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Welding Process Selection for Storage Tank by Integrated Data Envelopment Analysis and Fuzzy Credibility Constrained Programming Approach

Rahmad Wisnu Wardana, Eakachai Warinsiriruk, Sutep Joy-A-Ka

***Abstract*—**Selecting the most suitable welding process usually depends on experiences or common application in similar companies. However, this approach generally ignores many criteria that can be affecting the suitable welding process selection. Therefore, knowledge automation through knowledge-based systems will significantly improve the decision-making process. The aims of this research propose integrated data envelopment analysis (DEA) and fuzzy credibility constrained programming approach for identifying the best welding process for stainless steel storage tank in the food and beverage industry. The proposed approach uses fuzzy concept and credibility measure to deal with uncertain data from experts' judgment. Furthermore, 12 parameters are used to determine the most appropriate welding processes among six competitive welding processes.

***Keywords*—**Welding process selection, data envelopment analysis, fuzzy credibility constrained programming, storage tank.

I. Introduction

WELDING is a material joining process in which localised coalescence is produced throughout the faying surfaces of the workpiece. Coalescence (joining) is occurred either by heating materials to proper temperatures or by application of pressure. In some welding processes, filler materials are added during welding [1]. According to ISO 4063 [16], there are more than 90 different welding processes. These processes can be classified as arc welding, gas welding, resistance welding, energy beam welding and solid-state welding. Every welding process has advantages and disadvantages against each other.

The welding process selection among the available alternatives is one of the decision-making problems because it involves a wide range of criteria. Little research on multiple-criteria decision-making tools to welding process selection for specific applications has been published [2]-[8]. In order to make the best decision, a combination of data from academic (theory) expert opinion and welder (practice) expert opinion will be used. In this study, fuzzy DEA and credibility constrained programming are proposed for analysis both of experts. The proposed approach was used for selecting the most suitable welding process for stainless steel storage tank in the food and beverage industry to help welder, manufacturing, and supplier.

DEA was introduced by Charnes [9] for measuring the relative efficiency of a set of decision-making units (DMUs). DEA is used as our tool because it has many advantages such as simple modelling, non-parametric solution, optimised result and practical approach. However, experts' judgments are often imprecise or vague due to lack of their knowledge, and it can cause inaccuracy in decision making. To overcome those problems, fuzzy DEA and credibility constrained programming are used, this method also can enhancing the discriminating power in the DEA model.

The rest of the papers organised as follows. The proposed approach is used for select welding process in Section II. Some important points that are considered for welding process selection are defined in Section III. In Section IV, the result of using the proposed approach is discussed. Section V concludes the paper.

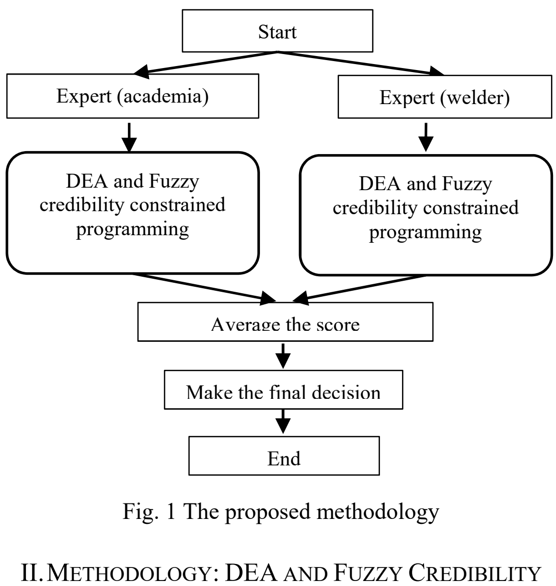

Fig. 1 The proposed methodology

II. Methodology: DEA and Fuzzy Credibility Constrained Programming Approach

Based on Fig. 1, the steps of the proposed methodology can be explained in the following form

Step 1. Determine an expert. Due to decision-making involving a wide range of information, one opinion from academia (theory) and one expert from welder (practice) will be used. Farther, the expert should

Rahmad Wisnu Wardana is Master Student and Eakachai Warinsiriruk is Doctor at Department of Industrial Engineering, Faculty of Engineering, Mahidol University, Thailand (e-mail: rahmadwisnu78@gmail.com, warinsiriruk@yahoo.com).

Sutep Joy-A-Ka is Doctor at Material Properties and Failure Analysis Laboratory, Material Properties Analysis and Development Centre, Thailand Institute of Scientific and Technological Research (e-mail: sutep@tistr.or.th).

have enough knowledge about welding process, the procedure for welding in the storage tank and know all of the parameters that be used for this research.

Step 2. Determine parameters for selecting the welding process. Specify maximizing parameter as outputs of DEA and minimizing parameter as inputs of DEA, which is known as methodological connection [10].

Step 3. Determine score C_j via model 2 based on experts (academia and welder) separately

Step 4. The average scores from both of experts are the final score.

Step 5. Make a final decision based on the final score.

TABLE I
LIST OF NOTATIONS IN THE PROPOSED MODEL

Notations	Definitions
E_j	The efficiency of *j*th DMUs (*j* = 1, ..., *J*).
C_j	The efficiency score of *j*th DMUs obtained by the proposed approach (*j* = 1, ..., *J*).
β	It intended for satisfying of the objective function.
α_j	It purposed to satisfy the efficiency rating constrained of *j*th DMUs (*j* = 1, ..., *J*).
u_r	The weight of the *r*th output (*r* = 1,..., *l*).
v_i	The weight of the *i*th input (*i* = 1,..., *k*).
y_{rj}	The *r*th output of *j*th DMU (*r* = 1,..., *l*, *j* = 1, ..., *J*).
y_{rj}^1	The fuzzy *r*th most pessimistic output of *j*th DMU (*r* = 1,..., *l*, *j* = 1, ..., *J*).
y_{rj}^2	The fuzzy *r*th most likely output of *j*th DMU (*r* = 1,..., *l*, *j* = 1, ..., *J*).
y_{rj}^3	The fuzzy *r*th most optimistic output of *j*th DMU (*r* = 1,..., *l*, *j* = 1, ..., *J*).
x_{ij}	The *i*th input of *j*th DMU (*i* = 1,..., *k*, *j* = 1, ..., *J*).
x_{ij}^1	The fuzzy *i*th most pessimistic input of *j*th DMU (*i* = 1,..., *k*, *j* = 1, ..., *J*).
x_{ij}^2	The fuzzy *i*th most likely input of *j*th DMU (*i* = 1,..., *k*, *j* = 1, ..., *J*).
x_{ij}^3	The fuzzy *i*th most optimistic input of *j*th DMU (*i* = 1,..., *k*, *j* = 1, ..., *J*).

A. DEA

CCR (Charnes-Cooper-Rhodes) is the most common DEA model. For presenting this model, suppose there are *j* DMUs (DMU1, DMU2, ..., DMU$_j$), each DMU has *k* inputs x_{ij} (i = 1,..., *k*) and *l* output Y_{rj} (r = 1,..., *l*). The following model is a linier programming model to solve CCR model.

$$E_j = max \sum_{r=1}^{l} u_r y_{rj},$$

Subject to:

$$\sum_{r=1}^{l} u_r y_{rj} - \sum_{i=1}^{k} v_i x_{ij} \leq 0, \forall j,$$

$$\sum_{i=1}^{k} v_i x_{ij} = 1$$

$$v_i, u_r \geq 0, \ \forall r, i, \quad (1)$$

The notation is presented in Table I.

From model (1), the maximum efficient score can be obtained by maximising the score of outputs for a given score of input. The interval of efficiency score is 0 to 1. If the efficient score of DMU equals 1 (E_j=1), that DMU is said to be efficient; otherwise, it is said to be inefficient. DEA is a non-parametric solution, and the most significant advantage of the non-parametric solution is that the weights (v_i, u_r) are determined by the model. Furthermore, DEA does not need a decision maker to set the weight to inputs and outputs.

B. DEA and Fuzzy Credibility Constrained Programming

The traditional model of DEA, the input and output data are assumed to be a crisp number. However, in the real situation, the judgments of experts are often imprecise. Meng and Liu [11] adopt credibility measure and fuzzy chance-constrained programming and combine with DEA to solve this problem. This approach can handle uncertainty data, and it supports different types of fuzzy number and the credibility measure to optimise the system performance.

In doing so, the model (1) is given as fuzzy events. Each scenario is analysed by the triangular fuzzy number of $y_{rj} = (y_{rj}^1, y_{rj}^2, y_{rj}^3)$ and $x_{ij} = (x_{ij}^1, x_{ij}^2, x_{ij}^3)$ where respectively the pessimistic number, the most likely number, and the optimistic number. The notation of the formula below is presented in Table I and the model as follows:

$$C_j = max \ (2\beta - 1) \sum_{r=1}^{l} u_r y_{rj}^1 + 2(1-\beta) \sum_{r=1}^{l} u_r y_{rj}^2$$

Subject to:

$$(2\beta - 1) \sum_{i=1}^{k} v_i x_{ij}^3 + 2(1-\beta) \sum_{i=1}^{k} v_i x_{ij}^2 = 1,$$

$$(2\alpha_j - 1)\left(-\sum_{i=1}^{k} v_i x_{ij}^1 + \sum_{r=1}^{l} u_r y_{rj}^3\right) + 2(1-\alpha_j)\left(-\sum_{i=1}^{k} v_i x_{ij}^2 + \sum_{r=1}^{l} u_r y_{rj}^2\right) \leq 0 \ \forall j,$$

$$u_r, v_i \geq 0, \quad \forall r, i, \quad (2)$$

TABLE II
SPECIFICATION OF MATERIAL

Chemical composition of stainless steel (WT %)								
JIS	AISI	C	Si	Mn	P	S	Ni	Cr
SUS304	304	0.08 Max	1.00 Max	2.00 Max	0.045 Max	0.03 Max	8.00 – 10.50	18.00 – 20.00

Mechanical properties									
Tensile Strength, MPa		Proof Strength, (offset 0.2%), MPa		Elongation (per cent in 50mm)		Hardness (Brinell)		Endurance (Fatigue) limit, MPa	
Typical	Min.	Typical	Min.	Typical	Min.	Typical	Min.	Typical	Min.
600	515	310	205	60	40	170	-	240	-

TABLE III
DESCRIPTION OF CRITERIA FOR EVALUATING THE WELDING PROCESS

No	Parameters	Description
1	Initial preparation required	Setting welding parameter (voltage, current, welding speed, gas flow rate, wire feed, etc), electrode or filler metal preparation, cleaning the base metal.
2	Welding procedures	Preheating requirement, number of passes required, interpass temperature maintenance and post-heating requirement.
3	Post-weld cleaning	Slag removal, spatter removal and gridding the weld reinforcement.
4	Capital cost	New equipment cost.
5	Operation factor	Welder skill.
6	Welder fatigue	Welder fatigue cause smoke, electrode changing, nozzle cleaning, etc.
7	Work safety level	Prevent from electrical hazard, eye hazard, chemical hazard
8	Thickness of parts	The thickness of base metal varies between 0.03 – 25 mm. Furthermore, the mean of thickness (thick to thin) is obtained
9	Weld-ability on base metal (stainless steel)	Weld bead appearance, porosity, lack of penetration, etc.
10	Use of consumables	Electrodes, filler wires, fluxes, shielding gas, etc.
11	Flexibility of welding position	Flat, horizontal, incline, etc.
12	Repair rate	Deposition rate.
13	Easy of automation	The capability of welding for fully automatic
14	Equipment portability	Equipment portability is referred to equipment easy to move because storage tank may be repaired in site.

TABLE IV
DATA FROM ACADEMIC EXPERT OPINION

	Parameter	Welding process																	
		SMAW			GMAW			GTAW			SAW			FCAW			PAW		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Input	Use of consumable	6.0	7.0	8.0	2.0	3.0	4.0	0.0	1.0	2.0	6.0	7.0	8.0	2.0	3.0	4.0	2.0	3.0	4.0
	Initial preparation required	0.0	1.0	2.0	2.0	3.0	4.0	4.0	5.0	6.0	6.0	7.0	8.0	2.0	3.0	4.0	4.0	5.0	6.0
	Welding procedure	4.0	5.0	6.0	4.0	5.0	6.0	6.0	7.0	8.0	2.0	3.0	4.0	4.0	5.0	6.0	6.0	7.0	8.0
	Post-weld cleaning	6.0	7.0	8.0	2.0	3.0	4.0	0.0	1.0	2.0	4.0	5.0	6.0	4.0	5.0	6.0	0.0	1.0	2.0
	Capital cost	0.0	1.0	2.0	4.0	5.0	6.0	4.0	5.0	6.0	6.0	7.0	8.0	4.0	5.0	6.0	6.0	7.0	8.0
	Welder skill need	4.0	5.0	6.0	4.0	5.0	6.0	6.0	7.0	8.0	0.0	1.0	2.0	4.0	5.0	6.0	6.0	7.0	8.0
	Welder fatigue	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0	0.0	1.0	2.0	4.0	5.0	6.0	6.0	7.0	8.0
	Work safety level	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0	6.0	7.0	8.0	4.0	5.0	6.0	2.0	3.0	4.0
Output	Flexibility of welding position	9.5	10	10.5	9.5	10	10.5	9.5	10	10.5	7.5	8	8.5	9.5	10	10.5	7.5	8	8.5
	Base metal	7.5	8	8.5	7.5	8	8.5	9.5	10	10.5	7.5	8	8.5	7.5	8	8.5	8.5	9	9.5
	Thickness of parts	7.6	8.1	8.6	8.5	9.0	9.5	9.1	9.6	10.1	7.2	7.7	8.2	8.4	8.9	9.4	8.6	9.1	9.6
	Repair rate	4.0	5.0	6.0	4.0	5.0	6.0	2.0	3.0	4.0	6.0	7.0	8.0	6.0	7.0	8.0	2.0	3.0	4.0
	Equipment portability	6.0	7.0	8.0	4.0	5.0	6.0	6.0	7.0	8.0	0.0	1.0	2.0	4.0	5.0	6.0	2.0	3.0	4.0
	Easy for automation	6.0	7.0	8.0	8.0	9.0	10.0	9.0	10.0	11.0	8.0	9.0	10.0	8.0	9.0	10.0	9.0	10.0	11.0

1 – The Pessimistic number, 2 – The most likely number, 3 – The optimistic number

The main characteristic of our proposed approach is β and α_j as scalars of credibility levels. β_j intended for satisfying of the objective function, and α_j is purposed to satisfy the efficiency rating constrained of jth DMU. The proposed approach has the self-dual property that is essential in a practical situation. The credibility value is very flexible between $0 \leq (\beta = \alpha_j) \leq 1$. However, usually, the credibility levels should be higher than 0.5 [11].

III. SELECTION OF WELDING PROCESS

Stainless steel is the common material in the food and beverage industry because it has suitable characteristics material. The reasons for the widespread use of stainless steel in the food and beverage industry are corrosion resistance, durability, ease of fabrication, heat resistance, flavour and colour protection, and cleanability [12]. In this paper, JIS SUS304 is used for the base metal of the storage tank, and the specifications of the base metal are shown in Table III.

The welding processes that are commonly employed [14], [15] and used in this investigation are: Shielded metal arc welding (SMAW), gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), submerged arc welding (SAW), flux cored arc welding (FCAW), and plasma arc welding (PAW).

The parameters related to welding process selection are taken from [14], and represented in Table III. Based on the methodological connection as defined in Section II, 8 parameters will become the input of DEA, while 6 parameters will become the output of DEA. Initial preparation required welding procedures, post-weld cleaning, capital cost, operation factor, welder fatigue, work safety level, and use of consumables becomes the input of DEA. Furthermore, the weld ability on base metal, thickness of parts, flexibility of welding position, repair rate, easy of automation and equipment portability becomes the output of DEA. The input and output data from the expert (academia) are shown in Table IV. Moreover, the input and output data from the expert (welder) are shown in Table V.

TABLE V
DATA FROM WELDER EXPERT OPINION

	Parameter	Welding process																	
		SMAW			GMAW			GTAW			SAW			FCAW			PAW		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Input	Use of consumable	6.0	7.0	8.0	2.0	3.0	4.0	0.0	1.0	2.0	6.0	7.0	8.0	2.0	3.0	4.0	0.0	1.0	2.0
	Initial preparation required	0.0	1.0	2.0	4.0	5.0	6.0	2.0	3.0	4.0	6.0	7.0	8.0	4.0	5.0	6.0	2.0	3.0	4.0
	Welding procedure	2.0	3.0	4.0	4.0	5.0	6.0	6.0	7.0	8.0	0.0	1.0	2.0	4.0	5.0	6.0	6.0	7.0	8.0
	Post-weld cleaning	6.0	7.0	8.0	0.0	1.0	2.0	0.0	1.0	2.0	6.0	7.0	8.0	6.0	7.0	8.0	0.0	1.0	2.0
	Capital cost	0.0	1.0	2.0	4.0	5.0	6.0	4.0	5.0	6.0	6.0	7.0	8.0	4.0	5.0	6.0	4.0	5.0	6.0
	Welder skill need	6.0	7.0	8.0	6.0	7.0	8.0	6.0	7.0	8.0	0.0	1.0	2.0	6.0	7.0	8.0	6.0	7.0	8.0
	Welder fatigue	4.0	5.0	6.0	2.0	3.0	4.0	6.0	7.0	8.0	0.0	1.0	2.0	2.0	3.0	4.0	6.0	7.0	8.0
	Work safety level	4.0	5.0	6.0	4.0	5.0	6.0	2.0	3.0	4.0	6.0	7.0	8.0	2.0	3.0	4.0	4.0	5.0	6.0
Output	Flexibility of welding position	9.5	10	10.5	9.5	10	10.5	9.5	10	10.5	6.5	7	7.5	9.5	10	10.5	9.5	10	10.5
	Base metal	8.5	9	9.5	8.5	9	9.5	9.5	10	10.5	7.5	8	8.5	8.5	9	9.5	9.5	10	10.5
	Thickness of parts	8.1	8.6	9.1	8.9	9.4	9.9	9.1	9.6	10.1	7.4	7.9	8.4	8.9	9.4	9.9	8.9	9.4	9.9
	Repair rate	4.0	5.0	6.0	4.0	5.0	6.0	2.0	3.0	4.0	6.0	7.0	8.0	4.0	5.0	6.0	2.0	3.0	4.0
	Equipment portability	6.0	7.0	8.0	4.0	5.0	6.0	4.0	5.0	6.0	0.0	1.0	2.0	4.0	5.0	6.0	4.0	5.0	6.0
	Easy for automation	6.0	7.0	8.0	9.0	10.0	11.0	9.0	10.0	11.0	8.0	9.0	10.0	8.0	9.0	10.0	8.0	9.0	10.0

1 – The Pessimistic number, 2 – The most likely number, 3 – The optimistic number

TABLE VI
THE FINAL SCORES OBTAINED BY PROPOSED APPROACH

Welding Process	Credibility level ($\beta = \alpha_j$)									
	0.6		0.7		0.8		0.9		1	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
SMAW	0.9060	3	0.8205	3	0.7420	4	0.6700	4	0.6040	4
GMAW	0.9055	5	0.8200	5	0.7410	5	0.6690	5	0.6025	5
GTAW	0.9125	1	0.8310	1	0.7560	1	0.6865	1	0.6220	1
SAW	0.8930	6	0.7975	6	0.7120	6	0.6355	6	0.5665	6
FCAW	0.9060	3	0.8205	3	0.7425	3	0.6705	3	0.6045	3
PAW	0.9065	2	0.8215	2	0.7435	2	0.6715	2	0.6055	2

IV. RESULT AND DISCUSSION

The final score that we got from the proposed model is shown in Table VI and Fig. 2. Notice that chance constraints should be greater than 0.5 ($\beta = \alpha_j \geq 0.5$) to satisfy the confidence level [15]. For $\beta = \alpha_j$= 0.6, GTAW has the highest final score of 0.9125. PAW is the second one with the final score of 0.9065, SMAW and FCAW is the third one with the final score of 0.9060, GMAW is the fifth one with the final score of 0.955 and SAW is the sixth one with the final score of 0.8930. GTAW is the best welding process because GTAW is very good in terms of the use of consumable, post-weld cleaning, the flexibility of welding position, weld-ability on the base metal, easy for automation, and capable weld in the many thicknesses of parts.

The discrimination power by using $\beta = \alpha_j$= 0.6 is still low as we can see in the score of SMAW and FCAW (0.9060). SMAW and FCAW have the same level of final score, and it is difficult to decide which welding process is better among them. In this case, increasing value of credibility level should be applied for increase the discrimination power.

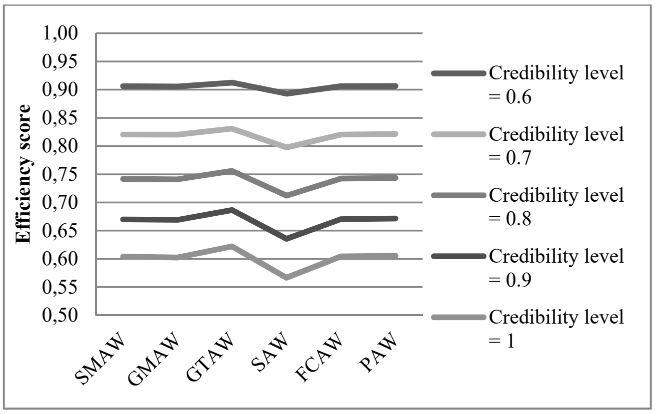

Fig. 2 Final score with different credibility levels

By using $\beta = \alpha_j$ = 0.7 as creditability level, GTAW has the highest final score of 0.8310. PAW is the second one with the final score of 0.8215, SMAW and FCAW still have the same final score of 0.8205, GMAW is the fifth one with 0.8200 and SAW is the sixth one with 0.7975. As we can see, by increasing credibility level to $\beta = \alpha_j = 0.7$, the discrimination power is still not enough to decide which welding process is better among SMAW and FCAW.

By using $\beta = \alpha_j = 0.8$ as creditability level, GTAW has the highest final score of 0.7560. PAW is the second one with the final score of 0.7434, FCAW is the third one with 0.7435, SMAW is the fourth one with 0.7420, GMAW is the fifth one with 0.7410 and SAW is the sixth one with 0.7120. As we can see, the credibility level plays an important role in distinguishing score between SMAW and FCAW.

As it was expected, the discrimination power will improve if we increase the credibility level, as we can see in the final score of each welding process (DMUs) that there is no welding process that has the same final score. Furthermore, the final score of the welding process (DMUs) decreases by increasing credibility level [15], as can be seen in Fig. 2.

V. Conclusion

Welding process selection usually depends on experiences or general application in the similar company. However, this approach mostly ignores many criteria that can affect the most appropriate welding process. In this paper, integrated DEA and fuzzy credibility constrained programming approach was used for select welding process for the storage tank by combination academic expert opinion and welder expert opinion. Based on the results of the proposed approach, GTAW is the most appropriate welding process, while SAW is not appropriate for the storage tank. The most considerable advantage of the proposed approach is that it does not require any predetermined weights, and it has been found that the approach has enough power to discriminate the welding process. Furthermore, this approach is capable of helping designer, supplier, and manufacturer to decide storage tank. In the future, this approach can be used for selection in another field.

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