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Development of Costing Model for Butt Joint Process using Mild Steel with Robotic GMAW: A Malaysian Context

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ABSTRACT

This paper is about the development of a costing model aimed at determining the pricing strategy for a component manufactured through the welding process. Cost estimation in welding processes is crucial for industries due to various influencing factors like welding time, length, and joint type. Calculating welding costs involves considering various methods and factors. One method compares theoretical filling metal amounts with on-site welding material consumption, factoring in the welding difficulty coefficient. Additionally, Time Driven Activity Based Costing (TDABC) is one of the costing methods used to analyze input data and estimate welding costs accurately and efficiently, specifically in the GMAW process. Moreover, a comprehensive costing model developed by ESAB incorporates variables such as labor costs, electrode expenses, shielding gas usage, and overall power costs. In this paper, the selected welding design configuration is a double V-groove butt joint using mild steel, ER70S-3 as filler wire, and S235 mild steel as substrate. Based on the chosen design, the welding cost model will be developed to analyze the cost of the butt joint welding process based on time-

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driven activity-based costing (TDABC) method. The outcome of this study is the total cost to manufacture the Double V-Groove butt joint project in terms of materials, labor, and equipment. Furthermore, subsequent efforts will be directed toward systematically enhancing the welding cost model to include a broader spectrum of materials, various part dimensions, and differing deposition rates.

Keywords: *Welding; Gas Metal Arc Welding; Double V-Groove; Mild Steel; Costing Model Analysis*

Introduction

The introduction of welding processes dates to the early stages of the last century, evolving into various techniques based on different energy sources [1]-[2]. These processes are crucial in fabrication and construction industries, with welding equipment, power sources, and consumables playing vital roles in their implementation [3]. Modeling and simulation have become essential tools in predicting welding outcomes, including geometry, microstructure, and mechanical performance, although the complexity of welding processes requires more data and computational time compared to other industrial applications [4]. Understanding the production of residual stress and distortion during welding involves the concept of inherent strain, which is crucial in analyzing and reproducing residual stresses through elastic analysis [5]. Overall, the history, development, and modern challenges in welding technology highlight its significance in various engineering fields, making it a fundamental aspect of mechanical engineering and related disciplines.

The welding process is a sophisticated metallurgical joining process characterized by the deliberate application of heat, pressure, or a combination thereof to affect the localized melting, coalescence, and subsequent solidification of materials at the joint [6]. This method exhibits specific traits that render it appropriate for a range of applications. Unlike conventional welding, which permits less precision of workpieces, this process enables the cost-effective joining of diverse metal types and thicknesses [7]. As an illustration, Gas Metal Arc Welding (GMAW) excels in accommodating variations in workpiece fit-up, making it a versatile choice for various welding scenarios [8]. Due to its cost-effectiveness and wide range of applications, this technique is one of the common methods in the joining process [9].

A previous study using a Metal Inert Gas (MIG) or GMAW welding process discovered that increasing the welding current increased penetration while reducing the voltage decreased penetration. Decreasing the arc travel rate increased penetration until it reached a minimum value based on arc power [11]. The research examined the relationship between GMAW process factors and bead geometry, concluding that arc current has the most significant impact. The study found that electrode polarity, diameter and extension, arc voltage, welding current, power source setting, travel speed, and flux all affect the weld deposit area [10].

Asea Brown Boveri (ABB) has led the way in robotic programming by creating software packages that empower engineers by simplifying the task of robotic programming. The creation of RobotStudio has granted individuals with little to no programming experience the ability to create simulations in minutes. This software has drastically shortened the time necessary to program robotic workstations. This has come to a precipice with the addition of user-programmed add-ins and smart components [12].

In the process of resource selection and product development, the utilization of a cost model stands as a crucial instrument. Particularly in early design evaluations, the necessity for a dependable and precise cost estimation tool becomes apparent. To assess manufacturing expenses associated with MIG welded joints, a method for cost estimation is employed [13]-[14]. The ESAB welding cost methodology delved into the estimation of costs of steel weldments produced through the four predominant arc welding techniques currently prevalent: Shielded Metal-Arc Welding (SMAW), GMAW, Flux-Core Arc Welding (FCAW), and Submerged Arc Welding (SAW). An in-depth cost model for the butt joint welding process chain, which encompasses the primary production processes, is depicted using a time-based activity-based costing method [15].

Moreover, the research delineates discrepancies in the costs associated with the deposition of weld metal, contingent upon the selection of the filler material and the employed welding methodology. These cost variations are attributable to an array of determinants, including the labor and overhead charges of the practitioner, the deposition rate and efficiency of the filler material, operational parameters, and the costs incurred from material and energy consumption. This investigation proposes a cost estimation model, grounded in the principles applicable to various welding techniques, notably the GMAW process. This model adheres to the costing framework suggested by ESAB for evaluating welding operations.

Upon thorough examination of the literature referenced in this investigation, it becomes clear that research on cost analysis models for additively manufactured components, especially within the oil and gas industry for items such as pipe flanges, is markedly insufficient. In light of this deficiency, the current study seeks to devise and assess a cost estimation model specifically for the fabrication of butt joints with double V-grooves utilizing the Robotic GMAW technique. This effort is directed toward establishing the preliminary market valuation for this nascent, potentially transformative manufacturing methodology.

Methodology

The analytical methodology is employed for the systematization of welding duration, electrode consumption, and shielding gas consumptions, contingent upon various preparatory and welding attributes. Within the ambit of cost analysis, each parameter is associated with a distinct formula, facilitating the conversion of material price or quantity inputs into requisite outcomes, such as the aggregate cost of the product in RM. According to ESAB, the primary constituents calculated to ascertain the expense of a singular welding product encompass the aggregate labor and overhead costs, the comprehensive cost of electrodes, the total amount of shielding gas required, the cumulative flux cost, and the overall power costs.

This manuscript offers an in-depth analysis of a comprehensive costing model, specifically for products crafted using GMAW, as illustrated in Figure 1. The MyCAT4W model meticulously evaluates key cost components essential to the production process, including material costs for raw materials necessary in additive manufacturing, equipment costs focusing on electricity and shielding gas essential for quality maintenance, and labor costs covering compensation for skilled personnel in operational and supervisory roles as shown in Table 1. This analysis aims to equip stakeholders with a thorough understanding of the economic factors crucial to GMAW product fabrication, thereby enhancing decision-making regarding the technology's adoption and optimization in relevant sectors.

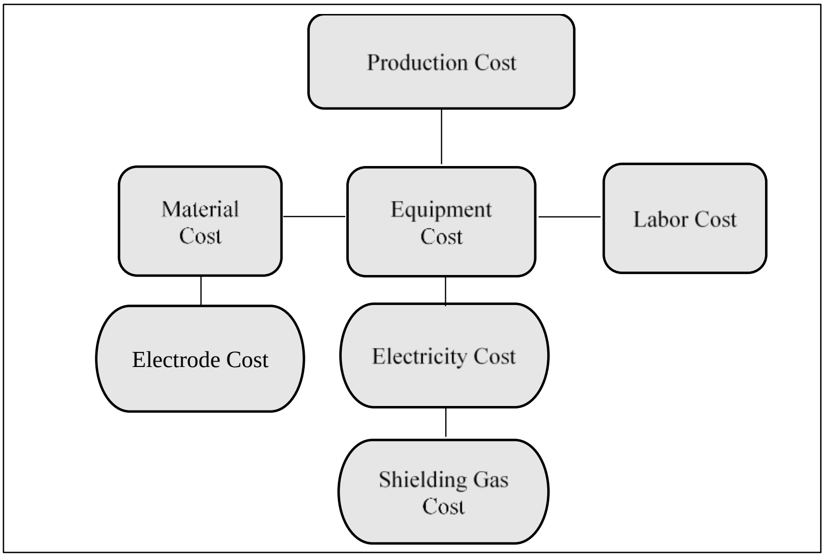

Figure 1: Costing model structure for the GMAW process [16]

Table 1: The costing model structure for the double V-groove butt joint component

Summation of total cost		
Material	**Equipment**	**Labor**
Total length of weldment	Total required shielding gas	Total time of welding
Total required weight and cost of electrode	Total cost of power (power source and robot)	Assumption of operating factor
Total cost of material	Total cost of equipment	Total cost of labor

Total cost of material

Total required weight and cost of electrode

The price of the electrode per kilogram makes up the second factor. The electrode's deposition effectiveness is the third consideration. The filler wire data book, the type of wire diameter, and the welding procedure are used to determine the deposition efficiency. The cost of an electrode is mostly determined by the electrode's weight. The weight of the electrode also must be considered in the total calculation of the butt joint welding cost which is described in Equation (1):

$$\begin{array}{c}\mathit{Total\ cost\ of}\\ \mathit{material}\end{array} = \begin{array}{c}\mathit{Cost\ of\ wire\ per}\ \times \mathit{total\ required}\\ \mathit{Weight\ of\ electrode}\end{array} \qquad (1)$$

where the cost per wire kg is determined by the roughly similar price of commercially sold filler wire and the total weight of the electrode is determined by the following equation:

$$\begin{array}{c}\mathit{The\ total\ required}\\ \mathit{weight\ of\ electrode}\end{array} = \frac{\mathit{Weight\ per\ meter}^{*} \times \mathit{length\ of\ weldment}}{\mathit{Deposition\ efficiency}} \qquad (2)$$

Total cost of labor

Total labor and overhead cost

The remuneration for the welder operator's hourly wage, which may vary depending on the welding method employed, is encompassed within the labor and overhead expenses. Given the hourly basis of labor and administrative outlays, extended project durations inevitably result in escalated costs. Moreover, the operational factor significantly influences project duration, as opting for a welding technique with a lower operational factor inherently extends the overall project time and amplifies labor and overhead expenditures. The operational factor delineates the duration a welding machine can operate without posing a risk to the operator, commonly assessed in intervals of ten minutes. Table 2 delineates the operational factors crucial for cost determination [16].

Table 2: Operating factor for various welding processes [17]

Welding process	**Operating factor assumption**	**Range of operation factor**
SMAW	25	15 to 40
GMAW – semi-automatic	45	15 to 60
GMAW – automatic	80	50 to 100
FCAW – semi-automatic	40	15 to 55
SAW – mechanized	40	40 to 90

Total labor and overhead costs are determined by the following equation:

$$\begin{matrix} Total\ cost\ of \\ labor\ and\ overhead \end{matrix} = \begin{matrix} Cost\ of\ labor\ and\ overhead\ per\ hour \times \\ Total\ time\ of\ overall\ project \end{matrix} \tag{3}$$

where the cost of labor and overhead per hour will follow the average wages in specific countries, in this case, Malaysia [18], and the total time of the project is described:

$$\begin{matrix} Total\ time\ of \\ the\ project \end{matrix} = \frac{Weight\ per\ meter^{*} \times length\ of\ weldment}{Deposition\ rate} \tag{4}$$

where weight per meter is described by the geometry shape of the heat-affected zone on double V–groove butt joint deposition multiplied by the total overall length of the weldment, and the deposition rate is based on Elektriska Svetsnings-Aktiebolaget (ESAB) [19]. Based on Equation (4), the total time to complete the overall project will consider the operating factor employing:

$$\begin{matrix} Total\ time\ of \\ overall\ project \end{matrix} = \frac{Total\ time\ of welding}{Operating\ factor\ assumption^{*}} \tag{5}$$

Total cost of equipment

Total required shielding gas

The formulation below is the GMAW criteria that is selected to determine the pricing based on the needed amount of shielding gas which is described in the following equation:

$$\begin{matrix} Shielding\ gas \\ required \end{matrix} = \begin{matrix} Shielding\ gas\ flow\ rate \text{ x } total\ time \\ of\ welding \end{matrix} \tag{6}$$

where the shielding gas flow rate is based on the standard set in Table 3.

Table 3: Gas flow rate

Shielding gas flow rate				
Wire diameter	0.9 mm	1.2 mm	1.6 mm	2 mm - 3.2 mm
L/min	14.2	16.5	18.9	21.1
m^3/hr	0.85	0.99	1.13	1.27

This leads to the final calculation to calculate the pricing based on shielding gas usage which also considers the commercial price of a similar whole cylinder of shielding gas:

$$\begin{matrix} \mathit{Total\ cost\ of\ shielding} \\ \mathit{gas\ to\ be\ purchase} \end{matrix} = \begin{matrix} \mathit{Total\ required\ shielding\ gas} \\ \mathit{cylinder\ price} \times \mathit{per\ cylinder} \end{matrix} \tag{7}$$

Another technique is investigated to determine the pricing based on the needed amount of shielding gas which is a modification with the implementation of ESAB. Given that it operates on the same principle as GMAW, the calculation below outlines the necessary amount of shielding gas to procure. As the basis, Boyle’s law is used to calculate the volume as shown in Equation (8). To calculate the shielding gas volume at atmospheric and residual pressure:

$$P_1V_1 = P_2V_2 \quad \mathit{and} \quad P_1V_1 = P_2^*V_2^* \tag{8}$$

$$\begin{matrix} \mathit{Ratio\ of\ usable\ shielding\ gas\ to} \\ \mathit{total\ shielding\ gas\ in\ cylinder} \end{matrix} = \frac{V_2^*}{V_2} = V_{ratio} \tag{9}$$

$$\begin{matrix} \mathit{Total\ required\ shielding} \\ \mathit{gas\ to\ be\ purchased} \end{matrix} = \frac{\mathit{Shielding\ gas\ required}}{V_{ratio}} \tag{10}$$

$$\begin{matrix} \mathit{Total\ gas} \\ \mathit{cylinder\ required} \end{matrix} = \frac{\mathit{Total\ required\ shielding\ gas\ to\ be\ purchased}}{V_2} \quad \mathit{or} \quad \frac{\mathit{Shielding\ gas\ required}}{V_2^*} \tag{11}$$

Due to constant temperature, the pressure and the volume of the shielding gas are inversely proportional to each other. The initial pressure, P_1 which is atmospheric pressure, and the initial volume, V_1 is calculated based on Equation (6). Therefore, the residual pressure, P_2, which can be measured, and volume, V_2 after completing the project can be calculated using Equation (8). Using the ratio of usable shielding gas, V_{ratio}, the total required shielding gas needed and the amount of shielding gas cylinder to be purchased can be obtained in Equation (10) and Equation (11), respectively.

Total power cost

The utilization of electrical power by the power source is contingent upon the welding process and various welding parameters, including voltage, current, and wire feed speed. The aggregate electrical power consumed by the welding robot within a specified timeframe is referred to as its power consumption. The parameters for this project can observed in Table 4 which were used in the power cost calculations.

Table 4: Experimental parameters for double V- groove joint process in the butt joint experiment

Process parameter	**Values**
Current (A)	120 - 130
Voltage (V)	27 - 29
Travel speed (mm/s)	5
Wire feed speed (m/min)	5
Gas composition (argon)	100%
Numbers of layers	3

The following equation establishes the calculation of the power cost:

$$Power = \frac{\frac{Cost}{kWh} \times Voltages \times Currents}{1000 \times Deposition\, rate} \tag{12}$$

The cost per kilogram of wire is derived from ESAB guidelines, taking into account the cost of electrical power, typically constituting less than 1%. The cost of the welding robot is computed by multiplying its wattage by the duration of its operation. The power source, denoting the apparatus furnishing electrical power for welding operations, such as a welding machine or power supply, can be elucidated by the subsequent equation:

$$Total\ cost\ of\ Power = Power \times Total\ welding\ time \times Tariff\ rate \tag{13}$$

where the total power is based on the capacity of a particular robotic welding equipment and the tariff rate is based on Tenaga Nasional Berhad (TNB) classification [20]. The projected power consumption for the project hinges on the travel speed of the Wired Arc Additive Manufacturing (WAAM) process employed to fabricate the pipe flange component. As a result, the power consumption for the project is derived from the rated power consumption of the robotic welding equipment operating at maximum speed. Factoring in the duration for which the equipment was utilized in the project, the cost of power for the robotic welding equipment can be determined using Equation (15) [21].

$$\begin{matrix}Estimated \\ power\ consumption\end{matrix} = \frac{Travel\ speed}{Maximum\ operating\ speed} \text{ x } Rated\ power \qquad (14)$$

$$\begin{matrix}Total\ cost\ of\ power \\ for\ robotic\ welding\end{matrix} = \begin{matrix}Estimated\ power\ consumption \times \\ Total\ welding\ time \times Tariff\ rate\end{matrix} \qquad (15)$$

Results and Discussion

Double V-groove for butt joint process model

For this welding design, the double V-groove aims to outline the geometric parameters, such as the angle, depth, and width of the V-grooves, as well as any additional dimensions relevant to the welding process as illustrated in Figure 2. By detailing the characteristics of the double V-groove model, this introduction sets the foundation for understanding its application in welding procedures and ensures clarity regarding the structural aspects of the joint design.

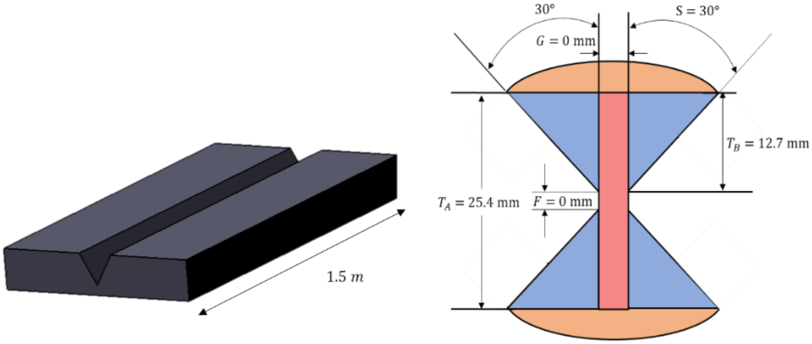

Figure 2: The design of double V-groove in automated GMAW

Double V-groove costing analysis

This project was performed using automated robotic welding equipment that utilized the GMAW process. The weldment was done based on the welding parameter in Table 5, as the length of the weldment is 1.5 m, and the joint process used in the project is a double V-groove.

Total cost of material

Important aspects to consider for the material cost of this project consist of the weight per meter, the weldment's length, and the cost of the electrode. Employing a calculation derived from an electrode density of 7800 kg/m^3, based on the material ER70S-3, the diagrams in Figure 3 show the dimension of the weldment area for a double V-groove.

Table 5: The information on the double V groove project

Project Information		
Details	**Values**	**Units**
Length of weldment	1.5	m
Type of welding process	GMAW	
Type of electrode/ wire	GMAW	
Current	120 - 130	A
Voltage	28 - 30	V
Type of joint	Double V-Groove	
Diameter of electrode/ wire	1.2	mm

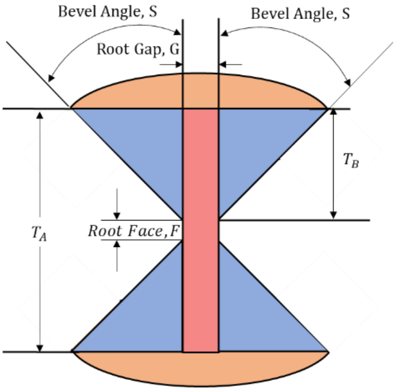

Figure 3: The dimension for double V-groove weldment

The calculation of the weight per meter will depend on the type of weld joint because every weld joint has different dimensions and shapes for example as shown in Figure 2, a geometric modeling approach is used to calculate the weight per meter and Tables 6, 7 and 8 show the V groove is divided into 3 sections which are section A, section B, and section C, respectively.

Table 9 shows the total cost for the material of the project. Once the value for the total required weight electrode has been obtained, the calculation for the total cost of the electrode can be performed by considering the commercial price of ER70S-3 wire per kg for RM 40.80.

Table 6: The calculation for weight for part A

Section A		
Details	**Values**	**Units**
Plate thickness, T_A	25.4	mm
Root gap, G	0	mm
Root face, F	0	mm
Cross-sectional area, A_A	0	mm^2
Weight per meter, W_A	0	kg/m
Total cross-sectional area, A_{TA}	0	mm^2
Total weight per meter, W_{TA}	0	kg/m

Table 7: The calculation weight per meter for part B

Section B		
Details	**Values**	**Units**
Bevel Thickness, T_B	12.7	mm
Bevel Angle, S	30	degree
Cross-sectional Area, A_B	46.56041	mm^2
Weight per meter, W_B	0.363171	kg/m
Total Cross-sectional Area, A_{TB}	186.2416	mm^2
Total Weight per meter, W_{TB}	1.452685	kg/m

Table 8: The calculation weight per meter for part C

Section C		
Details	**Values**	**Units**
Reinforcement width, W_C	14.6647	mm
Reinforcement height, H_C	1.59	mm
Formula : Area = W_C x H_C x 0.75		
Cross-sectional area, A_C	17.48765	mm^2
Weight per meter, W_C	0.136404	kg/m
Total cross-sectional area, A_{TC}	34.9753	mm^2
Weight per meter, W_{TC}	0.272807	kg/m
Total weight per meter	**1.725**	**kg/m**

Table 9: The total cost for the material of the project

Total cost of materials		
Details	**Values**	**Units**
Total required weight of electrode	2.70	kg
Total cost of electrode	189.00	RM

Total cost of labor

After calculating the material cost, the labor to perform this project needs to be calculated based on the total time of welding, the total time of the overall project, and the salary for this project that needs to be determined for the welding operator as demonstrated in Table 10.

Table 10: The total cost of labor for this project

Total cost of labour		
Details	**Value**	**Units**
Total time of welding	2	hours
Total time of overall project	3	hours
Total cost of labour	76.42	RM

Total cost of equipment

The cost for equipment of this project can be obtained through the necessary shielding purchased, the cost of shielding gas, and the total power cost for the robotic welding equipment and power source combined as shown in Table 11.

Table 11: The total cost of equipment for the project

Total cost of equipment		
Details	**Values**	
Total required shielding gas to be purchased	1	cylinder
Total cost of shielding gas	RM	201.36
Total cost of power	RM	4.67

Total cost of the project

Table 12 shows the overall cost of the four important components required for the double V-groove project. The appropriate calculation procedure has been developed to estimate the cost for the butt joint process following many modifications made to the ESAB-modified and Time Driven Activity Based (TDAB) costing method. The length of the weldment, the weight of the electrode, the type of welder (machine), the welding period, and the welding material all affect the ESAB-modified calculation technique. The material cost for this project is RM189.00, labor costs total RM76.42, and equipment costs of RM206.03, resulting in an overall cost of RM471.45.

Table 12: The summation of the total cost of the double V groove project

Total cost of double v groove project		
Details	**Values**	
Total cost of material	RM	189.00
Total cost of labour	RM	76.42
Total cost of equipment	RM	206.03
Total cost of welding	RM	471.45

Figure 4 illustrates the breakdown of the overall cost of the double V-groove butt joint project as a proportion of the total cost, highlighting the areas with the most significant welding costs. The equipment cost plays a major role in the overall cost of butt joint products due to the required shielding gas and power consumption. Using the ESAB modification method shows distinguished contributions to material costs, specifically accounting for 43.8% of the total cost in electrode usage to complete the double V-groove project.

The graph also indicates a 16.3% overall cost for labor whereas the total cost required for fabricating the double V-groove butt joint project using the automated GMAW process is RM471.45 excluding the component machining expenses. Therefore, the cost of GMAW-produced butt joints using the Time-Driven Activity-Based (TDAB) costing method can be compared within the Malaysian market.

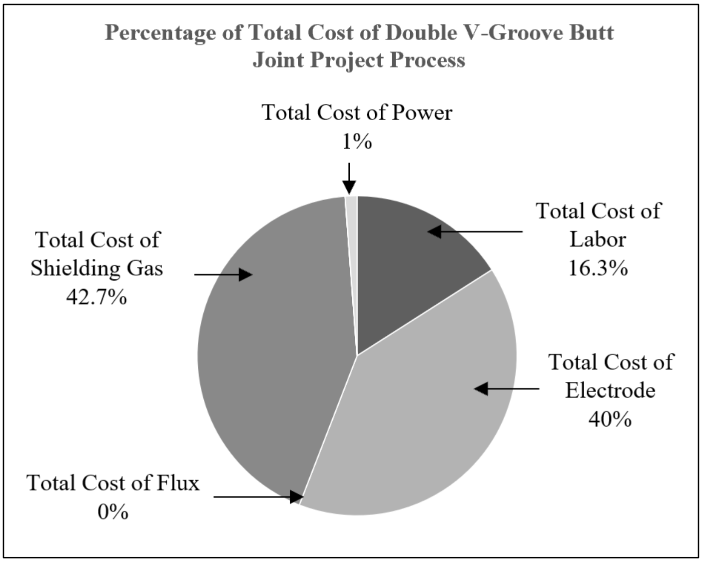

Figure 4: The illustration of the total cost of the double V-groove project

Conclusion

This research is centred on conducting a cost analysis of the Gas Metal Arc Welding (GMAW) process for creating a double V-groove butt joint. The primary objective of this study is to create a thorough cost model using ESAB with minor adjustments to estimate the production cost of the GMAW products. From the findings of this study, the following conclusions can be made:

i. The comprehensive costing model for the WAAM process has been successfully developed and implemented based on the Time-Driven Activity-Based (TDAB) approach.
ii. The cost of manufacturing the butt joint through GMAW is primarily determined by equipment expenses, particularly the necessary shielding gas. The shielding gas cost represents about 43.7% of the total cost while the cost of materials which is the electrode plays a significant role, accounting for around 40%. This is largely due to the use of electrodes, which are essential for producing the butt joint using the GMAW method.
iii. GMAW is a widely used arc welding process that offers several advantages over traditional welding methods, particularly in terms of control and efficiency.
iv. The costing model is adaptable and can be utilized in other nations, accounting for variations in currency values.

Moreover, this inquiry holds the potential to enhance the progression of research in GMAW within this specific domain by:

i. To implement post-processing and incurring the expenses into the costing analysis tool.
ii. To integrate a more comprehensive array of materials, account for diverse part dimensions, and consider varying deposition rates.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

One of the authors, Muhd Faiz Mat is a section editor of the Journal of Mechanical Engineering (JMechE). The author has no other conflict of interest to note.

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References

[1] F. Khoshnaw, “Chapter 1 - An introduction to welding of metallic materials”, in *Welding of Metallic Materials*, Elsevier, United Kingdom, 2023, pp. 1-35. https://doi.org/10.1016/B978-0-323-90552-7.00002-X

[2] S. Ramesh, “Introduction to Welding Processes”, in *Designing Weldments*, Scrivener, pp. 131-154, 2022. https://doi.org/10.1002/9781119865841.ch5

[3] R. Beygi, E. Marques, and L. F. M. da Silva, “Introduction. In: Computational Concepts in Simulation of Welding Processes”, in *Springer Briefs in Applied Sciences and Technology*, Springer, Portugal, 2022, pp. 1-11. https://doi.org/10.1007/978-3-030-97910-2_1

[4] N. Ma, D. Deng, N. Osawa, S. Rashed, H. Murakawa, and Y. Ueda, “Introduction to welding mechanics”, in *Welding Deformation and Residual Stress Prevention*, Elsevier, Japan, 2022, pp. 1-35. http://dx.doi.org/10.1016/B978-0-323-88665-9.00003-3

[5] S. M. Petrovich, P. V. Ivanovich, and V. E Vorisovna, Welding: Introduction to the Specialty, Infra-M Academic, 2020. https://doi.org/10.12737/1021002

[6] F. Khoshnaw, I. Krivtsun, and V. Korzhyk, “Chapter 2 - Arc welding methods”, in *Welding of Metallic Materials*, Elsevier, United Kingdom, 2023, pp. 37-71. https://doi.org/10.1016/B978-0-323-90552-7.00004-3

[7] T. Rayapandi and P. Suresh, “An Overview of Welding Methods for Advanced Materials: Testing and Evaluation”, in *Advanced*

Manufacturing Techniques for Engineering and Engineered Materials, IGI Global, Pennsylvania, 2022, pp. 198-225, https://doi.org/10.4018/978-1-7998-9574-9.ch012

[8] M. H. M. Hashim, A. M. T. Arifin, S. A. Osman, S. A. Osman, T. S. Kiat, and A. F. M. Salihin, "Study on MIG and TIG Weldment Behaviour Using Finite Element Approach", *Journal of Advanced Research in Applied Sciences and Engineering Technology*, vol. 46, no. 2, pp. 81–89, 2024. https://doi.org/10.37934/araset.46.2.8189

[9] X. Xie, S. Sun, J. Chen, J. Liu and H. Lan, "Welding process expert system based on Industrial Internet and neural network", *24th International Conference on Electronic Packaging Technology*, pp. 1-5, 2023. https://doi.org/10.1109/ICEPT59018.2023.10491962

[10] I.S. Kim, J.S. Son, I.G. Kim, J.Y. Kim, and O.S. Kim, "A Study on Relationship between Process Variables and Bead Penetration for Robotic CO2 Arc Welding", *Journal of Materials Processing Technology*, vol. 136, no. 1–3, pp. 139-145, 2003. https://doi.org/10.1016/S0924-0136(02)01126-3

[11] P. Sathiya, S. Aravinda, P.M. Ajith, B. Arivazhagan and A. Noorul Haq, "Microstructural Characteristics on Bead on Plate Welding of AISI 904 L Super Austenitic Stainless Steel Using Gas Metal Arc Welding Process", *International Journal of Engineering, Science and Technology*, vol. 2, no. 6, pp. 189-199, 2010. https://doi.org/10.4314/ijest.v2i6.63710

[12] V. Cohal, "A welding technology using RobotStudio", *Materials Science, Engineering and Chemistry Web of Conferences*, vol. 112, p. 03012, 2017. http://dx.doi.org/10.1051/matecconf/201711203012

[13] S. Chayoukhi, Z. Bouaziz, and A. Zghal, "Cost evaluation for welding process by using preparing features", *IFAC Proceedings Conference*, vol. 39, no. 3, pp. 813-818, 2006. https://doi.org/10.3182/20060517-3-FR-2903.00392

[14] S. Kumar and S. Nand, "Estimation and Comparison of Welding Cost of MIG & MAG Process on Mild Steel", *Recent Advances in Manufacturing Engineering & Techology*, pp. 55-59, 2011

[15] A. B. Ganorkar, R. R. Lakhe, and K. N. Agrawal, "Methodology for application of Maynard Operation Sequence Technique (MOST) for time-driven activity-based costing (TDABC)", *International Journal of Productivity and Performance Management*, vol. 68, no. 1, pp. 2-25, 2019. https://doi.org/10.1108/IJPPM-06-2017-0156

[16] S. Kokare, J.P. Oliveira, T.G. Santos, R. Godina, "Environmental and economic assessment of a steel wall fabricated by wire-based directed energy deposition", *Additive Manufacturing*, vol. 61, p. 103316, 2023. https://doi.org/10.1016/j.addma.2022.103316

[17] The Welding Institute, "*What typical duty cycles are achieved when arc welding?*", 2023. [Online]. Available: https://www.twi-

global.com/technical-knowledge/faqs/faq-what-typical-duty-cycles-are-achieved-when. (Accessed November 3, 2023)

[18] Economic Research Institute, "*Welder Salary in Kuala Lumpur, Malaysia*", 2024. [Online]. Available: https://www.erieri.com/salary/job/welder/malaysia/kuala-lumpur. (Accessed April 5, 2024)

[19] Elektriska Svetsnings-Aktiebolaget, "Filler Metal Databook Canada". 2024. [Online]. Available: https://assets.esab.com/assetbank-esab/action/viewAsset?id=22175&index=2&total=6&view=viewSearchItem. (Accessed March 12, 2024)

[20] Tenaga Nasional, *"Pricing & Tariffs"*, 2024. [Online]. Available: https://www.tnb.com.my/commercial-industrial/pricing-tariffs1. (Accessed December 6, 2023)

[21] R. Asari, "*Automotive Industrial Robot - Total Cost of Ownership"*, 2018. [Online]. Available: https://www.linkedin.com/pulse/automotive-industrial-robot-total-cost-ownership-rashidi-asari/. (Accessed July 17, 2024)