e-ISSN: 2550-164X

Available online at
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Journal of Mechanical Engineering SI 14 2025, 1 – 17.

Journal of Mechanical Engineering

Improving Weld Accuracy and Reducing Production Time through Fixture-Assisted TIG Welding

Mohd Haziq Asyraaf Abu Bakar[1], Nursyazwani Zulkefli[2], Aida Husna Ahmad[2], Saliza Azlina Osman[2], Tay Sin Kiat[1], Shahrul Azmir Osman[2*]

[1]Intec Precision Engineering Sdn. Bhd. Kawasan Perindustrian Nusa Gemilang, 73500 Gelang Patah, Johor, Malaysia
[2]Department of Mechanical Engineering, Faculty of Mechanical Engineering & Manufacturing, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia

ARTICLE INFO

Article history:
Received 05 September 2025
Revised 02 October 2025
Accepted 07 October 2025
Online first
Published 15 November 2025

Keywords:
Welding jigs
Time study
Manufacturing efficiency
Work measurement
Quality control

DOI:
10.24191/jmeche.v14i1.8780

ABSTRACT

Welding quality is a critical determinant of structural integrity and production efficiency in precision manufacturing. However, conventional steel frame fabrication processes often suffer from inconsistencies, dimensional inaccuracies, and extended setup durations due to the lack of standardized welding fixtures. This research investigates the influence of welding jig design on manufacturing performance and dimensional accuracy through a comparative analysis of conventional and jig-assisted welding methods. A case study approach was employed, integrating stopwatch time study techniques and quality assessment protocols to quantify productivity and precision improvements. Experimental procedures evaluated five complete fabrication cycles for each method using Westinghouse performance ratings, element-based time recording, and Coordinate Measuring Machine (CMM) distortion measurements across nine critical points. The findings indicate that the application of welding jigs substantially enhances process efficiency and product quality. Total fabrication time decreased from approximately 25.8 hours to 19.9 hours per frame, achieving a 23% improvement in productivity. Dimensional compliance increased from 75% to over 90% of measurements within specified tolerances. The most significant time savings were observed in primary welding operations, where setup and alignment tasks were minimized. These results provide empirical evidence that jig-assisted welding improves operational consistency, reduces operator dependency, and strengthens quality control in precision manufacturing. The study concludes that welding jigs represent a viable solution for achieving an optimal balance between efficiency and accuracy, supporting data-driven investment decisions in fixture development and process standardization within modern fabrication industries.

[2*] Corresponding author. *E-mail address*: shahrula@uthm.edu.my
https://doi.org/10.24191/jmeche.v14i1.8780

INTRODUCTION

Welding serves as a prevalent technique in the fabrication of steel frames, with the quality of welded connections bearing significant ramifications on the overall structural soundness of the end product. The welding procedure's duration and resultant quality may be influenced by factors such as operator proficiency, welding apparatus, and the design of welding fixtures (Ahmad Mir et al., 2022). Modern manufacturing environments demand consistent quality output while maintaining competitive production rates, creating challenges for manufacturers to balance efficiency with precision.

The implementation of welding jigs and fixtures has emerged as a critical solution to address these manufacturing challenges. A fixture, known as a jig, serves as a substantial support structure, maintaining stability in welding undertakings amidst pressure, heat, motion, and force (Said et al., 2023). Well-constructed jigs optimize welding operations by firmly holding parts together, enhancing precision, facilitating consistent replication of design fabrication, thus obviating the setup time requisite prior to machining, enhancing machining accuracy, augmenting production capacity, necessitating less skilled labour, and curbing production costs.

Despite the recognized benefits of welding jigs, limited empirical studies have quantified their impact on both time efficiency and quality outcomes in precision manufacturing environments. The existing welding procedure used in steel frame fabrication often lacks sufficient accuracy and consistency, leading to variations in welding quality and compromised structural integrity of final products. The absence of standardized time standards for welding processes results in inconsistent production timelines, delays, and difficulties in planning and scheduling.

This research addresses a critical gap in the literature by providing the first comprehensive empirical study that simultaneously evaluates time efficiency and dimensional quality outcomes of welding jigs specifically for Tungsten Inert Gas (TIG) welding applications in precision steel frame fabrication. Unlike previous studies that focused primarily on drilling fixtures (Said et al., 2023) or general machining jigs (Kumar et al., 2021), this investigation combines systematic time study methodology with detailed distortion analysis to quantify the dual benefits of fixture implementation in welding operations. The integration of Westinghouse performance rating systems with Coordinate Measuring Machine (CMM) assessments provides a novel methodological framework for evaluating welding fixture effectiveness in precision manufacturing environments.

The study objectives are: (1) to compare standard time procedures for both jig and non-jig welding processes, and (2) to analyse the distortion of frame structures for both methodologies after welding completion. The significance of this study extends beyond academic contribution, providing practical insights for manufacturing decision-makers regarding resource allocation, process optimization, and quality control implementation. The research was collaboration with Intec Precision Engineering Sdn. Bhd., focusing on frame fabrication processes that represent typical precision manufacturing applications.

LITERATURE REVIEW

Time study in manufacturing

Time study is a technique used to determine the time required for a qualified and well-trained person working at a normal pace to complete a specific task (Sotsek et al., 2022). This technique involves systematic observation and recording of the time taken to perform each element of an operation, with the aim of identifying opportunities for improving efficiency and productivity (Studynka & Aryanny, 2024). According to the International Labour Organization (ILO), time study is a work measurement technique that involves recording the times and rates of work for each element of a specific job carried out under

https://doi.org/10.24191/jmeche.v14i1.8780

specified conditions and analysing the data to obtain the time necessary for carrying out the job at a defined level of performance (Freivalds & Niebel, 2009). Contemporary research has validated the effectiveness of the stopwatch time study methodology in enhancing operational efficiency through systematic performance evaluation and standardized time establishment (Ahmad et al., 2025).

The stopwatch time study method is a conventional and widely used technique in time study and industrial engineering for assessing the duration of a worker's performance in a specific task (Budiman et al., 2019). This method employs a stopwatch to precisely document the time taken for each element of a job or task, aiming to establish the standard time required for that activity (Lukodono & Ulfa, 2017). The standard time serves as a foundation for setting performance benchmarks, distributing workloads, and managing resources (Freivalds & Niebel, 2009).

Standard time denotes the time required for an adequately skilled operator, working at a standard pace, to execute a defined task following a specified method (Safirin et al., 2022). This duration encompasses suitable allowances to enable the individual to recuperate from fatigue, and when necessary, an extra allowance to account for unforeseen elements that might arise. Standard time can be calculated using the formula:

$$Standard\ Time\ =\ Normal\ Time\ /\ (1\ -\ Allowance) \tag{1}$$

where; Normal Time = Average Observed Time × Performance Rating (Freivalds & Niebel, 2009).

Time study methodologies have evolved significantly, with various techniques being developed for different manufacturing contexts. Work sampling techniques provide alternative approaches to continuous observation methods, particularly useful for non-repetitive tasks (Pachghare & Dalu, 2014). The selection of appropriate time study techniques depends on factors such as task complexity, operator skill requirements, and production volume considerations (Puvanasvaran et al., 2013).

Performance rating systems

Performance rating denotes the evaluation of a worker's performance in relation to established standards during the observation and measurement of work activities (Safirin et al., 2022). The Westinghouse system is a comprehensive technique developed by the Westinghouse Electric Corporation to evaluate and rate the efficiency of workers in manufacturing and assembly environments. This method evaluates four factors to assess operator performance: skill, effort, conditions, and consistency (Cevikcan & Kilic, 2016; Freivalds & Niebel, 2009).

The Westinghouse system classifies each factor into six categories, ranging from poor to super skill, poor to excessive, poor to ideal, and poor to perfect, respectively. By taking these various elements into account, the Westinghouse system aims to offer a more nuanced and well-rounded evaluation of the worker's overall effectiveness in completing the assigned work (López et al., 2019).

Recent studies have demonstrated the practical application of the Westinghouse system in manufacturing environments, showing consistent evaluation criteria across different operational contexts (Mohd Azhar et al., 2024). The implementation of this systematic approach enables organizations to establish standardized performance benchmarks that account for individual operator capabilities and working conditions.

Table 1 shows an example performance rating application based on a manufacturing case study. The practical application of performance rating demonstrates significant variation among operators, ranging from 0.78 to 1.17, indicating the importance of individual assessment in time study applications (Mohd Azhar et al., 2024). This variation directly impacts normal time calculations and subsequent standard time establishment.

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Table 1. Example performance rating application

Factor	Operator 1	Operator 2	Operator 3	Operator 4
Work element	A, B, C	D	E, F, G	H, I, J, K, L
Skill	+0.06	+0.06	0.00	–0.16
Effort	+0.08	+0.05	0.00	–0.04
Conditions	0.00	0.00	0.00	0.00
Consistency	+0.03	+0.01	0.00	–0.02
Algebraic sum	+0.17	+0.12	0.00	–0.22
Performance rating	1.17	1.12	1.00	0.78

Allowances in time study

Allowances involve adjustments made to the observed time to accommodate factors that may impact a worker's performance but are beyond their control (El Mouayni et al., 2020). Allowances account for factors such as personal needs, unavoidable delays, and fatigue that can affect a worker's productivity. Allowances can be categorized into two main types: constant allowance and variable allowance (Freivalds & Niebel, 2009).

Constant allowance encompasses personal needs and basic fatigue allowances, representing additional time added to the actual time required to perform a task (Adhwarjee, 2013). Variable allowance accommodates unpredictable or varying factors that may influence a worker's performance, including abnormal posture, muscular force, atmospheric conditions, noise level, illumination levels, visual strain, mental strain, monotony, and tediousness (Yovi et al., 2021).

The determination of appropriate allowances requires a systematic analysis of working conditions and task requirements. Contemporary research has established comprehensive allowance frameworks that address both constant and variable factors affecting worker performance (Mohd Azhar et al., 2024). The Examples of allowances applied to different work elements are shown in Table 2.

Table 2. Example of allowances for work elements

Work Element	Work Element Description	Allowances (%)
A	Move parts from the waiting bay to the touch-up and cleaning workstation	12
B	Touch-up and cleaning process	15
C	Checked and moved the part to the waiting bay	12

The allowance percentages typically range from 11% to 16% depending on the nature of work elements, with higher allowances applied to tasks requiring greater attention, mental strain, or physical effort (Mohd Azhar et al., 2024). This systematic approach ensures that standard times reflect realistic working conditions while maintaining achievable performance targets.

Welding jigs and fixtures

Jigs and fixtures are indispensable tools in manufacturing and machining operations, serving as vital components in maintaining precision, uniformity, and productivity throughout the production process (Pandit & Pandit, 2023). Mass production aims to achieve high productivity and cost reduction by ensuring interchangeability for easy assembly. Production devices, commonly known as jigs and fixtures, typically consist of work holders equipped with tool guiding or setting arrangements.

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Jigs, furnished with tool guiding elements, direct tools to the precise positions on workpieces. In contrast, fixtures securely hold workpieces in the correct position during operations without guiding the tool. Both jigs and fixtures typically comprise three key elements: locating elements, which ensure precise positioning of workpieces; clamping elements, which securely hold workpieces during operations; and tool guiding and setting elements, which assist in guiding or setting tools accurately with respect to the workpiece (Okpala et al., 2024).

The advantages of jigs and fixtures include enhanced productivity by eliminating the need for individual marking, positioning, and frequent checking, thereby reducing operation time and increasing overall productivity. They facilitate uniform quality in manufacturing, eliminating the necessity for selective assembly as any part of the machine fits properly during assembly. Moreover, jigs and fixtures reduce the level of skill required for a job, enabling any average person to be trained in their use (Kumar et al., 2021). Recent studies have demonstrated significant time reductions through jig implementation, with drilling operations showing improvements from 3.45 minutes to 1.28 minutes when utilizing purpose-built fixtures (Said et al., 2023).

The design and implementation of jigs and fixtures require careful consideration of manufacturing requirements and operational constraints. Modern fixture design incorporates principles of rapid changeover and modularity to accommodate product variations while maintaining positioning accuracy (Arslane et al., 2025). The economic justification for fixture investment typically considers factors such as production volume, quality requirements, and labour cost reduction potential (Nee et al., 2012).

TIG welding and quality control

Tungsten Inert Gas (TIG) welding, also known as Gas Tungsten Arc Welding (GTAW), is a sophisticated fusion welding technique that has become integral to high-precision manufacturing industries (Vidyarthy & Dwivedi, 2016). The TIG process, characterized by its use of a non-consumable tungsten electrode and inert gas shielding, offers superior weld quality but is often considered slower compared to other welding methods.

Distortion arises from the uneven expansion and contraction of the welding metal and adjacent base metal during the heating and cooling phases of the welding process (Machado et al., 2019). The shrinkage stresses induced by welding give rise to various forms of distortion, including angular distortion, longitudinal shrinkage, transverse shrinkage, longitudinal sweep or camber, panel distortion, and rotational distortion. Controlling welding sequences can enhance tolerances, though predicting their outcomes proves challenging.

The optimization of TIG welding parameters significantly impacts both quality outcomes and processing efficiency. Advanced welding techniques incorporating automated controls and adaptive systems have demonstrated substantial improvements in consistency and reduction of operator-dependent variations (Farrokhi, 2022). The integration of real-time monitoring systems with traditional welding fixtures provides enhanced process control capabilities (Kashaev et al., 2018).

RESEARCH METHODOLOGY

Case study location and scope

This case study was performed at Intec Precision Engineering Sdn. Bhd. (Plant 3), Gelang Patah, Johor. The frame structure was based on Part no.: UTHM-IPE-0540N, involving evaluation of welding methods using fixture jigs versus non-jig approaches. Time studies were based on work elements including material handling, welding operations, post-weld processing, and quality control. Analysis focused on jig and non-

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jig welding impacts on production efficiency and output quality, particularly distortion within customer-specified tolerances.

Experimental design

Fig 1 shows the process flow chart. The research employed a comparative experimental design examining two distinct welding methodologies:

(i) Conventional welding without jigs: following existing fabrication procedures without specialized tooling.

(ii) Systematic welding with jigs: utilizing purpose-built jigs and fixtures designed specifically for the frame components.

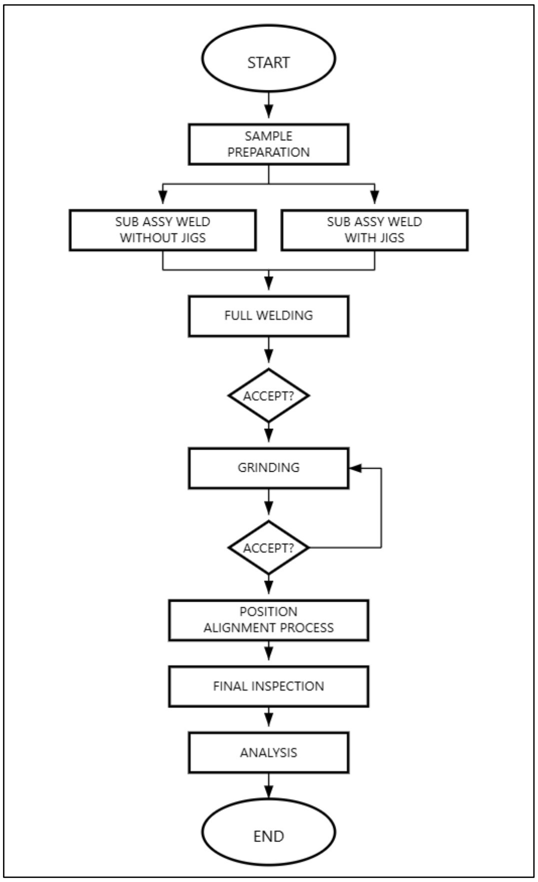

Fig. 1. Process flowchart.

Sample preparation

The procedure comprised three preparatory stages. Upon receipt of individual components from in-house suppliers, initial verification was conducted, primarily focusing on dimensional accuracy. Subsequently, upon confirming the quality of all components, operators commenced the kitting process and established requisite fabrication parameters.

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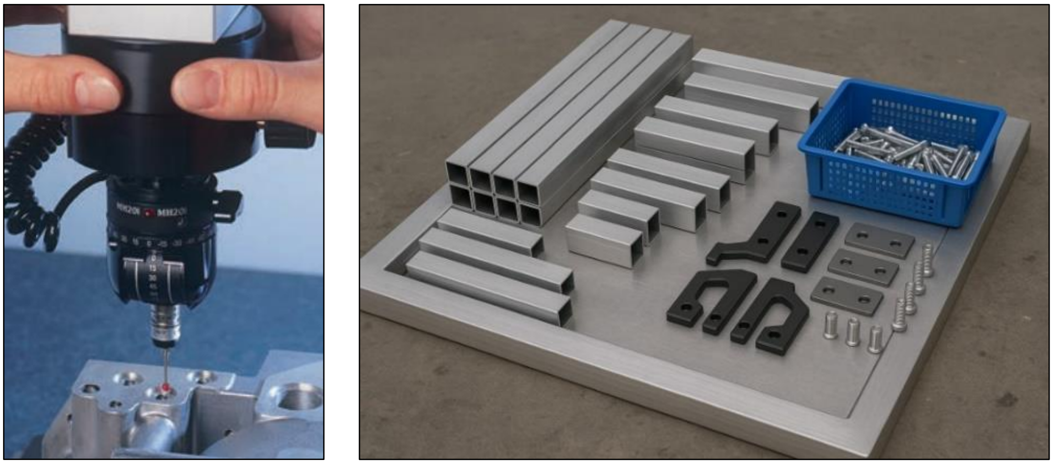
The fabrication process utilised a range of materials, including cold-rolled steel, hot-rolled steel, mild steel, and stainless steel. These material specifications were explicitly outlined in client drawings, mandating strict adherence. Two distinct types of components were employed: metal sheets of varying sizes and thicknesses, alongside machined bar stock and blocks. Fig 2(a) shows the Dimension checking, while Fig 2(b) shows the Kitting process for components. Fig 2(b) was generated using AI for illustration purposes and does not depict the actual design or proprietary components of the company, thereby ensuring confidentiality.



(a) (b)

Fig. 2. (a) Dimension checking and (b) kitting process for components.

Welding procedures

Sub-assembly weld without jig

Following sample preparation, workers initiated the welding of sub-assembly parts, adhering to the current product fabrication methodology that eschewed the use of jigs and fixtures. This approach allowed for baseline assessment of existing manufacturing processes. The welding process was strategically segmented into distinct sub-parts to facilitate streamlined fabrication and enable precise control over the dimensional aspects of each component.

Sub-assembly weld with jig

An alternative methodology incorporated the utilization of jigs and fixtures in the welding process of sub-assembly parts. The jigs and fixtures were systematically subdivided into sections that corresponded directly to the weld part sections, ensuring a one-to-one relationship between tooling and components. Each distinct section was designed to maintain critical dimensions and incorporated strategic stoppers to facilitate precise component fitment during fabrication. Fig 3(a) shows the Frame part sections, and Fig 3(b) shows the jigs sections. The image was generated using Artificial intelligence (AI) for illustration purposes and does not depict the actual design or proprietary components of the company, thereby ensuring confidentiality.

Work elements identification

The study identified specific work elements within the welding department process flow, as in Fig 4.

(i) Preparation/kitting: material preparation and component organisation

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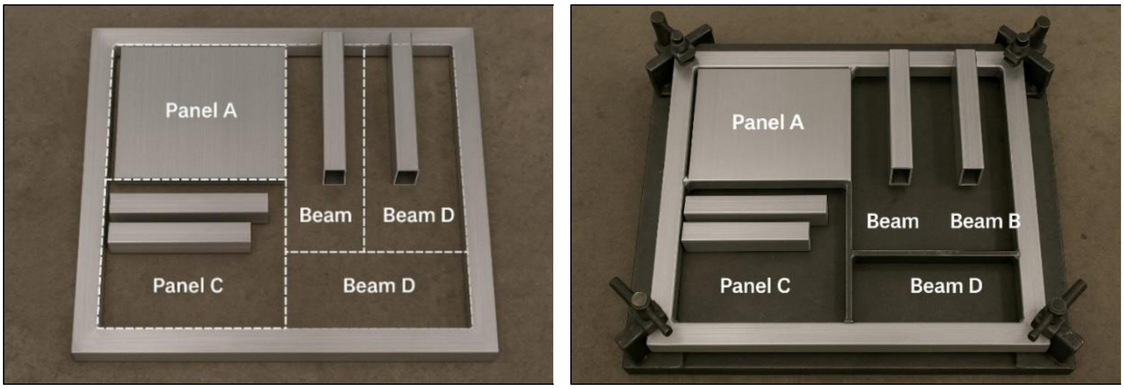
(ii) Welding operations: six distinct welding stages (bottom, panel, top, left, right, full weld)

(iii) Grinding: post-weld surface finishing

(iv) Distortion alignment: correction processes for dimensional accuracy

(v) Quality inspection: final verification procedures



(a) (b)

Fig. 3. (a) Frame part sections and (b) jig sections

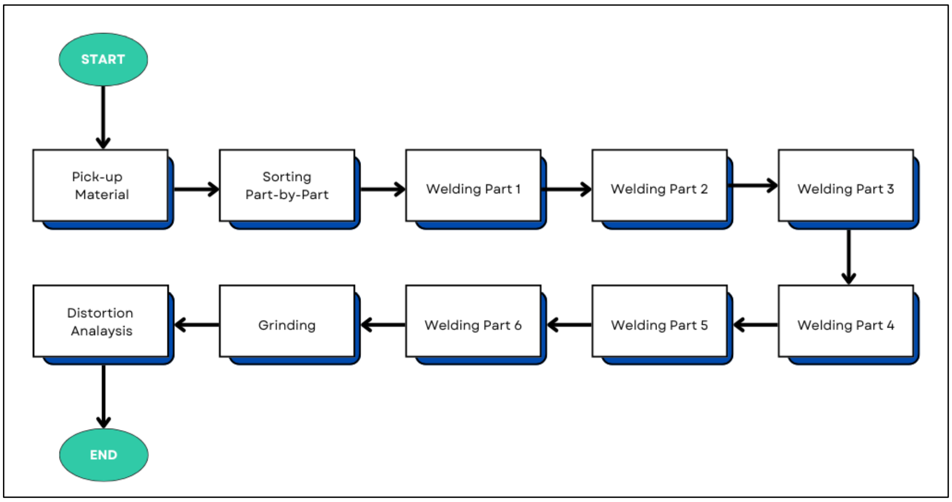


Fig. 4. Work element and process flow.

Data collection procedures

Data collection employed stopwatch time study techniques with five complete fabrication cycles analysed for each welding method (jig-assisted and conventional), totalling ten frames in the comparative study. The sample size of five cycles per method was determined based on industrial constraints, including production scheduling limitations, material availability, and facility access restrictions, while ensuring sufficient data for statistical reliability assessment following established time study protocols

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Time study methodology

Data collection employed stopwatch time study techniques with multiple observations for each work element, following established industrial engineering principles (Meyers & Stewart, 2002; Sotsek et al., 2022). The methodology followed systematic procedures:

(i) Observation setup: five complete cycles for each welding method

(ii) Time recording: precise measurement of each work element duration

(iii) Performance assessment: evaluation using the Westinghouse rating system

(iv) Data validation: verification of measurement consistency

Performance rating

Performance rating assessment utilized the Westinghouse system, evaluating operators based on four factors: skill, effort, conditions, and consistency (Cevikcan & Kilic, 2016; Freivalds & Niebel, 2009). Table 3 presents the performance rating breakdown for operators in respective processes.

Table 3. Performance rating of operators

Factor	Operator 1 (Welding)	Operator 2 (Alignment)	Operator 3 (Grinding)
Skill	+0.06	+0.06	0.00
Effort	+0.08	+0.05	0.00
Conditions	0.00	0.00	0.00
Consistency	+0.03	+0.01	0.00
Algebraic sum	+0.17	+0.12	0.00
Performance rating	1.17	1.12	1.00

Allowance rating

Allowances were established based on ILO recommendations and working conditions assessment (El Mouayni et al., 2020; Freivalds & Niebel, 2009). Table 4 shows the allowance percentages applied to different work elements.

Table 4. Allowance ratings for work elements

Work element	Personal	Fatigue	Standing	Force	Attention	Mental	Monotony	Tediousness	Total (%)
Preparation	5	4	2	1	2	1	0	0	15
Welding	5	4	2	1	2	1	1	2	18
Grinding	5	4	2	0	0	0	0	0	11
Alignment	5	4	2	0	0	0	0	0	11

Quality assessment

Distortion measurement

Distortion measurements were conducted using a CMM machine (Hexagon Romer Arm/7530-4792-UC) at nine critical areas across each frame. Measurements were compared against specified tolerances ranging from ±1.0 mm to ±1.5 mm, depending on the area's criticality.

https://doi.org/10.24191/jmeche.v14i1.8780

Template fitting test

Following alignment completion, comprehensive template fitting tests were conducted to verify dimensional accuracy and functional integrity. Templates were systematically applied to frame structures using corresponding thread sizes to ensure precise fitment, confirming all hole-to-hole dimensions adhered to customer-specified tolerances. Fig 5 shows the template testing. The image was generated using AI for illustration purposes and does not depict the actual design or proprietary components of the company, thereby ensuring confidentiality.

Fig. 5. Template testing.

Data analysis

Statistical analysis was performed to compare time efficiency and quality outcomes between jig and non-jig welding methods. Standard time calculations incorporated performance ratings and allowances to establish realistic benchmarks for each welding methodology, following established work measurement principles (Hartanti, 2016). While this study focused on dimensional accuracy and time efficiency as primary quality metrics, microstructural analysis, including hardness testing, tensile strength evaluation, and non-destructive testing, was excluded due to the industrial nature of the study and confidentiality constraints. These metallurgical assessments represent important areas for future research to complement the dimensional and efficiency findings presented in this study.

RESULTS AND DISCUSSIONS

Time efficiency analysis

The comprehensive time study analysis revealed substantial differences between jig-assisted and conventional welding methods across all manufacturing stages, consistent with findings from previous manufacturing efficiency studies (Taifa & Vhora, 2019) and recent fixture implementation research, which also demonstrated similar time reduction benefits (Said et al., 2023). Table 5 presents the detailed comparison of processing times extracted from the actual production data collected during the study.

https://doi.org/10.24191/jmeche.v14i1.8780

Table 5. Comparative time analysis - jig vs non-jig welding (average of 5 frames)

Process stage	Jig method (min:sec)	Non-jig method (min:sec)	Time difference
Preparation/Kitting	52:59	52:59	No change
Welding 1 (Bottom)	231:12	372:19	-141:07
Welding 2 (Panel)	98:29	103:44	+5:15
Welding 3 (Top)	35:49	35:18	-0:31
Welding 4 (Left)	9:18	9:08	-0:10
Welding 5 (Right)	9:06	7:56	-1:10
Welding 6 (Full Weld)	337:36	470:12	-132:36
Grinding	86:36	86:36	No change
Alignment	331:36	409:42	-78:06
Total process time	1192:41	1547:54	-355:13

The most significant improvements were observed in critical welding operations, where complex geometries and extended welding durations traditionally contributed to process inefficiencies, supporting the theoretical framework established in fixture design literature (Kunar & Mandal, 2025). Welding 1 (Bottom) demonstrated the greatest absolute time reduction of 141 minutes and 7 seconds, representing a substantial efficiency gain. This improvement can be attributed to consistent part positioning provided by the jig system, which eliminated repetitive alignment procedures and reduced setup requirements between welding passes, aligning with time study principles that emphasize setup time reduction (Sotsek et al., 2022).

Full welding operations (Welding 6), representing the most time-intensive stage in the fabrication process, showed considerable efficiency gains with a reduction of 132 minutes and 36 seconds. The jig system effectively maintained proper joint alignment throughout extended welding cycles, reducing the need for interim adjustments and rework activities (Oliveira et al., 2020). The controlled positioning also enabled more consistent travel speeds and heat input, contributing to both time savings and quality improvements as predicted by welding process theory (Ahmad Mir et al., 2022).

Standard time calculations and performance assessment

The establishment of standard times incorporated performance ratings determined through systematic observation using the Westinghouse evaluation system, following established work measurement methodologies (Cevikcan & Kilic, 2016; Freivalds & Niebel, 2009). Table 6 presents the performance rating breakdown for operators involved in different process stages.

Table 6. Performance rating assessment by work element

Work element	Operator type	Skill	Effort	Conditions	Consistency	Total rating
Welding operations	Operator 1	+0.06	+0.08	0.00	+0.03	1.17
Alignment process	Operator 2	+0.06	+0.05	0.00	+0.01	1.12
Grinding operations	Operator 3	0.00	0.00	0.00	0.00	1.00

Welding operations received the highest performance rating of 1.17, reflecting above-average operator skill levels and consistent effort throughout the observation period, which is consistent with performance rating studies in manufacturing environments (Safirin et al., 2022). The experienced welders demonstrated superior technique in both jig and non-jig scenarios, though the jig system enabled more consistent performance across different operators. Alignment procedures were rated at 1.12, acknowledging the

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skilled nature of distortion correction work, while grinding operations maintained a standard rating of 1.00 due to their routine nature.

Table 7 shows the standard time calculations incorporating both performance ratings and allowance factors established based on International Labour Organization recommendations and specific working conditions (El Mouayni et al., 2020; Freivalds & Niebel, 2009).

Table 7. Standard time analysis for critical operations

Work element	Method	Observed time (sec)	Performance rating	Normal time (sec)	Allowance (%)	Standard time (sec)
Welding 1	Jig	13,872	1.17	16,230	15	19,094
Welding 1	Non-jig	22,339	1.17	26,137	15	30,749
Welding 6	Jig	20,256	1.17	23,699	16	28,213
Welding 6	Non-jig	28,212	1.17	33,008	16	39,295
Alignment	Jig	19,896	1.12	22,283	11	25,032
Alignment	Non-jig	24,582	1.12	27,532	11	30,934

The calculated standard times provide realistic benchmarks for production planning and resource allocation, accounting for natural variations in operator performance and working conditions as recommended by time study literature (Hartanti, 2016). The integration of performance ratings and allowances into standard time calculations revealed that jig-assisted methods not only reduced observed times but also demonstrated improved consistency across operators, supporting the principle that fixtures reduce skill dependency in manufacturing operations (Joshi, 2003).

Quality assessment and distortion analysis

Dimensional accuracy assessment revealed significant improvements in overall manufacturing quality when utilizing welding jigs, consistent with fixture design principles that emphasize distortion control (Hunter et al., 2005). Table 8 presents the comprehensive distortion measurement data collected across nine critical areas for both welding methods.

Table 8. Distortion measurement analysis (average of 5 frames)

Area	Tolerance (mm)	Jig method		Non-jig method	
		Avg. reading (mm) (error ±0.1 mm)	Within spec.	Avg. reading (mm) (error ±0.1 mm)	Within spec.
Area 1	±1.0	0.92	4/5 frames	1.04	4/5 frames
Area 2	±1.0	1.04	5/5 frames	1.04	4/5 frames
Area 3	±1.5	0.74	5/5 frames	1.02	4/5 frames
Area 4	±1.5	0.94	5/5 frames	1.14	4/5 frames
Area 5	±1.5	1.64	4/5 frames	1.74	3/5 frames
Area 6	±1.0	1.02	5/5 frames	1.20	4/5 frames
Area 7	±1.0	0.66	5/5 frames	0.82	5/5 frames
Area 8	±1.5	1.42	4/5 frames	1.38	3/5 frames
Area 9	±1.5	1.68	4/5 frames	1.46	2/5 frames
Overall compliance		1.12	41/45 (91%)	1.20	33/45 (73%)

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The systematic measurement approach across nine critical areas provided a comprehensive evaluation of distortion characteristics and geometric compliance, following established quality assessment methodologies in welding applications (Machado et al., 2019). Areas with tighter tolerance requirements (±1.0 mm) showed consistent improvements when jigs were utilized, with Areas 1, 2, 6, and 7 demonstrating better dimensional control. The jig system effectively controlled thermal distortion through mechanical constraints and consistent heat distribution patterns, supporting the welding distortion theory that emphasizes the importance of constraint systems (Miller, 2006).

Critical measurement areas that traditionally exceeded tolerance limits demonstrated improved compliance rates when jigs were implemented. Area 9, which historically presented challenges due to its location in high-stress regions, showed improvement from 40% to an 80% compliance rate. The overall compliance improvement from 73% to 91% represents a significant quality enhancement that directly impacts customer acceptance and reduces rework requirements, consistent with quality control principles in precision manufacturing (Hartanti, 2016).

Process flow and workstation analysis

The analysis of processing time distribution across different workstations revealed important insights into bottleneck identification and resource allocation, following established principles in manufacturing system analysis (Taifa & Vhora, 2019). Table 9 presents the workstation-based time analysis showing the impact of jig implementation across different manufacturing stages.

Table 9. Workstation time distribution analysis

Workstation	Work elements	Jig method (min)	Non-jig method (min)	Impact level
Preparation	Kitting/setup	52.9	52.9	No impact
Primary welding	Weld 1, 6	568.8	842.5	High impact
Secondary welding	Weld 2,3,4,5	152.8	156.2	Low impact
Finishing	Grinding	86.6	86.6	No impact
Quality control	Alignment/inspection	331.6	409.7	Medium impact
Total		1192.7	1547.9	Overall reduction

Workstation analysis identified primary welding operations as the most significant beneficiary of jig implementation, with a reduction of 273.7 minutes representing the largest single improvement. This finding aligns with theoretical expectations from manufacturing systems theory, as complex welding operations benefit most from controlled positioning and reduced setup variations (Manladan et al., 2017). Secondary welding operations showed minimal impact due to their straightforward nature and shorter cycle times.

The quality control workstation, encompassing alignment and inspection procedures, demonstrated moderate improvements of 78.1 minutes. This reduction reflects the preventive benefits of controlled welding conditions, which minimize distortion and reduce subsequent correction requirements (Machado et al., 2019). The consistent improvement across multiple workstations indicates that jig benefits extend beyond immediate welding operations to affect downstream processes, supporting the systems approach to manufacturing improvement (Ma et al., 2012).

Economic and practical implications

The documented improvements translate directly to measurable economic benefits through multiple pathways, consistent with economic analysis principles in manufacturing optimization (Shukla et al., 2023). The total time reduction of 355 minutes per frame represents substantial labour cost savings and increased

https://doi.org/10.24191/jmeche.v14i1.8780

production capacity. Assuming standard labour rates and facility costs, this improvement enables additional production capacity within existing operational hours.

Quality improvements simultaneously reduce rework requirements and material waste, contributing additional cost savings. The improved compliance rate from 73% to 91% significantly reduces rejection rates and associated costs including material replacement, additional labour, and schedule delays. Customer satisfaction improvements through consistent quality delivery provide long-term competitive advantages, supporting quality management principles in manufacturing (Hartanti, 2016).

From a practical implementation perspective, the jig system demonstrated robust performance across varied operating conditions and operator skill levels. The mechanical design proved reliable throughout the study period, requiring minimal maintenance while providing consistent positioning accuracy. Training requirements for jig utilization were minimal, with operators adapting quickly to standardized setup procedures, supporting the principle that well-designed fixtures reduce training requirements (Joshi, 2003).

The scalability of jig implementation presents opportunities for broader application across similar manufacturing operations. The modular design approach enables adaptation to product variants while maintaining core benefits of controlled positioning and reduced setup complexity. Investment analysis indicates favourable return periods through combined time savings and quality improvements, consistent with manufacturing investment evaluation principles (Said et al., 2023).

CONCLUSION

This study demonstrates that welding jigs provide substantial improvements in precision manufacturing through 23% reduction in processing time (25.8 to 19.9 hours per frame) and enhanced dimensional compliance (73% to 91%). The most significant benefits occurred in critical welding operations, particularly primary welding stages, where complex geometries traditionally presented efficiency challenges. The jig system effectively eliminated repetitive setup procedures and reduced alignment requirements, while quality assessment outcomes confirmed superior control over thermal distortion patterns and reduced variation between individual frames.

From economic and practical perspectives, the documented improvements translate to measurable benefits, including direct labour cost reduction, increased production capacity, decreased rework requirements, and improved material utilization. The quality improvements simultaneously reduce rejection rates while enhancing customer satisfaction through consistent delivery of specification-compliant products. The relatively simple mechanical design ensures minimal maintenance requirements while providing robust performance across varied operating conditions, making the solution practical for widespread implementation.

The research establishes welding jigs as valuable tools for precision manufacturing environments seeking operational improvements. The quantitative evidence supports the business case for jig implementation while providing practical guidance for manufacturing professionals considering similar process enhancements. The systematic methodology employed provides a framework for evaluating fixture applications in broader manufacturing contexts, contributing to the understanding of how traditional industrial engineering principles can yield significant benefits in competitive manufacturing environments.

https://doi.org/10.24191/jmeche.v14i1.8780

ACKNOWLEDGEMENTS/ FUNDING

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through the Matching Grant [Q274] and Industrial Grant [M116]. The author would also like to thank the Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia, and Intec Precision Engineering Sdn. Bhd. for providing the necessary research facilities for this study.

CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: **study conception and design**: Mohd Haziq Asyraaf Abu Bakar, Tay Sin Kiat; **data collection**: Mohd Haziq Asyraaf Abu Bakar, Tay Sin Kiat; **analysis and interpretation of results**: Mohd Haziq Asyraaf Abu Bakar, Shahrul Azmir Osman, Saliza Azlina Osman; **draft manuscript preparation**: Mohd Haziq Asyraaf Abu Bakar, Nursyazwani Zulkefli, Shahrul Azmir Osman. All authors reviewed the results and approved the final version of the manuscript.

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