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A fuzzy approach to the evaluation of human factors in ultrasonic nondestructive examinations

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Abstract

Human factors are among the main elements affecting the reliability of nondestructive examinations (NDE). In a man-machine system, human reliability is affected by many factors (performance shaping factors) whose influence on reliability cannot be easily expressed quantitatively. This paper identifies and ranks 59 performance shaping factors by using a fuzzy reasoning method and proposes a procedure to measure them. This will determine the Quality Standard (QS) for a NDE system so that human reliability in ultrasonic nondestructive examinations can be qualitatively evaluated.

Keywords: Human reliability; Ultrasonic nondestructive examinations; Fuzzy sets; Human factors; Performance shaping factors

1. Introduction

After several decades, the welding industry has completely accepted standard nondestructive testing (NDT) as an inevitable but invaluable part of the production and maintenance of components. Its application has been regulated, acceptance criteria for weld discontinuities exist, schemes for personnel qualification are in place and equipment has evolved to a standard approaching perfection.

Ultrasonic inspection is one of the most widely used methods for nondestructive inspection. Its primary application in the inspection of metals is the detection and characterization of internal flaws (significant discontinuities or imperfections), it is also used in the detection of surface flaws, in the definition of bonds characteristics, in the measurement of thickness and extent of corrosion and, much less frequently, in the determination of physical properties, structure, grain size and elastic constants.

The main disadvantage of ultrasonic inspection as compared to other methods for nondestructive inspection is the extensive technical knowledge that is required for the development of inspection procedure, i.e., the human factor plays a very important role in the process.

In general, the parameter that describes the reliability of inspection techniques is Probability of Detection (POD). Broadly speaking, the inspection reliability is defined as the probability of not overlooking an

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existing defect and correctly sizing it. Whatever simple this definition may appear, it encompasses many complex issues ranging from the specification of the nature of defects to influencing factors related to the inspection instrumentation, product nature, the involved human factor and the available expertise for inspection data processing and assessment.

The probabilistic analysis is used in order to analyze system reliability rationally, i.e., objectively. It is based on the assumption that an equipment or human failure occurs at random. A failure of a single component may occur at random; a human error, however, does not necessarily occur in that way, since a human factor is composed of a large number of components (attributes or performance shaping factors) and its functional structure is very complex. By using the probabilistic approach, where the equipment and procedure are qualified, it is assumed that the operator correctly implements all the procedure's provisions and thus isolates the human factor elements.

The First European-American Workshop on the Determination of Reliability and Validation Method on NDE [20] gave origin to a conceptual model that has defined NDE Reliability (R) as:

$$R = f(IC) - g(AP) - h(HF), \quad (1)$$

where:

H effect of Human Factors, generally reducing the capability or effectiveness,

IC Intrinsic Capability of the system (technique and combination of techniques), generally considered as an upper bound,

AP effect of Application Parameters, such as access restrictions, surface state, generally reducing the capability of the nondestructive system.

A human error occurs when an action is taken that was “not intended by the actor; not desired by a set of rules or an external observer; or that led the task or system outside its acceptable limits” [20].

Human error usually arises from inadequacies of the system design. These inadequacies fall into three groups [19]. The first involves task complexity, i.e., humans have limited capacities for perceiving, attending, remembering, calculating, etc. Errors are likely to occur when the task requirements exceed these capacity limitations. The second group of inadequacies includes error-likely situations. This category refers to more general situational characteristics that predispose operators to make errors. It includes factors such as inadequate workspace and training procedures, as well as poor supervision. Finally, errors can also reflect individual differences. These differences are human attributes of the worker, such as abilities and attitudes. One of the important individual factors is susceptibility to stress and inexperience, which can produce a tenfold increase in human error possibility.

Human reliability in ultrasonic inspection depends on physical and mental factors. Some of the physical elements to consider include motor skills (eye-hand coordination, dexterity, flexibility, etc.), vision capabilities (color discrimination, near and far field visual acuity and field of vision); general physical condition and stamina to work for the required periods in given environment (to climb, kneel, bend, etc). The mental or cognitive process in a typical NDE task includes sensation, perception, short-term and long-term memory, decision making and a resulting action [21].

In man-machine systems there is always a degree of fuzziness, due to the following [6]:

- Inability to acquire and process an adequate amount of information about systems,
- Vagueness of the relationship between people and working environments,
- Vagueness of the human thought process.

Moreover, human reliability behavior is fuzzy in nature because human errors are produced in a fuzzy way and human behavior is fuzzy in nature [2]. Therefore, the use of a methodology based on fuzzy sets and fuzzy numbers is well suited to human reliability engineering. Instead of using probabilistic representation, a triangular fuzzy number, defined on the interval [0,1], is used here to characterize human reliability. The advantage of using a triangular fuzzy number is that it cannot only convey the most possible human reliability of a task but also reflect the fuzziness of the evaluation data [10].

In fact, human behavior is affected by many independent “Performance Shaping Factors” (PSFs), which represent the characteristics and circumstances of tasks in a discriminate manner [22]. The human reliability of a task can be determined from the expert's judgment. The degree of attendance of the PSFs is often expressed in linguistic terms.

Previous works on human reliability have already employed fuzzy sets [9, 10, 11, 13, 14, 15, 16, 17, 18 and 23], Belchior *et al.* [1] proposed a procedure for evaluating software quality requirements using fuzzy theory by determining a fuzzy Quality Standard (QS);

Oliveira *et al.* [11] developed the software QUALCORDIS - a domain-specific tool aimed at assisting identification of software quality requirements in Cardiology.

2. Human reliability evaluation

A qualitative evaluation of human reliability in ultrasonic nondestructive examinations is based on a procedure developed for measuring the attributes that determine the Quality Standard (QS) for a NDE system. The procedure for evaluation of human reliability in the nondestructive ultrasonic inspection follows the steps described below.

Step 1. Identification of the object of evaluation and the set of performance shaping factors.

In general, human behavior is affected by many Performance Shaping Factors (PSF), e.g., task environment, stress, motivation, etc. Some of them are external to the person and some are internal. The external PSFs include the entire work environment, especially equipment design and written procedures or oral instructions.

The internal PSFs represent the person's individual characteristics – skills, motivation and expectations that influence the performance. Psychological and physiological stresses result from a work environment in which the demands placed on the operator by the system do not conform to his capabilities and limitations [22].

Human reliability depends on the complex interaction between the fifty nine (59) attributes (linguistic variables) listed below. Thirty two (32) of them are external and twenty seven (27) are internal factors (psychological and physiological stressors). The PSFs largely determine whether human performance will be highly reliable, highly unreliable, or at some level in between.

PSF_1 Architectural features

PSF_2 Environmental features

PSF_3 Temperature

PSF_4 Humidity

PSF_5 Air quality

PSF_6 Lighting

PSF_7 Noise

PSF_8 Vibration.

PSF_9 Degree of general cleanliness

PSF_{10} Work hours / work breaks

PSF_{11} Availability and adequacy of equipment

PSF_{12} Shift rotation

PSF_{13} Organizational structure (authority, communication channel(s))

PSF_{14} Actions by supervisors, coworkers

PSF_{15} Rewards, recognitions, benefits

PSF_{16} Motor requirements (speed, strength, precision)

PSF_{17} Control display relationships

PSF_{18} Interpretation requirements

PSF_{19} Decision making requirements

PSF_{20} Frequency and repetitiveness

PSF_{21} Complexity of task

PSF_{22} Long and short term memory

PSF_{23} Calculating Requirements

PSF_{24} Feedback of results

PSF_{25} Team structure and communication

PSF_{26} Man-machine interface factors

PSF_{27} Design of equipment

PSF_{28} Tools

PSF_{29} Procedures Required

PSF_{30} Written or oral communications

PSF_{31} Work methods

PSF_{32} Plant policies

PSF_{33} Previous training/experience

PSF_{34} State of current practice or skill

PSF_{35} Personality and intelligence variables

PSF_{36} Motivation and attitudes

PSF_{37}	Emotional state
PSF_{38}	Attitudes based on influence of family
PSF_{39}	Group Identifications
PSF_{40}	Suddenness of psychological stressor
PSF_{41}	Duration of stress psychological
PSF_{42}	Task speed
PSF_{43}	Task load
PSF_{44}	Work risk
PSF_{45}	Threats (of failure, loss of job)
PSF_{46}	Monotonous, degrading or meaningless work
PSF_{47}	Long, uneventful vigilance
PSF_{48}	Distractions (noise, glare, movement, color)
PSF_{49}	Duration of stress physiologic
PSF_{50}	Fatigue
PSF_{51}	Pain or discomfort
PSF_{52}	Hunger or thirst
PSF_{53}	Temperature of operator
PSF_{54}	Radiation (physiological effect)
PSF_{55}	G-force extremes
PSF_{56}	Movement constriction
PSF_{57}	Oxygen Insufficiency
PSF_{58}	Atmospheric pressure extremes
PSF_{59}	Lack of physical exercise

Step 2. Establishment of a committee of decision-makers.

This is one of the most important steps in the procedure, since the experts are the sensors and the quality of information will depend on their hierarchical levels. In this work, nine experts (*A, B, C, D, E, F, G, H and I*) of high hierarchical level have been selected. They are known for their experience, knowledge and practice in ultrasonic nondestructive examinations.

Step 3. Establishment of the relative importance of each expert (PE_i).

This step is accomplished through an Expert Profile Identification Questionnaire (EPIQ), which consists of a set of questions with the objective of evaluating each expert's importance and thus assigning him a weight. This is always relative to the other experts' weights and will have an influence on the final result.

Step 4. Choice of linguistic values for the evaluation of human reliability attributes.

The linguistic values used for the evaluation of the level of importance of the factors were: *critical* (it has a great influence on human reliability), *conditional* (it has some influence on human reliability), *not very conditional* (it has an influence on human reliability) and *irrelevant* (it does not affect human reliability).

In order to evaluate the degree of attendance assigned to the PSFs by each operator, the following linguistic values have been used: *excellent, good, regular, fair* and *weak.*

Step 5. Assignment of fuzzy numbers to linguistic terms.

It has been shown that fuzzy numbers are very useful for representation and information processing under a fuzzy environment [5]. Here, triangular fuzzy numbers – identified, as usual, by the three parameters a, m, b – are associated to the linguistic terms above, as shown in Table 1.

Step 6. Assignment of degrees of attendance to the PSFs by experts.

This step consists of obtaining from the selected experts their opinion on the importance of each performance shaping factor, as well as obtaining from two operators (X_1, X_2) – working in the same environment at the site where they perform ultrasonic examinations – their judgment on the degree of attendance of each attribute. The experts' and operators' opinions are expressed by numbers associated to the previously defined linguistic terms, as shown in Table 2. The correspondence between the linguistic terms of each variable and these numbers is the following:

- level of importance: 3 - *critical*; 2 - *conditional*; 1 - *not very conditional*; 0 – *irrelevant*.
- degree of attendance: 4 – *excellent*; 3 - *good*, 2 - *regular*, 1 – *fair*; 0 – *weak.*

Table 1. Representation of linguistic values and triangular fuzzy numbers parameters.

Level of importance	a	m	b	Degree of attendance	a	m	b
critical	2	3	3	excellent	3	4	4
conditional	1	2	3	good	2	3	4
not very conditional	0	1	2	regular	1	2	3
irrelevant	0	0	1	fair	0	1	2
				weak	0	0	1

Table 2. Opinions about the level of importance and degree of attendance of the PSFs.

PSF	Expert judgment (level of importance)									Operator judgment (degree of attendance)	
1..59	A	B	C	D	E	F	G	H	I	X_1	X_2
PSF_1	3	0	1	0	1	0	2	2	3	3	3
PSF_2	3	2	2	2	2	1	3	2	3	3	3
PSF_3	3	2	1	3	2	1	3	2	3	3	3
PSF_4	3	2	1	2	2	1	2	1	3	4	3
PSF_5	3	2	1	1	2	1	3	2	3	3	3
PSF_6	3	1	1	3	2	1	2	0	3	3	3
PSF_7	3	2	2	3	2	1	3	1	3	1	1
PSF_8	3	2	1	3	2	1	3	1	3	2	2
PSF_9	3	0	1	1	2	1	3	1	3	4	4
PSF_{10}	3	3	2	2	2	2	3	3	2	3	3
PSF_{11}	3	3	2	3	2	2	3	3	3	3	3
PSF_{12}	2	2	2	2	2	1	3	3	3	3	3
PSF_{13}	2	1	1	2	2	2	3	2	3	3	3
PSF_{14}	2	1	2	1	2	1	3	1	3	3	3
PSF_{15}	2	1	2	1	2	1	3	1	3	0	0
PSF_{16}	3	3	1	2	2	3	3	2	2	3	3
PSF_{17}	3	3	2	2	2	3	3	2	2	3	3
PSF_{18}	3	3	2	3	2	3	3	2	3	4	3
PSF_{19}	3	2	3	3	2	3	3	3	3	4	4
PSF_{20}	3	2	1	2	3	1	3	2	2	2	2
PSF_{21}	1	1	1	1	2	2	3	2	2	3	3
PSF_{22}	1	0	1	0	2	1	1	3	2	3	3
PSF_{23}	2	3	1	2	2	2	2	3	3	3	3
PSF_{24}	2	1	1	2	3	2	3	3	3	3	3

Table 2 (continued). Opinions about the level of importance and degree of attendance of the PSFs.

PSF	Expert judgment (level of importance)									Operator judgment (degree of attendance)	
1..59	A	B	C	D	E	F	G	H	I	X_1	X_2
PSF_{25}	1	2	1	2	2	1	3	2	3	3	3
PSF_{26}	1	3	1	2	2	2	2	3	3	3	3
PSF_{27}	0	2	1	0	1	1	0	2	1	4	3
PSF_{28}	0	3	1	1	1	1	3	2	3	3	3
PSF_{29}	3	3	2	3	3	3	3	3	3	4	4
PSF_{30}	2	2	2	3	2	2	3	3	3	3	3
PSF_{31}	3	2	2	2	2	2	2	2	3	3	3
PSF_{32}	0	1	1	0	1	2	3	2	3	3	3
PSF_{33}	2	3	2	2	3	3	3	3	3	3	3
PSF_{34}	3	3	3	2	3	3	3	3	3	2	2
PSF_{35}	2	2	2	2	2	3	3	2	3	3	3
PSF_{36}	2	2	2	2	2	3	2	2	3	3	3
PSF_{37}	3	2	2	2	2	3	3	2	3	3	3
PSF_{38}	3	2	2	1	2	3	3	2	3	2	2
PSF_{39}	3	0	1	2	2	3	3	1	3	3	3
PSF_{40}	3	2	2	2	1	2	3	2	2	4	4
PSF_{41}	3	2	2	3	2	3	3	3	2	4	4
PSF_{42}	3	2	1	3	2	3	3	3	3	3	3
PSF_{43}	3	3	2	3	2	3	3	2	3	3	3
PSF_{44}	3	3	1	3	2	3	3	3	3	3	3
PSF_{45}	3	2	2	3	2	3	3	3	3	1	3
PSF_{46}	3	0	2	1	2	2	3	2	2	2	0
PSF_{47}	3	2	2	0	2	1	2	2	3	1	1
PSF_{48}	3	2	2	2	2	2	3	3	3	3	3
PSF_{49}	3	2	2	3	1	3	3	3	2	4	4
PSF_{50}	3	3	2	3	2	3	3	3	3	4	4
PSF_{51}	3	3	1	3	2	3	3	3	3	4	4
PSF_{52}	3	1	1	3	2	3	3	2	3	4	4
PSF_{53}	3	2	1	3	2	2	3	3	3	4	3
PSF_{54}	3	2	3	3	2	2	2	3	3	4	3
PSF_{55}	3	2	1	3	2	3	3	0	3	4	3
PSF_{56}	3	2	1	3	2	3	2	2	3	4	3
PSF_{57}	3	3	2	3	2	3	3	3	3	4	3
PSF_{58}	3	2	1	3	2	3	3	1	3	4	3
PSF_{59}	3	1	2	2	2	2	2	2	3	4	3

Step 7. Fuzzy treatment of the data provided by the experts and by the operators in the evaluation of each PSF considered.

In this step, the individual prognoses from each expert for the PSF are aggregated, generating a consensus for each evaluated attribute. This consensus is formally expressed as a fuzzy number.

The Hsi-Mei-Hsu and Chen-Tung-Chen´s model [7] is used to pool the expert's opinions: an aggregation procedure, called *similarity aggregation method* (SAM), is used for combining the opinion of each expert into a fuzzy number that represents the common opinion of those experts. The opinion of an expert *i* is expressed by a fuzzy number denoted by $\tilde{A}_i$.

The agreement degree (or similarity measure) $S(\tilde{A}_i, \tilde{A}_j)$ between two experts *i* and *j* can be determined by the proportion of the consistent area to the total area:

$$S(\tilde{A}_i,\ \tilde{A}_j) = \frac{\int_x \min(\mu_{\tilde{A}_i}(x), \mu_{\tilde{A}_j}(x))dx}{\int_x \max(\mu_{\tilde{A}_i}(x), \mu_{\tilde{A}_j}(x))dx} . \tag{2}$$

Once all the agreement degrees between the experts are measured, an agreement matrix (AM) can be built, giving an insight into the agreement between the experts.

$$AM = \begin{bmatrix} 1 & S_{12} & S_{13} & \dots\dots & S_{1n} \\ S_{21} & 1 & S_{23} & \dots\dots & S_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ S_{n1} & S_{n2} & S_{n3} & \dots\dots & 1 \end{bmatrix} . \tag{3}$$

The average agreement degree AAD_i of expert E_i (i = 1, ..., n) is given by:

$$AAD_i = \frac{1}{n-1}\sum_{\substack{j=1 \\ j\neq i}}^{n} S_{ij} . \tag{4}$$

The relative agreement degree RAD_i of expert E_i $(i = 1,\dots,n)$ is given by:

$$RAD_i = \frac{AAD_i}{\sum_{i=1}^{n} AAD_i} . \tag{5}$$

Now it is possible to calculate the consensus degree coefficient of expert E_i (CDC_k):

$$CDC_k = \frac{RAD_k * PE_i}{\sum_{i=1}^{n}(RAD_i * PE_i)} , \tag{6}$$

where PE_i is obtained through a questionnaire (see Step 3 in Section 2).

The aggregated opinions are given by the *overall* fuzzy number:

$$\tilde{N} = \sum_{i=1}^{n} CDC_i \times \tilde{A}_i . \tag{7}$$

The level of importance of each PSF is then expressed as a triangular fuzzy number, as shown in Table 3.

Step 8. Aggregation of the operator's opinions on the degree of attendance of the PSFs.

This is accomplished by performing the intersection (AND), by using the *min* operator [24], between the fuzzy numbers that represent the operators' opinions. The result is also shown in Table 3.

Step 9. Normalization.

Fuzzy numbers are normalized by readjusting all the truth membership values proportionally around the maximum membership value (experts' opinions: m = 2.88, operators' opinions: m = 4.0). The normalized values, shown in the column identified by *QS* in Table 4, constitute the quality standard of ultrasonic examination [4]. The fuzzy numbers that represent the degrees of attendance (*DA*) are shown in Table 4.

Step 10. Ranking.

One solution, generally the best, from a collection of possible solutions is now chosen. By observing the *QS* value for each attribute, the PSFs are ranked in accordance to their importance:

PSF_{29}, PSF_{34}, PSF_{19}, PSF_{50}, PSF_{57}, PSF_{11}, PSF_{18}, PSF_{33}, PSF_{43}, PSF_{44}, PSF_{45}, PSF_{51}, PSF_{54}, PSF_{42}, PSF_{41}, PSF_{10}, PSF_{17}, PSF_{30}, PSF_{37}, PSF_{48}, PSF_{49}, PSF_{53}, PSF_{16}, PSF_{35}, PSF_{38}, PSF_{52}, PSF_{56}, PSF_{58}, PSF_{3}, PSF_{7}, PSF_{12}, PSF_{23}, PSF_{24}, PSF_{31}, PSF_{36}, PSF_{55}, PSF_{59}, PSF_{40}, PSF_{26}, PSF_{20}, PSF_{8}, PSF_{2}, PSF_{5}, PSF_{13}, PSF_{14}, PSF_{39}, PSF_{4}, PSF_{25}, PSF_{46}, PSF_{47}, PSF_{6}, PSF_{15}, PSF_{9}, PSF_{21}, PSF_{28}, PSF_{32}, PSF_{22}, PSF_{1}, PSF_{27}.

Table 3. Aggregation of opinions of nine experts about the importance weight of each PSF and of two operators about the reference environments.

Factor	**Triangular Fuzzy number (aggregation of experts' opinions)**			**Triangular Fuzzy Number (aggregation of operators' opinions)**		
1...59	*a*	*m*	*b*	*a*	*m*	*b*
PSF_1	0.55	1.22	2.0	2.0	3.0	4.0
PSF_2	0.77	2.0	2.66	2.0	3.0	4.0
PSF_3	1.22	2.22	2.77	2.0	3.0	4.0
PSF_4	0.88	1.88	2.66	3.0	3.5	4.0
PSF_5	1.0	2.0	2.66	2.0	3.0	4.0
PSF_6	0.88	1.77	2.44	2.0	3.0	4.0
PSF_7	1.22	2.22	2.77	0.0	1.0	2.0
PSF_8	1.11	2.11	2.66	1.0	2.0	3.0
PSF_9	0.77	1.66	2.33	3.0	4.0	4.0
PSF_{10}	1.44	2.44	3.0	2.0	3.0	4.0
PSF_{11}	1.66	2.66	3.0	2.0	3.0	4.0
PSF_{12}	1.22	2.22	2.88	2.0	3.0	4.0
PSF_{13}	1.0	2.0	2.77	2.0	3.0	4.0
PSF_{14}	1.0	2.0	2.77	2.0	3.0	4.0
PSF_{15}	0.77	1.77	2.55	0.0	0.0	1.0
PSF_{16}	1.33	2.33	2.88	2.0	3.0	4.0
PSF_{17}	1.44	2.44	3.0	2.0	3.0	4.0
PSF_{18}	1.66	2.66	3.0	3.0	3.5	4.0
PSF_{19}	1.77	2.77	3.0	3.0	4.0	4.0
PSF_{20}	1.11	2.11	2.77	1.0	2.0	3.0
PSF_{21}	0.66	1.66	2.55	2.0	3.0	4.0
PSF_{22}	0.44	1.22	2.0	2.0	3.0	4.0
PSF_{23}	1.22	2.22	2.88	2.0	3.0	4.0
PSF_{24}	1.22	2.22	2.77	2.0	3.0	4.0
PSF_{25}	0.88	1.88	2.66	2.0	3.0	4.0
PSF_{26}	1.11	2.11	2.77	2.0	3.0	4.0
PSF_{27}	0.22	0.88	1.88	3.0	3.5	4.0
PSF_{28}	0.66	1.55	2.22	2.0	3.0	4.0
PSF_{29}	1.88	2.88	3.0	3.0	4.0	4.0
PSF_{30}	1.44	2.44	3.0	2.0	3.0	4.0

Table 3 (con.) Aggregation of opinions of nine experts about the importance weight of each PSF and of two operators about the reference environments.

Factor	Triangular Fuzzy number (aggregation of experts' opinions)			Triangular Fuzzy Number (aggregation of operators' opinions)		
1...59	*a*	*m*	*b*	*a*	*m*	*b*
PSF_{31}	1.22	2.22	3.0	2.0	3.0	4.0
PSF_{32}	0.66	1.44	2.22	2.0	3.0	4.0
PSF_{33}	1.66	2.66	3.0	2.0	3.0	4.0
PSF_{34}	1.88	2.88	3.0	1.0	2.0	3.0
PSF_{35}	1.33	2.33	3.0	2.0	3.0	4.0
PSF_{36}	1.22	2.22	3.0	2.0	3.0	4.0
PSF_{37}	1.44	2.44	3.0	2.0	3.0	4.0
PSF_{38}	1.33	2.33	2.88	1.0	2.0	3.0
PSF_{39}	1.11	2.0	2.55	2.0	3.0	4.0
PSF_{40}	1.11	2.11	2.77	3.0	4.0	4.0
PSF_{41}	1.55	2.55	3.0	30.	4.0	4.0
PSF_{42}	1.55	2.55	2.88	2.0	3.0	4.0
PSF_{43}	1.66	2.66	3.0	2.0	3.0	4.0
PSF_{44}	1.66	2.66	2.88	2.0	3.0	4.0
PSF_{45}	1.66	2.66	3.0	0.0	0.0	0.0
PSF_{46}	1.0	1.88	2.66	0.0	0.0	0.0
PSF_{47}	1.0	1.88	2.66	0.0	1.0	2.0
PSF_{48}	1.44	2.44	3.0	2.0	3.0	4.0
PSF_{49}	1.44	2.44	2.88	3.0	4.0	4.0
PSF_{50}	1.77	2.77	3.0	3.0	4.0	4.0
PSF_{51}	1.66	2.66	2.88	3.0	4.0	4.0
PSF_{52}	1.33	2.33	2.77	3.0	4.0	4.0
PSF_{53}	1.44	2.44	2.88	2.0	3.0	4.0
PSF_{54}	1.55	2.55	3.0	2.0	3.0	4.0
PSF_{55}	1.33	2.22	2.66	2.0	3.0	4.0
PSF_{56}	1.33	2.33	2.88	2.0	3.0	4.0
PSF_{57}	1.77	2.77	3.0	2.0	3.0	4.0
PSF_{58}	1.33	2.33	2.77	2.0	3.0	4.0
PSF_{59}	1.11	2.11	2.88	2.0	3.0	4.0

Table 4. Quality standard and degrees of attendance.

PSF (1-30)	QS	DA	PSF (31-59)	QS	DA
PSF_{1}	0.42	0.75	PSF_{31}	0.77	0.75
PSF_{2}	0.69	0.75	PSF_{32}	0.5	0.75
PSF_{3}	0.77	0.75	PSF_{33}	0.92	0.75
PSF_{4}	0.65	0.63	PSF_{34}	1	0.5
PSF_{5}	0.69	0.75	PSF_{35}	0.80	0.75
PSF_{6}	0.61	0.75	PSF_{36}	0.77	0.75
PSF_{7}	0.77	0.25	PSF_{37}	0.84	0.75
PSF_{8}	0.73	0.5	PSF_{38}	0.80	0.5
PSF_{9}	0.57	1	PSF_{39}	0.69	0.75
PSF_{10}	0.84	0.75	PSF_{40}	0.73	1
PSF_{11}	0.92	0.75	PSF_{41}	0.88	1
PSF_{12}	0.77	0.75	PSF_{42}	0.88	0.75
PSF_{13}	0.69	0.75	PSF_{43}	0.92	0.75
PSF_{14}	0.69	0.75	PSF_{44}	0.92	0.75
PSF_{15}	0.61	0	PSF_{45}	0.92	0
PSF_{16}	0.80	0.75	PSF_{46}	0.65	0
PSF_{17}	0.84	0.75	PSF_{47}	0.65	0.25
PSF_{18}	0.92	0.88	PSF_{48}	0.84	0.75
PSF_{19}	0.96	1	PSF_{49}	0.84	1
PSF_{20}	0.73	0.5	PSF_{50}	0.96	1
PSF_{21}	0.57	0.75	PSF_{51}	0.92	1
PSF_{22}	0.42	0.75	PSF_{52}	0.80	1
PSF_{23}	0.77	0.75	PSF_{53}	0.84	0.75
PSF_{24}	0.77	0.75	PSF_{54}	0.88	0.75
PSF_{25}	0.65	0.75	PSF_{55}	0.77	0.75
PSF_{26}	0.73	0.75	PSF_{56}	0.80	0.75
PSF_{27}	0.30	0.88	PSF_{57}	0.96	0.75
PSF_{28}	0.53	0.75	PSF_{58}	0.80	0.75
PSF_{29}	1	1	PSF_{59}	0.73	0.75
PSF_{30}	0.84	0.75			

The degree of attendance of the PSFs can be compared to a quality standard in order to assess human reliability in the inspection.

Step 11. Application of Pareto´s Principle.

The Pareto's Principle states that 20 % of something is always responsible for 80 % of the results (80/20 rule). For an analysis of human reliability in the ultrasonic non-destructive examination system, which is influenced by 59 performance shaping factors, 20 percent of the human reliability structure is formed by the 12 performance shaping factors with the highest level of importance. They are:

PSF_{29}, PSF_{34}, PSF_{19}, PSF_{50}, PSF_{57}, PSF_{11}, PSF_{18}, PSF_{33}, PSF_{43}, PSF_{44}, PSF_{45}, PSF_{51}.

These 20 % of performance shaping factors are responsible for 80 % of the results in human reliability during nondestructive examinations. The allocation of limited resources to improving the quality standard should then consider these factors primarily.

Step 12. Defuzzification.

This step is necessary for obtaining an indication of the degree of attendance of the operators to the quality standard. Defuzzification is performed through the weighted height method, where the degree of attendance (da_k) to each PSF_k (column identified by DA in Table 4) is multiplied by its quality standard (qs_k) and a weighted average R is obtained:

$$R = \frac{\sum_{k=1}^{n} qs_k \times da_k}{\sum_{k=1}^{n} qs_k} . \tag{8}$$

The application of (9) to the values of Table 4 gives an expected value of human reliability of 0.68. This falls between regular and good degree of attendance by the operators to the quality standard.

Step 13. Contributions to decision making.

The subject of the field of decision making is, as the name suggests, the study both of how decisions are actually made and how they can be made better or more successful [8].

The results obtained indicate that, in ultrasonic examinations, the performance shaping factors PSF_{29} (procedures required) and PSF_{34} (state of current practice) were considered as the most important ones.

The results also show that the least important factor to human reliability in ultrasonic examination is design of equipment. This means that an investment in this aspect is not worthwhile.

There are some attributes with the same degree of importance as, for example:

- Procedure required and state of current practice, with degree 1.
- Decision making requirements, fatigue and oxygen insufficiency, with degree 0.96.
- Availability and adequacy of equipment, interpretation requirements, previous training/experience, task load, work risk, threats (of failure, loss of job) and pain or discomfort, with degree 0.92.

Once the most important performance shaping factors have been established, resources can be allocated in order to improve their degrees of attendance.

Assuming that the 12 most important factors are fully attended to, the expected value of human reliability would increase from 0, 68 to 0,73, which is an improvement on the degree of attendance to the quality standard.

3. Conclusion

A new procedure for a qualitative evaluation of human reliability in ultrasonic inspection has been presented. This procedure makes use of fuzzy numbers and, in consequence, uncertainties involved in the evaluation procedure can be taken into account.

The findings of this study indicate that it is possible to determine the quality standard (QS) for a NDE system by using a fuzzy approach, so that a degree of attendance to this QS and an expected value of human reliability in a given physical environment can be obtained.

By knowing the quality standard and the degree of attendance to each of the performance shaping factors, resources can be allocated to those aspects which contribute most to the human reliability.

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