsiung 830, Taiwan
[b] Department of Industrial Engineering and Management, National Chiao Tung University, Hsinchu 300, Taiwan

ARTICLE INFO

Article history:
Received 23 November 2012
Received in revised form 8 February 2013
Accepted 8 February 2013
Available online 26 February 2013

Keywords:
Failure modes and effects analysis
Risk priority number
Grey relational analysis
Decision making trial and evaluation laboratory

ABSTRACT

Failure modes and effects analysis (FMEA) is used widely to improve product quality and system reliability, employing a risk priority number (RPN) to assess the influence of failures. The RPN is a product of three indicators—severity (*S*), occurrence (*O*), and detection (*D*)—on a numerical scale from 1 to 10. However, the traditional RPN method has been criticized for its four chief shortcomings: its (1) high duplication rate; (2) assumption of equal importance of *S*, *O*, and *D*; (3) not following the ordered weighted rule; and (4) failure to consider the direct and indirect relationships between failure modes (FMs) and causes of failure (CFs). To resolve these drawbacks, we propose a novel approach, integrating grey relational analysis (GRA) and the decision-making trial and evaluation laboratory (DEMATEL) method, to rank the risk of failure, wherein the GRA is used to modify RPN values to lower duplications and the ordered weighted rule is followed; then, the DEMATEL method is applied to examine the direct and indirect relationships between FMs and CFs, giving higher priority when a single CF causes FMs to occur multiple times. Finally, an actual case of the TFT-LCD cell process is presented to verify the effectiveness of our method compared with other methods in providing decision-makers more reasonable reference information.

1. Introduction

In the process of risk control, the first step is to eliminate the risks, which can be forecasted and removed, or to lower the possibility of the risk occurrence. Failure mode and effects analysis (FMEA) is primarily a risk assessment tool in risk control [1]. FMEA is used widely because it is simple to apply and understand, and it can be modeled using real situations. Many reports have discussed FMEA as a related subject. Ahmad et al. [2] proposed a new failure analysis method by integrating FMEA and failure time modeling that is based on the proportional hazard model to help engineers devise more effective maintenance strategies. Yang et al. [3] modified the Dempster–Shafer evidence theory under uncertainty to aggregate evaluation data by considering experts' opinions to solve risk evaluation problems. Chang and Cheng [4] combined fuzzy ordered weighted averaging (OWA) and the decision-making trial and evaluation laboratory (DEMATEL) approach to rank the causes of failure (CFs). However, the traditional FMEA method has several shortcomings. For instance, the severity (*S*), occurrence (*O*), and detection (*D*) indicators are discrete ordinal scales of measure; the calculation by multiplication is inappropriate [4–7]; and it ignores the relative importance between *S*, *O*, and *D* and assumes that they are assigned equal weight, which might not be true in practice [4–9]. Further, the FMEA method assumes that the risk priority number (RPN) is distributed

* Corresponding author. Tel.: +886 77403060.
E-mail address: evenken2002@yahoo.com.tw (K.-H. Chang).

1350-6307/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfailanal.2013.02.020

evenly from 1 to 1000, but only 120 numbers can be generated—that is, certain disparate combinations of *S*, *O*, and *D* have equal RPN values [6,7]. FMEA only considers the *S*, *O*, and *D* indicators, but other factors, such as failure cost, might have to be included to approximate the actual situation [6]. Lastly, FMEA fails to consider the direct and indirect relationships between failure modes (FMs) and CFs [10] and does not follow the OWA criteria [4,11], which were proposed by Yager [12], prioritizing attributes based on the ranks of these weighting vectors after aggregation.

Many scholars have made improvements with regard to these shortcomings. Sankar and Prabhu [13] proposed a new technique to prioritize failures for corrective actions in FMEA, called risk priority ranks (RPRs), which uses expert knowledge and the if-then rule to analyze CFs and FMs and ranks RPRs from the highest to lowest. RPR values, ranked 1 through 1000, are used to represent the 1000 possible combinations of *S*, *O*, and *D*. This approach mitigates the problems of high duplication rate and the assumed equal importance of *S*, *O*, and *D*, but ranking 1000 possible combinations of *S*, *O*, and *D* is difficult and time-consuming. Gilchrist [14] proposed an expected cost model as the basis for ranking FMs, using $EC = Cnp_fp_d$ to calculate the expected cost of failures, where C is the failure cost, n is the annual production quantity, and p_f is the probability of failure; p_d means that the probability is not detected. Chin et al. [6] used the group-based evidential reasoning approach to capture FMEA team members' opinions and employed the minimax regret approach to rank expected risk scores. Braglia [15] adopted the analytic hierarchy process (AHP) technique to develop a multiattribute failure mode analysis approach, which integrates four factors—chance of failure, chance of nondetection, severity, and expected cost—to rank causes of failure. Shahin [16] concluded that the severity indicator of traditional FMEA is determined by the designers' perspective, not according to the customers, and used the Kano model to convert it to a customer-oriented model.

Bowles and Pelaez [17] were the first to use a fuzzy logic-based approach for criticality analysis. Since its appearance, the fuzzy logic-based approach has been analyzed extensively by many groups. Chang et al. [8] applied a fuzzy logic approach to evaluate linguistic *S*, *O*, and *D* indicators directly and used grey theory to determine the risk priority of potential causes. Braglia et al. [5] combined the technique for order preference by similarity to ideal solution (TOPSIS) and triangular fuzzy numbers for failure criticality analysis. In this approach, fuzzy logic was used to assess *S*, *O*, and *D* and their relative weights of importance rather than generating precise numerical values. Other groups have used fuzzy logic to improve the traditional FMEA method [7,18], but these methods do not consider the direct and indirect relationships between FMs and CFs, which might cause biased conclusions.

Recently, Seyed-Hosseini et al. [10] first used the DEMATEL approach to analyze relationships between components and assigned new priorities to CFs and FMs. But, if all FMs are due to distinct causes (CFs), such ranking will equal the traditional RPN method. This study reports a novel approach to overcome these shortcomings, using the GRA to lower the high duplication rate and mitigates the violation of the ordered weighted rule in the RPN method and inputs the analysis results into DEMATEL to examine the relationships between components in a system.

In Section 2, the literature is reviewed briefly. A novel approach that integrates grey relational analysis and the DEMATEL method is proposed in Section 3. An actual case of FMEA of the thin-film transistor liquid crystal display (TFT-LCD) cell process is analyzed to demonstrate the effectiveness and feasibility of the proposed approach in Section 4. Finally, Section 5 discusses our conclusions.

2. Related work

2.1. FMEA overview

FMEA was developed by the US military in the late 1940s as an assessment method to improve the evaluation of the reliability of weapons and military systems, culminating in the publication of the military standard MIL-STD-1629 in 1949. However, it did not suit military requirements completely and was revised in 1980 to MIL-STD-1629A [19]. This method was adopted by the National Aeronautics and Space Administration (NASA) during the Apollo space missions in the 1960s. In 1985, the International Electrotechnical Commission (IEC) published an international standard of FMEA, IEC 60812, to analyze system reliability [20]. The automotive industry used FMEA as a risk assessment method in the product design stage and manufacturing process. In 1993, the Automotive Industry Action Group (AIAG) and American Society for Quality (ASQ) united Daimler Chrysler Corporation, Ford Motor Company, and General Motors Corporation to create an FMEA reference manual to meet QS-9000 requirements [21]. FMEA is viewed as a risk assessment tool for improving the analysis of quality, except by the military and automotive industry. Certain international quality organizations, such as the International Organization for Standard (ISO), use FMEA as an important analysis measure in the ISO-9000 series. Today, FMEA is used extensively in industries, such as the aviation, automotive, machinery, medical, food industry, and semiconductor industry.

Traditionally, FMEA uses the risk priority number (RPN) to evaluate the risk of failure. The RPN value is the product of *S*, *O*, and *D* on a scale from 1 to 10. When a CF has a higher RPN value, this failure influences the system more significantly and requires a higher priority. A typical set of failure factor rankings and criteria are defined in Table 1 [16].

2.2. Grey theory

Nearly all systems fail to capture information perfectly, and some existing information is uncertain due to limited knowledge and cognition. Deng [22] first proposed the grey theory in 1982 to deal with the analysis of systems that are plagued by

Table 1
Typical rankings of failure mode indices.

Level	*S*	*O*	*D*
1	No	Almost never	Almost certain
2	Very slight	Remote	Very high
3	Slight	Very slight	High
4	Minor	Slight	Moderate high
5	Moderate	Low	Medium
6	Significant	Medium	Low
7	Major	Moderately high	Slight
8	Extreme	High	Very slight
9	Serious	Very high	Remote
10	Hazardous	Almost certain	Almost impossible

incomplete information. In grey theory, according to the degree of availability of information, if the required internal information is entirely available, the system is a white system; if the required information is entirely unavailable, it is a black system. A system with partially available information is called a grey system. The grey theory includes six major components: grey generating, grey relational analysis (GRA), grey model, grey prediction, grey decision making, and grey control [23]. Under various circumstances and angles, the chief differences in the meaning of black, grey, and white can be observed, as in Table 2 [24].

Grey theory functions primarily on multi-input, incomplete, or uncertain information. GRA is one of the most important components of grey theory, which is suitable for solving problems with complicated relationships between multiple factors and variables. Suppose X is a factor set of grey relation, $X = \{X_0, X_1, \ldots, X_m\}$, where $X_0 \in X$ represents the reference sequence; $X_i \in X$ represents the comparative sequence, where $i = 1, 2, \ldots, m$. X_0 and X_i consist of n elements and can be expressed as follows [23,25]:

$$X_0 = (x_0(1), x_0(2), \ldots, x_0(k), \ldots, x_0(n)),$$

$$X_i = (x_i(1), x_i(2), \ldots, x_i(k), \ldots, x_i(n)) \quad \text{, where } i = 1, 2, \ldots, m \quad , k = 1, 2, \ldots, n.$$

$x_0(k)$ and $x_i(k)$ are the numbers of a reference sequence and comparative sequences at point k, respectively. The grey relational coefficient $\gamma(x_0(k), x_i(k))$ can be computed as follows:

$$\gamma(x_0(k), x_i(k)) = \frac{\min_i \min_k |x_0(k) - x_i(k)| + \zeta \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max_i \max_k |x_0(k) - x_i(k)|} \tag{1}$$

where $\zeta \in [0, 1]$ is of the distinguished coefficient; usually $\zeta = 0.5$.

Then, the grey relational grade can be computed as follows:

$$\gamma(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n} \gamma(x_0(k), x_i(k)) \tag{2}$$

2.3. DEMATEL method

The DEMATEL method was developed by the Battelle Memorial Institute of the Geneva Research Center, which studied and resolved complex social issues by constructing a causal relationship model of factors [26]. The steps of the DEMATEL method are as follows [4,10,27]:

Step 1. Calculate the initial average matrix by scores. Measuring the relationship between criteria requires that the comparison scale be designed with four levels, where scores of 0, 1, 2, and 3 represent "no influence," "low influence," "high

Table 2
Meaning of information.

	Black	Grey	White
Information	Unknown	Incomplete	Known
Appearance	Dark	Grey	Bright
Process	New	Replace old with new	Old
Property	Chaos	Complexity	Order
Methodology	Negative	Transition	Positive
Attitude	Indulgence	Tolerance	Seriousness
Conclusion	No result	Multiple solution	Unique solution

influence," and "very high influence," respectively. The initial direct-relation matrix Y is an $n \times n$ matrix that is obtained by pairwise comparisons in terms of influences and directions between criteria, in which y_{ij} is denoted as the degree to which criteria i affects criteria j.

$$Y = \begin{bmatrix} 0 & y_{12} & \dots & y_{1n} \\ y_{21} & 0 & \dots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1} & y_{n2} & \dots & 0 \end{bmatrix} \tag{3}$$

Step 2. Normalize the direct relation matrix.

Based on the initial direct-relation matrix Y, the normalized direct relation matrix H can be obtained through the following formulas:

$$s = \max_{1 \leqslant i \leqslant n}\left(\sum_{j=1}^{n} y_{ij}\right) \tag{4}$$

$$H = \frac{Y}{s} \tag{5}$$

Step 3. Calculate the total relation matrix.

The total relation matrix T can be obtained using formula (6), in which I is the identity matrix.

$$T = \lim_{k \to \infty}(H + H^2 + \cdots + H^k) = H(I - H)^{-1} \tag{6}$$

Step 4. Produce a causal diagram.

The sum of the rows and columns, denoted as R and C, respectively, can be obtained through formulas (7) and (8). A causal diagram can be generated by mapping the ordered pairs of $(R + C, R - C)$, where the horizontal axis $(R + C)$ is "Relation" and the vertical axis $(R - C)$ is "Influence".

$$T = [t_{ij}]_{n \times n}, \quad i,j = 1, 2, \ldots, n$$

$$R = \left[\sum_{j=1}^{n} t_{ij}\right]_{n \times 1} = [t_i]_{n \times 1} \tag{7}$$

$$C = \left[\sum_{j=1}^{n} t_{ij}\right]_{1 \times n} = [t_j]_{n \times 1} \tag{8}$$

3. Proposed integrates of GRA and the DEMATEL method

3.1. Reasons for using GRA and the DEMATEL method

The RPN method has been criticized as having four primary shortcomings: its (1) high duplication rate; (2) assumption of equal importance of S, O, and D; (3) not following the ordered weighted rule; and (4) failure to consider the direct and indirect relationships between FMs and CFs. Thus, to resolve these drawbacks, a novel method that integrates GRA and the DEMATEL is proposed. Because the combinations of S, O, and D are a discrete series and have an unknown statistical distribution, these conditions meet the characteristics of GRA. Take S, O, and D (10,10,10) as the reference series of all combinations, and the other combinations form the comparative series; then, 1000 grey relational grades can be calculated as the relative degree between the comparative and reference series—the higher grey relational grade indicates greater relativity to (10,10,10). The value of ζ affects computation of the grey relational grade when calculating grey relational coefficients, because S, O, and D only have 10 values each, and the 10 most disparate grey relational coefficients exist. This study lists different values of ζ and corresponding grey relational coefficients in Table 3. By Table 3, variations of grey relational coefficient can be charted as Fig. 1.

Fig. 1 shows that a smaller ζ value, such as 0.01, is more sensitive to a larger *SOD* value as the grey relational coefficient increases dramatically between 9 and 10 but experiences small changes with lower *SOD* values, such as 1–7. The change in smaller grey relational coefficients increase with a higher ζ, but *SOD* values have less influence on grey relational coefficients when $\zeta = 1$. Thus, our method requires a ζ value that possesses sufficient distinguishability for the increasing variation in grey relational coefficients and assigns a larger grey relational coefficient to a greater *SOD* value. Table 3 shows that the distance between grey relational coefficients of *SOD* values of 1 and 2 is 0.029412, even when ζ is 1. The change in grey relational coefficients over 0.02 for smaller *SOD* values means that sufficient distinguishability exists. When ζ is 0.3 and 0.4, all changes

Table 3
Grey relational coefficients for different ζ and *SOD* values.

SOD value	ζ							
	0.01	0.1	0.2	0.3	0.4	0.5	0.8	1
1	0.009901	0.090909	0.166667	0.230769	0.285714	0.333333	0.444444	0.500000
2	0.011125	0.101124	0.183673	0.252336	0.310345	0.360000	0.473684	0.529412
3	0.012694	0.113924	0.204545	0.278351	0.339623	0.391304	0.507042	0.562500
4	0.014778	0.130435	0.230769	0.310345	0.375000	0.428571	0.545455	0.600000
5	0.017682	0.152542	0.264706	0.350649	0.418605	0.473684	0.590164	0.642857
6	0.022005	0.183673	0.310345	0.402985	0.473684	0.529412	0.642857	0.692308
7	0.029126	0.230769	0.375000	0.473684	0.545455	0.600000	0.705882	0.750000
8	0.043062	0.310345	0.473684	0.574468	0.642857	0.692308	0.782609	0.818182
9	0.082569	0.473684	0.642857	0.729730	0.782609	0.818182	0.878049	0.900000
10	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000

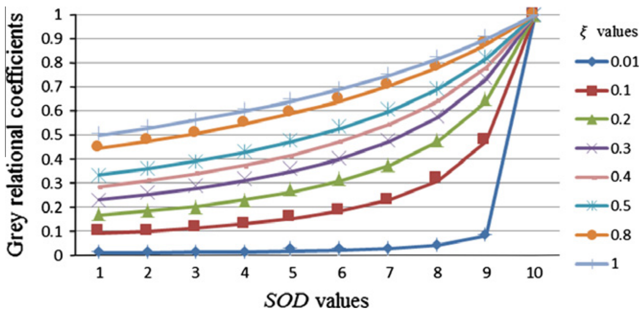

Fig. 1. Variation line charts of grey relational coefficients.

in grey relational coefficients are over 0.02, and as $\zeta = 0.3$, the distances exceed 0.05 with *SOD* values greater than 6. Thus, we assume that $\zeta = 0.3$.

When *S*, *O*, and *D* have equal weights, 1000 grey relational grades can be calculated by Eq. (2); the ranking is illustrated in Fig. 2. There are 220 unique values, and the highest number of duplications is 6. The duplication rate decreases from 88% in traditional FMEA to 78%, and maximum number of duplications declines from 24 to 6. Fig. 2 shows that the distribution is more uniform and satisfies the statistical assumptions of traditional FMEA better. Table 4 indicates that GRA improves some of the duplication problems of the traditional RPN method.

In summary, GRA considers the various influences of *SOD* values and gives *SOD* distinct weights on a case-by-case basis to simulate real-life situations. Moreover, GRA is expandable—if increases in *S*, *O*, and *D* are required, GRA can adapt immediately. The traditional RPN method fails to establish any relationship between CF and FM. The DEMATEL method analyzes direct and indirect relationships of alternatives in the system and considers that a single CF can cause the occurrence of multiple FMs, which will be given higher priority.

3.2. The proposed approach

The proposed method comprises 10 steps, of which Steps 3 to 5 are calculations of the grey relational grade and Steps 6 to 9 are the DEMATEL component. The procedure is as follows:

Step 1. List all FMs and CFs.

Based on historical data and past experiences, list the FMs and CFs of the entire system.

Step 2. Define the scales for the *S*, *O*, and *D* indicators, respectively.

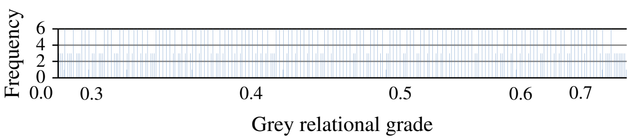

Fig. 2. Histogram of GRA of all possible combinations.

Table 4
Compare traditional RPN and GRA methods.

Traditional RPN	GRA
120 Unique RPN values Highest duplicated 24 times Almost all RPN values less than 500	220 Unique GRA values Highest duplicated 6 times GRA values are more uniformly distributed

For each CF, engineers highlight S, O, and D individually to establish the corresponding linguistic value.

Step 3. List all 1000 SOD combinations.

Let the 1000 combinations of SOD be matrix G, and set $g_i(k)$, $i = 1, 2, \ldots, 1000$, where $k = 1, 2, 3$ is i rows and k columns in matrix G. Here, assume S is the first column, O is the second column, and D is the third column. The matrix G can be expressed as $G = \begin{bmatrix} 10 & 10 & 10 \\ 10 & 10 & 9 \\ \vdots & \vdots & \vdots \\ 1 & 1 & 1 \end{bmatrix}$.

Step 4. Perform interval transformation.

The matrix X can be expressed as $X = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 0.88889 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}$.

Step 5. Construct the reference series and calculate the grey relational grade.

This report takes the largest value of SOD in matrix X as the reference series $x_0 = [x_0(1)\ x_0(2)\ x_0(3)] = [111]$, and the 1000 combinations are the comparative series $x_i = [x_i(1)\ x_i(2)\ x_i(3)]$ and $i = 1, 2, \ldots, 1000$. Calculate the grey relational coefficient $\gamma(x_0(k), x_i(k))$ by Eq. (1), and set $\zeta = 0.3$. Then, calculate the grey relational grades of the 1000 combinations per Eq. (2).

Step 6. Construct the initial relation matrix Y.

Use the results of Step 5 to construct the initial relation matrix Y.

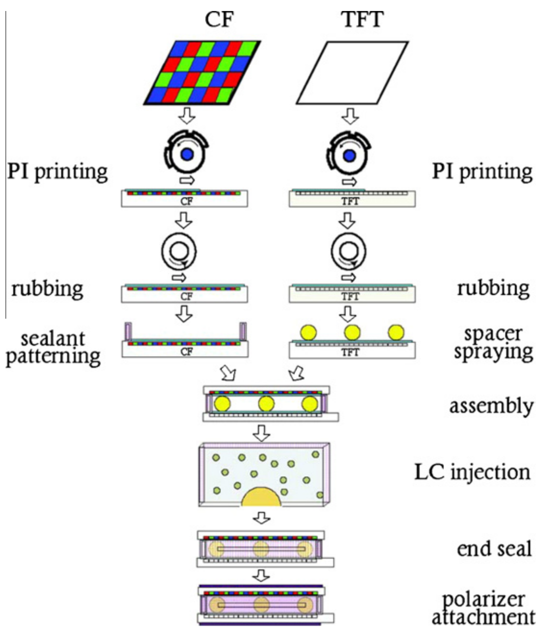

Fig. 3. Cell assembly process flow [28].

Step 7. Calculate the direct relative severity matrix (DRSM) and direct and indirect relative severity matrix (DIRSM).

Sum every row and every column of matrix Y, and use Eq. (4) to obtain maximum s of summed columns and rows. Normalize matrix Y per Eq. (5) to obtain normalized relative matrix H—i.e., the DRSM, which indicates the degree of influence of CF on FM in a traditional FMEA table.

Step 8. Calculate the values of $R - C$.

Use Eqs. (7) and (8) to calculate the values $R - C$ of matrix T.

Table 5
The FMEA of the TFT-LCD cell process.

No.	Failure mode	Cause of failure	S	O	D
1	Glass substrate cannot clear	Water quality problems	6	2	3
2	Glass substrate cannot clear	Insufficient equipment water volume and water pressure	6	3	3
3	Glass substrate cannot clear	Insufficient oscillator power	6	2	4
4	Glass substrate cannot clear	Defective roller br1ush	6	3	4
5	Glass substrate cannot clear	Insufficient ultra-violet (UV) lamp illuminance	6	2	3
6	Glass substrate cannot clear	Gas pipe puncture	6	2	6
7	Glass laminate scratch	Roller not rotate smoothly and defective sensor	6	2	6
8	Glass broken	Roller not rotate smoothly and defective sensor	7	2	3
9	Electrostatic discharge	Ion bar cannot remove static electricity	5	2	2
10	Electrostatic discharge	Equipment unground	5	1	2
11	Print position drift	Para position drift	5	3	6
12	Print position drift	Asahi Kasei photosensitive resin (APR) plate position drift	5	3	6
13	Non-uniform alignment film thickness	Inaccurate polyimide (PI) dropping volume	5	3	6
14	Non-uniform alignment film thickness	Anomaly roller press condition	5	3	2
15	Non-uniform alignment film thickness	Roller attrition	5	3	6
16	Non-uniform alignment film thickness	Parallelism error too large between roller and stage	5	3	2
17	Non-uniform alignment film thickness	APR plate broken	5	3	6
18	Non-uniform alignment film thickness	Non-uniform prebake temperature	5	2	6
19	Non-uniform PI film hardening	Program using mistake	4	2	2
20	Non-uniform PI film hardening	Heating plane breakdown	4	3	2
21	Color filter (CF) broken	Temperature too high	7	2	3
22	Non-uniform alignment strength	Anomaly roller press condition	5	3	6
23	Non-uniform alignment strength	Anomaly machine vibration	5	2	6
24	Non-uniform alignment strength	Rubbing cloth paste on wrong side	5	2	3
25	Non-uniform alignment strength	Program using mistake	5	3	3
26	Spacer gather	Spacer humidity too high	6	2	4
27	Spacer gather	Nozzle or stage heap too much spacer	6	2	4
28	Spacer gather	Spacer drop powder	6	2	4
29	Spacer repulsion	Electrostatic cannot eliminate	6	3	6
30	No spacer	Insufficient spacer	6	2	4
31	Silver dispensing drift	Wear and tear of dispensing tips	6	2	6
32	Silver dispensing drift	Dispensing tips position drift and miss dispensing	6	2	6
33	Anomaly silver dispensing area	Line2 dispenser Z direction drift	6	3	3
34	Anomaly silver dispensing area	Anomaly nitrogen pressure in line2	6	2	4
35	Anomaly silver dispensing area	Tips clogging	6	2	6
36	Anomaly silver dispensing area	Silver colloid metamorphism	6	2	3
37	Print position drift	Vibration drift	6	2	4
38	Print position drift	Screen position drift	6	1	2
39	Print position drift	Anomaly screen tension	6	3	3
40	Epoxy wire broken	Stencil clogging	6	3	6
41	Epoxy wire broken	Anomaly scraper	6	3	3
42	Anomaly epoxy wire	Scraper press amount too low	6	3	3
43	Anomaly epoxy wire	Anomaly sealant volume and viscosity in printing	6	2	3
44	Anomaly gap	Use wrong glass fiber size	6	1	3
45	Anomaly gap	Use wrong Au ball size	6	1	3
46	Registration precision drift	Para position drift	6	2	4
47	Registration precision drift	UV colloid miss dispensing and too few and too much	6	2	6
48	Registration precision drift	Insufficient ultra-violet (UV) lamp illuminance	6	2	3
49	Glass broken	Foreign matter on up and down fixed disk	7	2	6
50	Non-uniform glass substrate pressure	Defective sponge and jig	6	3	6
51	Non-uniform glass substrate pressure	Degree of machine press drift	6	3	3
52	Non-uniform glass substrate pressure	Adverse human operator and wrong gasket number	6	2	6
53	Epoxy incomplete hardening	Anomaly temperature	6	1	2
54	Edge banding blend through	Insufficient UV colloid blend through	6	2	6
55	Edge banding blend through	UV colloid unhardened	6	3	3
56	Defect etching	Glue overflow to glass lateral	6	7	6

Step 9. Rank the priority for assessing CF.

The $R - C$ value is ranked from the highest to lowest, which removes CF from the risk priority ranking.

Step 10. Analyze the results and provide suggestions.

4. Numerical verification and comparison

In this section, we use an actual case of the thin-film transistor liquid crystal display (TFT-LCD) cell process from a professional LCD manufacturer in Taiwan to demonstrate our proposed approach. The TFT-LCD manufacturing process is divided

Table 6
The RPN of the TFT-LCD cell process.

No.	Failure mode	Cause of failure	*S*	*O*	*D*	RPN
1	FM1	CF1	6	2	3	36
2	FM1	CF2	6	3	3	54
3	FM1	CF3	6	2	4	48
4	FM1	CF4	6	3	4	72
5	FM1	CF5	6	2	3	36
6	FM1	CF6	6	2	6	72
7	FM2	CF7	6	2	6	72
8	FM3	CF7	7	2	3	42
9	FM4	CF8	5	2	2	20
10	FM4	CF9	5	1	2	10
11	FM5	CF10	5	3	6	90
12	FM5	CF11	5	3	6	90
13	FM6	CF12	5	3	6	90
14	FM6	CF13	5	3	2	30
15	FM6	CF14	5	3	6	90
16	FM6	CF15	5	3	2	30
17	FM6	CF16	5	3	6	90
18	FM6	CF17	5	2	6	60
19	FM7	CF18	4	2	2	16
20	FM7	CF19	4	3	2	24
21	FM8	CF20	7	2	3	42
22	FM9	CF13	5	3	6	90
23	FM9	CF21	5	2	6	60
24	FM9	CF22	5	2	3	30
25	FM9	CF18	5	3	3	45
26	FM10	CF23	6	2	4	48
27	FM10	CF24	6	2	4	48
28	FM10	CF25	6	2	4	48
29	FM11	CF26	6	3	6	108
30	FM12	CF27	6	2	4	48
31	FM13	CF28	6	2	6	72
32	FM13	CF29	6	2	6	72
33	FM14	CF30	6	3	3	54
34	FM14	CF31	6	2	4	48
35	FM14	CF32	6	2	6	72
36	FM14	CF33	6	2	3	36
37	FM5	CF34	6	2	4	48
38	FM5	CF35	6	1	2	12
39	FM5	CF36	6	3	3	54
40	FM15	CF37	6	3	6	108
41	FM15	CF38	6	3	3	54
42	FM16	CF39	6	3	3	54
43	FM16	CF40	6	2	3	36
44	FM17	CF41	6	1	3	18
45	FM17	CF42	6	1	3	18
46	FM18	CF10	6	2	4	48
47	FM18	CF43	6	2	6	72
48	FM18	CF5	6	2	3	36
49	FM3	CF44	7	2	6	84
50	FM19	CF45	6	3	6	108
51	FM19	CF46	6	3	3	54
52	FM19	CF47	6	2	6	72
53	FM20	CF48	6	1	2	12
54	FM21	CF49	6	2	6	72
55	FM21	CF50	6	3	3	54
56	FM22	CF51	6	7	6	252

into three major steps: array assembly process, cell assembly process, and module assembly process. Fig. 3 shows the cell assembly process flow [28], and the FMEA of the TFT-LCD cell process is shown in Table 5.

4.1. Solution based on the traditional RPN method

The traditional RPN method used *S*, *O*, and *D* indicators, which describe each failure mode on a scale of 1 to 10. The RPN value is the product of the *S*, *O*, and *D* indicators. Therefore, $RPN = S \times O \times D$. The CF that has a higher RPN value is assumed to be more important and is given a higher priority. The RPN of the TFT-LCD cell process is shown in Table 6.

Table 7
The grey relational grade of TFT-LCD cell process.

No.	Failure mode	Cause of failure	*S*	*O*	*D*	Grey relational grade
1	FM1	CF1	6	2	3	0.311224
2	FM1	CF2	6	3	3	0.319895
3	FM1	CF3	6	2	4	0.321889
4	FM1	CF4	6	3	4	0.330560
5	FM1	CF5	6	2	3	0.311224
6	FM1	CF6	6	2	6	0.352769
7	FM2	CF7	6	2	6	0.352769
8	FM3	CF7	7	2	3	0.334790
9	FM4	CF8	5	2	2	0.285107
10	FM4	CF9	5	1	2	0.277918
11	FM5	CF10	5	3	6	0.343995
12	FM5	CF11	5	3	6	0.343995
13	FM6	CF12	5	3	6	0.343995
14	FM6	CF13	5	3	2	0.293779
15	FM6	CF14	5	3	6	0.343995
16	FM6	CF15	5	3	2	0.293779
17	FM6	CF16	5	3	6	0.343995
18	FM6	CF17	5	2	6	0.335324
19	FM7	CF18	4	2	2	0.271673
20	FM7	CF19	4	3	2	0.280344
21	FM8	CF20	7	2	3	0.334790
22	FM9	CF13	5	3	6	0.343995
23	FM9	CF21	5	2	6	0.335324
24	FM9	CF22	5	2	3	0.293779
25	FM9	CF18	5	3	3	0.302450
26	FM10	CF23	6	2	4	0.321889
27	FM10	CF24	6	2	4	0.321889
28	FM10	CF25	6	2	4	0.321889
29	FM11	CF26	6	3	6	0.361440
30	FM12	CF27	6	2	4	0.321889
31	FM13	CF28	6	2	6	0.352769
32	FM13	CF29	6	2	6	0.352769
33	FM14	CF30	6	3	3	0.319895
34	FM14	CF31	6	2	4	0.321889
35	FM14	CF32	6	2	6	0.352769
36	FM14	CF33	6	2	3	0.311224
37	FM5	CF34	6	2	4	0.321889
38	FM5	CF35	6	1	2	0.295364
39	FM5	CF36	6	3	3	0.319895
40	FM15	CF37	6	3	6	0.361440
41	FM15	CF38	6	3	3	0.319895
42	FM16	CF39	6	3	3	0.319895
43	FM16	CF40	6	2	3	0.311224
44	FM17	CF41	6	1	3	0.304035
45	FM17	CF42	6	1	3	0.304035
46	FM18	CF10	6	2	4	0.321889
47	FM18	CF43	6	2	6	0.352769
48	FM18	CF5	6	2	3	0.311224
49	FM3	CF44	7	2	6	0.376335
50	FM19	CF45	6	3	6	0.361440
51	FM19	CF46	6	3	3	0.319895
52	FM19	CF47	6	2	6	0.352769
53	FM20	CF48	6	1	2	0.295364
54	FM21	CF49	6	2	6	0.352769
55	FM21	CF50	6	3	3	0.319895
56	FM22	CF51	6	7	6	0.426551

Matrix Y	CF1	CF2	CF3	…	CF50	CF51	FM1	FM2	FM3	…	FM21	FM22
CF1							36					
CF2							54					
CF3							48					
⋮				0								
CF50											54	
CF51												252
FM1												
FM2												
FM3												
⋮				0						0		
FM21												
FM22												

Fig. 4. Corresponding initial relation matrix Y of the TFT-LCD cell process.

4.2. Solution based on the grey relational grade method

The S, O, and D indicators are assumed to have equal importance in this case to determine the 56 corresponding grey relational grades of Table 5 for the 1000 SOD combinations, shown in Table 7.

4.3. Solution based on the DEMATEL method

Based on Table 6, the TFT-LCD cell process has 22 FMs and 51 CFs, which can form a 73-by-73 matrix. According to the results of Table 6, we can obtain the initial relation matrix Y of the TFT-LCD cell process, as shown in Fig. 4.

We calculate the corresponding DRSM of the TFT-LCD cell process per Eqs. (4) and (5), and the initial relation matrix Y in Fig. 4; the result is shown in Fig. 5.

Calculate the $R-C$ values of matrix T per Eqs. (7) and (8); the result is shown in Table 8.

4.4. Solution based on the proposed method

The proposed method uses the grey relational grades in Table 7 as input information of initial relation matrix Y, shown in Fig. 6.

DRSM	CF1	CF2	CF3	…	CF50	CF51	FM1	FM2	FM3	…	FM21	FM22
CF1							0.1429					
CF2							0.2143					
CF3							0.1905					
⋮				0								
CF50											0.2143	
CF51												1
FM1												
FM2												
FM3												
⋮				0						0		
FM21												
FM22												

Fig. 5. Corresponding DRSM of the TFT-LCD cell process.

Table 8
Prioritization of CFs for the TFT-LCD cell process by DEMATEL technique.

No.	$R-C$	No.	$R-C$	No.	$R-C$	No.	$R-C$	No.	$R-C$
CF1	0.1429	CF16	0.3571	CF31	0.1905	CF46	0.2143	FM10	−0.5714
CF2	0.2143	CF17	0.2381	CF32	0.2857	CF47	0.2857	FM11	−0.4286
CF3	0.1905	CF18	0.2421	CF33	0.1429	CF48	0.0476	FM12	−0.1905
CF4	0.2857	CF19	0.0952	CF34	0.1905	CF49	0.2857	FM13	−0.5714
CF5	0.2857	CF20	0.1667	CF35	0.0476	CF50	0.2143	FM14	−0.8333
CF6	0.2857	CF21	0.2381	CF36	0.2143	CF51	1.0000	FM15	−0.6429
CF7	0.4524	CF22	0.1190	CF37	0.4286	FM1	−1.2619	FM16	−0.3571
CF8	0.0794	CF23	0.1905	CF38	0.2143	FM2	−0.2857	FM17	−0.1429
CF9	0.0397	CF24	0.1905	CF39	0.2143	FM3	−0.5000	FM18	−0.6190
CF10	0.5476	CF25	0.1905	CF40	0.1429	FM4	−0.1190	FM19	−0.9286
CF11	0.3571	CF26	0.4286	CF41	0.0714	FM5	−1.1667	FM20	−0.0476
CF12	0.3571	CF27	0.1905	CF42	0.0714	FM6	−1.5476	FM21	−0.5000
CF13	0.4762	CF28	0.2857	CF43	0.2857	FM7	−0.1587	FM22	−1.0000
CF14	0.3571	CF29	0.2857	CF44	0.3333	FM8	−0.1667		
CF15	0.1190	CF30	0.2143	CF45	0.4286	FM9	−0.8929		

Matrix Y	CF1	CF2	CF3	…	CF50	CF51	FM1	FM2	FM3	…	FM21	FM22
CF1							0.311224					
CF2							0.319895					
CF3				0			0.321889					
⋮												
CF50											0.319895	
CF51												0.426551
FM1												
FM2												
FM3				0						0		
⋮												
FM21												
FM22												

Fig. 6. The initial relation matrix Y of the TFT-LCD cell process by GRA.

DRSM	CF1	CF2	CF3	…	CF50	CF51	FM1	FM2	FM3	…	FM21	FM22
CF1							0.4527					
CF2							0.4653					
CF3				0			0.4682					
⋮												
CF50											0.4653	
CF51												0.6204
FM1												
FM2												
FM3				0						0		
⋮												
FM21												
FM22												

Fig. 7. Corresponding DRSM of the TFT-LCD cell process by GRA.

According to Eq. (4), the maximum s is 0.687559. We calculate the corresponding DRSM of the TFT-LCD cell process based on Fig. 6; the result is shown in Fig. 7.

Calculate the $R-C$ values of matrix T by integrating the GRA and DEMATEL approach; the results is shown in Table 9.

4.5. Comparisons and discussion

In comparing the results of the four methods (traditional RPN method, grey relational grade method, DEMATEL method, and the proposed method), differences between our method and the other techniques can clearly be seen in Table 10.

From Tables 5 and 10, integrating the grey relational analysis and DEMATEL approaches provides several advantages.

(1) The proposed approach can reduce the occurrence of duplicate risk rankings.

Based on Table 10, the duplication rate of the RPN method is 67.9%, and 66.1% for the GRA method, 60.8% for the DEMATEL method, and 56.9% for the proposed approach.

(2) The proposed approach follows the ordered weighted criteria of the S, O, and D indicators.

Table 9
Prioritization of CFs for the TFT-LCD cell process by integration of the GRA and DEMATEL approaches.

No.	$R-C$	No.	$R-C$	No.	$R-C$	No.	$R-C$	No.	$R-C$
CF1	0.4527	CF16	0.5003	CF31	0.4682	CF46	0.4653	FM10	1.4045
CF2	0.4653	CF17	0.4877	CF32	0.5131	CF47	0.5131	FM11	0.5257
CF3	0.4682	CF18	0.8350	CF33	0.4527	CF48	0.4296	FM12	0.4682
CF4	0.4808	CF19	0.4077	CF34	0.4682	CF49	0.5131	FM13	1.0261
CF5	0.9053	CF20	0.4869	CF35	0.4296	CF50	0.4653	FM14	1.8991
CF6	0.5131	CF21	0.4877	CF36	0.4653	CF51	0.6204	FM15	0.9909
CF7	1.0000	CF22	0.4273	CF37	0.5257	FM1	2.8326	FM16	0.9179
CF8	0.4147	CF23	0.4682	CF38	0.4653	FM2	0.5131	FM17	0.8844
CF9	0.4042	CF24	0.4682	CF39	0.4653	FM3	1.0343	FM18	1.4339
CF10	0.9685	CF25	0.4682	CF40	0.4527	FM4	0.8189	FM19	1.5040
CF11	0.5003	CF26	0.5257	CF41	0.4422	FM5	2.3636	FM20	0.4296
CF12	0.5003	CF27	0.4682	CF42	0.4422	FM6	2.8432	FM21	0.9783
CF13	0.9276	CF28	0.5131	CF43	0.5131	FM7	0.8029	FM22	0.6204
CF14	0.5003	CF29	0.5131	CF44	0.5473	FM8	0.4869		
CF15	0.4273	CF30	0.4653	CF45	0.5257	FM9	1.8552		

Table 10
Ranking comparison for the TFT-LCD cell process by various methods.

No.	FM	CF	Value				Ranking			
			RPN	GRA	DEMATEL	Proposed method	RPN	GRA	DEMATEL	Proposed method
1	FM1	CF1	36	0.311224	0.1429	0.4527	41	40	40	40
2	FM1	CF2	54	0.319895	0.2143	0.4653	23	33	25	33
3	FM1	CF3	48	0.321889	0.1905	0.4682	30	25	32	26
4	FM1	CF4	72	0.330560	0.2857	0.4808	12	24	13	25
5	FM1	CF5	36	0.311224	0.2857	0.9053	41	40	13	4
6	FM1	CF6	72	0.352769	0.2857	0.5131	12	6	13	11
7	FM2	CF7	72	0.352769	0.4524	1.0000	12	6	4	1
8	FM3	CF7	42	0.334790	0.4524	1.0000	39	22	4	1
9	FM4	CF8	20	0.285107	0.0794	0.4147	50	53	46	49
10	FM4	CF9	10	0.277918	0.0397	0.4042	56	55	51	51
11	FM5	CF10	90	0.343995	0.5476	0.9685	5	14	2	2
12	FM5	CF11	90	0.343995	0.3571	0.5003	5	14	8	18
13	FM6	CF12	90	0.343995	0.3571	0.5003	5	14	8	18
14	FM6	CF13	30	0.293779	0.4762	0.9276	46	50	3	3
15	FM6	CF14	90	0.343995	0.3571	0.5003	5	14	8	18
16	FM6	CF15	30	0.293779	0.1190	0.4273	46	50	43	47
17	FM6	CF16	90	0.343995	0.3571	0.5003	5	14	8	18
18	FM6	CF17	60	0.335324	0.2381	0.4877	21	20	23	22
19	FM7	CF18	16	0.271673	0.2421	0.8350	53	56	22	5
20	FM7	CF19	24	0.280344	0.0952	0.4077	49	54	45	50
21	FM8	CF20	42	0.334790	0.1667	0.4869	39	22	39	24
22	FM9	CF13	90	0.343995	0.4762	0.9276	5	14	3	3
23	FM9	CF21	60	0.335324	0.2381	0.4877	21	20	23	22
24	FM9	CF22	30	0.293779	0.1190	0.4273	46	50	43	47
25	FM9	CF18	45	0.302450	0.2421	0.8350	38	47	22	5
26	FM10	CF23	48	0.321889	0.1905	0.4682	30	25	32	26
27	FM10	CF24	48	0.321889	0.1905	0.4682	30	25	32	26
28	FM10	CF25	48	0.321889	0.1905	0.4682	30	25	32	26
29	FM11	CF26	108	0.361440	0.4286	0.5257	2	3	5	8
30	FM12	CF27	48	0.321889	0.1905	0.4682	30	25	32	26
31	FM13	CF28	72	0.352769	0.2857	0.5131	12	6	13	11
32	FM13	CF29	72	0.352769	0.2857	0.5131	12	6	13	11
33	FM14	CF30	54	0.319895	0.2143	0.4653	23	33	25	33
34	FM14	CF31	48	0.321889	0.1905	0.4682	30	25	32	26
35	FM14	CF32	72	0.352769	0.2857	0.5131	12	6	13	11
36	FM14	CF33	36	0.311224	0.1429	0.4527	41	40	40	40
37	FM5	CF34	48	0.321889	0.1905	0.4682	30	25	32	26
38	FM5	CF35	12	0.295364	0.0476	0.4296	54	48	49	45
39	FM5	CF36	54	0.319895	0.2143	0.4653	23	33	25	33
40	FM15	CF37	108	0.361440	0.4286	0.5257	2	3	5	8
41	FM15	CF38	54	0.319895	0.2143	0.4653	23	33	25	33
42	FM16	CF39	54	0.319895	0.2143	0.4653	23	33	25	33
43	FM16	CF40	36	0.311224	0.1429	0.4527	41	40	40	40
44	FM17	CF41	18	0.304035	0.0714	0.4422	51	45	47	43
45	FM17	CF42	18	0.304035	0.0714	0.4422	51	45	47	43
46	FM18	CF10	48	0.321889	0.5476	0.9685	30	25	2	2
47	FM18	CF43	72	0.352769	0.2857	0.5131	12	6	13	11
48	FM18	CF5	36	0.311224	0.2857	0.9053	41	40	13	4
49	FM3	CF44	84	0.376335	0.3333	0.5473	11	2	12	7
50	FM19	CF45	108	0.361440	0.4286	0.5257	2	3	5	8
51	FM19	CF46	54	0.319895	0.2143	0.4653	23	33	25	33
52	FM19	CF47	72	0.352769	0.2857	0.5131	12	6	13	11
53	FM20	CF48	12	0.295364	0.0476	0.4296	54	48	49	45
54	FM21	CF49	72	0.352769	0.2857	0.5131	12	6	13	11
55	FM21	CF50	54	0.319895	0.2143	0.4653	23	33	25	33
56	FM22	CF51	252	0.426551	1.0000	0.6204	1	1	1	6

From Tables 5 and 10, CF2 has an RPN value of 54 (S, O, and D are 6, 3, and 3, respectively) and the $R-C$ value is 0.2143 (DEMATEL method). CF3 has an RPN value of 48 (S, O, and D are 6, 2, and 4, respectively), and the $R-C$ value is 0.1905 (DEMATEL method). This result demonstrates that according to the RPN and DEMATEL methods, CF2 has a higher priority than CF3. In this example, a maximum of six appears in both combinations. In CF2, the value of O is higher than in CF3. In CF3, the value of D is higher than in CF2. Any decision-maker should give higher allocation resources to defend the most dangerous scenario; thus, he should choose the highest value of 4 in CF3 as a higher priority. Therefore, CF3 is more important than CF2. In the proposed approach, CF2 and CF3 had $R - C$ values of 0.4653 and 0.4682, respectively, which gives CF3 higher priority than CF2.

(3) The proposed approach must consider the direct and indirect relationships between FM and CF.

Our approach should give a higher priority when a single CF causes multiple FMs. From Table 10, CF5 causes 2 failure modes to occur (FM1 and FM18), as do CF7 (FM2 and FM3); CF10 (FM5 and FM18); CF13 (FM6 and FM9); and CF18 (FM7 and FM9). These five CFs should be given higher priority than the other CF. However, they are not given higher priority by the RPN and GRA methods. Based on these comparisons, the proposed approach is effective and generates more ideal ranking results for various indicator combinations.

5. Conclusions

The traditional RPN method is used widely because it is easy to calculate and understand. However, it has a serious shortcoming, in that the RPN elements have many duplicate numbers. The GRA method can effectively solve this problem. But, it does not consider the direct and indirect relationships between FMs and CFs. Thus, the rankings per the RPN and GRA methods might fail to satisfy actual needs. We have developed an easy and effective approach to improve the ranking problems of the traditional RPN that lowers the high duplication rate and assigns priorities the follow the ordered weighted criteria by GRA; moreover, it uses the DEMATEL method to consider relationships between alternatives. To illustrate the proposed method and compare it with other RPN methods, the TFT-LCD cell process is adopted as an example. We also compared the simulation results between the traditional RPN, grey relational grade, DEMATEL [12], and proposed methods. Our results demonstrate that the proposed approach effectively circumvents traditional RPN method drawbacks and adapts flexibly to real-world situations.

The proposed method can help decision-makers limit confusion in assessing risk and has the following advantages:

(1) The proposed method has a lower high duplication rate than the traditional RPN method.
(2) The proposed method follows the ordered weighted criteria and generates more ideal ranking results.
(3) The proposed method considers the direct and indirect relationships between FMs and CFs and gives higher priority when a single CF causes multiple FMs, helping decision-makers to make more ideal determinations.
(4) The proposed method is an easily operated tool that does not require other programming or software to obtain ranking results.

Acknowledgements

The authors would like to thank the National Science Council of the Republic of China, for financially supporting this research under Contract Nos. NSC 99-2410-H-145-001, NSC 100-2410-H-145-001, and NSC 101-2410-H-145-001.

References

[1] Chang KH, Chang YC, Wen TC, Cheng CH. An innovative approach integrating 2-tuple and LOWGA operators in process failure mode and effects analysis. Int J Innov Comput I 2012;8(1B):747–61.
[2] Ahmad R, Kamaruddin S, Azid IA, Almanar IP. Failure analysis of machinery component by considering external factors and multiple failure modes – a case study in the processing industry. Eng Fail Anal 2012;25:182–92.
[3] Yang J, Huang HZ, He LP, Zhu SP, Wen D. Risk evaluation in failure mode and effects analysis of aircraft turbine rotor blades using Dempster–Shafer evidence theory under uncertainty. Eng Fail Anal 2011;18(8):2084–92.
[4] Chang KH, Cheng CH. Evaluating the risk of failure using the fuzzy OWA and DEMATEL method. J Intell Manuf 2011;22(2):113–29.
[5] Braglia M, Frosolini M, Montanari R. Fuzzy TOPSIS approach for failure mode, effects and criticality analysis. Qual Reliab Eng Int 2003;19(5):425–43.
[6] Chin KS, Wang YM, Poon GKK, Yang JB. Failure mode and effects analysis using a group-based evidential reasoning approach. Comput Oper Res 2009;36(6):1768–79.
[7] Kutlu AC, Ekmekcioglu M. Fuzzy failure modes and effects analysis by using fuzzy TOPSIS-based fuzzy AHP. Expert Syst Appl 2012;39(1):61–7.
[8] Chang CL, Wei CC, Lee YH. Failure mode and effects analysis using fuzzy method and grey theory. Kybernetes 1999;28(9):1072–80.
[9] Xiao N, Huang HZ, Li Y, He LP, Jin T. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. Eng Fail Anal 2011;18(4):1162–70.
[10] Seyed-Hosseini SM, Safaei N, Asgharpour MJ. Reprioritization of failures in a system failure mode and effects analysis by decision making trial and evaluation laboratory technique. Reliab Eng Syst Safe 2006;91(8):872–81.
[11] Chang KH. Evaluate the orderings of risk for failure problems using a more general RPN methodology. Microelectron Reliab 2009;49(12):1586–96.
[12] Yager RR. On ordered weighted averaging aggregation operators in multicriteria decision-making. IEEE Trans Syst Man Cy 1988;18(1):183–90.
[13] Sankar NR, Prabhu BS. Modified approach for prioritization of failures in a system failure mode and effects analysis. Int J Qual Reliab Manage 2001;18(3):324–35.
[14] Gilchrist W. Modelling failure modes and effects analysis. Int J Qual Reliab Manage 1993;10(5):16–23.
[15] Braglia M. MAFMA: multi-attribute failure mode analysis. Int J Qual Reliab Manage 2000;17(9):1017–33.
[16] Shahin A. Integration of FMEA and the Kano model: an exploratory examination. Int J Qual Reliab Manage 2004;21(7):731–46.
[17] Bowles JB, Pelaez CE. Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. Reliab Eng Syst Safe 1995;50(2):203–13.
[18] Chang KH, Cheng CH. A risk assessment methodology using intuitionistic fuzzy set in FMEA. Int J Syst Sci 2010;41(12):1457–71.
[19] US Department of Defense Washington, D.C. Procedures for performing a failure mode effects and criticality analysis. US MIL-STD-1629A; 1980.

[20] International electrotechnical commission, Geneva. Analysis techniques for system reliability- procedures for failure mode and effect analysis. Geneva, IEC 60812; 1985.
[21] Automotive industry action group (AIAG). Potential failure mode and effect analysis (FMEA) reference manual. FMEA reference manual 4th edition; 2008.
[22] Deng JL. Control problems of grey systems. Syst Control Lett 1982;1(5):288–94.
[23] Deng JL. Introduction to grey system theory. J Grey Syst 1989;1(1):1–24.
[24] Lin Y, Chen M, Liu S. Theory of grey systems: capturing uncertainties of grey information. Kybernetes 2004;33(2):196–218.
[25] Pramanik S, Mukhopadhyaya D. Grey relational analysis based intuitionistic fuzzy multi-criteria group decision-making approach for teacher selection in higher education. Int J Comput Appl 2011;34(10):21–9.
[26] Gabus A, Fontela E. Perceptions of the world problematique: communication procedure, communicating with those bearing collective responsibility. Geneva, Switzerland: Battelle Geneva Research Centre; 1973.
[27] Tseng ML. A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach. Expert Syst Appl 2009;36(4):7738–48.
[28] Chung SH, Tai YT, Pearn WL. An effective scheduling approach for maximizing polyimide printing weighted throughput in cell assembly factories. IEEE Trans Electron Pack Manuf 2009;32(3):185–97.