

Selection of Welding Process for Repairing Shredder Hammer by Integrated Data Envelopment Analysis (DEA) and P-robust Technique

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Abstract. The Selection of the welding process is one of the most significant decision-making problems, and it involves a wide range of information following the type of product. Hence, the automation of knowledge through a knowledge-based system will significantly enhance the decision-making process and simplify for identifying the most appropriate welding processes. The aims of this paper for explicates a knowledge-based system developed for recognising the most suitable welding processes for repairing shredder hammer by using data envelopment analysis (DEA) and p-robust technique. The proposed approach is used for ranking six welding processes which are commonly used, namely shielded metal arc welding (SMAW), flux cored arc welding (FCAW), submerged arc welding (SAW), oxyacetylene gas welding (OAW), gas tungsten arc welding (GTAW), and gas metal arc welding (GMAW). In order to determine the best welding process among competitive welding processes for repairing of shredder hammer, ten parameters are used, namely the availability of consumable, welding process type (manual and automatic), flexibility of welding position, weld-ability on base metal, initial preparation required, welding procedures, post-weld cleaning, capital cost, operating factor, and deposition rate. Furthermore, the sensitivity analysis of regret value (p) is investigated in three cases proposed.

1 Introduction

Thailand is the fourth-largest sugar producer and the second largest sugar exporter in the world [1]. In the sugar industry, the shredder hammer is used to shred sugarcane billets and pulverise sugarcane billet into a fibrous mat [2]. Generally, the shredder machine has 90-250 of shredder hammers that rotate on a rotor at around 1000 RPM, and it can process sugarcane at 7,000-15,000 tonnes/day [3]. The shredder machine is essential for the sugar industry, but the cost that involved in the operation of shredder machine is expensive because the service life of shredder hammer is relatively short.

The shredder hammer needs to be checked for balance to prevent something that can damage the machine. The vibration monitoring system is the system for check balance of shredder hammer, if the shredder hammer broken during operation, this machine has to stop. The shredder hammer consists of carbon steel as the base metal, and hard-facing is stacked on the base metal using welding process. The hard-facing is a form surfacing that is applied to reduce wear, abrasion, impact, erosion, galling, and cavitation [4].

Typically, the selection of welding process depends on experiences or follows the general application in the similar companies. However, this strategy often ignores many criteria or parameters that can be affecting the

suitable welding process selection. Therefore, knowledge management is a critical element for a better decision. The knowledge from an expert will significantly benefit if using the advanced method for analysis it.

A little of research has been done about welding process selection, but none of them deals with selecting welding process use hard-facing for repairing shredder hammer. Darwish [5] studied about welding process selection used confidence level for each qualifier. Ravisankar [6] used analytic hierarchic process (AHP) as a method for welding process selection of high strength aluminium alloys to fabricate butt joint. Jafarin and Vahdat [7] Studied about the selection of welding process selection used AHP at high-pressure vessel manufacturing. Balasubramanian [8] used AHP for welding process selection of hard-facing on carbon steel. As is seen, The AHP method is a popular method for welding process selection, but the issue of AHP is the weight of criteria by a judgment of decision maker. It means if the judgment is changed, the final ranking will change as well. So the limitation of AHP depends on the decision maker's judgment.

This paper aims to propose welding process selection for repairing shredder hammer by integrated data envelopment analysis (DEA) and p-robust technique to support a decision of welder, manufacturing, and

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Table 1. List of notation in the proposed model.

Notations	Definitions
u_r^a	The weight of the r th output according to the a th expert's opinions ($r = 1, \dots, m, a = 1, \dots, A$).
u_r	The weight of the r th output ($r = 1, \dots, m$).
v_i^a	The weight of the i th input according to the a th expert's opinions ($i = 1, \dots, n, a = 1, \dots, A$).
x_{ih}^a	The i th input of DMU _{h} according to the a th expert's opinions ($i = 1, \dots, n, o = 1, \dots, n, s = 1, \dots, S$).
y_{rh}^a	The r th output of DMU _{h} according to the a th expert's opinions ($r = 1, \dots, m, h = 1, \dots, H, a = 1, \dots, A$).
P	The relative regret value to control relative regret.
w_a	The weight of a th experts opinion ($a = 1, \dots, A$).
E_{ah}	The efficiency of h th DMU with the input and output data obtained according to the a th expert's opinions
E_{ah}^*	The ideal efficiency score from a th expert view ($h = 1, \dots, H, a = 1, \dots, A$).
E_h	The efficiency of h th DMU ($h = 1, \dots, H$)

supplier. Data envelopment analysis (DEA) was introduced by Charnes [9] to obtain the efficiency score of decision-making units (DMUs) by comparing how creatively this DMU transform inputs into outputs. Moreover, DEA does not need a decision maker to set the weight to the inputs and the outputs. Due to in this paper uses group decision-making and the information of experts is valuable, integrated DEA and p-robust are used to consider all the opinion of expert without losing any information.

2 Methodology: integrated DEA and p-robust technique

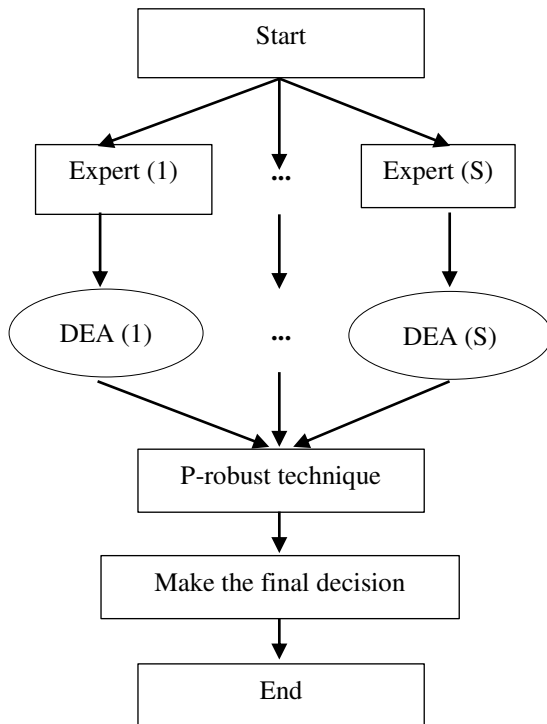


Fig. 1. The proposed of methodology.

2.1 Determination of the experts

An expert is someone that has extra weight because of their qualifications, experience and other signal authority [10]. Due to decision-making is involving a wide range of information, five opinion of the expert from academia (theory) and five opinion of the expert from welder

(practice) will be used. Furthermore, the experts should have enough knowledge about welding process, procedures for repairing shredder hammer and all of the parameters that be used for welding process selection in this research.

Due to use many experts opinion for making decisions, this is very potential to happen dissent of experts. Although expert opinions differ from each other, the final decision must be robust in the uncertain situation. Therefore, data envelopment analysis (DEA) and p-robust technique are applied to deal with this problem.

2.2 Data envelopment analysis (DEA)

CCR (Charnes-Cooper-Rhodes) model is the most common DEA models. Suppose there are h DMUs, each of DMUs have n inputs x_{ih} ($i = 1, \dots, n$) and m output Y_{rh} ($r = 1, \dots, m$). The efficiency of DMU is the division of the weighted sum of outputs (virtual output) by the weighted sum inputs (virtual input). Supposed DMU has efficiency score equals 1 ($E_h = 1$), it means the DMU is efficient; otherwise, it is inefficient. The following model is referred to as input-oriented DEA model:

$$\begin{aligned}
 E_{ah} &= \max \sum_{r=1}^m u_r^a y_{rh}^a \\
 \text{Subject to:} \\
 \sum_{r=1}^m u_r^a y_{rh}^a - \sum_{i=1}^n v_i^a x_{ih}^a &\leq 0, \quad \forall h \\
 \sum_{i=1}^n v_i^a x_{ih}^a &= 1 \\
 v_i^a, u_r^a &\geq 0 \quad \forall r, i, a
 \end{aligned} \tag{1}$$

The notations are representing in **Table 1**.

DEA can be used as a tool for making decision-making process because of some advantage of this method as mention in the previous research [11, 12]. The main problem with this method when we use group decision making is model (1) only to achieve the ideal efficiency scores based on each expert's opinion separately. If we want to get the average score, it needs to run the model (1) several times and then get aggregate the final score. The aggregate result should satisfy against the overlapping opinion of the expert, which is known as "ambiguity". In this situation, it is necessary to

Table 2. Specifications of base metal (shredder hammer).

Chemical composition medium carbon steel (WT %)							Mechanical properties		
Standard	Grade	C	Si	Mn	P	S	Thickness	Tensile Strength	Hardness, Brinell
JIS G4051	S45C	0.42-0.48	0.15-0.35	0.60-0.90	0.030 less	0.035 less	45 – 150 mm	569 Mpa (standard), 686 Mpa (Quenching, Tempering)	160 – 220 HB

Table 3. Description of criteria for evaluating the welding process.

No	Criteria	Description
1	weld-ability on base metal	Weld bead appearance, porosity, lack of penetration, etc.
2	Initial preparation required	Setting welding parameter (voltage, current, welding speed, gas flow rate, and wire feed, etc.), electrode or filler metal preparation, cleaning the base metal.
3	Welding procedures	Preheating requirement, number of passes required, interpass temperature maintenance and post-heating requirement.
4	Post-weld cleaning	Slag removal, spatter removal and gridding the weld reinforcement.
5	Capital cost	New equipment cost.
6	Operation factor	Welder skill's need.
7	Availability of consumables	Electrodes, filler wires, fluxes, shielding gas, etc.
8	Welding process type	The capability welding for manual (case 1) or fully automatic (case 2 and 3).
9	Flexibility of welding position	Flat, horizontal and incline.
10	Deposition rate	Penetration in crack, and repair rate (pieces/hours).

have the p-robust technique to overcome these problems. The integrated DEA and p-robust technique can analyse different opinion of experts all at once and also satisfy the ambiguity.

2.3 DEA and p-robust technique

Integrated DEA and p-robust technique are introduced by Fasanghari [13]. In this paper, the efficiency score of DMU_h for each expert is an independent scenario. Suppose that we have $a = 1, 2, \dots, A$ set of scenarios, and E_{ah}^* is the ideal efficiency of h th DMUs in a th scenarios associated with a th expert. In order to resolve ambiguity in the group decision making, the efficiency score will be controlled by a relative regret. The relative regret is a relative difference between the aggregated solution and ideal solution. The model of integrated DEA and p-robust technique as follows:

$$E_h = \max \sum_{a=1}^A w_a \sum_{r=1}^m u_r y_{rh}^a$$

Subject to:

$$\sum_{i=1}^n v_i^a x_{ih}^a = 1, \quad \forall a,$$

$$\sum_{r=1}^m u_r y_{rh}^a - \sum_{i=1}^n v_i^a x_{ih}^a \leq 0, \quad \forall h, a,$$

$$\sum_{r=1}^m u_r y_{rh} \geq (1 - p) E_{ah}^*, \quad \forall a,$$

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

The model (2) is a kind of stochastic programming that has the objective function for maximising the

expected efficiency of o th DMU. Where w_a is the weight of a th opinion of experts and $\sum_{r=1}^m u_r y_{rh} \geq (1 - p) E_{ah}^*, \forall a$ donates constraints associated with all opinion of experts. The constraints do not allow a value more than $(p * 100)$ % of the ideal efficiency score for the final efficiency score. The value of p is flexible for control the relative regret. The constraint becomes inactive if $p = \infty$ and the score become infeasible if p is very small. The information of expert's opinion is valuable, this method very suitable to use analysing all the opinion of expert without losing any information. Therefore, this method can control the relative regret to increase accuracy and satisfaction of the group decision making.



Fig. 2. The shredder hammer.

Table 4. Description of the 3 cases.

Case	Description	Parameters	Welding process
1	The investor (SME) has limited capital cost, and also has the limitation of welder's skill. Welding process by using manual welding.	Initial preparation required, Welding procedures, Post-weld cleaning, Capital cost, Operator factor, Weld-ability of base metal, Easy for manual, Availability of consumable, Flexibility of welding position and Repair rate.	SMAW OAW GTAW
2	The investor (SME) wants to change from manual to automatic welding. They have limited capital cost and have the limitation of welder's skill.	Initial preparation required, Welding procedures, Post-weld cleaning, Capital cost, Operator factor, Weld-ability of base metal, Easy for automation, Availability of consumable, Flexibility of welding position and Repair rate.	FCAW SAW GTAW GMAW
3	The investor (SME) wants to change from manual to automatic welding. They have limited capital cost, and there is no limitation for welder's skill.	Initial preparation required, Welding procedures, Post-weld cleaning, Capital cost, Weld-ability of base metal, Easy for automation, Availability of consumable, Flexibility of welding position and Repair rate.	FCAW SAW GTAW GMAW

3 Selection of welding process

The application that was investigated is the shredder hammer as given in Figure 2. The base metal that is used for the shredder hammer is medium-low carbon steel, and the specifications are presented in table 2. As mentioned before, hard-facing using welding process is used for repairing the shredder hammer. During a discussion with the experts and consider some critical point in the welding process selection for repairing shredder hammer, this paper proposes six welding

process be investigated. Namely shielded metal arc welding (SMAW), flux cored arc welding (FCAW), submerged arc welding (SAW), oxyacetylene gas welding (OAW), gas tungsten arc welding (GTAW), and gas metal arc welding (GMAW). Some critical criteria that are considered in the welding process selection for repairing shredder hammer are taken from Ferjutz and Davis [15], as given in Table 3.

Due to the primary goal of DEA is to determine the efficiency of decision-making units (DMUs), while multiple criteria decision making (MCDM) is used for ranking or selecting from a set of the alternative that has conflicting criteria. The "methodological connection" is necessary used for apply DEA as MCDM. The methodological connection between MCDM and DEA is to specify maximising criteria as outputs of DEA and minimising criteria as inputs of DEA [14]. The criteria that bigger value is better called maximising and the criteria whose lower is better called minimising.

Based on methodological connection, the inputs of DEA are initial preparation required, welding procedures, post-weld cleaning, capital cost, and operation factor. Furthermore, the outputs of DEA are weld-ability on the base metal, availability of consumables, easy of manual or automation for welding process, the flexibility of welding position, and deposition rate.

4 Result and discussion

Due to the capital cost and welder skill are criteria that be affected by the investor. So these situations can change in several conditions. Therefore, this paper is done in the three cases, shown in Table 4. First of all, we solve model (1) to get the ideal efficiency score (E_{ah}^*) from 10 experts without considering p-robust constraint to control relative regret. The results are shown in Table 5 for three cases. Based on the outcome, many welding processes get the efficiency score of 1 according to the opinion of 10 experts. Due to the score of efficiency for three cases have many scores of 1, it means the

Table 5. Ideal efficiency according 10 experts and 3 cases.

Case 1										
Welding process	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10
SMAW	1	1	1	1	1	1	1	1	1	1
OAW	1	1	1	1	1	1	1	1	1	1
GTAW	1	1	1	1	1	1	0.994	1	1	1
Case 2										
Welding process	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10
FCAW	1	1	1	1	1	1	1	1	1	1
SAW	1	1	1	1	1	1	1	1	1	1
GTAW	1	1	1	1	1	1	1	1	1	1
GMAW	1	0.998	0.996	1	0.994	0.998	1	0.998	1	0.994
Case 3										
Welding process	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10
FCAW	1	1	1	0.996	1	1	1	1	1	1
SAW	1	0.929	1	0.984	1	1	1	1	1	1
GTAW	1	1	1	1	1	1	1	1	1	1
GMAW	1	0.998	0.996	1	0.994	1	1	0.998	1	0.994

discrimination power of basic DEA is not satisfying and impossible to decide about the best welding process for each case. Therefore, the final of efficiency score should be only one score and robust. These mean that the final efficiency based on ten experts should not change to various inputs and outputs of DEA in the uncertain situation.

Table 6. The efficiency scores are obtained by proposed approach.

Case 1		Case 2		Case 3	
Welding process	Score	Welding process	Score	Welding process	Score
SMAW	0.996	FCAW	0.994	FCAW	0.994
OAW	0.995	SAW	0.996	SAW	0.879
GTAW	0.976	GTAW	0.969	GTAW	0.978
		GMAW	0.990	GMAW	0.992

After solving model (1), we need to solve model (2) to get final efficiency score for each case with same inputs and output like when solving a model (1). Let the regret value (p) for case 1 equal to 0.15, regret value (p) for case 2 equal to 0.19, and regret value (p) for case 3 equal to 0.22. Let the weight of experts' opinion have the same value ($w_1, w_2, \dots, w_{10} = 0.1$), and the result is showed in Table 6 or Figure 3. As it can be seen from Table 6 or Figure 3, case 1 denotes SMAW has the highest score with the final efficiency score of 0.996. OAW is the second one with the final efficiency score of 0.995 and GTAW is the third one with the final efficiency score of 0.976. In case 2, SAW has the highest score with the final efficiency score of 0.996. FCAW is the second one with the final efficiency score of 0.994, the third one is GMAW with the final efficiency score of 0.990, and the last one is GTAW with the final efficiency score of 0.969. In case 3, FCAW has the highest score with the final efficiency score of 0.994. GMAW is the second one with the final efficiency score of 0.992, GTAW is the third one with the final efficiency score of 0.978, and the last one is SAW with the final score efficiency score of 0.879.

In case 1, the highest final efficiency score belongs to SMAW and OAW (see Table 6 or Figure 3) because

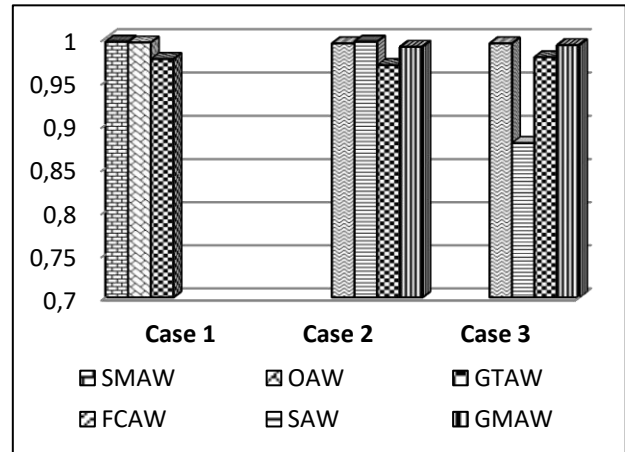


Fig. 3. The graphical final efficiency score in 3 cases.

they are a success to satisfy capital cost and welder skill needs with the lower value than GTAW. For GTAW has the lowest final efficiency score because of GTAW also has the lower value of deposition rate than SMAW and OAW. So when capital cost and welder skill needs are limited by using manual welding, the value of SMAW and OAW will rise rapidly.

In case 2, the highest final efficiency score belongs to SAW (see Table 6 or Figure 3) because of SAW has the lowest value of welder skill need than another welding process. However, the final efficiency score of SAW and FCAW is not too much different because the capital cost value of FCAW is better than SAW.

In case 3, when the parameter like welder skill needs is not limited, the final efficiency of SAW decrease rapidly because of the superiority of SAW is only in the welder skill needs. Moreover, the final efficiency score of SAW lower than GTAW because of GTAW better than SAW in term of the flexibility of welding position (especially in horizontal position and incline position).

As can see from three cases above, the suitable welding process can change because of the different parameter that uses. The three problems shown are a common problem in manufacturing especially for repairing the shredder hammer.

Table 7. The result of sensitivity analysis for different regret value (p).

Case 1										
Welding process	regret value (p)									
	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20
SMAW	0.981	0.984	0.990	0.993	0.996	0.997	0.997	0.997	0.997	0.997
OAW	0.988	0.992	0.993	0.994	0.995	0.996	0.996	0.996	0.996	0.996
GTAW	Inf.	Inf.	Inf.	Inf.	0.976	0.982	0.982	0.986	0.986	0.986
Case 2										
Welding process	regret value (p)									
	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25
FCAW	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994
SAW	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996	0.996
GTAW	Inf.	Inf.	Inf.	0.969	0.978	0.978	0.978	0.978	0.978	0.978
GMAW	0.981	0.984	0.987	0.990	0.992	0.992	0.992	0.992	0.992	0.992
Case 3										
Welding process	regret value (p)									
	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25	0.26	0.27
FCAW	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994
SAW	Inf.	Inf.	Inf.	Inf.	0.879	0.882	0.888	0.891	0.897	0.900
GTAW	Inf.	0.969	0.978	0.978	0.978	0.978	0.978	0.978	0.978	0.978
GMAW	0.988	0.991	0.992	0.992	0.992	0.992	0.992	0.992	0.992	0.992

5 Sensitivity analyses

Now, this section study effect of relative regret value on the final efficiency score. As mentioned before, “the regret value and p-robust constraint” control the relative difference between final efficiency score (E_n) and the ideal solution from a experts (E_{ah}^*) or known as “relative regret”. Table 7 shows the sensitivity analysis for three cases that we proposed. As we can see it the Table 7, the final efficiency score gets infeasible if regret value (p) < 0.15 for case 1, (p) < 0.19 for case 2, and (p) < 0.22 for case 3. Whereas, the lowest acceptable of regret value is (i) ≥ 0.15 for case 1, (p) ≥ 0.19 for case 2, and (p) ≥ 0.22 for case 3.

The p-robust constraint $\{\sum_{r=1}^m u_r y_{rh} \geq (1 - p)E_{ah}^*, \forall a\}$ does not allow the final efficiency score more than ($p \times 100$) % of ideal efficiency. Due to the lowest acceptable of regret value of case 1 is (p) ≥ 0.15 , it means “the p-robust constraints and regrets value” able to handle up to 15% of relative regret. Also, case 2 can handle up to 19% of relative regret and case 3 can handle up to 22% of relative regret. However, notice that a large regret value (p) has a side effect of the inconsistency of experts’ opinion in the results.

6 Conclusions

Welding process selection usually depends on experiences or general application in similar companies. However, this approach mostly ignores many criteria that can be affecting the suitable welding process selection. In this paper, ten opinions of expert will be analysed by integrated data envelopment analysis (DEA) and p-robust technique to select welding process for repairing shredder hammer. The most advantage of the proposed approach is that regret value (p) and p-robust constraints that control the relative regret base on ten opinions of experts. The result should not change to various inputs and outputs of DEA in the uncertain situation. The main contribution of this study can support the decision of welder, manufacturing and supplier base on three cases proposed concerning limitation of capital cost and welder skill. For future research, the approach can be used for welding process selection in another area like a storage tank. Furthermore, because of the discrimination power of this method can be said still low, TOPSIS method can be used and combine with our proposed approach to get more discrimination power.

References

1. OCSB (Office of the Cane and Sugar Board) Thailand sugar production report, Retrieved on January 9, 2004 from <http://www.ocsb.go.th> (2017).
2. L. Yin, D. Authurs, S. Wright, L. Santarossa, Fracture and wear in shredder tungsten carbide tips in the sugar cane shredding process (2014).
3. L. G. Santarossa, S. I. Anderson, Int. Sugar J. **28**, 280-289 (2014).

4. K. Ferjutz, J.R. Davis, ASM handbook: volume 6: welding, brazing, and soldering, ASM International, Materials Park, OH (1993).
5. S. Darwish, A. Al Tamimi, S. Al-Habdan, A knowledge base for metal welding process selection, International Journal of Machine Tools and Manufacture **37(7)**, 1007-1023 (1997).
6. V. Ravisankar, V. Balasubramanian, C. Muralidharan, Selection of welding process to fabricate butt joints of high strength aluminium alloys using analytic hierarchic process, Materials & design **27(5)**, 373-380 (2006).
7. M. Jafarian, S.E. Vahdat, A fuzzy multi-attribute approach to select the welding process at high pressure vessel manufacturing, Journal of Manufacturing Processes **14(3)**, 250-256 (2012).
8. V. Balasubramanian, R. Varahamoorthy, C. Ramachandran, C. Muralidharan, Selection of welding process for hardfacing on carbon steels based on quantitative and qualitative factors, The International Journal of Advanced Manufacturing Technology **40(9-10)**, 887-897 (2009).
9. A. Charnes, W.W. Cooper, E. Rhodes, Measuring the efficiency of decision making units, European journal of operational research **2(6)**, 429-444 (1978).
10. T. Farrington-Darby, J.R. Wilson, The nature of expertise: A review, Applied ergonomics **37(1)**, 17-32 (2006).
11. A. Shabani, R.F. Saen, S.M.R. Torabipour, A new benchmarking approach in Cold Chain, Applied Mathematical Modelling **36(1)**, 212-224 (2012).
12. R. Lohtia, N. Donthu, I. Yaveroglu, Evaluating the efficiency of Internet banner advertisements, Journal of Business Research **60(4)**, 365-370 (2007).
13. M. Fasanghari, M.S. Amalnick, R.T. Anvari, J. Razmi, A novel credibility-based group decision making method for Enterprise Architecture scenario analysis using Data Envelopment Analysis, Applied Soft Computing **32**, 347-368 (2015).
14. J. Sarkis, A comparative analysis of DEA as a discrete alternative multiple criteria decision tool, European journal of operational research **123(3)**, 543-557 (2000).
15. K. Ferjutz, J.R. Davis, ASM handbook: volume 6: welding, brazing, and soldering, ASM International, Materials Park, OH (1993).