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
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.

### 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 \( x_{ij} \) (\( i = 1, \ldots, k \)) and \( l \) output \( y_{rj} \) (\( r = 1, \ldots, l \)). The following model is a linier programming model to solve CCR model.

\[
E_j = \max \sum_{r=1}^{l} u_r y_{rj} - \sum_{i=1}^{k} v_i x_{ij} \leq 0, \forall j.
\]

Subject to:

\[
\sum_{i=1}^{k} v_i x_{ij} = 1, \quad v_r, u_r \geq 0, \forall r, i.
\]

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 \((v_i, u_i)\) 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:

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

Subject to:

\[
(2\beta - 1) \sum_{r=1}^{l} v_r x_{ij}^3 + 2(1 - \beta) \sum_{r=1}^{l} v_r x_{ij}^2 = 1,
\]

\[
(2\alpha - 1)(-\sum_{r=1}^{l} v_r x_{ij}^3 + \sum_{r=1}^{l} v_r y_{rj}^3) + 2(1 - \alpha)(-\sum_{r=1}^{l} v_r x_{ij}^2 + \sum_{r=1}^{l} v_r y_{rj}^2) \leq 0, \forall j,
\]

\[
u_r, v_i \geq 0, \forall r, i.
\]

### Table II

**SPECIFICATION OF MATERIAL**

<table>
<thead>
<tr>
<th>Chemical composition of stainless steel (WT %)</th>
<th>JIS</th>
<th>AISI</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUS304</td>
<td>304</td>
<td>0.08 Max</td>
<td>1.00 Max</td>
<td>2.00 Max</td>
<td>0.045 Max</td>
<td>0.03 Max</td>
<td>8.00 – 10.50</td>
<td>18.00 – 20.00</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>JIS</th>
<th>AISI</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, MPa (offset 0.2%)</td>
<td>Typical</td>
<td>Min.</td>
<td>Typical</td>
<td>Min.</td>
<td>Typical</td>
<td>Min.</td>
<td>Typical</td>
<td>Min.</td>
<td>Typical</td>
</tr>
<tr>
<td>600</td>
<td>515</td>
<td>310</td>
<td>205</td>
<td>60</td>
<td>40</td>
<td>170</td>
<td>-</td>
<td>240</td>
<td>-</td>
</tr>
</tbody>
</table>
The main characteristic of our proposed approach is $\beta$ and $\alpha_j$ as scalars of credibility levels. $\beta_j$ intended for satisfying of the objective function, and $\alpha_j$ is purposed to satisfy the efficiency rating constrained of $j$th 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 cleanliness [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
weldability 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**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SMAW</th>
<th>GMAW</th>
<th>GTAW</th>
<th>SAW</th>
<th>FCAW</th>
<th>PAW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Welding process</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use of consumable</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Initial preparation required</td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Welding procedure</td>
<td>2.0</td>
<td>3.0</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Post-weld cleaning</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Capital cost</td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Welder skill need</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Welder fatigue</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Work safety level</td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>8.0</td>
<td>9.0</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>Base metal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thickness of parts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Repair rate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Post-weld cleaning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Capital cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Welder skill need</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Welder fatigue</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Work safety level</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Flexibility of welding position</strong></td>
<td>9.5</td>
<td>10.0</td>
<td>10.5</td>
<td>10.0</td>
<td>10.5</td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Base metal</strong></td>
<td>8.5</td>
<td>9.5</td>
<td>9.5</td>
<td>10.5</td>
<td>10.5</td>
<td>9.5</td>
</tr>
<tr>
<td><strong>Thickness of parts</strong></td>
<td>8.1</td>
<td>8.6</td>
<td>9.1</td>
<td>9.4</td>
<td>9.9</td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Repair rate</strong></td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
</tr>
<tr>
<td><strong>Post-weld cleaning</strong></td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>Capital cost</strong></td>
<td>0.0</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
<td>8.0</td>
</tr>
<tr>
<td><strong>Welder skill need</strong></td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>Welder fatigue</strong></td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>8.0</td>
<td>9.0</td>
<td>10.0</td>
</tr>
<tr>
<td><strong>Work safety level</strong></td>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>8.0</td>
<td>9.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>

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

### TABLE VI
**THE FINAL SCORES OBTAINED BY PROPOSED APPROACH**

<table>
<thead>
<tr>
<th>Welding Process</th>
<th>0.6 Score</th>
<th>Ranking</th>
<th>0.7 Score</th>
<th>Ranking</th>
<th>0.8 Score</th>
<th>Ranking</th>
<th>0.9 Score</th>
<th>Ranking</th>
<th>1 Score</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>0.9060</td>
<td>3</td>
<td>0.8205</td>
<td>3</td>
<td>0.7420</td>
<td>4</td>
<td>0.6700</td>
<td>4</td>
<td>0.6040</td>
<td>4</td>
</tr>
<tr>
<td>GMAW</td>
<td>0.9055</td>
<td>5</td>
<td>0.8200</td>
<td>5</td>
<td>0.7410</td>
<td>5</td>
<td>0.6690</td>
<td>5</td>
<td>0.6025</td>
<td>5</td>
</tr>
<tr>
<td>GTAW</td>
<td>0.9125</td>
<td>1</td>
<td>0.8310</td>
<td>1</td>
<td>0.7560</td>
<td>1</td>
<td>0.6865</td>
<td>1</td>
<td>0.6220</td>
<td>1</td>
</tr>
<tr>
<td>SAW</td>
<td>0.8930</td>
<td>6</td>
<td>0.7975</td>
<td>6</td>
<td>0.7120</td>
<td>6</td>
<td>0.6355</td>
<td>6</td>
<td>0.5665</td>
<td>6</td>
</tr>
<tr>
<td>FCAW</td>
<td>0.9060</td>
<td>3</td>
<td>0.8205</td>
<td>3</td>
<td>0.7425</td>
<td>3</td>
<td>0.6705</td>
<td>3</td>
<td>0.6045</td>
<td>3</td>
</tr>
<tr>
<td>PAW</td>
<td>0.9065</td>
<td>2</td>
<td>0.8215</td>
<td>2</td>
<td>0.7435</td>
<td>2</td>
<td>0.6715</td>
<td>2</td>
<td>0.6055</td>
<td>2</td>
</tr>
</tbody>
</table>

**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 ($\beta = \alpha / \alpha$ ≥ 0.5) to satisfy the confidence level [15]. For $\beta = \alpha / \alpha = 0.6$, 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 $\beta = \alpha / \alpha = 0.6$ 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.

By using $\beta = \alpha / \alpha = 0.7$ as credibility 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 credibility 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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REFERENCES