Research Article

A framework for welding process selection

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Abstract

This paper develops a framework to differentiate welding processes, for industrial purposes, according to two families of criteria. It is constructed as a phase-wise decision support system that reviews objects with physical and economic criteria. The first phase excludes the non-functioning processes from the panel, and catching the best candidate processes are left to the second phase. The second phase is an integrated mechanism that weights the active criteria versus the goal using a FUZZY-AHP system and then it ranks the candidates using a FUZZY-TOPSIS system. Both phases operate linked with parallel and accessible database and knowledge-base to accommodate a large variety of welding factors (alternative welding processes and welding criteria) and allow inserting new ones. This framework is mechanized as a portable software, and then validated based on existing cases. The proposed framework is advantageous with having a flexible opened structure that can manage existing and expected industrial problems.

Keywords Welding process selection · MCDM · FUZZY AHP · FUZZY TOPSIS

1 Introduction

The manufacturing assemblies includes a large variety of welding methods. Furthermore, the design of a welding process involves several physical and economic factors even with using the same method. Thus, the selection of a welding method and its process design becomes a hard task. Conventionally, this task still depends mainly on the experience of manufacturing engineers linked with a few factors, mostly the discontinuity (an element of quality) and cost with a few number of welding processes. In the matter of fact, such routine becomes insufficient while the number of alternative processes increases for the same product as seen from Darwish et al. [10], and Jayant and Singh [17]. Therefore, it becomes essential to develop comprehensive systems to solve the welding process selection (WPS) problem with least time and effort. Any successful selection system should comprise an opened database collecting all information of welding methods/processes, products, and materials in addition to a dynamic knowledge-base. The latter contents enable defining, determining, and storing the exact welding problem factors.

It is obvious that the complexity of WPS problem increases as the problem factors increase, and in turn, the number of process differentiation criteria increases. Thus, the WPS represents an NP-hard problem that can't be solved with rough approaches. The WPS is a typical multicriteria decision making (MCDM) problem. Thus, MCDM methods such as TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), AHP (Analytic Hierarchy Process) and their FUZZY versions become the most relevant to construct a successful system for the current purpose as seen later in this paper.

Several approaches were developed to solve the WPS problem. Most of these approaches are limited to small problems. These approaches can be categorized as Just advisory or guiding, simple methodological, and integrated methodological approaches.

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However, this paper reviews the most relevant approaches and that related to the purpose. For instance,. Darwish et al. [10] developed a knowledge-base system for solving the WPS problem and then experimented 30 welding processes. Their system includes the factors of product type, material type and thickness, method of use, quality level, joint type and welding position. Their system needs to a prescreening for the available welding processes. Also, they introduced a methodology to determine the most suitable joining technology based on highlighting the candidate processes that found capable of joining under given conditions. Their selection methodology comprises criteria like joint function (load type and strength), joint technical information (joint configuration and material type), joint spatial information (material thickness and size) and economic factors (production volume and required skills). The corresponding criteria are stored in a database and implemented in a software. Such systems merely candidate welding processes without robust selection mechanism. Yeo and Neo [32] explored quantitively the effect of welding methods on the environment and WPS using AHP with Crisp values.

Later, Silva et al. [27] demostrated a sequential mathematical approach for WPS based on quality and cost in Crisp values. They applied to SMAW, GTAW and two versions of GMAW processes. Balasubramanian et al. [3] reported a specific procedure for WPS using AHP with Crisp values in fabracting cruciform joints of ASTM 517 'F' grade steel. They differentiated the SMAW, FCAW and SAW processes based on the qualitative criteria of initial preparation required, availability of consumables, welder skill requirement, welding procedures, quality of the weld, fatigue of the operator, post weld cleaning, ease of automation, and positional welding capability. Correia and Ferraresi [9] used their WPS method to compare SAW and GMAW processes based on operational costs and non-quality costs in Crisp values for a specific application.

More robust WPS systems were introduced such as that introduced by Esawi and Ashby [12] who described a methodology for joining method selection implemented in a software; where a search engine isolates the processes that meet design requirements of material, joint geometry and loading where the information about joining processes with respect to each criterion are stored in a database. The processes are isolated and then ranked based on the relative equipment cost or production rate; that is more relevant. Balasubramanian et al. [4] applied AHP in a Crisp manner for WPS in fabricating hardface boiler grade steels. They differentiated SMAW, GMAW, GTAW, SAW and PTAW processes based on quantitative and qualitative factors. Their method reported PTAW as the best process for this application. Jafarian and Vahdat [16] described a WPS system consists of a knowledge-base and a FUZZY-AHP-TOPSIS system and used this to differentiate nine important welding processes considering the criteria of operator factor, alloy class, material thickness, capital cost, deposition rate, design application, joint configuration, welding position, equipment portability, and filler metal utilization. Their system indicated that GTAW, PAW and EBW are the most suitable methods for welding the high pressure vessel. Mirhedayatian et al. [24] proposed a FUZZY-TOPSIS system for WPS in repairing nodular cast iron engine block. For this purpose, they compared SAW, PAW, TIG, GMAW, FCAW, SMAW, OFW, EBW and LBW processes.

More recent, Jayant and Singh [17] simply used a knowledge-base AHP system to decide a process for welding high pressure vessel. They differentiated five welding processes based on the criteria of design applications, joint configuration, welding position, capital cost, deposition rate, thickness of parts, weld quality, material class, welding procedure, operator factor filler, metal utilization, and equipment portability. Capraz et al. [8] used AHP and TOPSIS to select a process for welding plain carbon stainless steel storage tank. They used AHP to weight the criteria according to experts' opinion and used TOPSIS to rank available welding processes. They applied to MMAW, MIG, MAG, GTAW and SAW processes. However, the existing directions of solving the WPS problem vary according to the differentiation principle adopted.

The remaining of this paper is organized as follows. The proposed framework and its auxiliaries are described in Sect. 2 and demonstrated with case studies in Sect. 3. The sensitivity of the proposed framework is examined in Sect. 4. Concluding remarks are presented in Sect. 5. The paper also contains two appendices; Appendix 1 abbreviates the welding processes and Appendix 2 includes the procedural tables.

2 The proposed framework

The welding factors and sub-factors are found classified in several forms. This can be reviewed from Darwish et al. [10], Yeo and Neo [32], Silva et al. [27], Balasubramanian

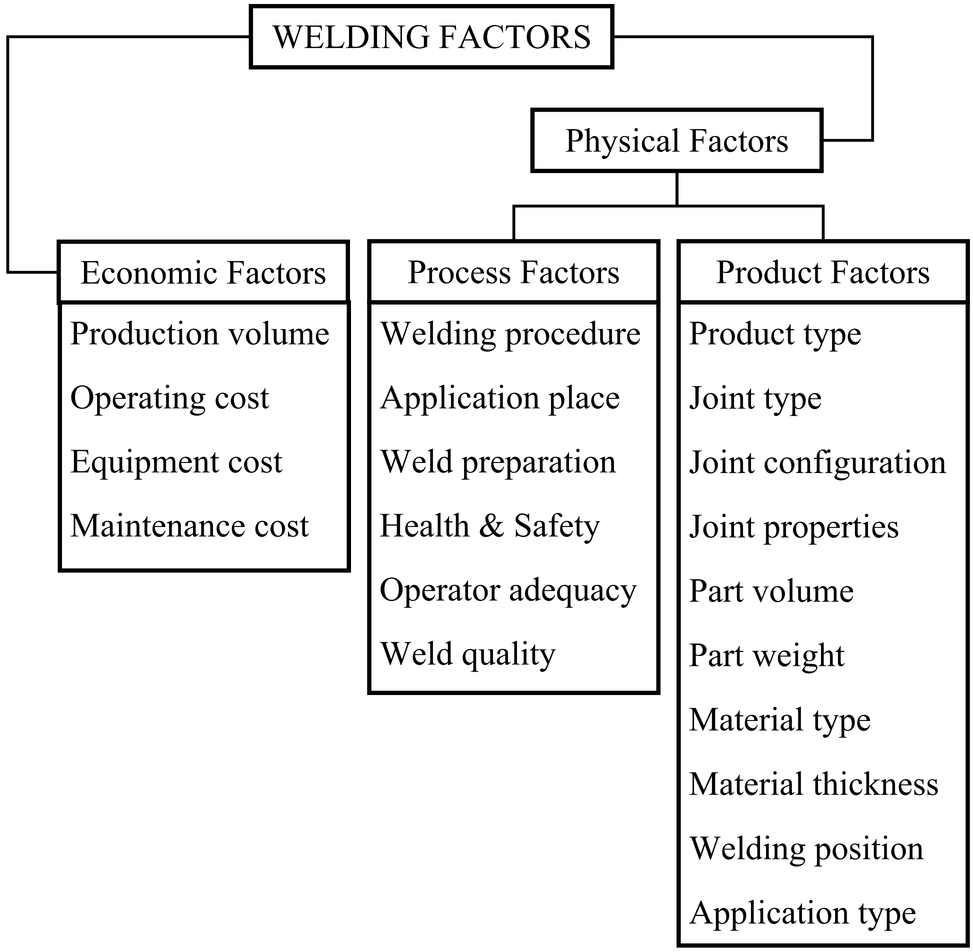

Fig. 1 The main welding factors

et al. [3], Brown et al. [7], Esawi and Ashby [12], Correia and Ferraresi [9], Balasubramanian et al. [4], Jafarian and Vahdat [16], and Mirhedayatian et al. [24]. However, this paper summarizes the main welding factors as shown in Fig. 1, which can be further classified.

Figure 2 explores the proposed framework for welding process selection. This framework is mainly an integrated MCDM system. The inception of this layout was introduced by Omar et al. [26]. The *database and knowledge-base* are constructed to include the welding factors and their related information of a group of 49 welding processes those abbreviated in Appendix 1. Based on the source/cause of coalescence between the welded parts, this group is classified as follows.

- Pressure welding processes
  - Fusion welding processes
    RSW, RSEW, RPW, HFW, FW, SW, CD-SW.
  - Non-fusion welding processes
    UW, DFW, RLW, EXW, ICW, BCW, DCW, CEXW, FGW, FSW, FRW, USW.
- Non-pressure welding processes
  - Homogenous welding processes
    SMAW, MIG, FCAW-G, FCAW-S, PE-TIG, TIG, SAW, P-MIG, L-MIG, PAW, EGW, ESW, EBW-V, EBW-NV, LBW, GW.
  - Heterogeneous welding processes
    TB, DFB, DB, FB, IB, RB, BZW, TS, DFS, DS, FS, IS, RS and THW.

To construct the *database and knowledge-base*, the relationships regarding the former welding processes with welding criteria are organized from four aiding sources—textbooks, papers, and database of international welding companies and field visits for Egyptian international companies such as Suzuki Egypt and GS for Engineering & Construction. Refer to Tables 4–14 in Appendix 2. Table 4 of welding companies is collected and arranged according to the factors and purpose. Tables 12 and 14 are also based on Table 4. Then, some relationships are set in a linguistic form, which will be transformed using the FUZZY logic. (Notice that Table 4 is concerned with some criteria and most of the welding processes.) Tables of Appendix 2

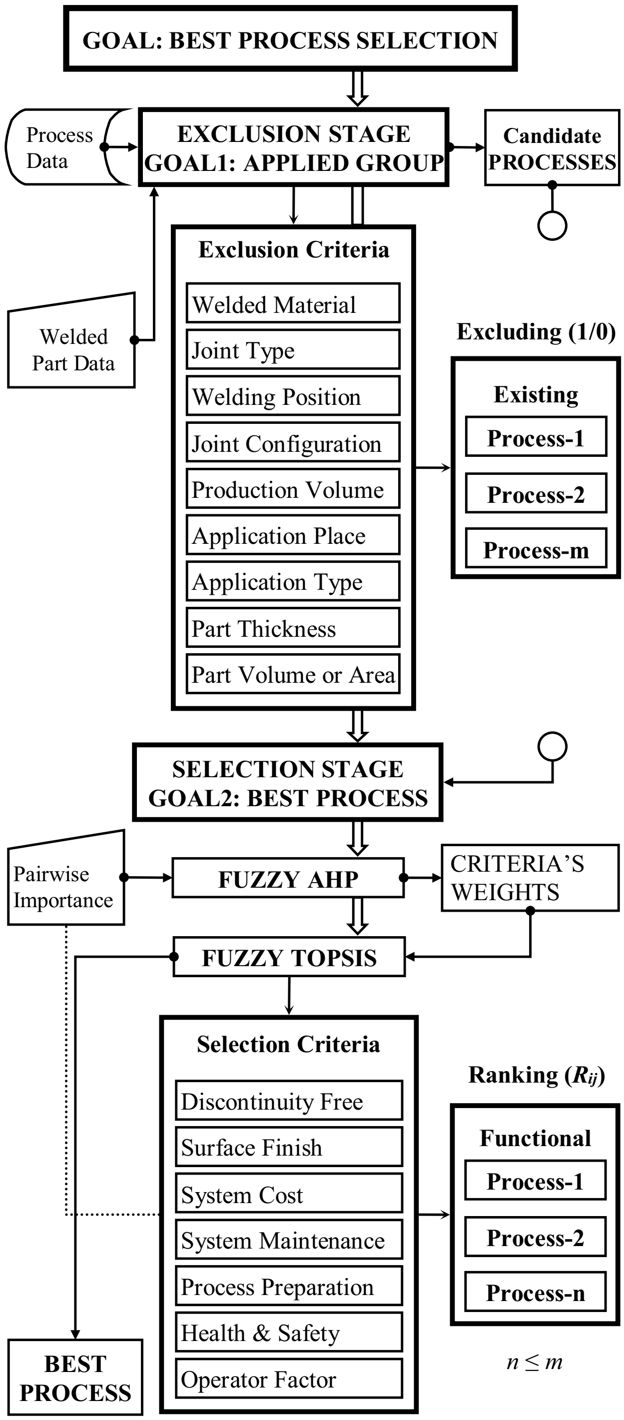

Fig. 2 Proposed framework for welding process selection

are associated with the used aiding sources with different degrees as shown in Table 1.

Making a decision about the best welding process for a given product is completed in two phases—*exclusion phase and selection phase*. Assisted by the engineers' opinions and other information, the AHP method is used to weight the welding criteria diffused with FUZZY logic (FUZZY-AHP) such as that followed in Huang et al. [15]. The TOPSIS method is used to find the final ranking of welding processes diffused with FUZZY logic (FUZZY-TOPSIS) such as that followed in Junior et al. [22].

The exclusion phase identifies the *functional candidate* group of welding processes amongst those submitted first and fathoms the other processes. Thus, the given welding processes are reduced to those meet working circumstances of *nine factors*—maximum and minimum welded part volume, material type, maximum and minimum joint thickness, production volume, weld position, joint type, applicable joint configuration, weld place, and possible applications.

The selection phase ranks the functional candidate group using FUZZY-TOPSIS method based on next *seven factors*—welding equipment cost, operator factor, maintenance complexity of welding equipment due to machine structure, surface finish, process preparation, health & safety, and weld discontinuity free.

This framework is programmed in MATLAB environment and it can be introduced as software for users with the graphical user interface shown in Fig. 3. The user only feeds the information displayed. For each factor, the user selects from a pop-up-menu. The program is constructed to display the most preferable welding processes on the solution screen cell while other results are stored internally. The user supplies information about the relative importance (pairwise comparison matrix) of the seven selection criteria in criteria weights determination panel based on AHP Saaty's scale {1/9, 1/8, …, 1/2; 1, 2, …, 9}. Other information are also supplied following the instructions on the interface.

3 Demonstration

The framework is applied to three typical cases from industry (Figs. 4, 5, 6). The purpose is to find the best welding process for each application. The output becomes a list grades all welding processes as the best one on the top and so on. Table 15 in the Appendix 2 represents the pairwise comparison matrix of AHP for all cases.

To verify the results of the selection process, the FUZZY linguistic values of the seven selection criteria are judgmentally reviewed. From the other side, the current field practice validates the framework decisions. In addition, for the first two cases, the selected welding processes highly satisfy the physical and economic requirements of the weld. However, the selected welding process for the third case doesn't highly satisfy the required weld strength even this selection is the same as applied in the field practice.

Table 1 Degree of involvement between the framework database and the aiding sources

Aiding source	Tables in Appendix 2										
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11
Houldcroft [14]		***	***	***	***	***	***	***			
Dawes [11]											*
Alia et al. [2]		**	*	*	***	*	***	**			
Oates [25]		***	**	***	***	**	***	***			**
Bralla [6]		*	*	**	**	***	***	***		***	
Blunt and Balchin [5]											***
Harris [13]											**
Ainali et al. [1]		***				**	*	*			*
Weman [31]											*
Vianco et al. [29]		***	*	*	*	*	***	**			**
Jenny [21]		***	*	***	***	**	***	***			**
Jenney and O'Brien [18–20]		***	***	***	***	***	***	***			**
Webber et al. [30]											**
Swift and Booker [28]		***	***	***	***	***	***	***		***	***
Jayant and Singh [17]										**	
International companies database	***								***		*
Field visits for international Egyptian companies											***
Minister of Innovaion and Advanced Education & Apprenticeship and Industry Training [23]											*

*Fair involvement; **strong involvement; ***very strong involvement

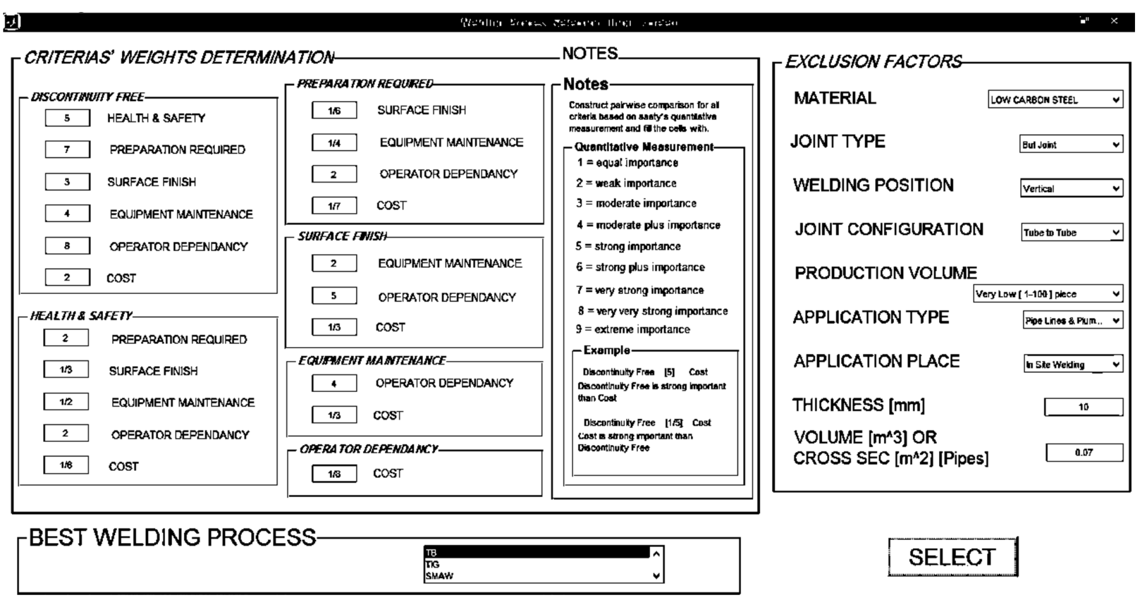

Fig. 3 The graphical user interface of the proposed framework

Outer diameter	300 mm
Occupied space	0.07 m^3
Thickness	10 mm
Material	Low carbon steel
Type of joint	Butt
Welding position	Horizontal
Joint configuration	Tube to tube
Production volume	50
Type of application	Plumbing
Place of application	In site
Result top three processes: TB→TIG→SMAW.	

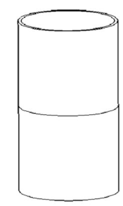

Fig. 4 A plumbing butt joint welding

Outer diameter	300 mm
Occupied space	0.07 m^3
Thickness	10 mm
Material	Mild steel
Type of joint	Butt
Welding position	Flat
Joint configuration	Tube to tube
Production volume	1500
Type of application	Piping
Place of application	Can be moved
Result top three processes: SAW→PE-TIG→FCAW-S.	

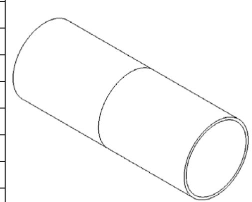

Fig. 5 A piping butt joint welding

Dimensions	1000 mm × 500 mm
Occupied space	0.001 m^3
Thickness	1 mm
Material	Medium carbon steel
Type of joint	Lap
Welding position	Flat
Joint configuration	Plate to plate
Production volume	1000
Type of application	Automotive
Place of application	Can be moved
Result top three processes: TS→BZW→TB.	

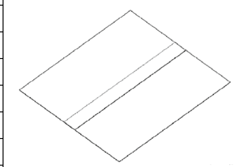

Fig. 6 An automotive lap joint welding

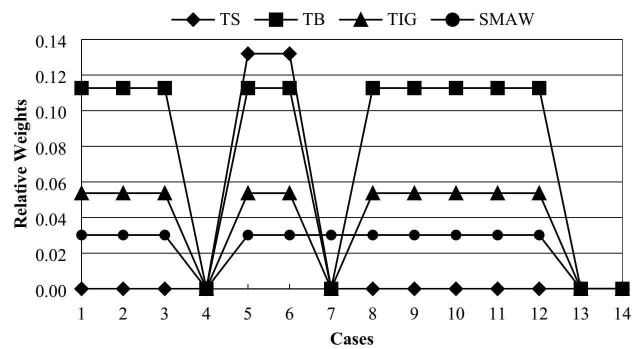

Fig. 7 Weights of candidate welding processes to the examined cases

4 Sensitivity analysis

It remains to examine the sensitivity of the proposed framework to potential changes in the inherent welding factors both qualitative and quantitative. In other words, for the same welding application, a selected welding process may be altered if one or more factors change. For this purpose, Table 2 explores fourteen cases extracted from ***plumping welding application type*** with application place 'in-site welding' and 'part volume of 0.07 m^3', i.e., it is allowed to change six exclusion factors. Furthermore, it taken in consideration to impose extreme cases to further examine the robustness of the exclusion process as cases 4, 13 and 14.

Table 3 and Fig. 7 summarizes the sensitivity analysis of the proposed framework in terms of the fourteen cases addressed in Table 2 based on the relative weight (closeness). The candidate welding processes of this experiment are found TS, TB, TIG and SMAW, and cases 4, 13 and 14 are refused by all welding processes. Referring to the plumping application of Fig. 4, it is found that TB process is the best welding process and as it can be seen from Fig. 7 that TB still apply and dominate as a best process for the examined cases (57% of cases) followed by TS (14% of cases) and then SMAW (7% of cases). Notice that the changes in the exclusion factors bring the TS process to the best panel and postpone the TIG process (Table 3). However, TB seems to be the most appropriate welding process for the

Table 2 Different cases of the plumping application with fixed place and part volume

Case	Exclusion Factor					
	Welded material	Joint type	Welding position	Joint configuration	Production volume	Part thickness (mm)
1	Low carbon steel	Butt	Horizontal	Tube to tube	50	10
2	Low carbon steel	Butt	Flat	Tube to tube	50	10
3	Low carbon steel	Butt	Over head	Tube to tube	50	10
4	Low carbon steel	Butt	Horizontal	Tube to tube	1500	10
5	Low carbon steel	Butt	Horizontal	Tube to tube	50	5
6	Low carbon steel	Butt	Horizontal	Tube to tube	50	2
7	Low carbon steel	Butt	Horizontal	Tube to tube	50	20
8	Mild steel	Butt	Horizontal	Tube to tube	50	10
9	Medium carbon steel	Butt	Horizontal	Tube to tube	50	10
10	Low carbon steel	T-joint	Horizontal	Tube to plate	50	10
11	Mild steel	Butt	Horizontal	Tube to bar	50	10
12	Mild steel	Butt	Horizontal	Tube to tube	300	10
13	Mild steel	T-joint	Horizontal	Tube to plate	1500	5
14	Mild steel	T-joint	Vertical	Tube to plate	1500	5

Table 3 Weights of candidate welding processes to the examined cases

Welding process	Case														% of cases
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
TS	0.00	0.00	0.00	0.00	**0.13**	**0.13**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14
TB	**0.11**	**0.11**	**0.11**	0.00	0.11	0.11	0.00	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**	0.00	0.00	57
TIG	0.05	0.05	0.05	0.00	0.05	0.05	0.00	0.05	0.05	0.05	0.05	0.05	0.00	0.00	00
SMAW	0.03	0.03	0.03	0.00	0.03	0.03	**0.03**	0.03	0.03	0.03	0.03	0.03	0.00	0.00	07
Best process	TB	TB	TB	None	TS	TS	SMAW	TB	TB	TB	TB	TB	None	None	78

The bold numbers were used to indicate the highest relative closeness value to identify the best welding process

plumping welding application type. Thus, the framework is sensitive to the significant changes in welding factors.

Intuitively, the welding application type is the most determinant of the best welding process followed by 'part thickness' and then 'production volume'. The results proved that any significant changes in 'part thickness' can alter the selected process; for instance if all part thicknesses becomes 5 mm, the TS process will replace the TB process in this experiment. This property enables the welding engineers to set a range of any quantitative factor in which a specific welding process still apply.

5 Conclusions

This paper introduces and applies a modular decision framework for welding process selection avoiding several shortcomings of exiting methods. It filters the submitted processes twice through a sequence of two sets of robust criteria including new ones such as health & safety and system maintenance. This is actuated with an integrated powerful decision making engine. Thus, it can ensure the right decision of differentiating a wider range of industrial processes whatever the complexity of products and welding processes including recent situations. Furthermore, this framework can easily accommodate other criteria and evaluation functions since it becomes an inception for a portable software. This framework is verified and then validated with current industrial cases. The framework sensitivity to changes in the exclusion welding factors is also examined with hypothetical cases based on an industrial application. For a coming extension, the framework will be equipped with additional bundles of factors. A mechanical bundle will be merged to include factors such as weld strength to obtain more accurate and precise selection and to avoid such shortcoming of the third case.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix 1: Abbreviations of the considered welding processes

BCW	Butt cold welding	IB	Induction brazing
BZW	Braze welding	ICW	Indentation cold welding
CD-SW	Capacitor discharge stud welding	IS	Induction soldering
CEXW	Co-extrusion welding	LBW	Laser beam welding
DB	Dip brazing	L-MIG	Laser metal inert gas
DCW	Drawing cold welding	MAG	Metal active gas
DFB	Diffusion brazing	MIG	Metal Inert gas
DFS	Diffusion soldering	MMAW	Manual metal arc welding
DFW	Diffusion welding	OFW	Oxy acetylene welding
DS	Dip soldering	PAW	Plasma arc welding
EBW	Electron beam welding	PE-TIG	Penetration enhanced
EBW-NV	Electron beam welding-non vacuum	P-MIG	Plasma metal inert gas
EBW-V	Electron beam welding-vacuum	PTAW	Plasma transferred arc welding
EGW	Electro gas welding	RB	Resistance brazing
ESW	Electro slag welding	RLW	Roll welding
EXW	Explosive welding	RPW	Resistance projection welding
FB	Furnace brazing	RS	Resistance soldering
FCAW	Flux cored arc welding	RSEW	Resistance seam welding
FCAW-G	Flux cored arc welding-gas	RSW	Resistance spot welding
FCAW-S	Flux cored arc welding-shielded	SAW	Submerged arc welding
FGW	Forge welding	SMAW	Shielded metal arc welding
FRW	Friction welding	SW	Stud welding
FS	Furnace soldering	TB	Torch brazing
FSW	Friction stir welding	THW	Thermite welding
FW	Flash welding	TIG	Tungsten inert gas
GMAW	Gas metal arc welding	TS	Torch soldering
GTAW	Gas tungsten arc welding	USW	Ultrasonic welding
GW	Gas welding	UW	Upset welding
HFW	High frequency welding		

Appendix 2

See Tables 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15.

Table 4 Some guiding International welding companies regrading some welding criteria and their weights

No.	Company	Factor	Country
1	Lincoln Electric	Equipment cost and maintenance	USA
2	The Monty	Equipment cost and welded part volume	Canada
3	Nelson Stud Welding	Equipment cost	USA
4	SCIAKY Inc.	Equipment cost and maintenance	USA
5	EPB Ltd.	Equipment cost	France
6	USA Weld	Equipment cost	USA
7	The Welders Warehouse	Equipment cost	UK
8	Image Industries	Equipment maintenance	USA
9	The Fabricator	Equipment maintenance	USA
10	Modern Welding	Equipment maintenance	USA
11	Government of South Australia	Equipment maintenance	Australia
12	DBG	Equipment maintenance	UK
13	OKUMA	Equipment maintenance	USA
14	MTI Manufacturing Technology Inc.	Equipment maintenance	USA
15	T.J. Snow	Welded part volume	USA
16	Alumbra	Welded part volume	Sweden
17	Culaser	Welded part volume	Turkey
18	TWI	Welded part volume	UK
19	RV Machine Tools	Welded part volume	India
20	Pressure Welding Machines	Welded part volume	UK
21	Nabertherm	Welded part volume	Germany
22	SOHO	Welded part volume	China
23	Wincoo Machine	Equipment cost	China
24	NBXIN Chang	Equipment cost and welded part volume	China
25	KIAIND	Equipment cost and welded part volume	China
26	MORAN	Equipment cost	China
27	FS Welder	Equipment cost and welded part volume	China
28	Suzuki Egypt	All selection factors	Egypt
29	GS for Engineering & Construction	All selection factors	Egypt

Table 5 Materials that can be welded by sample processes

Process	Low carbon steel	Mild steel	Medium carbon steel	High carbon steel
SMAW	Yes	Yes	Yes	Yes
MIG	Yes	Yes	Yes	Yes
FCAW-G	No	Yes	No	No
FCAW-S	No	Yes	No	No
PE-TIG	Yes	Yes	Yes	Yes
TIG	Yes	Yes	Yes	Yes

Table 6 Maximum and minimum part thickness for sample processes

Process	Minimum thickness (mm)	Maximum thickness (mm)
SMAW	1.6	38
MIG	0.5	80
FCAW-G	1.5	12
FCAW-S	1.5	12
PE-TIG	0.2	30
TIG	0.2	10

Table 7 Applicability of sample processes to some joints

Process	Butt joint	Corner joint	T joint	Lap joint	Edge joint
SMAW	Yes	Yes	Yes	Yes	Yes
MIG	Yes	Yes	Yes	Yes	Yes
FCAW-G	Yes	Yes	Yes	Yes	Yes
FCAW-S	Yes	Yes	Yes	Yes	Yes
PE-TIG	Yes	Yes	Yes	Yes	Yes
TIG	Yes	Yes	Yes	Yes	Yes

Table 8 Applicability of sample processes to weld positions

Process	Flat	Horizontal (2G)	Horizontal (2F)	Vertical	Overhead
SMAW	Yes	No	Yes	Yes	Yes
MIG	Yes	No	No	No	No
FCAW-G	Yes	No	Yes	Yes	Yes
FCAW-S	Yes	No	No	Yes	Yes
PE-TIG	No	No	Yes	No	Yes
TIG	No	No	No	No	Yes

Table 9 Applicability of sample processes to part configurations

Process	Plate to plate	Bar to bar	Bar to tube	Bar to plate	Tube to tube	Tube to plate
SMAW	Yes	Yes	Yes	Yes	Yes	Yes
MIG	Yes	No	Yes	Yes	Yes	Yes
FCAW-G	Yes	No	Yes	Yes	Yes	Yes
FCAW-S	Yes	No	Yes	Yes	Yes	Yes
PE-TIG	Yes	No	Yes	No	Yes	Yes
TIG	Yes	Yes	Yes	Yes	Yes	Yes

Table 10 Applications of some processes

Process	Ship building	Bridge building	Pressure vessels	Heavy machinery	Pipelines/plumbing
SMAW	Yes	No	Yes	Yes	Yes
MIG	Yes	No	No	No	No
FCAW-G	Yes	No	Yes	Yes	Yes
FCAW-S	Yes	No	No	Yes	Yes
PE-TIG	No	No	Yes	No	Yes
TIG	No	No	No	No	Yes

Table 11 Applicability of sample processes to some places

Process	In site	Movable parts	Continuous welding
SMAW	Yes	Yes	No
MIG	Yes	Yes	Yes
FCAW-G	Yes	Yes	Yes
FCAW-S	Yes	Yes	Yes
PE-TIG	Yes	Yes	Yes
TIG	Yes	Yes	Yes

Table 12 Maximum part volume/section area for sample processes

Process	Volume/area (m^3 or m^2)
RPW	0.52272 m^2
HFW	5.76 m^3
FW	0.1 m^2
UW	0.001024 m^2
DFW	550.3992324 m^3
RLW	8.55 m^3
EXW	66 m^3
ICW	0.00189 m^2
BCW	0.0009 m^2

Table 13 Production volume for sample processes

Process	Very low	Low	Medium	High	Very high
SMAW	Yes	Yes	No	No	No
MIG	No	No	Yes	Yes	No
FCAW-G	No	No	Yes	Yes	No
FCAW-S	No	No	Yes	Yes	No
PE-TIG	No	No	Yes	No	No
TIG	Yes	Yes	No	No	No

Table 14 Sample processes weighted relative to the selection criteria

Process	System cost	Operator factor	System maintenance	Surface finish	Preparation	Health and safety	Discontinuity Free
SMAW	V. low	V. high	V. low	Med.	Med.	V. high	V. low
MIG	Low	High	High	High	High	V. high	Low
FCAW-G	Low	High	High	High	High	High	Low
FCAW-S	Low	High	Med.	High	Med.	High	Low
PE-TIG	V. low	Low	Med.	V. high	High	V. high	Low
TIG	V. low	V. high	Med.	V. high	High	V. high	Low

Table 15 Pairwise comparison matrix of selection criteria for the cases

Criteria	System cost	Operator factor	System maintenance	Surface finish	Preparation	Health and safety	Discontinuity free
System cost	1	8	3	3	7	8	1/2
Operator factor	1/8	1	1/4	1/5	1/2	1/2	1/8
Maintenance	1/3	4	1	1/2	4	2	1/4
Surface finish	1/3	5	2	1	6	3	1/3
Preparation	1/7	2	1/4	1/6	1	1/2	1/7
Health and safety	1/8	2	1/2	1/3	2	1	1/5
Discontinuity free	2	8	4	3	7	5	1

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