A New Model For Traceability Evaluation based on Costs-Benefits Analysis FMECA Principles and Fuzzy Sets Techniques

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Abstract

Quality Certification according to ISO9000 standards requires that firms have to be able to track every jobs, assembling steps, and equipment needful to realize each product.
Another aspect of a traceability system is the possibility, for each type of product, to locate on the market every delivered ones on which analysis and/or corrective actions has to be made, due to an unconformity found on a certain component or on a certain job (customer-oriented traceability). This last feature can give real advantages in terms of customer satisfaction, safety and firm image, therefore its establishment is often related to high costs due to the startup of dedicated procedures for parts identification, information systems, human resources, etc. The best choice, in this case is to submit to this type of traceability procedure a set of components that, from an analysis of the bill of materials, are recognized as critical in terms of certain critical parameters such as safety, cost, product functionality, etc.
In this paper we wish to give a practical decision supporting tool useful to identify, for an industrial product, which specific components have to be traced. In our prototype system the well known cost benefits analysis, FMECA principles and Fuzzy Sets techniques have been implemented in a structured approach to define, inside the bill of materials, which components have to be submitted to the traceability procedure.

1. Structure of the system

Our approach is structured according to three sequential steps. The first one is related to the development of a specific procedure, based on a cost/benefits analysis of the Bill of Materials (BoM) for the determination of the minimum number of parts to be traced (*Critical number*).
The second step is related to the definition, according to FMECA principles, of a *Criticality index* for each part of the product, while to define the specific parts to be traced (*Critical set*) a system based on Fuzzy Sets theory has been developed.
The three main steps in which the proposed system has been conceived and developed can be summarized as follows:

1. Cost/benefits analysis for the BoM, finalized to the determination of the minimum number of parts to be traced (*Critical number* - $\mathbf{C_n}$);
2. Implementation of FMECA principles for the BoM oriented to the definition of a *Criticality Index* - $\mathbf{I_c}$ that has to be able to give a measure of part criticality with respect to the traceability;
3. Fuzzy Sets-based approach for the identification of the parts to trace (*Critical set* - $\mathbf{I_x}$) on the basis of the values of $\mathbf{I_c}$ and $\mathbf{C_n}$ related to the BoM.

1.1 Cost-Benefits Analysis applied to Traceability: The model

The model built for this section has been structured by a classification of the part-flaw costs into the following cost items:

1. Product disassembling costs - $\mathbf{C_s}$
2. Component refurbishment/replacing costs - $\mathbf{C_r}$;
3. Failure analysis costs - $\mathbf{C_A}$;
4. Localization costs for the products where each part(s) has been assembled on - $\mathbf{C_L}$

While the costs related to the traceability setup have been classified in:

1. Fixed costs related to hardware and software allowance - $\mathbf{C_F}$;
2. Variable costs related to additional human resources needful for products identifying and component marking on the production lines, systems management and maintenance, etc - $\mathbf{C_V}$;

In addition to the above given classification let be:

- **N** – total number of product realized
- **n** – total number of parts to be traced (critical set);
- $\mathbf{I_r = n/N}$ – Traceability Index **(0)**
- $\mathbf{Q_m}$ – medium lot size
- $\boldsymbol{\alpha_m}$ – average of flaws found on $\mathbf{Q_m}$

On the basis of the given positions we have first evaluated the costs related to the traceability startup and maintenance, with the assumption that variable costs, for each unit of product, can be expressed by a linear function of I_r. In this way the total costs - C_T - can be given by the following relation:

$$\mathbf{C_T = C_F + NI_rC_V} \qquad \mathbf{(1)}$$

After that we have evaluated the benefits that can be obtained from a traceability system in terms of flaw costs reduction. With this aim we have defined a function that can be expressed by the sum of

- product disassembling costs - C_s;
- parts replacement/refurbishment - C_r
- failure analysis costs - C_A;
- localization costs - C_L.

With respect to (1) the C_s and C_T functions have been obviously assumed as fixed with the increasing/decreasing of the number of the parts underwent to the traceability procedure while the main problem has been related to the effective determination of a function-type for C_A and C_L.
With this aim we have analyzed the historical data about parts failure (which is ever formed during the tests of the product prototypes) of certain firms operating in several production areas. As a survey of this analysis the best fitting function for C_A and C_L sum has resulted to be an hyperbolic one decreasing with the growth of the parts traced (and so when $\mathbf{I_r}$ is increased) which can also describe well the relevant reduction of

localization times (the main objective of a Traceability System) with the increasing of the number of parts submitted to the traceability system.

In this way the global $\mathbf{I}_r$ function of traceability costs ($\mathbf{C_{dr}}$), can be given by the following relation

$$\mathbf{C_{dr} = \alpha_m Q_m(C_s + C_r) + \alpha_m Q_m(C_A + C_L)/I_r} \quad \textbf{(2)}$$

The relation (2) can be minimized with respect to I_r, obtaining the final relation

$$\mathbf{I_r = [\alpha_m Q_m(C_A + C_L)/NCv]^{1/2}} \quad \textbf{(3)}$$

From (3) and (0) it is possible for the user to have the value - *n* - of the critical sets of parts to be traced.

1.2 Determination of the Critical Set: FMECA Analysis and Fuzzy Sets

The second step of the system is realized with a BoM analysis conceived in a similar fashion of that made with FMECA technique concepts.
With this aim we have classified the criticality of each part in terms of the following features, recognized as relevant for the traceability system.

- Average of the faulty parts come back from the market - A_F
- Maintenance cost - V
- Safety of the product related to a possible fault of the part - S
- Traceability required to the supplier by the main contractor - C
- Damaging of the firm image related to the product malfunction due to a fault occurred on one of its parts - P

According to FMECA principles the criticality index $\mathbf{I_c}$ related to each part included into the bill of materials of the product is given by a relation like the following

$$\boldsymbol{I_c} = \frac{c_1 V_F + c_2 V + c_3 S + c_4 C + c_5 P}{c_1 + c_2 + c_3 + c_4 + c_5} \quad \textbf{(4)}$$

where c_i are the weights related to each factor.

1.2.1 The Fuzzy approach

For the evaluation of the weights included into (4) and the determination of the $\mathbf{I_c}$ value we have realized a system which uses the Fuzzy Set Technique to merge the available information related to the several fault features and to have a well fitted representation of each feature with respect to the uncertainty related to its evaluation. The system uses the database of the faults occurred during the product prototype test phase and is structured as follows:

$I=\{i_i\}$ the corrective actions made on each component of the product;
$E=\{e_j\}$ the faults occurred in terms of negative effects measured by certain defined parameters which are related to predefined sets (speech universe) as follows

$$\begin{aligned} &V = [V_i]\ i = 1,\ldots,n \\ &S = [S_j]\ j = 1,\ldots, m \\ &C= [C_h]\ h= 1,\ldots, k \\ &P = [P_x]\ x = 1,\ldots,w \end{aligned} \qquad (5)$$

Each element of (5) is related to weighted indexes $\boldsymbol{R_u}$ ($u=1,\ldots,U$) where $\boldsymbol{U}$ is the number of the defined membership functions (G_U - Figure 1). The U value, as well known, depends by the required level of detail needful to describe the specific parameter.

See Figure 1

In this way, for each component included into the analysis, $\mathbf{I_c}$ will be related to the above parameters, each of that characterized by the U values of the corresponding membership functions.
The determination of the global membership function is finally made with one of the well known inference rules (e.g. *minmax* rule) for each component, obtaining the following U-dimensional vector

$$\mathbf{H^j = [m_{ej}(G_1),\ldots., m_{ej}(G_U)]} \qquad (6)$$

From (6) it is possible to construct a binary part-event incidence matrix (*IxJ*) which relates each event with the i-esimus part through the U-dimensional vector K^i

$$\mathbf{K^i = \Sigma_{j=1,\ldots,J'}\, w_j H^j} \qquad (7)$$

where $\boldsymbol{w_j}$ is a coefficient introduced to take into account of certain binary features (e.g. traceability of the components already included into the product supply contract, critical-safety component, etc.). $\boldsymbol{I_c}$ (4) is given by the weighted membership function that, for the i-esimus part, has the highest fuzzy value, i.e. to say:

$$\mathbf{I_c = G^i = u \setminus max_{u=1,\ldots,U}\{K_u{}^i\}} \qquad (8)$$

The $\mathbf{I_c}$ values - one for each component of the BoM - given by the (8) can be ordered in decreasing way obtaining a ***Priority Parts Array*** in which the higher will be its values the higher will be the traceability priority of the related component.
The *n* components of the above computed *Critical number* - $\mathbf{C_n}$**,** given by (3) with the highest I_c values are able to define the *Critical set* of those part that are to be submitted to the traceability procedure.

2. Case Study

We present the test of the fuzzy prototype system in a firm operating in telecommunication area as supplier. The analysis has been made during the test of a set of prototype products for a new city-mobile telecommunication system (DECT). A sample of the analysis conducted is given by the following three main parameters

- Time of stop of the test due to the fault;
- Maintenance costs due to the faulty part;
- Number of faults, due to the same part, occurred to the product during the selected test period.

In table 1 we report the analysis for three of the partnumbers (PN), X, X_1, X_2 failed during the tests with the values of each of the three selected parameters.

See Table 1

Figure 2 shows an example of the membership functions for the maintenance costs, with the related speech universe, while in figure 3 we report the membership functions which have been selected to give the fuzzy value for the time of stop of each prototype.

See Figure 2

See Figure 3

In table 2 we give the values of $\mathbf{m(g)}^T$ (6) for the three selected partnumbers from which, with (8), it is possible to have the values of I_c. From its analysis it is possible to see how the I_c value is the higher for the PN X_1 (0,35 - high) while I_c is smaller for partnumbers X and X_2. The final step is to reorganize in decreasing order the values of I_c, giving the right priority to those parts which are critical in terms of the selected traceability requirements.

See Table 2

3. Conclusions

In this paper we have presented a new approach to the development of a decision-based method oriented to traceability design and implementation. The model realized can be summarized by the following features

- It is able to take into account every features which can be retrieved on a complex industrial product, being in this way flexible with respect to the production context;
- It is simple and fast to implement and can be related with the tests failure database, which is ever formed during the prototyping test of the new products;
- It is based on the combined use of cost-benefit analysis and Fuzzy Logic Theory through a specific model which can be fast customizable to each production reality.

The industrial case where the model has been applied has given excellent results in terms of critical parts individuation and failures reduction, obtaining an improvement about critical parts localization of 27% and a global reduction of parts failures of about 20%.
The results obtained has been relevant and have led to the conclusion that a *customer-oriented* traceability for a complex industrial product has to be sized due to the condition of retrieving, inside the Bill of Materials, the critical components for which the identification and trace procedure is able to give the expected advantages for both firm and customers.
The approach presented can be improved toward the direction of a better fuzzy features representation and to the extension of the system to the definition of the *product features* to be traced. An approach to realize these tasks will be the further developments of this work.

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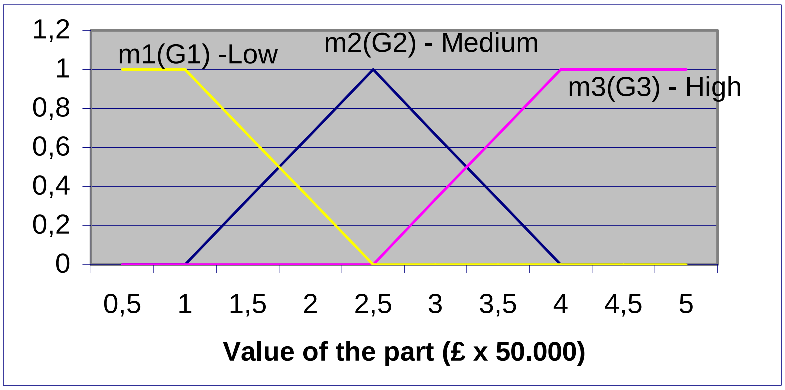

Figure 1 - example of membership function for one of the defined parameters (Value of the part).

Table 1: the main parameters used for the system (costs in Italian Currency)

Failure Date	PN	Time of stop (hours)	Maintenance cost (M£)	Number of the faults occurred
06-mar	X	0.5	0.1	2
23-mar	X	1	0,18	3
25-mar	X	0,1	0,2	1
28-mar	X	0,3	0,5	1
29-mar	X	0,5	0,5	2
06-apr	X	0,7	0,41	3
13-apr	X_1	0,3	1	4
14-apr	X	0,4	0,3	3
14-apr	X	0,2	0,2	3
18-apr	X	0,8	0,21	2
22-apr	X	0,3	0,31	1
23-apr	X	9,5	0,15	5
24-apr	X	4,5	1,3	3
28-apr	X	8	2,2	1
28-apr	X	9,5	4,3	3
30-apr	X	2,1	0,3	2
30-apr	X	9	1,2	1
05-maj	X	5	1	1
10-maj	X	1,5	1	1
17-maj	X_1	6,5	1	1
17-maj	X_1	1,85	0,7	2
23-maj	X_1	3,95	0,6	1
25-maj	X_1	1,5	0,75	1
01-jun	X	1,8	0,4	1
10-jun	X_1	6,5	2,5	1
10-jun	X	1,2	0,3	1
10-jun	X	2,8	1,3	1
13-jun	X	2,9	0,3	1
15-jun	X_2	8,5	1,7	4
17-jun	X	9,5	0,3	3
19-jun	X	6	1,3	1
19-jun	X	1	0,32	3
23-jun	X	6,5	1,1	1
27-jun	X_2	1,3	0,6	4
27-jun	X_1	2,8	0,2	2
28-jun	X_1	1,7	0,7	1
10-jul	X	6,5	0,4	4
10-jul	X	6	1,35	1
13-jul	X	6	1,3	3
13-jul	X	1,5	0,34	1
14-jul	X_2	1,2	0,4	3
06-sep	X_1	1,8	0,3	5
14-sep	X_2	4	2,4	1
20-sep	X_1	6	1,3	3
08-oct	X	9	2,36	1
27-oct	X_1	1,2	1,31	3

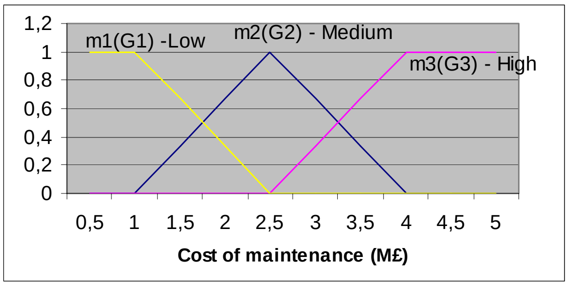

Figure 2: Membership functions related to the maintenance costs

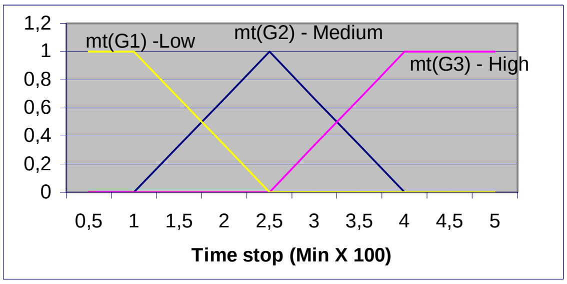

Figure 3: Membership functions related to the time stops of the prototype

Table 2: A sample of the numerical results obtained from the procedure

X			X_1			X_2		
m(G1)	m(G2)	m(G3)	m(G1)	m(G2)	m(G3)	m(G1)	m(G2)	m(G3)
1	0	0	0	0	0	0,5	0	0,5
0	0	0	0	0	0	0,75	0,25	0
0	0	0	0,2	0	0	0,6	0,4	0
0	0,4	0	0	0	0	0,5	0	0,5
0	0	0	0,2	0	0	0,5	0	0,5
0	0	0	0	0	0	0,63	0,38	0
0,3	0	0	0	0,36	0,64	0	0	0
0	0	0	0	0	0	0,79	0,21	0
0	0,1	0	0,3	0	0	0,5	0,37	0,13
0,4	0	0	0	0	0	0,5	0,37	0,13
0	0	0	0	0	0	0,5	0,17	0,33
0,2	0	0,3	0	0	0	0,54	0,46	0
0	0	0,45	0,1	0	0	0,83	0,17	0
0,37	0	0,56	0,68	0	0	0,6	0,4	0
0,12	0,2	0	0	0	0	0,54	0,46	0
0,34	0	0	0,5	0	0	0,5	0	0,5
0	0,34	0,56	0	0	0	0,56	0,44	0
0,45	0,56	0,45	0	0	0	0,79	0,21	0
0,57	0,57	0,45	0	0	0	0,5	0,17	0,33
0,78	0,67	0	0,35	0,37	0,29	0	0	0
0	0	0	0,5	0	0,5	0	0	0
0	0	0	0	0,36	0,64	0	0	0
0	0	0	0,23	0,46	0,54	0	0	0
0	0	0,23	0,34	0	0	0,5	0	0,5
0,68	0,32	0,34	0	0	0	0	0	0
0,12	0,22	0	0	0	0	0,5	0,37	0,13
0	0,34	0	0	0	0	0,5	0	0,5
0	0	0	0	0	0	0,5	0	0,5
0	0	0	0,19	0,51	0,31	0	0	0
0	0	0	0	0	0	0,54	0,46	0
0	0	0	0	0	0	0,71	0,29	0
0	0	0	0,11	0	0	0,52	0,48	0
0	0	0	0,34	0	0	0,68	0,32	0
0,5	0,33	0,17	0	0	0	0	0	0
0	0	0	0,25	0,44	0,31	0	0	0
0	0,57	0,56	0,78	0,36	0,64	0	0	0
0	0,34	0	0	0	0	0,68	0,32	0
0,2	0,34	0	0	0	0	0,71	0,29	0
0	0	0	0	0	0	0,71	0,29	0
0	0	0	0	0	0	0,5	0,2	0,3
0,5	0,4	0,1	0	0	0	0	0	0
0	0	0	0	0,36	0,64	0	0	0
0,88	0,12	0	0	0	0	0	0	0
0	0	0	0,38	0,35	0,28	0	0	0
0	0	0	0	0	0	0,56	0,44	0
0	0	0	0	0,65	0,35	0	0	0
7,41	5,82	4,17	5,45	4,22	5,14	18,24	7,92	4,85
43%	33%	**24%**	37%	28%	**35%**	59%	26%	**16%**