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ORIGINAL ARTICLE

A hierarchical fuzzy axiomatic design methodology for ergonomic compatibility evaluation of advanced manufacturing technology

Aide Maldonado · Jorge Luis García · Alejandro Alvarado · Cesar Omar Balderrama

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Abstract Advanced manufacturing technology (AMT) is a relevant resource that has been extensively used in modern industries around the world with the aim of being competitive and maintaining high levels of quality and performance. There is a wide variety of tools and models available in the literature to support AMT selection and evaluation processes. Usually, they consist of analyses of tangible aspects, such as cost, time, speed, precision, among others; however, some other important aspects are commonly neglected, that is, the case of human factors and ergonomic characteristics. This paper presents a new methodology for the evaluation of ergonomic compatibility of AMT. This methodology may be considered as a decision aid; thus, decision makers might perform their duties in a more complete manner taking into account ergonomic attributes. Fuzzy axiomatic design applications are state of the art methods for decision making, and this paper contributes with a unique application for ergonomic compatibility evaluation for AMT. The first part of the paper presents the findings of an extensive literature review about important ergonomic attributes of AMT. Then, those attributes were originally structured following a multi-attribute axiomatic design approach for AMT ergonomic evaluation under a fuzzy environment. Also, a unique ergonomic compatibility survey was proposed for data collection and an original procedure was developed for AMT evaluation, a numerical example is provided. The ergonomic compatibility concept was tested and validated using the Cronbach's alpha test ($\alpha \geq 0.7$), finding that the instrument is suitable for the measurement of the proposed construct.

Keywords Axiomatic design · Fuzzy logic · Ergonomic compatibility · Advanced manufacturing technology

A. Maldonado (✉) · J. L. García · A. Alvarado
Department of Industrial and Manufacturing Engineering,
Autonomous University of Ciudad Juárez,
Ave. del Charro 450 Norte,
C.P. 32310 Cd. Juárez, Chihuahua, Mexico
e-mail: amaldona@uacj.mx

A. Maldonado
Graduate Studies and Research Division,
Ciudad Juárez Institute of Technology,
Ave. Tecnológico No. 4090,
Cd. Juárez, Chihuahua, Mexico

C. O. Balderrama
Department of Industrial Design,
Autonomous University of Ciudad Juarez,
Ave. del Charro 450 Norte,
C.P. 32310 Cd. Juárez, Chihuahua, Mexico

1 Introduction

Advanced manufacturing technology (AMT) has played a major role in the development and evolution of the manufacturing industry worldwide. AMT includes usually computer-based technologies such as computer-controlled numerical control machines (CNC), automatic guided vehicle systems, and computer-aided design (CAM) [1]; also, there are included robotics, rapid prototyping, and environmentally sustainable technologies that have become an integral part of manufacturing. These technologies have been experimented continue, gradual but also radical changes, and to face this trend, manufacturing industries have to select appropiate manufactuirng strategies, materials, processes, tools, equipment, and machines [2]. In this way, decision makers (DMs) continuously face the problem of evaluating equipment among an extensive variety of alternatives; besides, planning and selection processes often involve multiple attributes and conflicting criteria. Although AMT has been broadly used around the world and there are evaluation tools and models available, publications on this subject are limited and evaluation models regarding planning and selection of AMT equipment with the adequate ergonomic criteria are scarce.

In the first part of this paper, an extensive literature review was made and organized to generate a more complete group of ergonomic attributes for AMT evaluation. Then, a novel fuzzy axiomatic design approach is described for the ergonomic compatibility evaluation of AMT, specifically an ergonomic compatibility survey and procedure are proposed and applied as part of the assessment. These methods are considered unique since they help to define in a more complete manner the ergonomic compatibility attributes during the evaluation of AMT; also, it supports gathering information from experts for the evaluation of these attributes. This methodology enables the measurement of the ergonomic incompatibility content (EIC) by a unique adaptation of the information axiom from the axiomatic design theory under fuzzy environment for ergonomic attribute evaluation purposes. Finally, this methodology is described by a numerical example for the ergonomic compatibility evaluation of three alternatives of CNC milling machines.

1.1 Problem definition

Selection of equipment plays an important role in the design of an effective manufacturing system; however, publications on this subject are limited [3]. Additionally, models found for planning and selecting AMT are considered deficient of human factors and ergonomic (HFE) and safety aspects since they are limited or underestimated in importance. In consequence, the lack of attention to ergonomic issues may lead to potential ergonomic and safety risks for which DMs are often unaware when AMT is acquired.

The evaluation of HFE and safety attributes seems to be less tangible than engineering ones for DMs; therefore, these attributes are not considered adequately. One of the reasons might be that it cannot found an appropriate evaluation approach for the definition of ergonomic compatibility requirements (attributes) for AMT evaluation. In response to this problem, this paper contributes with a unique fuzzy axiomatic design approach for ergonomic compatibility evaluation for AMT. Contribution also involves proposing a new survey and procedure that could help to determine ergonomic attributes and measure the ergonomic compatibility of an "artefact system" concerning an artificial product—AMT—in this case. AMT designs must satisfy multiple ergonomic requirements; this is considered as a complex problem that will be faced from a novel multi-attributive axiomatic design approach.

1.2 Objectives

The general objective of this work is to present a new multi-attribute axiomatic design methodology for ergonomic compatibility evaluation of AMT. Particular objectives are: to deploy the ergonomic compatibility requirements (attributes) of AMT equipment generated from extensive literature review and a pragmatic perception proposing a hierarchy structure for them. Furthermore, other objectives are to propose a new ergonomic compatibility survey and a unique procedure for ergonomic compatibility evaluation using the EIC in a fuzzy environment.

2 Literature review

HFE is defined by Karwowski [4] as a unique and independent discipline that focuses on the nature of human–artefact interactions; it is viewed from the unified perspective of science, engineering, design, technology, and management of human-compatible systems including a variety of natural and artificial products and living environments. Ergonomic compatibility is a construct used in this work and it is defined as evoking the concepts of human–system and human–artefact compatibility introduced by Karwowski [5, 6] which emanate from the need of having comprehensive treatment of compatibility in human factor discipline. It intends to measure, in a subjective way, the probability of a design to satisfy ergonomic requirements using the EIC. For this purpose, the theory of axiomatic design extended by Helander [7, 8] and adopted by Karwowski [9] was applied. Both authors are introducing ergonomics theory for design and evaluation purposes and offer an interpretation of the independence axiom and information axiom addressing ergonomic designs. Particularly, from the latter emerges the ergonomic incompatibility content. Also, the science of artefact–human (system) compatibility (Symvatology) was considered, as it tries to develop a quantitative way of measuring such compatibility [10, 11]. The proposed methodology can help to identify and evaluate the ergonomic compatibility attributes of the artefact system involved in the selection of AMT equipment using the ergonomic incompatibility content in a fuzzy environment. About the application of the information axiom—IA—for evaluation and selection purposes relative to equipment and facilities, several authors in this matter were compiled by Maldonado et al. [12] and Kulak et al. [13], reporting that evaluation with IA has important advantages that other methodologies cannot offer. Also, fuzzy axiomatic design approaches are found in the state of the art methods for decision making and very few applications have been generated since its creation; they were compiled in the works of the mentioned authors. This paper contributes with a unique application for the ergonomic compatibility evaluation for AMT.

Ergonomic evaluation of AMT presents some difficulties since ergonomic compatibility requirements (attributes) are not precisely determined in the literature; besides, it involves the evaluation of qualitative aspects and its complexity and vagueness make a problem even harder to solve. For Karwowski [4], advanced technologies with human interaction constitute complex systems that require a high level of integration; in this way, the design integration of the interactions between hardware (computer-based technology), organization (organizational structure), information system, and people (human skills and training) must be evaluated in such design. The ergonomic compatibility attributes (ECA) were established in this research under this premise that was the base of the literature search, but also a design manual for ergonomics of workspaces and machines design by Corlett and Clark [14] was used. An affinity diagram was made and a more complete group of attributes was attained in this paper. Table 1 shows the list of authors specifying which author focuses on which ECA as an aid to the review of existing literature. It was created to organize the information revealing the source and classification of attributes for the proposed model. Some of the included items are main attributes in some works, whereas they are divided into some sub-attributes in some other works; also, in some works, they were considered individually in the study of AMT.

In this way, AMT ECA were divided into five main attributes: compatibility with human technical skills and training (A11), compatibility with physical workspace (A12), usability (A13), equipment emission requirements (A14), and organizational requirements (A15). The main attribute A11 includes two sub-attributes: compatibility with user's technical skill level (A111) and compatibility with training (A121). The main attribute A12 includes five sub-attributes: access to machine and clearances (A121), horizontal and vertical reaches (A122), adjustability of design (A123), postural comfort of design (A124), and physical work and endurance of design (A125).

The main attribute A13 includes seven sub-attributes: controls' design compatibility (A131), controls' physical distribution (A132), visual workspace design (A133), information load (A134), error tolerance (A135), man machine functional allocation (A136), and design for maintainability (A137). The main attribute (A14) includes four sub-attributes: temperature (A141), vibration (A142), noise (A143), and residual materials (A144). The main attribute (A15) includes two sub-attributes: rate of work machine compatibility (A151) and job content machine compatibility (A152). Table 2 lists and describes the attributes for evaluation purpose.

Table 2 explains the ergonomic compatibility outcomes for a comfortable, safe, effective, or satisfactory interaction among the human operator, the AMT, and the environment. Experts or judges must define desirable rates for them and evaluate AMT alternatives according to their experience using subjective opinions with linguistic terms.

The sub-attributes were classified as tangible and intangible and were divided into benefit attributes and cost attributes from a human–artefact perspective. A benefit attribute is found when it is ergonomically desirable to maximize its adaptability (positive influence); in other words, the ideal design range, expressed as ergonomic functional requirement (EFR), would tend to be around the maximum values in the linguistic scale. A cost attribute is found when minimal exposure (negative influence) is ergonomically desirable or the ideal design range expressed as EFR would tend to be around the minimum values in the linguistic scale, all of them were considered as tangible. The majority of sub-attributes were considered as intangible benefit attributes excluding sub-attributes (A125, A141, A142, A143, and A144).

3 Methodology

The establishment of attributes and sub-attributes was made from an extensive literature review as it was explained in the previous section and as it is shown in Table 1. The generation of attributes was made and structured with an affinity diagram as a preliminary step to develop the methodology.

The methodology of this approach was divided into three main parts: Part 1 describes a new multi-attribute hierarchy structure which is derived from the literature review and affinity diagram; this structure is shown in Fig. 1. Part 2 describes the ergonomic compatibility evaluation survey (ECS) proposed by Maldonado et al. [15]. Finally, in part 3, the fuzzy axiomatic design method is explained for guiding the decision to the best alternative using the ergonomic incompatibility content in a fuzzy environment.

3.1 Part 1. Multi-attribute hierarchy

The goal of any multi-attribute methodology is to find a meaningful index from multidimensional data to evaluate competing alternatives. In this case, the ergonomic compatibility attributes will help measure the accomplishment of the goal of compare alternatives and find the best one using the EIC. In the structure shown in Fig. 1, the attributes are derived hierarchically from a main goal, and the main attributes were established quite theoretically and became less so as one follows the hierarchy down. Note that the main attributes and sub-attributes are all limited in number to seven. This is so, according to Miller [16], in which this number represents the maximum amount of information that an observer can give us about an object on the basis of an absolute verdict.

3.2 Part 2. Ergonomic compatibility evaluation survey

In this methodology, within the axiomatic approach, the determination of ergonomic design ranges (EDRs) and ergonomic system ranges (ESRs) is required for the evaluation of every ergonomic compatibility sub-attribute of AMT alternatives. A new ECS was designed to collect the information of the evaluations and also for the determination of the relative importance of the attributes and sub-attributes. The opinions of a group of experts must be used; face to face interviews were needed to answer the survey. The survey includes 95 questions divided into four parts. In the first part, importance

Table 1 List of authors

Source	Ergonomic compatibility main attributes (ECMA)				
	A11 Human skills and training compatibility	A12 Physical work space compatibility	A13 Usability	A14 Equipment emissions requirements	A15 Equipment design organizational requirements
Corlett and Clark [14]	A111, A112	A121, A122, A123, A124, A125	A131, A132, A133, A134, A135, A138	A141, A142, A143	A151, A152
Handbook of standards and guidelines in ergonomics and human factors W. Karwowski (ed.) [10]; Chapters 8, 10, 12, 16, 19, and 21		A122, A123, A124, A125	A131, A132, A133, A134, A135, A138	A141, A142, A143	
UK Defence Standardization 0025 part 1 [Ministry of Defence; 22]		A122, A123, A124, A125	A131, A132, A133, A134, A135, A138		
Mital et al. [23]; Mital and Pennathur [24]	A111, A112		A135, A134		A151
Bayo-Mariones [25]	A111, A112				
Johnson and Wilson [26]			A135, A136, A137		
Endsley [27]			A134		
Sarter and Woods [28]	A111, A112		A134		A151, A152
Lee and Salvendy [29]			A131, A132, A133, A134, A135, A138		
Genaidy et al. [30]		A124, A125			A151, A152
Erensal and Albayrak [31]					A151, A152
Hunter [32]		A121, A122, A123, A124, A125			
Genaidy et al. [32]		A121, A122, A123, A124, A125		A141, A142, A143	A151, A152
Genaidy et al. [33]; Genaidy and Karwowski [34]		A121, A122, A123, A124, A125	A133, A134	A141, A142, A143	A151, A152
Bruseberg [35]	A111, A112	A121, A122, A123, A124, A126	A131, A132, A133, A134, A135, A137, A138		
Ruckart and Burgess [36]			A134, A135, A136		
Siemieniuch and Sinclair [37]			A134, A135, A136		
Stanton [38]	A112		A134, A135, A136		A151, A152
Kesseler and Knapen [39]			A133, A134, A135		
Dul et al. [40]; Ergonomic Standards	A111, A112				
Helander [7]			A133, A134, A135		
Besnard and Cacitti [41]			A133, A134, A135		
Vieira and Kumar [42]		A124, A125			A151, A152
Balogh et al. [43]		A124, A125			
Kaber and Endsley [44]			A136		A151, A152
Stanton [45]			A135, A134		
Kumar [46]		A124, A125			

Table 2 Description of the ergonomic attributes

Attribute	Description
A11 *Human skills and training compatibility:* Set of attributes that define the compatibility of the equipment with technical skills and training of users	
A111 Skill level compatibility	Attribute of design of equipment regarding its adaptability to differences on technical skills of users. (Allowing safe and efficient operation for expert and novice users)
A112 Training compatibility	Attribute of design of equipment in terms of the training required (quality and duration) that will be available taking into account needs of users
A12 *Physical workspace compatibility:* Set of attributes that define the compatibility of equipment with the physical workspace through the allowance of comfortable reaches and postures as well as taking into account the strength and endurance required for its operation promoting safety and effectiveness	
A121 Access to machine and clearances	Attribute of design of equipment concerning the allowance of mobility and secure access to arms, hands, legs, head, trunk, and knees of the operator through its space and clearances
A122 Horizontal and vertical reaches	Attribute of design of equipment concerning the allowance of comfortable, safe, and effective human vertical and horizontal reaches (upper and lower extremities)
A123 Adjustability of design	Attribute of design of equipment concerning the allowance of adjustment and/or change on its physical structure (size, position, etc.) or on its components that would be satisfactory to operator
A124 Postural comfort of design	Attribute of design of equipment regarding the allowance of neutral and diverse body postures for a safe and effective operation
A125 Physical work and endurance of design	Attribute of design of equipment concerning the level of physical work and endurance that will required of operator during interaction
A13 *Usability:* Set of attributes that promotes easiness of use on design of equipment	
A131 Compatibility of design of controls	Attribute of design of equipment regarding the type and design of controls and sensors (as buttons, knobs, levers, switches, stoppage sensors of movement, etc.) providing an effective and safe operation
A132 Physical distribution of controls	Attribute of design of equipment regarding the physical distribution (location) of the controls (buttons, knobs, levers, switches, etc.) providing a safe and effective manipulation
A133 Visual workspace design	Attribute of design of equipment concerning the size and location of screens and displays of information: size and type of characters used, colors, contrast, resolution, and brightness facilitating human visual tasks during human–machine interaction
A134 Information load	Attribute of design of equipment which allows and facilitates a safe and effective operation through a satisfactory human understanding, learning, and processing of the information (visual, auditory, and sensory) during human–machine interaction
A135 Error tolerance of design	Attribute of design of equipment which allows and facilitates to the operator the management and prevention of errors, through simple and clear messages and dialogues on the human–machine interface
A136 Man–machine functional allocation of design	Attribute design of equipment concerning difficult tasks for operator such as quick response, short-term storing information, high accuracy, and repeatability, among others

Table 2 (continued)

Attribute	Description
	re allocated in the equipment design preferable to the machine
A137 Design for maintainability	Attribute of design of equipment considering whether a simple, rapid, effective, and safe maintenance tasks will be allowed during repairing, installation, and dismantling, transportation, loading, cleaning, assembling, and disassembling among other maintenance activities
A14 *Equipment emission requirements:* Set of attributes related to temperature, vibration, noise, and residual materials generated by the equipment and may adversely affect operator and/or environment	
A141 Temperature	Attribute of design of equipment related to the temperature (hotness/coldness) emitted by the equipment and its components and hat may adversely affects operator and/or environment
A142 Vibration	Attribute of design of equipment which is related to the vibration emitted by the equipment and that may adversely affect operator and/or environment
A143 Noise	Attribute of design of equipment related to the noise emitted by the equipment and its components and that may adversely affect human operators and/or environment
A144 Residual materials	Attribute of design of equipment related to the amount and kind of residual materials generated by the equipment and its components and that may dversely affect the operator and/or environment
A15 *Equipment design organizational requirements:* Set of attributes that define the compatibility of equipment with the pace and speed of work as well as with the total content of the work according human limitations and capabilities	
A151 Rate of work machine compatibility	Attribute of design of equipment considering that it avoids or prevents inappropriate pace and speed of work for operator
A152 Total work content machine compatibility	Attribute of design of equipment considering the prevention of excessive force application, long-term awkward postures, repetitive tasks, and high-risk task (i.e., manual handling of loads) on complementary tasks of the machine operation (total content of work)

is assigned for the attributes and sub-attributes using a linguistic scale; in the second part, EDRs and ESRs are determined for the sub-attributes using linguistic scales. In the third part, crisp pairwise comparisons using crisp analytic hierarchical process (AHP) proposed by Saaty [17] were conducted to obtain the importance weights by means of software *Expert*

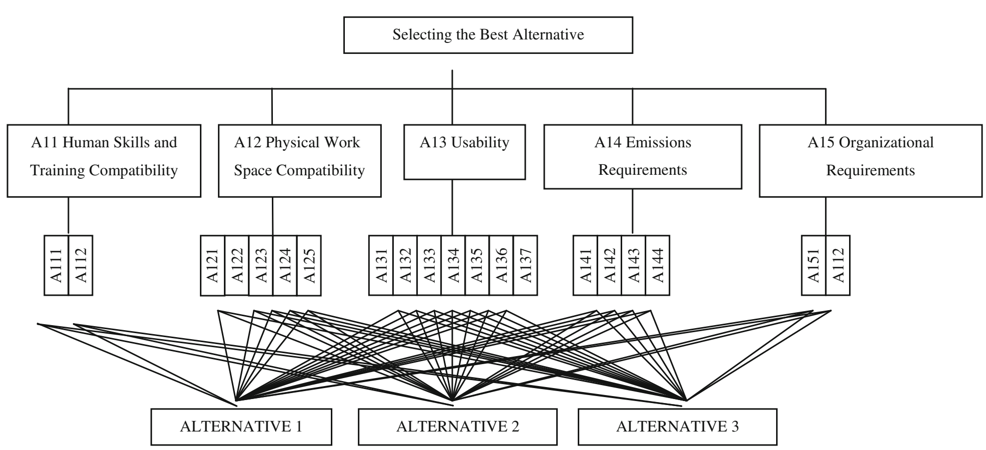

Fig. 1 Selection of the best alternative

Choice© [18]. Finally, in the fourth part, experts validate the minimum set of ergonomic attributes that would be included in the evaluation for AMT.

3.3 Part 3. Fuzzy axiomatic design method for ergonomic compatibility evaluation of AMT

Once the information is obtained from the ECS, information is processed. This procedure is considered new for the evaluation of ergonomic attributes for AMT. For this, the procedure includes five phases. These phases are explained below.

Phase 1

- *Step 1:* Determine the alternatives to consider in the evaluation; where A_i=(1, 2… n) is the number of alternatives.
- *Step 2:* Determine the attributes to evaluate, establishing the EFRs to be evaluated; where B_j=(1, 2… m) is the quantity of attributes. Table 2 shows the attribute description for AMT ergonomic evaluation used for the ECS.
- *Step 3:* Constitute the group of experts; where k=(1, 2… k) is the number of experts.
- *Step4:* Choose appropriate linguistic terms for the evaluation of the attributes using linguistic terms according to Table 7. Such ratings are based on the numerical approximation system for conversion scales used by Celik et al. [19] and Chen and Hwang [20] and were proposed by Karhaman and Çebi [21] for similar purposes.
- *Step 5:* Assess the importance of each attribute using linguistic terms.
- *Step 6:* The experts evaluate subjectively each attribute of each alternative using linguistic terms. These evaluations help determine the design range (DR) denoted by the fuzzy number (α,β,θ) and system range (SR) denoted by the fuzzy number (a,b,c) for each attribute; where m_{ijk}=(for i=1, 2… n, j=1, 2… m, k=1, 2… k) are ratings for each alternative and every attribute by each expert.

Phase 2

- *Step 1:* Convert the linguistic terms of importance and the ratings assigned to each attribute to a numeric value. For this step, conversion scales previously explained were used.
- *Step 2:* Aggregate the importance of the opinion of the experts to obtain the weight of each attribute through pairwise comparisons of AHP methodology using the geometric means.
- *Step 3:* Determine the DR for each attribute from the opinions of experts and corollary number 6 of axiomatic design theory in which the largest allowable design range in stating EFRs is specified. Figure 2 shows the linguistic terms and their corresponding fuzzy numbers and membership functions used for intangible attributes, and Fig. 3 shows the ones used for tangible attributes.
- *Step 4:* Aggregate the opinion of experts on the assigned rating of each attribute to each alternative obtaining the system range applying Eq. 1.

$$m_{ij} = \frac{1}{k}\left[m_{ij1} \oplus m_{ij2} \oplus \ldots.. \oplus m_{ijk}\right] \tag{1}$$

- *Step 5:* Develop decision matrixes to the assigned importance, DR, and SR for each attribute and each alternative.

Phase 3

About the definition of the membership functions (MF) or $\mu(x)$ for EFR, linguistic terms and membership functions used for DR determination are based on the proposed methodology of Celik et al. [17] and were explained previously in phase 2, step 3. For system range determination, the membership functions were obtained by Eqs. 2 and 3, for benefit and cost attributes, respectively, where X_i, α, and θ are shown in Fig. 4.

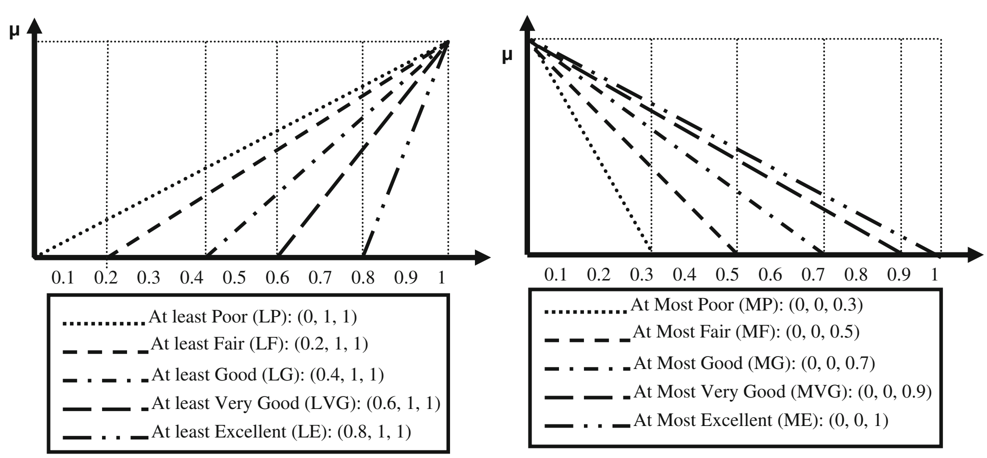

Fig. 2 Design range membership functions for intangible attributes

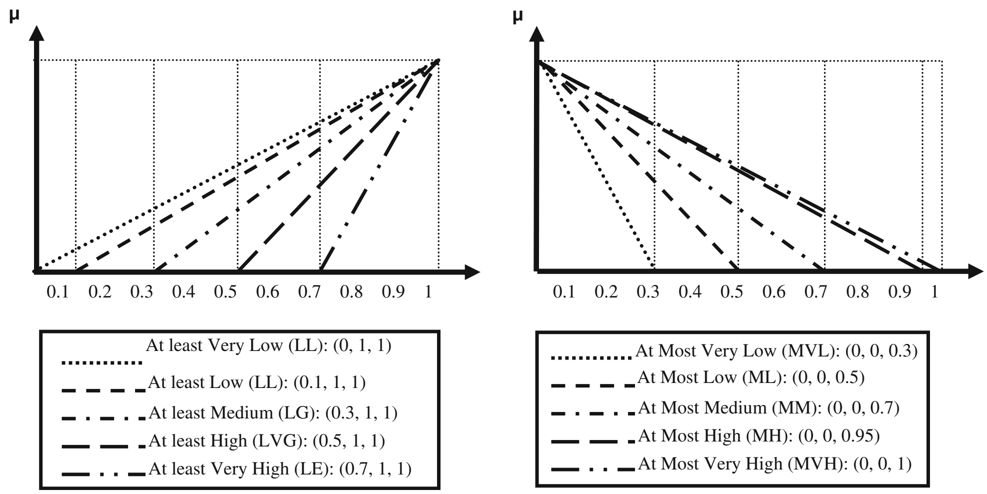

Fig. 3 Design range membership functions for tangible attributes

$$\mu(x) = \frac{X_i - \alpha}{\theta - \alpha}, \text{for benefit attributes} \quad (2)$$

$$\mu(x) = \frac{\alpha - X_i}{\theta - \alpha}, \text{for cost attributes} \quad (3)$$

Phase 4

On this phase, the EIC is obtained. This is made for each attribute and every alternative using an adaptation of the information axiom under fuzzy environment and with its respective weight. Figure 4 shows the SR, DR, and the common area (CA). This area represents the probability of satisfying the established DR. Equation 4 is used to calculate the system range area, and Eq. 5 is used to obtain common area.

$$\text{System area (SA)} = (c - a) \times 1/2 \quad (4)$$

$$\text{Common area(SA)} = [\mu(X_i) \times (c - \alpha)] \times \frac{1}{2} \quad (5)$$

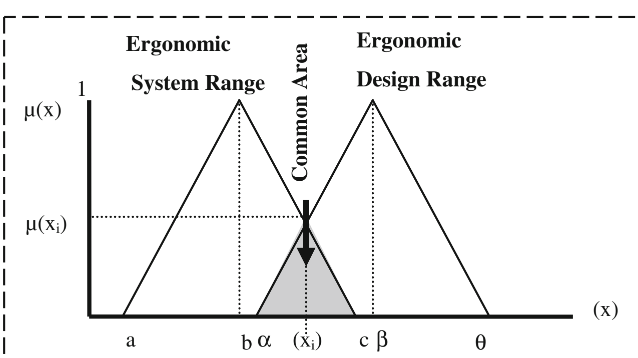

Fig. 4 Ergonomic system range, ergonomic design range, and common area

$$\text{EIC} = \log_2 \frac{\text{Area of ergonomic system design(triangular fuzzy number)}}{\text{common area}} \quad (6)$$

$$\text{TWEIC} = \sum_{i=1}^{w} w_i \text{EIC}_i \quad (7)$$

The EIC for each ergonomic compatibility sub-attribute is obtained using Eq. 6.

Phase 5

In this phase, the total weighted ergonomic incompatibility content (TWEIC) is obtained for each alternative using Eq. 7. The alternative which has the minimum EIC is chosen as the best selection. The measure units used for obtaining TWEIC are named “ints.” According to Karwowski [9, 10], the proposed units for the measurement for artefact–human incompatibility (ints) are parallel and numerically identical to the measure of information (bits) utilized by the information axiom from the axiomatic design theory.

4 Results

Results of this work are explained in this section. First, the description of the ECS is presented, then the results given by the proposed fuzzy axiomatic design methodology are explained; a numerical example will be provided to clarify the results.

4.1 Ergonomic compatibility evaluation survey

Participant experts were invited from the academic and industrial fields, and they were carefully trained about the attributes and their description to achieve a good understanding of this research. Starting the evaluation and selection process, complete information about AMT alternatives was presented to them; as experts, they must have an excellent knowledge about human–machine interaction with every AMT alternative. Also, they answered the survey individually via face to face interviews.

Part 1

The first part of the survey was designed to collect information about the given importance on every attribute and sub-attribute for the evaluation and selection of AMT equipment. From question 1 to question 25, the experts were asked to establish the degree of importance of each attribute and sub-attribute. Linguistic terms were given; however, a crisp 1 to 5 Likert scale was applied to use the data numerically. This part of the survey was validated by Cronbach's alpha test ($\alpha \geq 0.7$); however, it was not used for weighting the attributes. Otherwise, it can be used as reference for future applications using some other ranking methodologies for ergonomic compatibility attributes. Table 3 presents the first five questions of this part as an example.

Table 3 Ergonomic compatibility evaluation survey part 1

ERGONOMIC COMPATIBILITY EVALUATION FOR THE SELECTION OF AMT ALTERNATIVES

PART I

ASSESSMENT OF THE IMPORTANCE OF ERGONOMIC ATTRIBUTES AND SUBATTRIBUTES

The attributes that have been addressed in this evaluation, can influence the purchase or selection decision on any of the alternatives of Advanced Manufacturing Technology (AMT) and requires you to assign a degree of importance, according to the scale provided in the corresponding table. It was chosen a scale that is easy to understand for you.

INSTRUCTIONS:

It will be presented questions which are then arranged in tables in which you can answer. Please mark your response according to the following:

Assign the importance of the attributes and subattributes according to the following scales:

SCALE 1

Very low	Low	Medium	High	Very high

DEGREE OF IMPORTANCE WITH RESPECT TO THE FINAL GOAL OF SELECTING THE BEST ALTERNATIVE CONSIDERING ERGONOMIC ATTRIBUTES

Just select in the table below in the appropriate column depending on the degree of importance assigned to each attribute. With regard to the ultimate goal of select the best alternative of AMT.

Question 1 What degree of importance do you assign to the main attribute Human Skills and Training Compatibility (C. with S. and T.)?

Question 2 What degree of importance do you assign to the main attribute Physical Workspace Compatibility(WSC)?

Question 3 What degree of importance do you assign to the main attribute Usability?

Question 4 What degree of importance do you assign the Equipment Emissions' Requirements (EER)?

Question 5 What degree of importance do you assign to Organizational Requirements (Org. R.)?

With respect to Ergonomic Attributes	Degree of Importance for each attribute with respect to the final goal.					
Questions	Attribute	Very low	Low	Medium	High	Very High
1	S/T Compatibility	☐	☐	☐	☐	☐
2	WS Compatibility	☐	☐	☐	☐	☐
3	Usability	☐	☐	☐	☐	☐
4	EER	☐	☐	☐	☐	☐
5	Org. R.	☐	☐	☐	☐	☐

Part 2

The second part of the survey was designed for the ergonomic compatibility evaluation of AMT alternatives. From question 26 to question 45, experts were asked to define desirable ergonomic rates for each sub-attribute for the selection of AMT using linguistic terms, and then they must evaluate each alternative using the same linguistic terms. Different linguistic term scales were used for tangible and intangible attributes. Table 4 presents the question scheme for an intangible attribute evaluation as an example.

Part 3

The third part of the survey was designed to assign an importance weight to each attribute and sub-attribute. From questions 45 to 94, the experts were asked to make pairwise

Table 4 Ergonomic compatibility evaluation survey part 2

PART II

EVALUATION PROCESS FOR ERGONOMIC SUBATTRIBUTES

In this section you will be asked to answer questions divided in two subsections (a) and (b), which are explained below. Linguistic terms have been used for a better understanding. First, you must recommend a desirable rate for AMT equipment regarding each sub attribute. Then, assign to every AMT alternative the correspondent rate according to the sub-attribute in each case. There will be used one of the following two scales:

SCALE 2

Very low	Low	Medium	High	Very High

SCALE 3

Poor	Regular	Good	Very Good	Excellent

EVALUATION OF ALTERNATIVES WITH RESPECT TO ERGONOMIC SUBATTRIBUTES

Question 26 Evaluate the equipment by regarding its adaptability under different user's technical skill level (i.e. it allows a safe and efficient operation by experts and novice users) (Compatibility with Skill).

(a) What should be the minimum desirable ergonomic rate for AMT equipment regarding it allows a safe operation under different user's technical skill level (Compatibility with Skill)?

Question 26 (a)	A111 Compatibility with Skill	**DESIRABLE ERGONOMIC RATE**				
		Poor	Regular	Good	Very Good	Excellent
		☐	☐	☐	☐	☐

(b) What rate would you assign to each alternative with respect to the sub attribute Compatibility with Skill?

Question 26 (b)	A111 Compatibility with Skill	**Alternative**	**RATE**				
			Poor	Regular	Good	Very Good	Excellent
		X	☐	☐	☐	☐	☐
		Y	☐	☐	☐	☐	☐
		Z	☐	☐	☐	☐	☐

Table 5 Ergonomic compatibility evaluation survey part 3

PART III

ANALYTIC HIERARCHY PROCESS

C. INSTRUCTIONS: With respect to comparing and selecting the best AMT alternative, answer the following Questions using the paired comparison matrix. If the attribute on the left is more important than its counterpart in the right side, place the √ to the left side of the importance "Equally Important" under the importance level you prefer. If the attribute on the left is less important than its counterpart in the right side, place the √ to the right side of the importance "Equally Important" under the importance level you prefer.

Question 46 How important is Compatibility with user´s Technical Skills and Training when it is compared with Compatibility with Physical Space?

Question 47 How important is Compatibility with user´s technical Skill and Training when it is compared with Usability?

Question 48 How important is Compatibility with the user´s technical Skill and Training when it is compared with Emissions Requirements?

Question 49 How important is Compatibility with the user´s technical Skill and Training when it is compared with Organizational Requirements?

Question 50 How important is Compatibility with Physical Space when it is compared with Usability?

Question 51 How important is Compatibility with Physical Space when it is compared with Emissions' Requirements?

Question 52 How important is Compatibility with Physical Space when it is compared with Organizational Requirements?

Question 53 How important is Usability when compared with Emissions' Requirements?

Question 54 How important is Usability when it is compared with Organizational Requirements?

Question 55 How important are the Emissions Requirements when compared with Organizational Requirements of the equipment?

Paired comparison matrix

Importance of an attribute with respect to another in the Selection of Best Alternative Ergonomic											
Questions	Attributes	Absolutely more important	Strongly most importantly	Moderately more important	Weakly more important	Equally important	Weakly more important	Moderately more important	Strongly most importantly	Absolutely more important	Attributes
46	C. with H Skill and Training	☐	☐	☐	☐	☐	☐	☐	☐	☐	C. with Physical Space
47	C. with Skill and Training	☐	☐	☐	☐	☐	☐	☐	☐	☐	Usability
48	C. with Skill and Training	☐	☐	☐	☐	☐	☐	☐	☐	☐	Emissions Requirements
49	C. with Skill and Training	☐	☐	☐	☐	☐	☐	☐	☐	☐	Organizational Requirements
50	Compatibility with Physical Space	☐	☐	☐	☐	☐	☐	☐	☐	☐	Usability
51	Compatibility with Physical Space	☐	☐	☐	☐	☐	☐	☐	☐	☐	Emissions Requirements of the equipment

52	Compatibility with Physical Space	☐	☐	☐	☐	☐	☐	☐	☐	☐	Organizational Requirements
53	Usability	☐	☐	☐	☐	☐	☐	☐	☐	☐	Emissions Requirements
54	Usability	☐	☐	☐	☐	☐	☐	☐	☐	☐	Organizational Requirements
55	Emissions Requirements	☐	☐	☐	☐	☐	☐	☐	☐	☐	Organizational Requirements

comparisons among attributes and sub-attributes according to each level following the AHP methodology. Table 5 presents one question scheme of evaluation as an example.

Part 4
The last part of the survey was designed to validate the minimum set of ergonomic attributes that must be included in the evaluation. All attributes and sub-attributes were listed, and experts individually select those ones that must be included in the evaluation for the selection of AMT. In this research, all the listed attributes were chosen at least for one expert.

4.2 Determination of design range, system range, and evaluation AMT alternatives

For this, the basis for a fuzzy axiomatic design was used and functional requirements were determined. These requirements must be defined for each attribute by triangular fuzzy numbers. Then, each alternative is evaluated with respect to EFR of each attribute via fuzzy numbers. To obtain EFR design ranges, experts must rate each alternative according to each attribute and sub-attribute. Design ranges (α,β,θ) can be decided among experts' opinions and corollary 6 of axiomatic design theory; therefore, the widest range must be selected. Also, the linguistic terms and membership functions shown in Figs. 2 and 3 were used for intangible and tangible attributes, respectively. Ergonomic system range (a, b,c) was obtained after aggregation procedures. Then, obtaining the ergonomic incompatibility content was made for every sub-attribute, attribute, and each alternative. A numerical example is provided to clarify these results.

4.3 Numerical example

In this example, three CNC milling machines were evaluated. Results are summarized below; some *steps* are exposed for one attribute only.

Phase 1

- Step 1 Five attributes and 20 sub-attributes (explanation of attributes was described above).
- Step 2 The manufacturing laboratory has three alternatives of CNC milling machines—alternatives *X*, *Y*, and *Z*.
- Step 3 Eight experts evaluated the alternatives; all experts had vast experience in the manufacturing and academic fields.
- Step 4 Five linguistic terms were used according Table 7.
- Step 5 The importance of each attribute was obtained via pairwise comparisons of AHP methodology using the ergonomic compatibility survey. The used terms and values according Saaty's methodology are shown in Table 6.
- Step 6 Experts' subjective evaluations were made using the ECS (Tables 3, 4, and 5).

Phase 2

- Step 1 The linguistic terms and their correspondent fuzzy numbers are shown for attribute A135 only in Table 8.
- Step 2 In this step, results obtained from AHP pairwise comparisons using Expert Choice software are shown in Table 9.
- Step 3 Determine design range for each attribute from experts' opinions. In this case, corollary 6 of axiomatic design was used to establish the

Table 6 Linguistic scale for the attributes importance weight

Linguistic term	Weight value
Very low (VL)	1
Low (L)	3
Medium (M)	5
High (H)	7
Very high (H)	9

Table 7 Linguistic scales for evaluation (rating) of sub-attributes using fuzzy triangular numbers

Linguistic term	Triangular fuzzy numbers
Tangible attributes	
Very low (VL)	(0,0,0.3)
Low (L)	(0,0.25,0.5)
Medium (M)	(0.3.0.5,0.7)
High (H)	(0.5,0.75,1)
Very high (VH)	(0.7,1,1)
Intangible attributes	
Poor (P)	(0,0,0.3)
Regular (R)	(0.2,0.35,0.5)
Good (G)	(0.4,0.55,0.7)
Very good (VG)	(0.6,0.75,0.9)
Excellent (E)	(0.8,1,1)

EFRs, with the widest range among expert opinions which were: EFR_{A111}: at least good, EFR_{A112}: at least good, EFR_{A121}: at least excellent, EFR_{A122}: at least regular, EFR_{A123}: at least good, EFR_{A124}: at least regular, EFR_{A125}: low, EFR_{A131}: at least good, EFR_{A132}: at least good, EFR_{A133}: at least good, EFR_{A134}: at least good, EFR_{A135}: at least good, EFR_{A136}: at least very good, EFR_{A137}: at least very good, EFR_{A141}: low, EFR_{A142}: low, EFR_{A143}: low, EFR_{A144}: low, FR_{A151}: at least good, and EFR_{A152}: at least very good.

Step 4 As an example, system range for sub-attribute A135 for alternative X is calculated from Eq. 1:

$$X_{A_{135(1)}} = \left(\tfrac{1}{8}\right)(0.2 + 0.6 + 0.6 + 0.2 + 0.4 + 0.4 + 0.6 + 0) = 0.38$$
$$X_{A_{135(2)}} = \left(\tfrac{1}{8}\right)(0.3 + 0.75 + 0.75 + 0.35 + 0.55 + 0.55 + 0.75 + 0) = 0.51$$
$$X_{A_{135(3)}} = \left(\tfrac{1}{8}\right)(0.5 + 0.9 + 0.9 + 0.5 + 0.55 + 0.7 + 0.9 + 0.3) = 0.68$$

So, aggretated system range is:

Table 8 Evaluation of sub-attribute A135

Expert	Evaluation	A135
E1	R	(0.2 0.35 0.5)
E2	VG	(0.6 0.75 0.9)
E3	VG	(0.6 0.75 0.9)
E4	R	(0.2 0.35 0.5)
E5	G	(0.4 0.55 0.7)
E6	G	(0.4 0.55 0.7)
E7	VG	(0.6 0.75 0.9)
E8	P	(0 0 0.3)
System range		(0.38 0.51 0.68)

Table 9 Attribute and sub-attribute weights obtained by AHP using Expert Choice© software

	A11	A12	A13	A14	A15	A111	A112	A121	A122	A123	A124	A125	A131
w AHP	0.262	0.178	0.318	0.121	0.120	0.37	0.63	0.280	0.175	0.267	0.17	0.107	0.081

	A132	A133	A134	A135	A136	A137	A141	A142	A143	A144	A151	A152
w AHP	0.11	0.12	0.246	0.20	0.148	0.09	0.15	0.24	0.33	0.26	0.41	0.58

Table 10 Decision matrix for sub-attribute compatibility with skills (A_{112}) and compatibility with training (A_{111})

Alternative	A_{111}	A_{112}
X	(0.55 0.70 0.85)	(0.48 0.63 0.78)
Y	(0.48 0.63 0.78)	(0.23 0.34 0.53)
Z	(0.33 0.46 0.63)	(0.45 0.59 0.74)
w AHP	0.370	0.630

$$X_{A_{135}} = [0.38,\ 0.51,\ 0.68]$$

Step 5 Developed matrixes with system range and weights are shown as example in Table 10, for sub-attributes compatibility with skill (A_{112}) and compatibility with training (A_{111}) only.

Phase 3

Determination of MF is done in this phase. As an example for attribute A_{135} for alternative X: design range: At least good, with its correspondent fuzzy number (0.4,1,1), and system range (0.38,0.51,0.68), where X_i=0.614, and design range values α=0.4, θ=1. Calculation of MF is made using Eq. 2 as follows:

$$\mu_{(X_i)} = \left(\frac{0.614 - 0.4}{1 - 0.4}\right) = 0.358$$

Phase 4

Results for this phase are shown as example for the calculation of the EIC for sub-attribute A_{135}. SA is obtained using Eq. 4, CA is obtained using Eq. 5, and EIC is obtained using Eq. 6.

Ergonomic system range area (SA) result is:

$$\mathrm{SA} = [(0.68 - 0.38) \times (1/2)] = 0.15$$

The common area result is

$$\mathrm{CA} = [0.358 \times (0.68 - 0.4) \times (1/2)] = 0.049.$$

Then, the ergonomic incompatibility content result is obtained below in the units called ints:

$$\mathrm{EIC}_{A_{135}} = \log_2[(0.15/0.049] = 1.609$$

Phase 5

Results of this phase are explained for obtaining the TWEIC for each alternative. One of the most important advantages of the model is about the additive character of the information axiom. In this case, calculations of EIC using Eq. 7 for each level of hierarchy will be shown for alternative X only as example below.

Second level of hierarchy sub-attributes

$$\mathrm{EIC}_{\mathrm{A11}-X} = [(0.37 \times 0.447) + (0.63 \times 0.778)] = 0.655$$

$$\mathrm{EIC}_{\mathrm{A12}-X} = [(0.28 \times 0.268) + (0.17 \times 0.314) + (0.26 \times 0.65) + (0.17 \times 0.524) + (0.10 \times 2.201)] = 0.606$$

$$\mathrm{EIC}_{\mathrm{A13}-X} = \left[(0.08 \times 4.056) + (0.11 \times 1.381) + (0.12 \times 0.927) + (0.214 \times 4.056) + (0.20 \times 1.609) + (0.14 \times 0.573) + (0.09 \times 0.75)\right] = 2.068$$

$$\mathrm{EIC}_{\mathrm{A14}-X} = [(0.15 \times 2.561) + (0.24 \times 3.014) + (0.33 \times 0.1.361) + (0.26 \times 1.361)] = 1.91$$

$$\mathrm{EIC}_{\mathrm{A15}-X} = [(0.41 \times 1.116) + (0.58 \times 0.498)] = 0.746$$

First level of hierarchy, main attributes:

$$\mathrm{TWEIC}_X = [(0.262 \times 0.655) + (0.178 \times 0.606) + (0.318 \times 2.068) + (0.121 \times 1.910) + (0.120 \times 0.746)] = 1.268$$

Complete results are exposed in the ergonomic compatibility content multi-attribute diagram of Fig. 5. In this diagram, weight values are shown for every sub-attribute just above to the ergonomic incompatibility content values for all alternatives. Correspondingly, for alternative Y, there is a result of TWEIC_Y=1.595 ints, and for alternative Z, there is a result of TWEIC_Z=1.044 ints. These results guide the selection of alternative Z as the best alternative for our

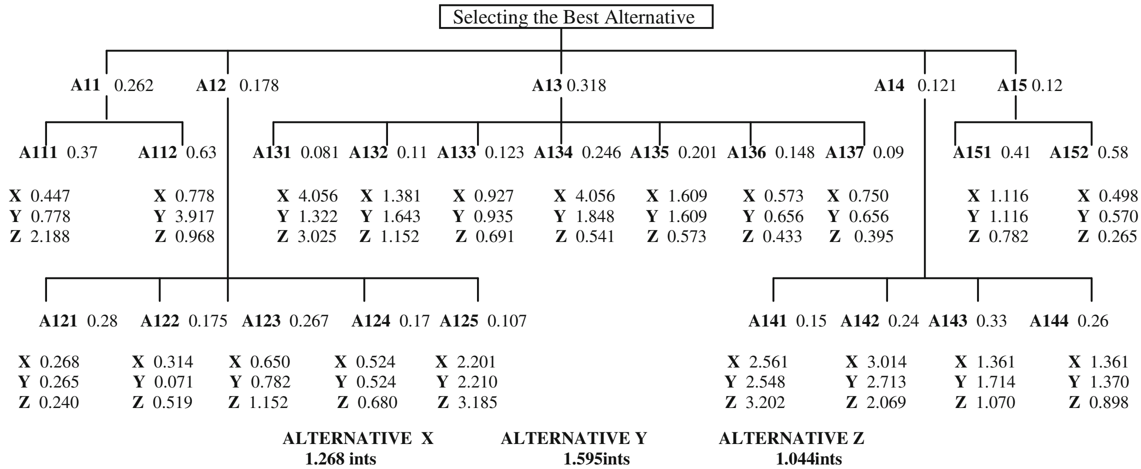

Fig. 5 Ergonomic compatibility content multi-attribute diagram

goal. From an axiomatic design approach, alternative *Z* is the one that could better satisfy the EFRs when it is compared with the other available alternatives.

The utilization of the proposed survey helps to obtain valuable assessments from experts about the importance of ergonomic attributes; also, it is an effective way to gather information about the evaluation of ergonomic attributes of AMT alternatives. Additionally, the proposed procedure achieves the measurement for the ergonomic compatibility by means of the weighted EIC using a novel fuzzy axiomatic design approach to compare and select AMT. The uniqueness of the procedure is in proposing the evaluation of ergonomic compatibility attributes, creating an effective way of collecting, defining, and mathematically aggregating experts' opinions for the assessment of ergonomic attributes using a state of the art methodology. Ergonomic compatibility attributes have been neglected in actual methods for AMT evaluation and selection, and this procedure enables decision makers to include them effectively. Also, by proposing the EIC as a unit for measurement of the construct, this measurement is a unique adaptation of the information axiom under fuzzy environment for the ergonomic compatibility evaluation application.

5 Conclusions

This paper presents a list of ergonomic attributes for AMT evaluation and contributes proposing a new hierarchical structure for them. Also, it proposed a novel methodology for evaluation purposes. It includes an ergonomic compatibility survey for group decision making under incomplete information, in which experts emit their opinions in linguistic terms, and a mathematical procedure for data treatment. This multi-attribute fuzzy axiomatic approach is given and it is found to be useful to manage complex problems where considerable amounts of quantitative and qualitative attributes are involved, as in this case, a unique application is made concerning ergonomic compatibility attributes for AMT evaluation and selection. The EIC is a construct used for this paper in an original form, may help to measure the probability of an AMT design to satisfy ergonomic desirable design ranges for every sub-attribute of the model, given as linguistic terms from opinion of experts in a fuzzy environment. The use of the weighted EIC includes the importance of each attribute and sub-attribute as a part of the evaluation. The use of this new methodology allows DM to obtain an ergonomic perspective in their AMT selection decisions; a guide to more complete and better decisions about AMT. This potentially may lead to a more effective implementation and use of this technology taking into consideration human capabilities and limitations.

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