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Sai Sasank Pothamsetti
Minnesota State University, Mankato

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Comparative Study of Robotic and Manual Welding in A Low Volume-High Mix Manufacturing Environment: Case Study of Lift Ring

By

Sai Sasank Pothamsetti

A Thesis Submitted in Partial Fulfillment of the
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Sai Sasank Pothamsetti

This Thesis has been examined and approved by the following members of the student's committee.

Advisor

Committee Member

Committee Member

Contents

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Disclaimer

This thesis paper represents the collaborative efforts of five students, Aditya Suggula, Mayank Srinivasa Murthy, Niloufer Sarah, Poorna Pragna Mysore and Sai Sasank Pothamsetti, each investigating different segments of the subject matter. While the theoretical framework and foundational concepts may appear identical, underscoring our unified approach and understanding, specific portions of our work, notably the MTM1 analysis and MOST analysis, were undertaken as joint efforts. These sections were collaboratively developed to leverage our collective expertise, ensuring a rigorous and comprehensive examination. Beyond these shared analyses, the calculations and subsequent analyses within our individual papers are distinct, reflecting the unique contributions and insights of each student. This dual approach—combining collaborative and individual efforts—ensures a cohesive theoretical foundation while embracing diversity in analytical perspectives and conclusions across our varied parts.

COMPARATIVE STUDY OF ROBOTIC AND MANUAL WELDING IN A LOW VOLUME-HIGH MIX MANUFACTURING ENVIRONMENT: CASE STUDY OF LIFT RING

SAI SASANK POTHAMSETTI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN MANUFACTURING ENGINEERING TECHNOLOGY

MINNESOTA STATE UNIVERSITY, MANKATO
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[April 2024]

ABSTRACT

A comparative study of robotic and manual welding in a low volume high mix manufacturing environment focusing on a truck body part named the lift ring to see if there is a benefit of incorporating robotic welding into the production line. By utilizing predetermined time studies such as Methods Time Measurement 1(MTM-1) and Maynard’s Operation Sequence Technique (MOST) in conjunction with normal time and motion study to see which method of time study can be used to extrapolate the times of production for higher number of parts. MTM-1 and MOST were used for a detailed time and motion analysis which were then used to evaluate the efficiency and cost implications and feasibility of incorporating a co-bot welder to execute the tasks of an experienced human welder. Necessity to do the cost analysis and comparison of the co-bot is understanding of the additional cost related to robotic welding such as the fixture costs which include the design cost and fabrication cost, the programming costs, and the common welding costs. The MTM-1, MOST and normal time study was performed, and it was found that MTM-1 is closer to actual in the case of Manual welding, and MOST is closer to the actual time in case of Robotic welding. With the average welding process times used for the cost analysis, the robotic welding breaks even in less than 16 days with the daily working hours being 6. If the robotic welding process is optimized by 5%, the break-even will be in less than 10 days, and if it is optimized by 10% , the break-even will be less than a week.

COMPARATIVE STUDY OF ROBOTIC AND MANUAL WELDING IN A LOW VOLUME-HIGH MIX MANUFACTURING ENVIRONMENT: CASE STUDY OF LIFT RING

In the manufacturing sector, a substantial volume of components undergoes welding, stamping, and machining across diverse industries, including companies like TBEI, which specializes in Truck Bodies and Equipment. This equipment includes heavy lifting hooks, dumper buckets, and lifting rings designed to move hefty loads. Within the manufacturing process, particularly during welding, a pivotal question arises regarding the potential for automation or robotization on the shop floor. While many shop floor activities, such as inventory control and CNC machining, are commonly automated, the welding process, especially manual arc welding for design-critical equipment in smaller industries, remains largely untouched by automation or robotics, unlike the prevalent use of spot-welding automation in more prominent automotive sectors.

This study addresses this disparity by conducting a time-motion analysis of skilled human welders. The ultimate goal is to automate the manual arc welding process under low volume, high mix conditions using the lifting D ring weld procedure as a subject for the study and analysis.

Welding

Welding is a process of joining materials, and it can be broadly categorized into three groups: fusion welding, pressure welding, and brazing/soldering. Each group consists of various welding methods, chosen based on factors like the materials being joined and the desired functionality of the final product. (Giachino, (1973).)

Types of Welding:

1. Fusion Welding:

   Fusion welding involves melting the base materials or combining them with a welding rod. This category includes methods like arc welding, electron beam, gas, and laser welding. These methods use different energy sources, such as electrical, chemical, or light, to create the necessary heat for melting and joining.

2. Brazing/Soldering:

   In brazing/soldering, a filler material (brazing paste) is applied to the joining sections. This category includes induction heating brazing, torch brazing (flame brazing), light beam, and laser brazing. The energy sources for these methods can be electrical, chemical, or light.

Fusion Welding:

Fusion welding, a term frequently used but not universally understood, entails heating two or more objects and joining them without external pressure. (Giachino, (1973).) Depending on the job requirements, filler materials may be incorporated during fusion welding. This distinguishes fusion welding from non-fusion welding, which utilizes lower heat levels, ensuring the base metal does not melt. Examples of non-fusion welding include soldering, pressure welding, and brazing.

Before delving into fusion welding, it is essential to understand welding as a manufacturing process (KEYENCE America, n.d.). Recent research by the American

Welding Society highlights the substantial impact of welding, which contributes to 50% of the gross domestic product in the United States. Welding involves utilizing heat to attach two or more similar or non-identical items, with the use of a filler optional based on the nature of the work.

Types of Fusion Welding. Fusion welding, by definition, involves joining heat to connect two edges of either the same or different materials. The heated portions melt and, upon cooling, fuse. In cases of a significant gap between the two pieces, filler material may be employed. The heating process introduces a heat-affected zone within the materials, subjecting the base material to various stages.

Fusion welding occurs when the molten components of the base material mix with the molten filler. This process employs heat to produce an exterior junction at the weld point or melt the material in the joining zone. The FC-120 Gasless Flux Cored Wire Inverter Welding Machine is recognized as a top tool for executing various forms of fusion welding.

Fusion welding is Categorized based on the heat source. Common fusion welding styles include ACR welding and various forms of fusion arc welding (Shielded Metal Arc Welding, Tungsten Inert Gas Welding, Metal Gas Arc Welding, Submerged Arc Welding, Plasma Arc Welding, and Flux Cored Arc Welding). Gas welding, high-energy welding (Electron Beam Welding and Laser Welding), resistance welding (for seams and spot resistance welding), and friction welding (rotary, spot, linear, and stir friction welding) are also prevalent.

Arc Welding.

- Overview: Arc welding stands out as the most popular and widely used type of fusion welding. It relies on an electric arc to join two or more objects of the same or similar materials.

- Process: The electric arc generated in arc welding can reach temperatures of up to 6,000 degrees Fahrenheit, making it capable of melting even the toughest metals. This process involves creating a molten pool at the welding point, allowing the objects to fuse seamlessly.
- Special Features: Arc welding is not confined to conventional settings; it can be performed underwater, making it particularly advantageous for offshore welding projects where traditional welding methods might face challenges.

Laser Welding.

- Laser welding is a technique that employs a lens to focus light with high directivity and convergence, creating a high-energy density beam utilized as the primary heat source.
- By manipulating the laser beam output, penetration welding with a narrow width compared to the depth becomes feasible. Additionally, brazing and soldering can be achieved by melting and joining an alloy with a lower melting point than the base material.
- Notable advancements in laser output efficiency underscore the significance of laser welding in the future of manufacturing. This segment provides an overview of the common technologies employed in laser welding.

Principles of laser welding.

- Modulating the intensity and spot size of the laser beam emitted by a laser processing machine facilitates the welding and engraving of letters and patterns on the surface of base materials and cutting operations.
- In laser welding, a significantly stronger laser beam than those used in other processes is the heat source for melting and joining base materials. Employing a

high-power output laser necessitates precise control over the beam convergence properties, including wavelength and energy density, and laser beam qualities, such as intensity and beam mode. Despite these requirements, laser welding proves versatile, accommodating delicate applications while excelling in joining both thick and thin plates.

Induction Welding.

- Overview: Induction welding distinguishes itself by relying on a unique principle that does not involve direct contact between an object's surface and the heat source.
- Process: Instead of direct contact, a wrapped coil is employed to create a magnetic field, which, in turn, induces heat in the metal. The magnetic field rapidly heats the metal surfaces, causing them to melt and fuse.
- Advantages: Induction welding offers rapid heating and minimal distortion, making it suitable for specific applications with critical precision and efficiency.

Oxyfuel Welding.

- Overview: Oxyfuel welding is a chemical-based fusion welding process that utilizes a flame to heat and join surfaces, with oxygen as the primary fuel source.
- Process: The fundamental principle is the reliance on oxygen to fuel the fire, creating a hot flame exceeding 4,500 degrees Fahrenheit. This intense heat is applied to the surfaces, allowing them to reach the molten state and fuse.
- Versatility: Oxyfuel welding is versatile and finds application in various industries, particularly where a portable and easily controllable heat source is required.

Solid Reactant Welding.

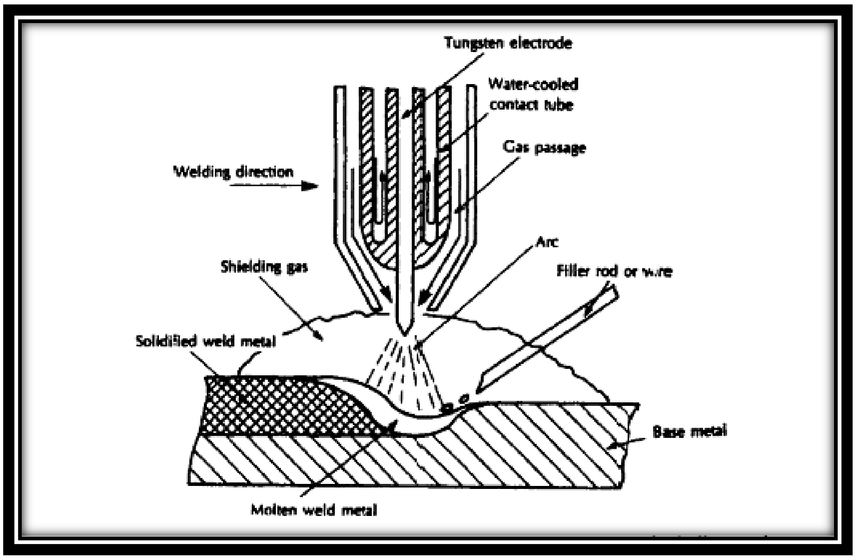
- Overview: Solid reactant welding is a fusion welding type that leverages chemical reactions with specific materials to achieve the joining process.
- Process: Certain compounds can generate heat when mixed. Solid reactant welding utilizes this principle, initiating chemical reactions that produce the required heat to join two or more objects.
- Applications: This type of fusion welding is applied in scenarios where chemical reactions can be harnessed for welding purposes, offering a unique approach to joining materials.

Non-Consumable (Non-Fusible) Electrode Type.

TIG Welding (Tungsten Inert Gas Welding). TIG welding, also known as Gas Tungsten Arc Welding (GTAW), falls under the non-consumable electrode category. TIG (Tungsten Inert Gas) welding employs an inert gas in the welding process. This particular arc welding method is characterized by its spark-free nature and is suitable for welding various metals, including stainless steel, aluminum, and iron. Non-consumable tungsten is the discharge electrode, while an inert gas such as argon or helium acts as the shielding gas. The process initiates an arc within the inert gas, utilizing the generated arc heat to melt and weld the base material. Despite the use of filler material, instances of spatter are minimal due to the inert gas's comprehensive coverage of the weld area, ensuring a stable arc.

Figure 1

TIG welding (Messler, 1999)



A semi-automatic TIG welding machine comprises essential components, including the welding power supply, welding torch, and a gas cylinder with a gas flow controller. Additional instruments may be incorporated, especially when using a water-cooled torch or filler material in wire form.

The choice of electric current polarity (positive or negative) depends on the base material, necessitating a controller in the welding power supply to select the appropriate polarity accordingly. (Messler, 1999)

The welding process in TIG welding involves various classifications based on factors such as AC or DC power usage, the application of pulse or non-pulse current, and whether a filler wire is utilized.

The choice of AC or DC is contingent upon the base material being used. Additionally, the option of pulse or non-pulse current is available. Pulse TIG welding, for instance, involves the alternating change of welding current at a constant frequency between pulse current and base current. This results in periodic melting of the base material during the pulse current and subsequent cooling during the base current, creating weld spots resembling a string of beads. Furthermore, TIG welding can be categorized into two types based on a filler wire: cold and hot. Cold wire welding utilizes a standard filler wire, while hot wire welding preheats the wire by passing a current through it. Hotwire welding offers the advantage of increasing the deposition rate per unit time, allowing for quicker completion of the welding process. This addresses the time-consuming aspect of TIG welding, where high-quality welds are achieved but may take longer due to the gradual melting of the required filler material.

Table 1

Weld parameters for TIG welding

Output current	**Pulse**	**Frequency**
Direct current (DC)	Yes	Low frequency (0.5 Hz to 20 Hz)
		Medium frequency (20 Hz to 500 Hz)
		High frequency (20 kHz or higher)
	No	-
Alternate current (AC)	Yes	Low frequency (0.5 Hz to 20 Hz)
		Medium frequency (20 Hz to 500 Hz)
	No	

Key Features of TIG Welding include:

- Precision Welding: TIG welding allows for precise and intricate welds, making it suitable for applications where accuracy is crucial.
- Clean Welds: Using inert gas prevents atmospheric contamination, producing clean and high-quality welds.
- Versatility: TIG welding applies to various materials, including exotic metals and thin sheets.

Plasma Welding.

- Plasma welding is another non-consumable electrode type that shares similarities with TIG welding but utilizes a more focused plasma arc. Characteristics of plasma welding include:
- Increased Energy Density: The focused plasma arc increases energy density, allowing deeper penetration into the material.
- Enhanced Welding Speed: Plasma welding is known for its increased welding speed, contributing to efficiency in various applications.
- Narrower Heat-Affected Zone: The concentrated heat minimizes the size of the heat-affected zone, reducing potential distortions.

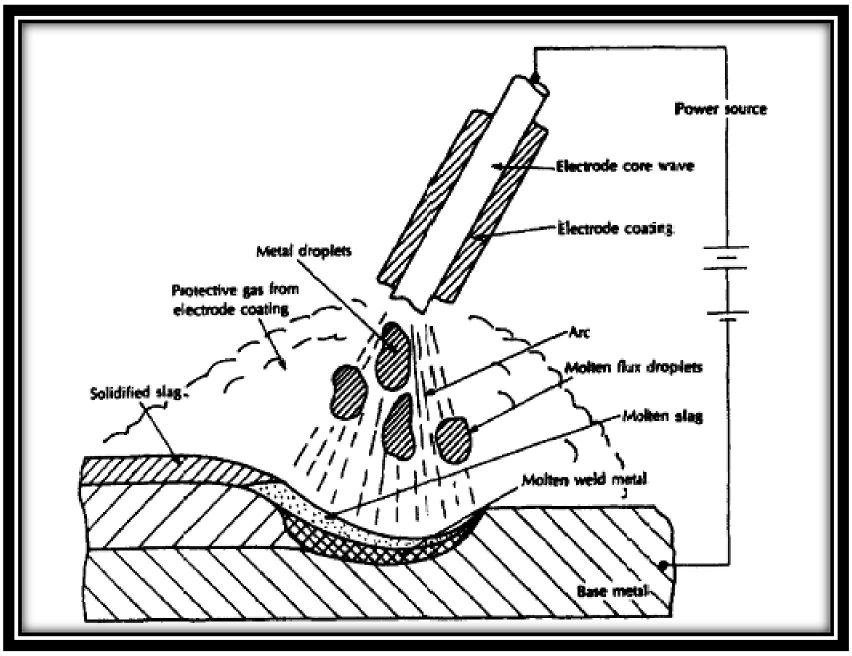
Consumable (Fusible) Electrode Type.

Shielded Metal Arc Welding (SMAW). Shielded Metal Arc Welding, commonly known as stick welding, is a consumable electrode type where a coated electrode is used. Shielded metal arc welding (SMAW) illustrates consumable (fusible) electrode-type arc welding. It employs a metal rod (known as a shielded metal arc welding rod) crafted from the same material as the base material, serving as the electrode. The arc between the electrode's core wire and the base material functions as the heat source.

The resulting molten metal is enveloped by the gas and glass-like slag produced from the shield of the core wire. This process boasts the advantage of being less susceptible to interference from wind or other external disturbances at the worksite due to the shielding provided by the gas and slag. Additionally, a shielding tube forms at the tip of the welding rod. SMAW has a rich history. It is often performed manually and earned the moniker manual arc welding. While its prevalence has diminished with the proliferation of automatic or semi-automatic MAG welding machines utilizing carbon dioxide (CO2), SMAW continues to find applications owing to its merits of facilitating quick and straightforward welding indoors and outdoors, coupled with relatively inexpensive equipment. (Messler, 1999)

Figure 2

Shielded Metal Arc Welding (SMAW) (Messler, 1999)



Features of SMAW include:

- Versatility: SMAW is versatile and can be applied to various materials and joint configurations.

- Portability: It is suitable for outdoor and remote applications, offering portability and ease of use.
- Cost-Effective: SMAW equipment is generally more affordable, making it a cost-effective choice for specific applications.

MAG Welding (Metal Active Gas Welding). Metal Active Gas Welding, or MAG welding, is a consumable electrode type that employs a continuously fed wire and a shielding gas with active components. MAG (Metal Active Gas) welding, or CO2 arc welding or CO2 welding, is a form of arc welding that employs an active gas, typically carbon dioxide (CO2) or a gas mixture of argon and CO2. Primarily utilized for automatic or semi-automatic welding of ferrous metals, MAG welding is unsuitable for nonferrous metals like aluminum due to the chemical reactions involving CO2.

In automatic or semi-automatic MAG welding, a coiled welding wire is an electrode, replacing the welding rod used in manual shielded metal arc welding. The coiled wire is connected to the wire feed unit and automatically directed to the torch tip by a feed roller driven by an electric motor. Upon passing through the contact tip, the wire is energized.

The welding process involves striking an arc between the wire and the base material. This simultaneous melting of the wire and base material creates a weld. Throughout this process, shielding gas is introduced through a nozzle into the weld area and its surroundings, forming a protective shield around the arc and weld pool, preventing exposure to the atmosphere. CO2 gas, a gas mix of argon and CO2, or a mix of argon with a small percentage of oxygen can be used as the shielding gas. Compared to shielded metal arc welding, MAG welding boasts a faster deposition rate, where the electrode transforms into weld metal. This results in increased work efficiency, which is attributed to deep penetration into the base material. Other notable advantages include high-quality weld metal and the ability to achieve automatic welding by installing the welding torch on a robot.

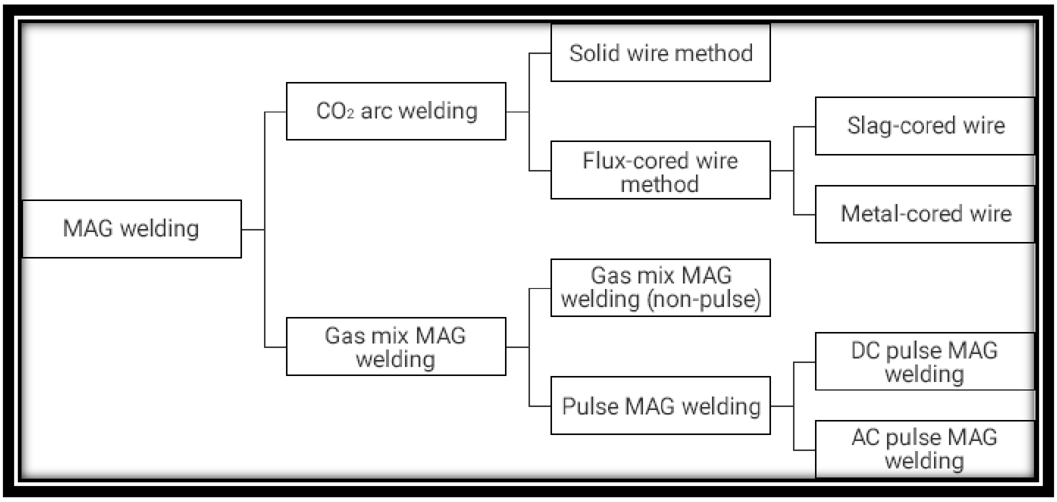
A semi-automatic MAG welding machine mainly consists of the following:

- Welding power supply
- Wire feed unit
- Welding torch
- Gas cylinder

The feed unit must feed the wire at a constant speed. Consequently, a constant-voltage characteristic power supply is generally used for the welding power supply. The wire feed unit is a continuous speed feeding type.

Figure 3

Flow chart on the different MAG welding techniques.



Key attributes include:

- High Productivity: MAG welding offers high deposition rates, making it suitable for rapid welding applications.
- Automated Processes: MAG welding is commonly used in automated systems, enhancing efficiency and precision.

- Adaptability: It is suitable for various materials and thicknesses, providing versatility in welding processes.

MIG Welding (Metal Inert Gas Welding). MIG welding, or Gas Metal Arc Welding (GMAW), is similar to MAG welding but typically uses inert gases for shielding. MIG (Metal Inert Gas) welding is another arc welding method. Similar to TIG welding, it utilizes an inert gas as a shielding gas. MIG welding belongs to the consumable electrode type, involving a discharge electrode that melts during welding. (Understanding the Fusion Welding Process - Arc Machines, n.d.)

This welding technique is commonly employed for joining stainless steel or aluminum alloy workpieces, and the choice of shielding gas depends on the specific metal to be welded. The electrode in MIG welding is a coiled welding wire, connected to the wire feed unit, which automatically moves to the torch tip through a feed roller powered by an electric motor. The wire is energized upon passing through the contact tip, initiating an arc between the wire and the base material. Simultaneously melting the wire and base material, this process forms the weld. Throughout the operation, shielding gas is delivered through a nozzle into the weld area and its surroundings to create a protective shield around the arc and weld pool, preventing exposure to the atmosphere.

Figure 4

MIG Welding. (Messler, 1999)

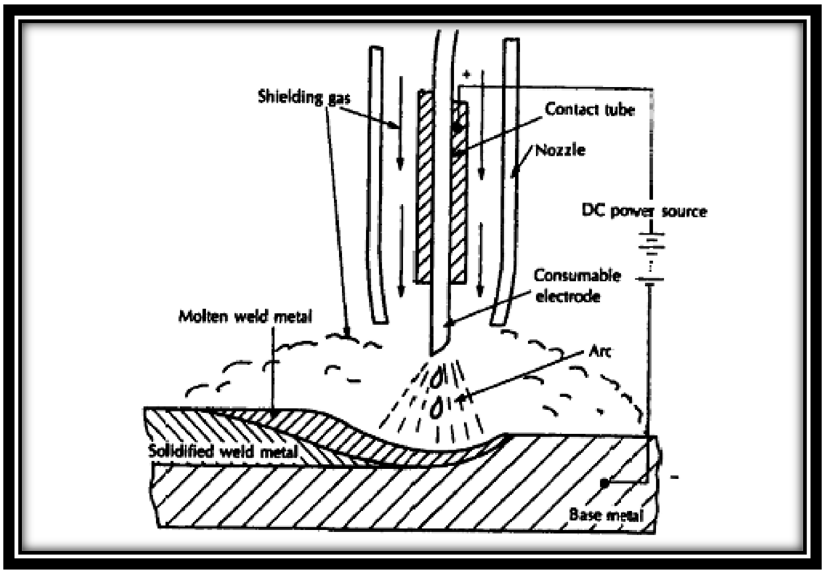


Table 2

Classification of MIG Welding.

Classification of MIG welding	**Pulse**	**Welding method**
Direct current (DC)	No	Short-arc MIG welding
		Spray MIG welding
		Large-current MIG welding
	Yes	Pulse MIG welding
		Low-frequency superimposed pulse MIG welding.
Alternate current (AC)	Yes	AC pulse MIG welding
		Low-frequency superimposed AC pulse MIG welding.
DC + AC	Yes	AC/DC composite pulse MIG welding

Notable features of MIG welding include

- Ease of Use: MIG welding is known for its user-friendly nature, making it suitable for beginners and manual applications.
- High Productivity: The continuous wire feeding mechanism contributes to high productivity in various welding processes.
- Reduced Cleanup: MIG welding minimizes spatter and fumes, reducing the need for extensive post-weld cleanup.

Electro gas Arc Welding (EGW). Electro-gas Arc Welding is a consumable electrode type that involves welding in a vertical position with a continuously fed consumable electrode and a gas shield. The Electro gas arc welding (EGW)technique was developed to facilitate efficient vertical position welding of thick plates with stable penetration. The primary shielding gas employed in EGW is commonly CO2, although variations using argon gas, gas mixes of argon and CO2, oxygen, or helium are also prevalent. Flux-cored wires, which generate slag to form a clean bead, are predominantly utilized for welding wire, although solid wires find application in specific cases. The welding power supply is typically a DC constant-voltage or constant-current (drooping) characteristic power supply.

During the process, the weld pool is enclosed by the end of the base material, a copper shoe, and a fire-resistant backing. Vertical position welding is executed upwards, preventing the dripping of molten metal and enabling the welding of a thick plate in a single pass (one operation). Noteworthy advantages include a rapid deposition rate facilitated by a large current, high efficiency, and a relatively substantial margin for groove accuracy due to minimal angular distortion.

EGW finds application in welding vertical butt joints of various products, including ship's shell plates, bridges, storage tanks, and pressure vessels.

Characteristics of EGW include:

- Vertical Welding: EGW is particularly effective for vertical welding of thick plates, providing high-quality welds.
- High Deposition Rates: The process allows for high deposition rates, improving efficiency in specific applications.
- Reduced Distortion: Electro-gas arc welding reduces distortion due to its vertical welding orientation.

Applications of Fusion Welding:

Fusion welding finds extensive applications in constructing significant structures like airplanes, bridges, ships, pressure tanks, and welded pipes. Its versatility allows the merging of various materials, regardless of thickness, owing to the substantial heat levels generated during the process.

Fusion Welding in Different Materials:

- Metal Joining: Fusion welding involves intense heat to unite two or more metal pieces. Unlike soldering, fusion welding melts the base metal and may require a filler material to create a junction. As the molten components cool, they come together to produce a weld bead, resulting in a final product more durable than the starting material.
- Plastics Joining: Fusion welding is applicable in joining polymers, whereas solvent welding employs adhesives. The process involves washing and drying surfaces, applying pressure and heat to the molten component, and finally cooling the molten components to solidify the link between the two polymers.
- Wood Materials Joining: Fusion welding for wood components requires heat production through mechanical friction. This involves subjecting materials to high pressure, followed by linear friction, generating heat to fuse two wooden components. The process is simple,

eliminating the need for nails or adhesive, and results in a more robust finished product while preserving the original design.

Pros and Cons of Fusion Welding.

Pros:

- Use of Filler Material: Fusion welding allows the use of filler material when joining two wide sections.
- No External Pressure: The absence of external pressure preserves the initial shape of the welded components.
- Minimal Edge Design and Preparation: Fusion welding does not necessarily require intricate edge design and preparation, simplifying the process.
- Durable Welded Joints: Fusion welding produces robust joints between parent materials.
- Suitable for Industrial Processes: Fusion welding's speed and simplicity make it well-suited for various industrial applications.

Cons:

- Challenges with Dissimilar Materials: Joining two materials with different melting points can be challenging.
- Stress and Damage: Fusion welding may induce stress and damage on the welded component due to the need for fusion and solidification.
- Alteration of Parent Material: The original structure of the parent material changes the heating process.

- Heat-Affected Zone Weakness: The linked parts create a heat-affected zone, generally considered the weakest point in the entire structure.

Other Unique forms of welding.

- Electron Beam (light beam) Welding:
- Pressure Welding
- Friction welding

Electron Beam Welding. Electron beam (EB) welding relies on the emission of electrons in a vacuum tube or Braun tube. This welding method is primarily executed in a vacuum, known as high-vacuum welding. It stands out for its ability to minimize distortion across various applications, accommodating thick to thin plates and intricate welding requirements. In recent advancements, electron beam welding machines have been designed to operate effectively without a perfect vacuum (low-vacuum welding machines) or by incorporating a moving electron gun (moving electron gun welding machines), broadening the scope of potential applications.

Applications for electron beam welding include ship's shell plates, bridges, storage tanks, aircraft parts, and electronic components. In the realm of electronic components, a process known as electron beam sealing is employed to seal crystal oscillators that require joining in a vacuum. This involves vacuum brazing sealing, achieved by melting the filler material between a metal lid and a ceramic package through heat conduction induced by the electron beam. (Sterkenburg, 2021)

Pressure Welding: Pressure welding is a fundamental technique in metal joining processes. Unlike fusion welding, where heat is the primary agent, pressure welding requires force to create a solid and durable bond between materials. This process is extensively used in various industries due to its efficiency, precision, and versatility.

Types of Pressure Welding:

- Cold Welding
    1. Cold welding occurs at or near room temperature without applying external heat. This technique is particularly suitable for materials with high ductility.
    2. Commonly used in joining similar metals, cold welding relies on clean surfaces and high pressure to create a strong bond.
- Explosion Welding
    1. Explosion welding utilizes explosive forces to create a high-velocity collision between two materials, leading to their metallurgical bonding.
    2. This technique is effective for joining dissimilar metals, offering advantages in terms of versatility and compatibility.
- Ultrasonic Welding
    1. Ultrasonic welding employs high-frequency ultrasonic vibrations to generate localized heat and pressure, facilitating welding.
    2. Ultrasonic welding offers rapid and precise bonding, commonly used to assemble plastics and non-ferrous metals.

Friction Welding:

- Friction welding involves rotating one component against another, generating heat through friction. Once the materials reach a plastic state, pressure is applied to achieve a solid weld.
- This technique is versatile, applicable to similar and dissimilar materials, and particularly effective in joining cylindrical components.
- This technique induces high-speed friction between the base materials, be it metal or resin, causing them to soften through the generated heat. Subsequently, pressure is applied to facilitate their joining.

- Notably considered an environmentally friendly joining method, it eliminates the need for an external heat source beyond friction heat. Additionally, it removes the necessity for welding rods or flux, and unlike arc welding or gas welding, it produces no spatter or gas.
- Friction welding can be precisely controlled based on friction thrust (pushing force), rotation speed, and time. With these parameters numerically controlled, friction welding can be automated without human intervention, making it widely utilized in factory automation (FA).
- A notable variant of friction welding is Friction Stir Welding (FSW), which has garnered significant attention. In this process, a cylindrical tool with a probe (protrusion) rotates at high speed, and the tool is moved so that the probe digs along the joining section with high pressure.
- The tool's rotational motion softens the base materials, stirring the area around the weld to induce plastic deformation and atomic bonding between the materials.

Brazing/Soldering Welding (Messler, 1999):

Brazing. Brazing, a welding method utilizing filler materials with high melting points, encompasses various techniques. Torch brazing utilizes a conventional gas welding torch for heat, while induction heating brazing employs high-frequency induction heating. Controlled atmosphere brazing inside a vacuum furnace without flux involves heating and cooling the base and filler materials. These methods find applications in the non-oxidizing brazing of stainless steel and the automated joining of titanium and ceramic workpieces.

In recent times, laser brazing has emerged as a noteworthy brazing technique. Laser brazing utilizes light energy (laser) to melt a wire-shaped filler material supplied between base materials for joining. This process minimizes the melting of the base materials, resulting in reduced thermal deformation. Consequently, lightweight, and highly rigid joining can be achieved without compromising product design.

Resistance spot welding was traditionally employed for joining automobile roofs, side panels, and trunk lids. This involved additional processes like creating a groove for resistance spot welding and covering the part with molding to conceal the groove and weld spots. Laser brazing, on the other hand, preserves the appearance of the base material, eliminating the need for processes such as working the groove and preparing molding. Moreover, laser brazing significantly enhances joint strength and joining speed compared to resistance spot welding, making it a preferred choice in the automotive and other industries, particularly in Europe and Japan.

Soldering. In brazing and soldering, soldering is a joining method employing filler materials with low melting points. In contrast to brazing, soldering harnesses a light beam as its heat source. This section delves into the intricacies of soldering, a technique frequently employed for detailed joining work. Traditional soldering relies on heat generated by an electric current, often facilitated by a soldering iron. Variants of soldering methods encompass dip and reflow soldering, where components are united by immersing them in molten solder.

Light beam soldering has gained prominence in recent years, particularly in producing electronic components within the realm of factory automation. In this process, light emanating from a high-power source is collected by a reflector and precisely focused on the welding point. Soldering is then executed utilizing the energy derived from the light. Leveraging solders with low melting temperatures (soft filler materials) and enabling the utilization of robots for meticulous joining proves invaluable for assembly automation and the mass production of heat-sensitive electronic components.

Welding Automation:

The realm of welding has undergone a transformative shift, propelled by the widespread adoption and decreasing costs of factory automation (FA) equipment due to advancements in digital technology. This evolution has seen welding methods progress from manual to semi-automatic to fully automatic welding. Simultaneously, the integration of robot welding has witnessed substantial growth, particularly in industries like automotive, where it has become an indispensable component for optimizing welding processes. This surge in robot usage is bolstered by cutting-edge instruments such as sensors, displacement meters, controllers, and programmable logic controllers (PLCs), which enable swift, precise detection, and feedback control. The incorporation of robots into welding procedures is on a steady rise.

Robotic Welding:

Robotic welding entails employing a robotic arm to grasp and maneuver the welding torch, with the robot programmed to execute a specific torch movement pattern to achieve the desired weld. Equipped with sensors, the robot continually monitors the welding process, making adjustments as required (Chen, 2014) (Wang, 2020) (Zheng, 2022) (Pedersen, 2016) (Lopes, 2017).

Controlled by a specialized computer program tailored for welding, the robot receives torch movement and manipulation instructions. It also integrates feedback from monitoring sensors to adapt during the welding process. A typical robotic welding system comprises various essential components harmonizing to automate welding tasks:

- Robot: This is primarily responsible for physically executing the welding, typically realized through a multi-axis robotic arm under computer control.

- Welding Equipment: Encompasses the welding power source, torch, and additional equipment like wire feeders, gas supplies, and control panels.
- Control System: This involves the computer orchestrating robot movements, the power supply for welding equipment, and other peripherals such as sensors and cameras.
- Programming: This involves utilizing specialized software that enables users to define robot movements, power supply parameters, and other necessary settings for the welding process.

The operation of the robotic welding system:

1. The robot is instructed to follow a specific pattern tailored to the shape of the workpiece.

2. Activating the welding equipment, the welding torch is brought into contact with the workpiece.

3. Utilizing feedback from sensors, cameras, or other peripherals, the robot's control system adjusts its position and movement to ensure a consistent weld along the workpiece edges.

4. The robot progresses along the programmed path, executing the welding process as it advances.

5. Upon completion of welding, the robot and welding equipment are deactivated, and the workpiece is removed.

Notably, the robotic welding system can incorporate advanced technologies such as machine vision, sensor-based feedback control, and artificial intelligence to enhance its performance, precision, and flexibility.

List of sensors & systems necessary for the robots to function:

Systems:

- Control Systems
- Programming
- Machine Vision
- 2D machine vision
- Open CV

Sensors:

- Camera-based sensors
- Force Based Sensors
- Position Sensors
- Temperature Sensors
- Current Sensors
- Gas Sensors
- Proximity Sensors

Features of the robot for welding purposes. Several essential characteristics are necessary for a robot to engage in welding which includes (Lei, 2020) (Pires J. N., 2006) (Xu, 2017):

1. Substantial payload capacity: Welding robots need to support the weight of welding equipment and execute welding tasks effectively.

2. Precise and consistent performance: Achieving consistent, high-quality welds demands robots with precise movements and repeatability.

3. Sturdy construction: Maintaining rigidity and stiffness is crucial for welding robots to ensure accurate welding.

4. Swift motion and acceleration: Efficient welding requires robots capable of swift movement and rapid acceleration.

5. Resistance to high temperatures: Welding robots should endure high temperatures and harsh conditions inherent in welding processes.

6. Management of welding torch: Robots must manage the welding torch adeptly, maintaining a steady distance and angle relative to the workpiece.

7. Versatility in welding processes: Welding robots must accommodate various welding techniques such as MIG, TIG, and Stick welding.

8. Incorporation of safety measures: Robots should include safety features like emergency stop buttons, light curtains, and fire suppression systems to safeguard operators from welding hazards.

9. Adaptability: Flexibility is essential for welding robots to operate effectively across diverse environments and tasks.

Robots for welding:

Various types of robots are commonly employed for welding purposes (Herath, 2022) (Siciliano, 2016) (Kurfess, 2018) (Tsai, 1999):

1. Articulated Robots: Equipped with multiple rotary joints facilitating multidirectional movement, articulated robots boast high payload capacity and precision, rendering them ideal for welding tasks. Their adaptability and versatility in welding applications are well-documented (Yoshikawa, 1985) (Tomei, 1990).

2. SCARA Robots: Featuring two parallel rotary joints for movement in the X-Y plane, SCARA robots excel in precision and repeatability, making them a suitable choice for welding tasks (de Luca, 2005) (Pires J. N., 2007).

3. Delta Robots: With three parallel rotary joints enabling movement in the X-Y-Z plane, delta robots offer high precision and repeatability, particularly advantageous for welding tasks requiring swift speed and acceleration (Isla, 2013) (Craig, 2018).

4. Cartesian Robots: Possessing three linear joints facilitating movement in the X-Y-Z plane, Cartesian robots exhibit high precision and repeatability, making them well-suited for welding tasks necessitating utmost accuracy and precision (Tomei, 1990) (de Luca, 2005).

5. Collaborative Robots (Co-bots): Engineered for safe interaction with humans, collaborative robots find utility in welding applications. Lightweight and user-friendly, they are programmable for a wide array of tasks (Groover, 2008) (Dhillon, 2002).

Table 3

Types of robots used in welding.

Type of Robot	**Advantages**	**Disadvantages**	**Examples**
Articulated Robots	High payload capacity, high flexibility, and versatility are widely used in welding applications.	High cost, high maintenance requirements, high complexity	Fanuc Robotics' Arc Mate series, ABB Robotics' IRB series, KUKA Robotics' KR series
SCARA Robots	High precision and repeatability, well-suited for welding applications	Limited work envelope, high cost	Epson Robots' LS series, Adept Technology's Quattro series, Denso Robotics' VS series
Delta Robots	High precision and repeatability, high speed and acceleration well-suited for welding applications	Limited work envelope, high cost	Staubli Robotics' TX series, KUKA Robotics' KR AGILUS series, ABB Robotics' IRB 120 series

Cartesian Robots	High precision and repeatability, well-suited for applications that require high accuracy and precision	Limited work envelope, high cost	Yaskawa Motoman's MH series, FANUC Robotics' LR Mate series, ABB Robotics' IRB 120 series
Collaborative Robots (Co-bots)	Lightweight and easy to use, can be programmed to perform a wide range of tasks, safe to work alongside humans	Limited payload capacity, lower precision, and repeatability compared to traditional robots, not suitable for heavy-duty welding tasks	Universal Robots' UR series, KUKA Robotics' LBR iiwa series, ABB Robotics' YuMi series

Co-bots – Collaborative Robots in Welding:

Co-bots, or collaborative robots, represent a robotic system engineered to collaborate with humans within a shared workspace. They typically possess smaller frames and greater flexibility compared to traditional industrial robots, incorporating sensors and safety features to ensure safe operation in close proximity to humans. Co-bots find various applications in robotic welding in reconfigurable systems. One key advantage is their flexibility and adaptability. Due to their compact size and flexibility, co-bots can seamlessly integrate into reconfigurable systems and transition between workstations as required.

Another benefit of employing co-bots for robotic welding within reconfigurable systems is their capacity to operate safely alongside humans. This fosters a more efficient and flexible workflow, with co-bots assuming tasks deemed hazardous or monotonous for human workers. Furthermore, co-bots can be outfitted with machine vision systems, enabling real-time monitoring of the welding process to identify defects or deviations from desired weld specifications. This capability facilitates prompt adjustments to enhance weld precision and quality. Moreover, co-bots often have sensors and safety features to detect and respond to environmental changes or obstacles. This capability proves invaluable in reconfigurable systems where co-bots must adapt to varying workstations and tasks.

In summary, leveraging co-bots for robotic welding in reconfigurable systems offers numerous advantages, including enhanced flexibility, adaptability, safety, and superior quality control. Their ease of integration and mobility between workstations are particularly beneficial in environments where system layouts and functions undergo constant modifications.

Examples of Co-bots. Numerous instances exist where co-bots are employed for welding tasks within low-volume production settings. Some illustrations encompass:

- The Universal Robots UR10 co-bot is frequently utilized for arc welding, resistance welding, and spot welding in low-volume production scenarios. Renowned for its ease of programming and adaptability, it seamlessly integrates with diverse welding tools like torch holders, wire feeders, and fume extractors.
- The Fanuc CR-35iA co-bot is explicitly engineered for MIG welding in low-volume production environments. Its compact design and substantial payload capacity make it suitable for various welding applications.
- The KUKA LBR iiwa co-bot, characterized by its lightweight and compact structure, ideally suited for effortless integration into low-volume production settings. It commonly undertakes spot welding, tack welding, and other precision welding duties.
- The ABB IRB 1200 co-bot is tailored for spot, seam, and precision welding tasks. Compact and adaptable, it seamlessly integrates into low-volume production environments.

- The Yaskawa Motoman MH50 co-bot is a versatile option capable of undertaking MIG welding, TIG welding, and other welding assignments. It is specifically designed for low-volume production settings and interfaces with a variety of welding tools.

These examples underscore just a fraction of the co-bots utilized for welding within low-volume production environments. Optimal co-bot selection hinges on factors such as the specific welding techniques employed, the layout and dimensions of the production area, and the precise demands of the task at hand.

Time and motion study:

Time and motion analysis is a systematic strategy for analyzing labor procedures, identifying inefficiencies, and increasing efficiency in industrial settings. This methodology is built on various time study methodologies, each with its own advantages and uses. It is used to minimize unnecessary work, organize the remaining work in the best possible sequence, standardize suitable work procedures, and define precise time standards for the task. In Time and motion study, fundamental motions or sets of motions that are challenging to assess using traditional stopwatch time study procedures accurately are assigned primary motion times, synthetic timings, or predefined times. Instead, timing devices like motion picture cameras or videotape machines can measure extremely short parts, and these times are calculated by analyzing a large sample of diverse actions. The synthetic results combine logical groupings of basic motions (therbligs) and are predefined to forecast standard times for newly created activities arising from modifications to the methods.

History of time study:

Industrial engineering and management methods have developed around time and motion analysis to improve productivity and efficiency at work. This method examines and quantifies the amount of time and fundamental movements required to complete activities to determine standard labor durations. The development of time and motion studies over a century ago is reflected in its history, significantly impacting contemporary engineering and management techniques.

The Genesis: Frederick W. Taylors scientific management. In the late 19th century, Frederick W. Taylor, who is frequently hailed as the father of scientific management, laid the groundwork for the study of time and motion. Through his groundbreaking research, Taylor (1911) popularized the idea of breaking down tasks into their fundamental motions and timing these to determine the most productive ways to do a task. His groundbreaking book "The Principles of Scientific Management," which promoted a scientific method of examining work processes, set the foundation for later research (Taylor, 1911).

The Gilbreths innovations. Frank B. and Lillian M. Gilbreth developed the methodology by adding the notion of therbligs, or the fundamental movements needed to do work, building on Taylor's concepts. Motion picture cameras were a breakthrough that the Gilbreths used to examine workers' movements. This allowed for extensive motion analysis and the creation of better work procedures (Gilbreth & Gilbreth, 1917).

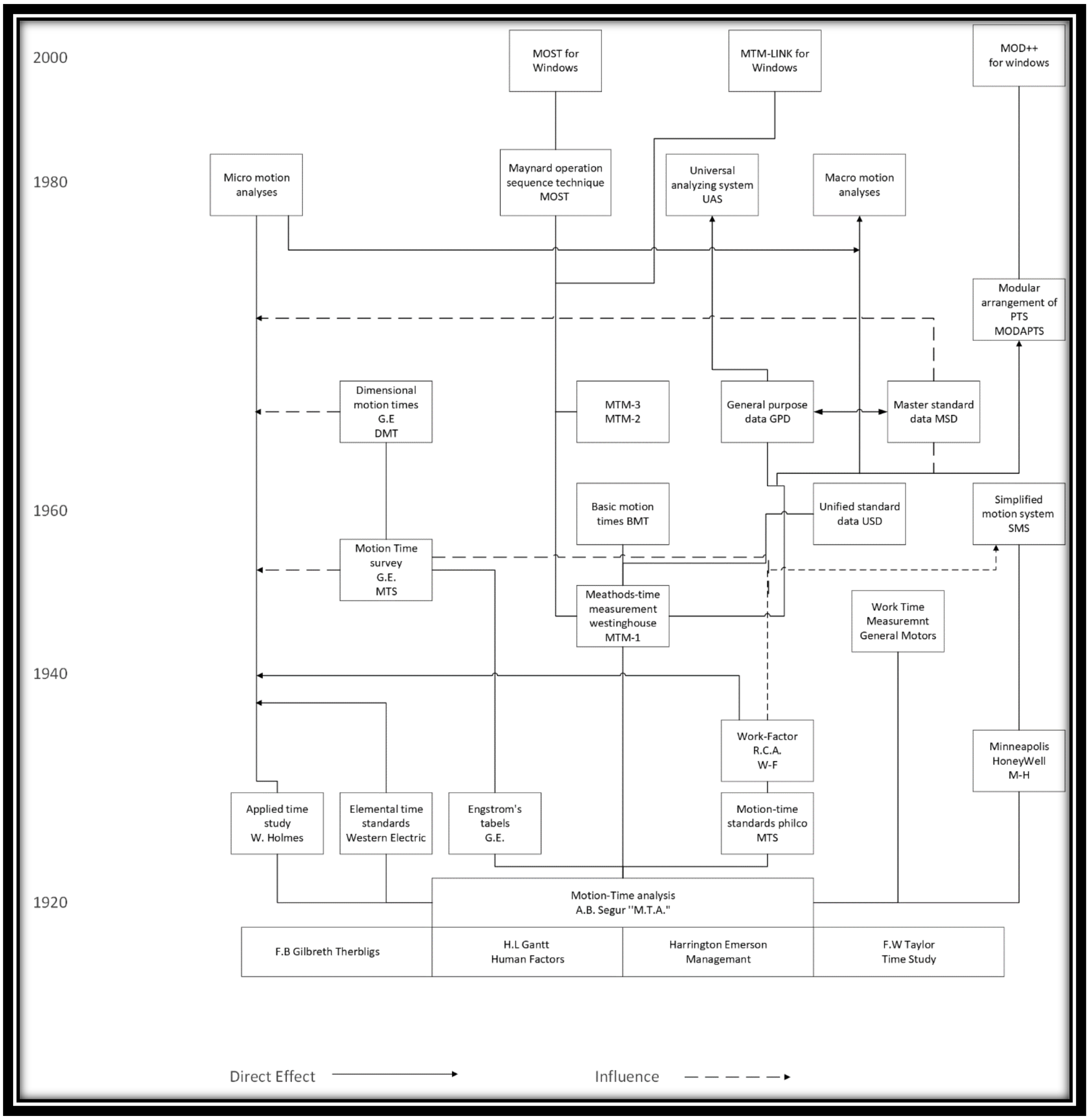
Mid-20th-century development. Time and motion studies became widely accepted in various sectors during the 1920s and 1940s. Under the influence of Gilbreths and others, the approaches changed to consider worker weariness and ergonomics (Barnes, 1980). In order to swiftly and precisely calculate work rates following World War II, there was a trend toward the use of fundamental motion times and preset time systems, such as Work Factor, Methods-Time Measurement (MTM), and the Maynard Operation Sequence Technique (MOST) (Maynard, 1948).

Modern Applications. Modern time and motion studies have incorporated cutting-edge technologies since the late 20th century. Computer simulations, software, and recording technologies have expedited the process, making it suitable for a variety of industries outside of traditional manufacturing, such as healthcare and services. The goal is to balance ergonomics, worker satisfaction, and production (Sullivan, 2002).

Predetermined time systems: MTM and MOST. Methods-Time Measurement (MTM) and the Maynard Operation Sequence Technique (MOST) are notable developments in time and motion studies approaches. MTM, created in the 1940s, offers a methodical way to examine jobs and establish time requirements using predetermined motion timings. This method is further improved by MOST, a derivation of MTM, which provides effective methods for determining work rates (Maynard, 1948) (Zandin, 2001).

Figure 5

History of Time and Motion Study.



Types of Time and Motion study methodologies:

The techniques that supported time and motion studies changed dramatically as technology advanced. These studies were initially mainly manual in nature, requiring each move to be meticulously recorded and examined by hand. Although efficient, this method required much time and was prone to human mistakes. The development of electronic technology as we entered the digital era completely changed how time and motion investigations are carried out. These contemporary approaches use computing capacity to group motions together according to their similarities, improving analytical accuracy and efficiency. This change improved productivity and operational performance by streamlining the process and enabling a more sophisticated and nuanced understanding of workflows. The many time and motion study types are listed below.

MTM-1(Methods - Time Measurement-1). By providing time values for the seven basic motions—reach, move, turn, grip, position, disengage, and release—MTM-1 establishes the foundation. Its methodology involves examining motion picture videos frame by frame across a variety of work areas, then rating and tabulating the results to ascertain how different attributes, like weight and distance, affect the motion times. With the introduction of MTM-1, manual operations were systematically broken down into their component motions, and time criteria were assigned in advance that considered the specifics of each motion. This system is the foundation for further MTM tiers and specialized systems that concentrate on intricate and particular motion analysis.

MTM-2(Methods - Time Measurement-2). Designed to extend the application of MTM to places where the level of information in MTM-1 could be too costly, MTM-2 breaks down data into less complex, synthesized groups that are appropriate for most motion sequences. The major focus of MTM analysis is still on single and combined fundamental motions, but it is expanded to cover a broader range of tasks. MTM-2 offers a compromise between detail and practicality, and it excels in tasks where the manual phase of the work cycle requires fewer intricate or simultaneous hand movements.

MTM-3(Methods - Time Measurement-3). MTM-3 is a further simplification that aims to reduce time at the expense of some accuracy. It is most appropriate for activities where the main goal is to achieve moderately accurate and relatively quick time standards. MTM-3 simplifies analysis for tasks that do not require the fine detail of MTM-1 or MTM-2 by narrowing the system down to only four categories of manual motions. This is a practical option where speed is of the essence.

Specialized Systems: MTM-V, MTM-C, and MTM-M. Beyond the general-purpose systems of MTM-1, MTM-2, and MTM-3, the MTM family includes specialized systems tailored to specific industry needs. MTM-V addresses the unique requirements of metal-cutting operations, which are particularly beneficial in short-run machine shops. MTM-C caters to the banking and insurance industries, providing standards for clerical-related tasks. Lastly, MTM-M offers a solution for evaluating operator work in microminiature manufacturing, a growing field where traditional time study methods fall short.

MOST (Maynard Operation Sequence Technique). The MOST system originated from the MTM system and was created to meet the demand for faster analysis without compromising accuracy. Maxi-MOST, Mini-MOST, and Basic-MOST are the three stages of analysis that make up the structured approach, each of which is designed to accommodate varying operation lengths and frequencies. These vary from very short and frequent jobs that are best studied by Mini-MOST to long, uncommon operations that are best analyzed by Maxi-MOST. For operations of moderate length and frequency, Basic-MOST acts as an intermediary.

The time study analysis of the welding processes in this work was conducted using the MTM-1 and MOST methodologies. MTM-1 provides a comprehensive and detailed version of the time and motion study, while MOST is the most recent and extensively utilized technique among all time and motion studies. We aimed to determine which of the two approaches worked better for a comparable procedure.

Applications of Time and Motion Study.

1. Improving Work Methods:

   Time and motion studies are utilized to evaluate current work practices and pinpoint opportunities for improvement. By dissecting tasks into their individual acts, inefficiencies or pointless motions can be removed, resulting in more productive and efficient work processes.

2. Labor Cost Reduction:

   Streamlining operations can shorten task completion times. Because workers can accomplish more activities in the same period, this time reduction can result in significant labor cost reductions.

3. Productivity Enhancement:

   Time and motion studies can result in notable increases in productivity by carefully analyzing and optimizing each motion and step in a process. To do this, duties are streamlined, unnecessary effort is decreased, and elimination unnecessary steps

4. Ergonomic Improvements:

   Time and motion studies also examine employees' physical movements to create workflows that lessen fatigue and injury risk. This may promote a better work environment and lower the risk of musculoskeletal problems at work.

5. Quality Improvement:

   Standardizing the most effective work practices identified by time and motion studies can minimize variability in task execution. As procedures become more standardized, quality may increase.

6. Workforce Allocation and Capacity Planning:

   These studies assist firms in comprehending the amount of time needed for various jobs and procedures, which is essential for capacity planning. Comprehending the actual duration of jobs aids in more precise workload estimation and efficient workforce distribution.

7. Performance Measurement and Benchmarking:

   Time and motion studies offer a benchmark for measuring performance by creating standards based on the most productive work practices. These benchmarks can compare employee performance and pinpoint areas needing development.

Methods - Time Measurement (MTM-1):

A foundational method in the time and motion study field, the Methods-Time Measurement (MTM) system, specifically MTM-1, is designed to optimize productivity through the analysis of manual work processes. MTM-1 is distinguished by its precise and methodical approach, which deconstructs manual tasks into basic motions that are each given a preset time standard. This section explores MTM-1's operational mechanics and offers information on its methodology and use in industrial engineering.

Core Ideas of MTM-1. The core concept of MTM-1 is that every manual labor can be broken down into a set of fundamental movements. These movements include, but are not limited to, reach, move, turn, grasp, position, disengage, and release. The process is based on a thorough analysis of tasks to identify these constituent motions and the application of specified time values to each based on empirical data collecting and considerable research.

The MTM-1 Methodology (Maynard, 1948).

- Manual Operation Analysis:

The first stage in the MTM-1 process involves thoroughly examining the manual operation under study. This means breaking down the operation into its individual movements. For this kind of study, it's frequently necessary to record and analyze the motions involved in the work using high-speed motion picture cameras or video analysis.

- Finding the Basic Motions:

After the operation has been recorded, the following stage is to find the basic motions that the task requires. The MTM system's standardized collection of fundamental motions is the foundation for this identification procedure. Depending on the type of task being carried out, each of these motions—known as therbligs—is categorized (e.g., reaching for an object, moving an object, rotating an object).

- Time Value Assignment:

Each recognized basic motion is assigned a preset time value. Time measurement units, or TMUs, are used to express these time values. One TMU is equal to 0.036 seconds. The time values are obtained by thoroughly examining the motion's characteristics and the environment in which it is performed, accounting for variables including distance traveled, object weight, and motion complexity.

- Calculation and Evaluation:

Several parameters that affect the duration of each motion are taken into consideration while rating and tabulating the motion picture analysis data. This involves examining motion properties, like reach and item weight, when moving an object. Precise time standards calculation is aided by comprehensive tables and charts that offer time values for many scenarios.

- Calculation of Standard Times:

The overall time required for a task can be determined by adding up the times for each of the fundamental motions involved. The total indicates how long a worker would typically need to complete the assignment under typical working circumstances.

- Allowance Incorporation:

The tabulated numbers only take fundamental motions' direct times into consideration. To create a thorough time standard for the activity, extra time must be allotted for personal needs, exhaustion, and inevitable delays on top of the basic time.

Figure 6

Normal Time Values for MTM motion element - Reach (R)

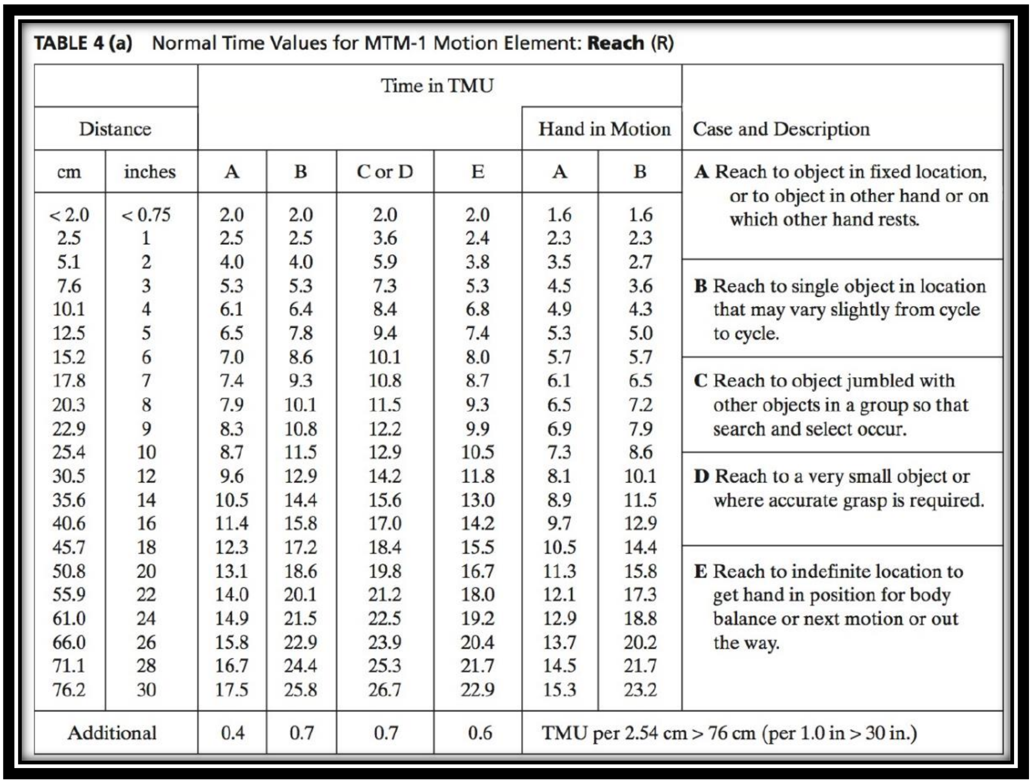


TABLE 4 (a) Normal Time Values for MTM-1 Motion Element: **Reach** (R)

Distance		Time in TMU						Case and Description
						Hand in Motion		
cm	inches	A	B	C or D	E	A	B	
< 2.0	< 0.75	2.0	2.0	2.0	2.0	1.6	1.6	**A** Reach to object in fixed location, or to object in other hand or on which other hand rests.
2.5	1	2.5	2.5	3.6	2.4	2.3	2.3	
5.1	2	4.0	4.0	5.9	3.8	3.5	2.7	
7.6	3	5.3	5.3	7.3	5.3	4.5	3.6	**B** Reach to single object in location that may vary slightly from cycle to cycle.
10.1	4	6.1	6.4	8.4	6.8	4.9	4.3	
12.5	5	6.5	7.8	9.4	7.4	5.3	5.0	
15.2	6	7.0	8.6	10.1	8.0	5.7	5.7	
17.8	7	7.4	9.3	10.8	8.7	6.1	6.5	**C** Reach to object jumbled with other objects in a group so that search and select occur.
20.3	8	7.9	10.1	11.5	9.3	6.5	7.2	
22.9	9	8.3	10.8	12.2	9.9	6.9	7.9	
25.4	10	8.7	11.5	12.9	10.5	7.3	8.6	
30.5	12	9.6	12.9	14.2	11.8	8.1	10.1	**D** Reach to a very small object or where accurate grasp is required.
35.6	14	10.5	14.4	15.6	13.0	8.9	11.5	
40.6	16	11.4	15.8	17.0	14.2	9.7	12.9	
45.7	18	12.3	17.2	18.4	15.5	10.5	14.4	
50.8	20	13.1	18.6	19.8	16.7	11.3	15.8	**E** Reach to indefinite location to get hand in position for body balance or next motion or out the way.
55.9	22	14.0	20.1	21.2	18.0	12.1	17.3	
61.0	24	14.9	21.5	22.5	19.2	12.9	18.8	
66.0	26	15.8	22.9	23.9	20.4	13.7	20.2	
71.1	28	16.7	24.4	25.3	21.7	14.5	21.7	
76.2	30	17.5	25.8	26.7	22.9	15.3	23.2	
Additional		0.4	0.7	0.7	0.6	TMU per 2.54 cm > 76 cm (per 1.0 in > 30 in.)		

Figure 7

Normal Time Values for MTM motion element - Grasp (G)

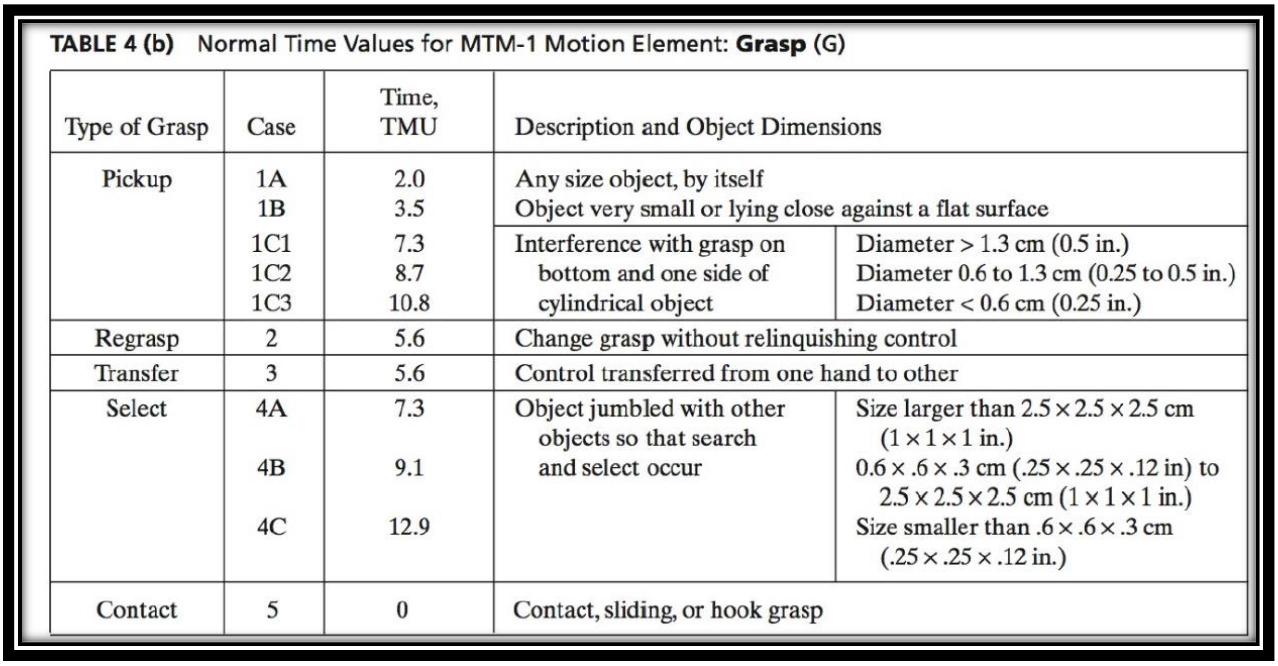


TABLE 4 (b) Normal Time Values for MTM-1 Motion Element: **Grasp** (G)

Type of Grasp	Case	Time, TMU	Description and Object Dimensions	
Pickup	1A	2.0	Any size object, by itself	
	1B	3.5	Object very small or lying close against a flat surface	
	1C1	7.3	Interference with grasp on bottom and one side of cylindrical object	Diameter > 1.3 cm (0.5 in.)
	1C2	8.7		Diameter 0.6 to 1.3 cm (0.25 to 0.5 in.)
	1C3	10.8		Diameter < 0.6 cm (0.25 in.)
Regrasp	2	5.6	Change grasp without relinquishing control	
Transfer	3	5.6	Control transferred from one hand to other	
Select	4A	7.3	Object jumbled with other objects so that search and select occur	Size larger than 2.5 × 2.5 × 2.5 cm (1 × 1 × 1 in.)
	4B	9.1		0.6 × .6 × .3 cm (.25 × .25 × .12 in) to 2.5 × 2.5 × 2.5 cm (1 × 1 × 1 in.)
	4C	12.9		Size smaller than .6 × .6 × .3 cm (.25 × .25 × .12 in.)
Contact	5	0	Contact, sliding, or hook grasp	

Figure 8

Normal Time Values for MTM motion element - Move (M)

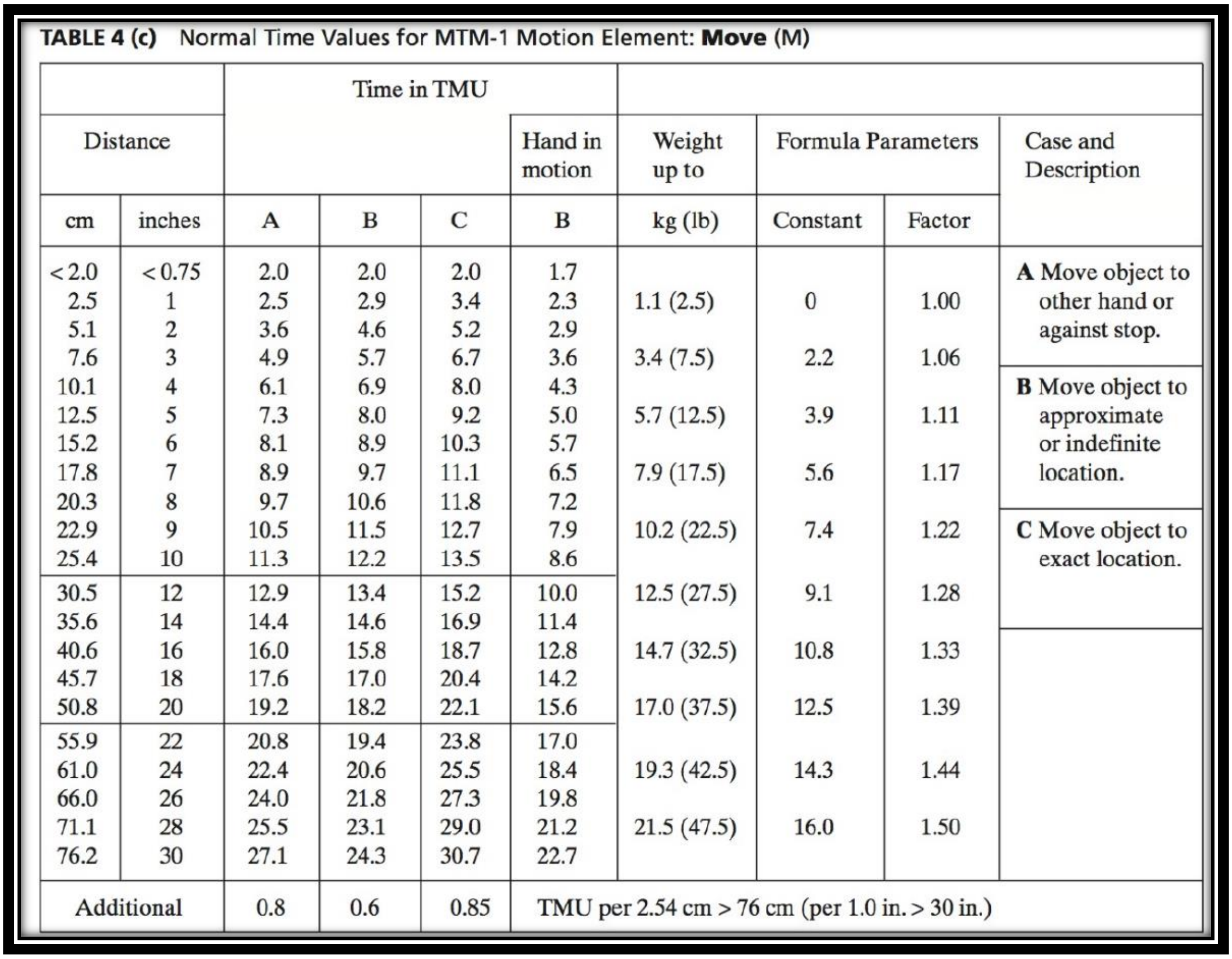


TABLE 4 (c) Normal Time Values for MTM-1 Motion Element: **Move** (M)

Distance		Time in TMU			Hand in motion	Weight up to	Formula Parameters		Case and Description
cm	inches	A	B	C	B	kg (lb)	Constant	Factor	
< 2.0	< 0.75	2.0	2.0	2.0	1.7				**A** Move object to other hand or against stop.
2.5	1	2.5	2.9	3.4	2.3	1.1 (2.5)	0	1.00	
5.1	2	3.6	4.6	5.2	2.9				
7.6	3	4.9	5.7	6.7	3.6	3.4 (7.5)	2.2	1.06	
10.1	4	6.1	6.9	8.0	4.3				**B** Move object to approximate or indefinite location.
12.5	5	7.3	8.0	9.2	5.0	5.7 (12.5)	3.9	1.11	
15.2	6	8.1	8.9	10.3	5.7				
17.8	7	8.9	9.7	11.1	6.5	7.9 (17.5)	5.6	1.17	
20.3	8	9.7	10.6	11.8	7.2				
22.9	9	10.5	11.5	12.7	7.9	10.2 (22.5)	7.4	1.22	**C** Move object to exact location.
25.4	10	11.3	12.2	13.5	8.6				
30.5	12	12.9	13.4	15.2	10.0	12.5 (27.5)	9.1	1.28	
35.6	14	14.4	14.6	16.9	11.4				
40.6	16	16.0	15.8	18.7	12.8	14.7 (32.5)	10.8	1.33	
45.7	18	17.6	17.0	20.4	14.2				
50.8	20	19.2	18.2	22.1	15.6	17.0 (37.5)	12.5	1.39	
55.9	22	20.8	19.4	23.8	17.0				
61.0	24	22.4	20.6	25.5	18.4	19.3 (42.5)	14.3	1.44	
66.0	26	24.0	21.8	27.3	19.8				
71.1	28	25.5	23.1	29.0	21.2	21.5 (47.5)	16.0	1.50	
76.2	30	27.1	24.3	30.7	22.7				
Additional		0.8	0.6	0.85	TMU per 2.54 cm > 76 cm (per 1.0 in. > 30 in.)				

Figure 9

Normal Time Values for MTM motion element - Position (P)

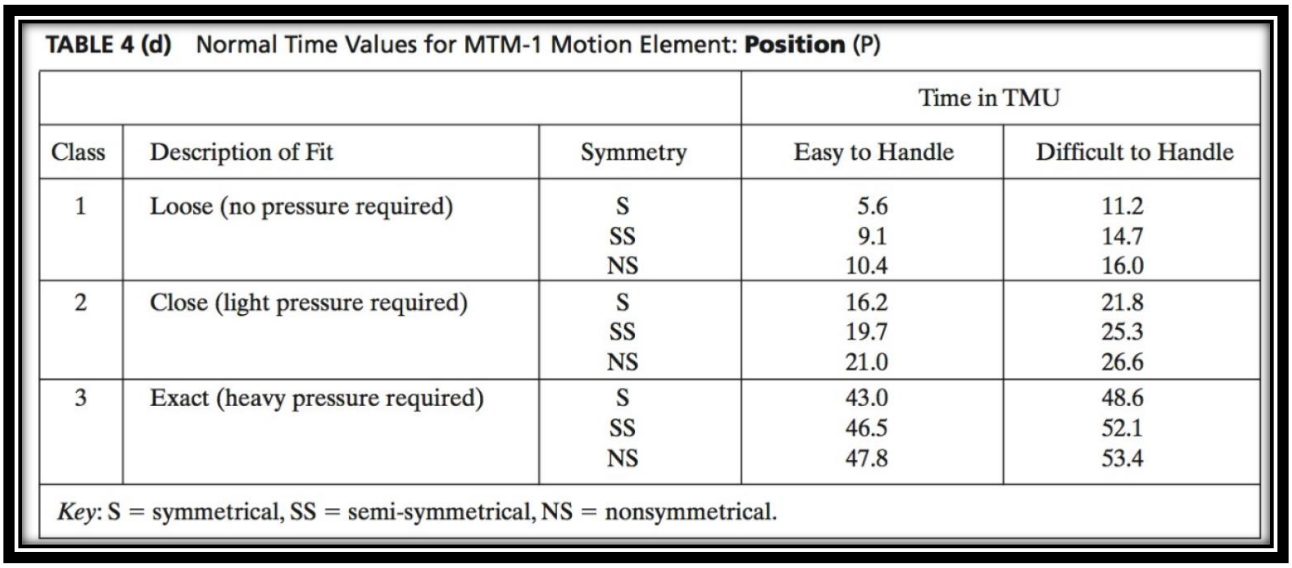


TABLE 4 (d) Normal Time Values for MTM-1 Motion Element: **Position** (P)

			Time in TMU	
Class	Description of Fit	Symmetry	Easy to Handle	Difficult to Handle
1	Loose (no pressure required)	S	5.6	11.2
		SS	9.1	14.7
		NS	10.4	16.0
2	Close (light pressure required)	S	16.2	21.8
		SS	19.7	25.3
		NS	21.0	26.6
3	Exact (heavy pressure required)	S	43.0	48.6
		SS	46.5	52.1
		NS	47.8	53.4

Key: S = symmetrical, SS = semi-symmetrical, NS = nonsymmetrical.

Figure 10

Normal Time Values for MTM motion element - Release (R)

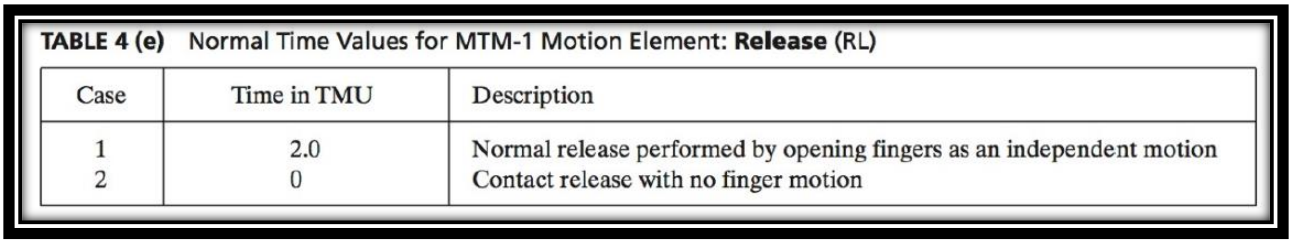


TABLE 4 (e) Normal Time Values for MTM-1 Motion Element: **Release** (RL)

Case	Time in TMU	Description
1	2.0	Normal release performed by opening fingers as an independent motion
2	0	Contact release with no finger motion

Figure 11

Normal Time Values for MTM motion element - Apply Pressure (AP)

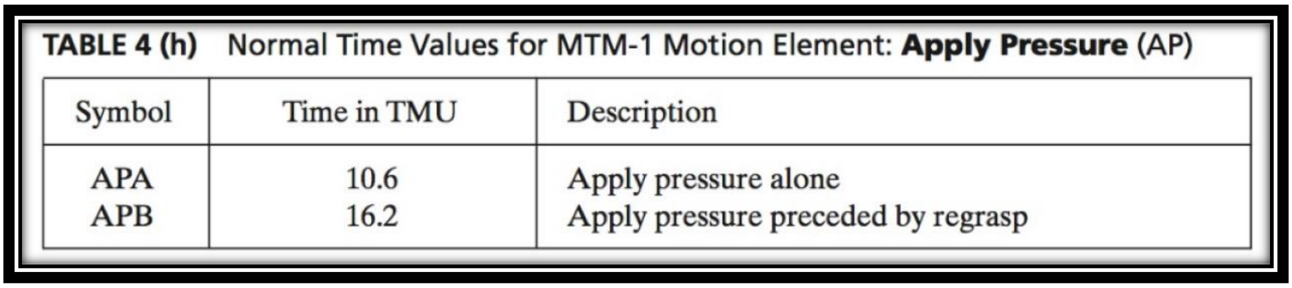


TABLE 4 (h) Normal Time Values for MTM-1 Motion Element: **Apply Pressure** (AP)

Symbol	Time in TMU	Description
APA	10.6	Apply pressure alone
APB	16.2	Apply pressure preceded by regrasp

Figure 12

Normal Time Values for MTM motion element- Body, Leg, and Foot motions

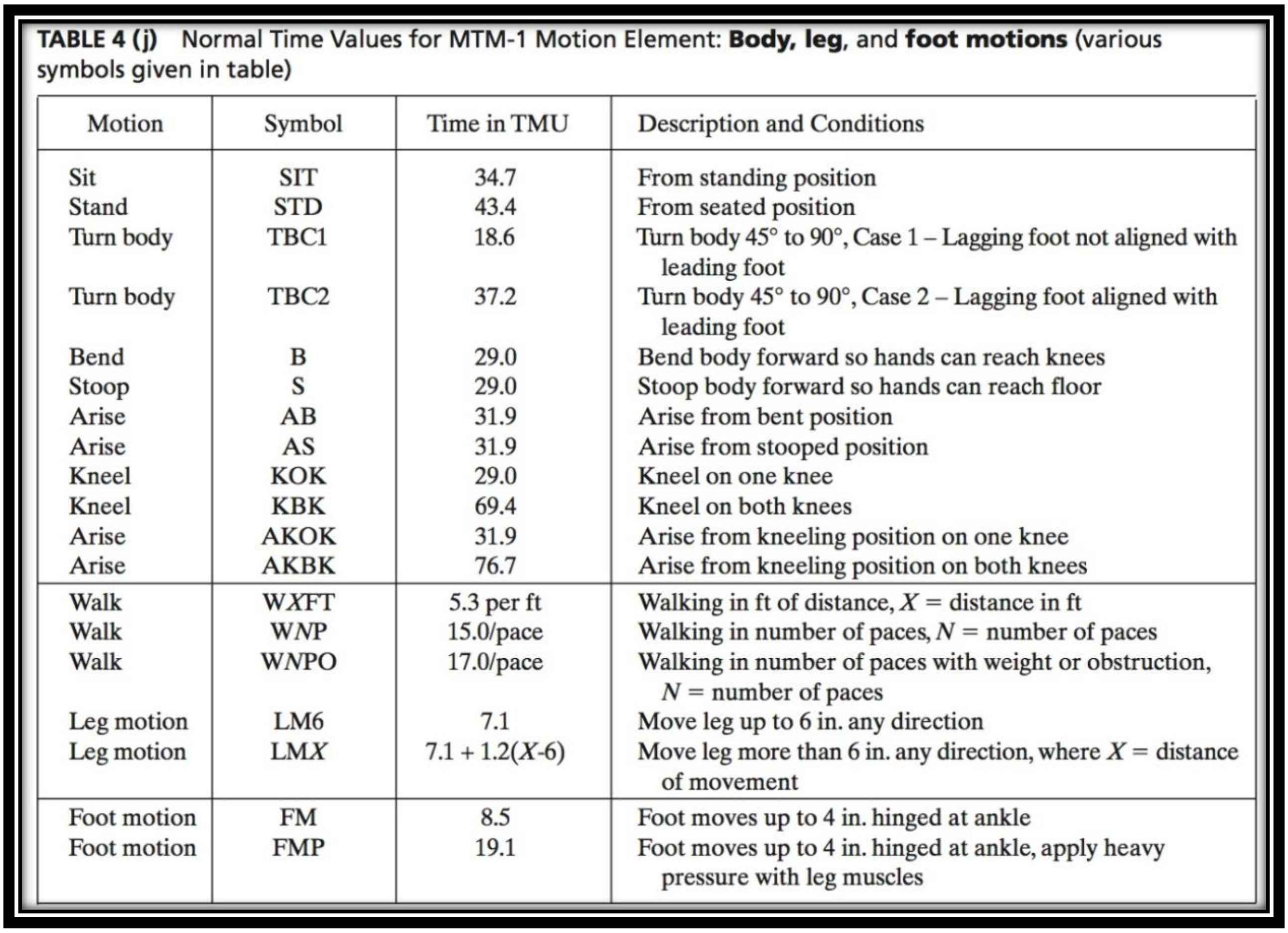


TABLE 4 (j) Normal Time Values for MTM-1 Motion Element: **Body, leg,** and **foot motions** (various symbols given in table)

Motion	Symbol	Time in TMU	Description and Conditions
Sit	SIT	34.7	From standing position
Stand	STD	43.4	From seated position
Turn body	TBC1	18.6	Turn body 45° to 90°, Case 1 – Lagging foot not aligned with leading foot
Turn body	TBC2	37.2	Turn body 45° to 90°, Case 2 – Lagging foot aligned with leading foot
Bend	B	29.0	Bend body forward so hands can reach knees
Stoop	S	29.0	Stoop body forward so hands can reach floor
Arise	AB	31.9	Arise from bent position
Arise	AS	31.9	Arise from stooped position
Kneel	KOK	29.0	Kneel on one knee
Kneel	KBK	69.4	Kneel on both knees
Arise	AKOK	31.9	Arise from kneeling position on one knee
Arise	AKBK	76.7	Arise from kneeling position on both knees
Walk	W*X*FT	5.3 per ft	Walking in ft of distance, *X* = distance in ft
Walk	W*N*P	15.0/pace	Walking in number of paces, *N* = number of paces
Walk	W*N*PO	17.0/pace	Walking in number of paces with weight or obstruction, *N* = number of paces
Leg motion	LM6	7.1	Move leg up to 6 in. any direction
Leg motion	LM*X*	7.1 + 1.2(*X*-6)	Move leg more than 6 in. any direction, where *X* = distance of movement
Foot motion	FM	8.5	Foot moves up to 4 in. hinged at ankle
Foot motion	FMP	19.1	Foot moves up to 4 in. hinged at ankle, apply heavy pressure with leg muscles

MOST (Maynard Operation Sequence Technique):

The Maynard Operation Sequence Technique (MOST) is a highly structured, predetermined time measurement system designed to streamline the establishment of time standards for manual work tasks. Developed by Zandin in 1980 and initially applied at Saab-Scania in Sweden in 1967, MOST is an evolution of the Methods-Time Measurement (MTM) system, engineered to offer a faster yet equally precise alternative for time analysis. This methodology significantly reduces the time required to establish standards, performing analyses at least five times faster than MTM-1 without a notable sacrifice in accuracy. MOST is distinguished by its applicability across a wide spectrum of operations. It is categorized into three hierarchical levels based on the task's frequency and duration: Maxi-MOST, Basic-MOST, and Mini-MOST. (NIEBEL, 1988) (Freivalds, 2014).

MOST Structure. MOST is organized into three levels to accommodate various operation lengths and frequencies:

- Maxi-MOST: This level is tailored for long, infrequent operations ranging from 2 minutes to several hours that occur less than 150 times per week. It offers rapid analysis with a trade-off in precision, suitable for tasks with high variability.
- Basic-MOST: This is the intermediate level, optimized for tasks lasting 0.5 to 3 minutes. It is also the most commonly applied level, designed for operations that do not fit the criteria for Maxi-MOST or Mini-MOST.
- Mini-MOST: Applies to very short, highly repetitive tasks under 1.6 minutes in length, repeated more than 1500 times a week. Mini-MOST is characterized by its detailed and precise analysis, catering to operations with minimal variability.

MOST Sequence Models. MOST methodology revolves around three basic sequence models, each targeting specific types of movements or tool interactions. These are:

1. General Move: Focuses on the free spatial movement of an object through the air.
2. Controlled Move: Pertains to movements where the object either remains in contact with a surface or stays attached to another object.
3. Tool and Equipment Use: Deals with common hand tools and equipment.

Operational Phases and Sub activities. In MOST, tasks are analyzed through a sequence of operational phases and sub-activities:

- Get: Involves reaching for an object, possibly with body motion or steps, and gaining manual control. This phase uses sub-activities like Action Distance (A), Body Motion (B), and Gain Control (G).

- Put: Entails moving the object to a new location, potentially with body motion, and placing it at a specified location, utilizing sub-activities such as Placement (P).
- Return: Describes the action of returning to the workstation, mainly involving the Action Distance (A) sub-activity.

Each sub-activity is defined by index values correlating to the relative difficulty, which are subsequently converted into time values in TMUs by scaling.

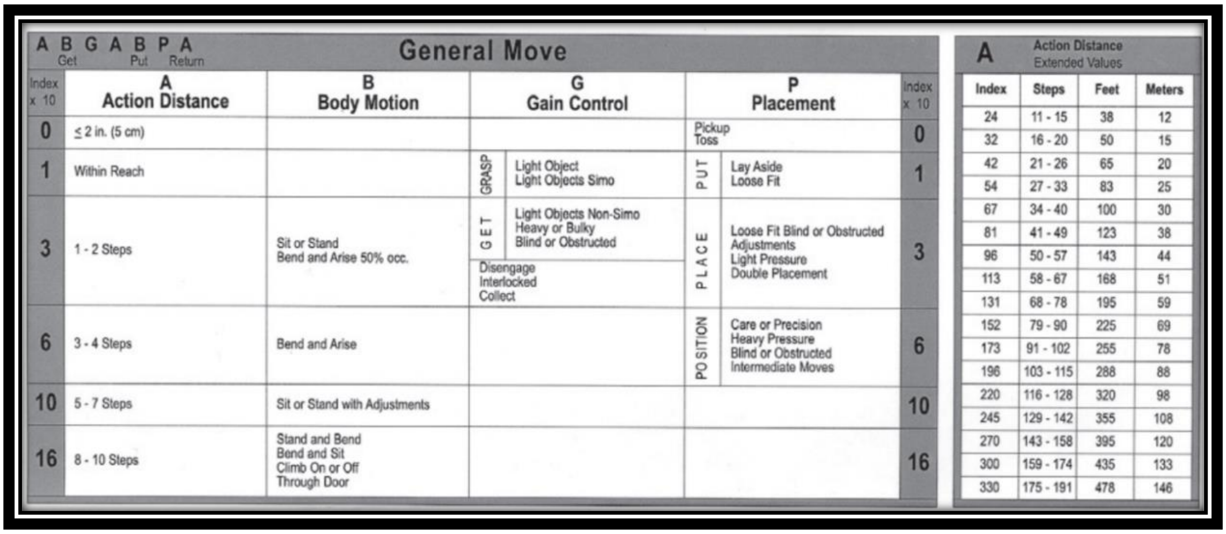
Analysis and Application. In applying MOST, tasks are broken down into their constituent actions, identified with the appropriate sequence model, and analyzed using the defined sub-activities and index values. This breakdown enables the precise calculation of time standards for manual operations, incorporating considerations for body movements, control levels, and tool use.

For example, a task involving picking up an object, placing it elsewhere, and returning to the original position would be analyzed by breaking down the movements into A, B, G, A, B, P, and A sequences, assigning index values to each sub-activity, and calculating the total time in TMUs.

Advantages and Implementation. MOST's structured approach allows for rapid and accurate time standard establishment across a broad range of manual tasks. Its hierarchical system—spanning MaxiMOST, BasicMOST, and Mini-MOST—enables tailored analysis suited to the specific characteristics of each operation. Furthermore, the methodology's division into general move, controlled move, and tool use sequences ensures comprehensive coverage of manual work types. In practice, MOST facilitates the efficient design and optimization of work processes, contributing to productivity improvement and effective labor planning. Its capability for rapid analysis with minimal accuracy compromise makes it a preferred method for industrial engineers.

Figure 13

MOST Time Values for General Move



A B G A B P A
Get Put Return

General Move

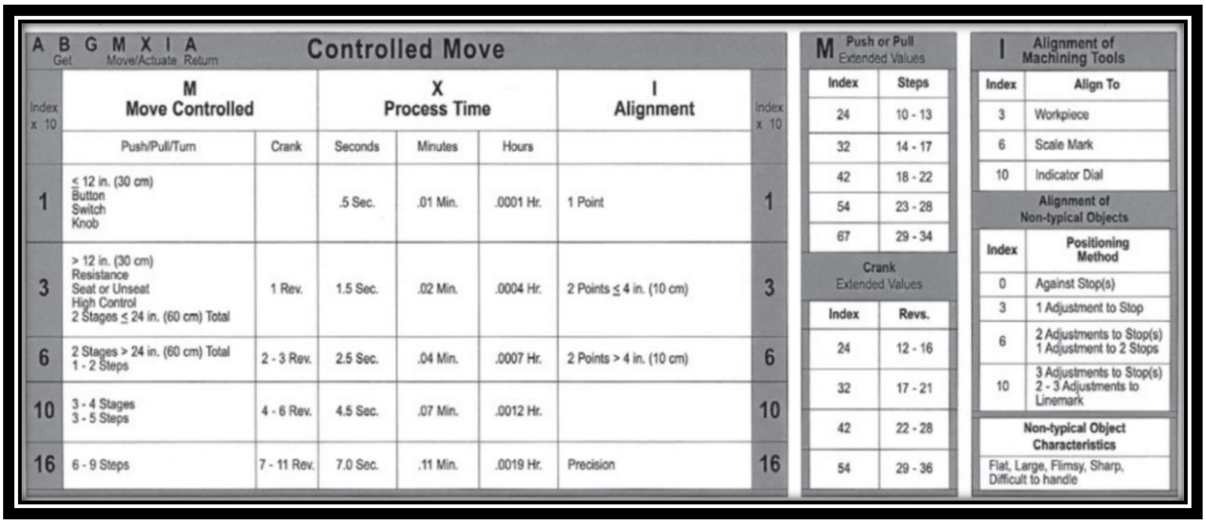
Index x 10	A Action Distance	B Body Motion	G Gain Control	P Placement	Index x 10
0	≤ 2 in. (5 cm)			Pickup Toss	0
1	Within Reach		GRASP Light Object Light Objects Simo	PUT Lay Aside Loose Fit	1
3	1 - 2 Steps	Sit or Stand Bend and Arise 50% occ.	GET Light Objects Non-Simo Heavy or Bulky Blind or Obstructed Disengage Interlocked Collect	PLACE Loose Fit Blind or Obstructed Adjustments Light Pressure Double Placement	3
6	3 - 4 Steps	Bend and Arise		POSITION Care or Precision Heavy Pressure Blind or Obstructed Intermediate Moves	6
10	5 - 7 Steps	Sit or Stand with Adjustments			10
16	8 - 10 Steps	Stand and Bend Bend and Sit Climb On or Off Through Door			16

A Action Distance
Extended Values

Index	Steps	Feet	Meters
24	11 - 15	38	12
32	16 - 20	50	15
42	21 - 26	65	20
54	27 - 33	83	25
67	34 - 40	100	30
81	41 - 49	123	38
96	50 - 57	143	44
113	58 - 67	168	51
131	68 - 78	195	59
152	79 - 90	225	69
173	91 - 102	255	78
196	103 - 115	288	88
220	116 - 128	320	98
245	129 - 142	355	108
270	143 - 158	395	120
300	159 - 174	435	133
330	175 - 191	478	146

Figure 14

MOST Time Values for Controlled Move



A B G M X I A
Get Move/Actuate Return

Controlled Move

Index x 10	M Move Controlled		X Process Time			I Alignment	Index x 10
	Push/Pull/Turn	Crank	Seconds	Minutes	Hours		
1	≤ 12 in. (30 cm) Button Switch Knob		.5 Sec.	.01 Min.	.0001 Hr.	1 Point	1
3	> 12 in. (30 cm) Resistance Seat or Unseat High Control 2 Stages ≤ 24 in. (60 cm) Total	1 Rev.	1.5 Sec.	.02 Min.	.0004 Hr.	2 Points ≤ 4 in. (10 cm)	3
6	2 Stages > 24 in. (60 cm) Total 1 - 2 Steps	2 - 3 Rev.	2.5 Sec.	.04 Min.	.0007 Hr.	2 Points > 4 in. (10 cm)	6
10	3 - 4 Stages 3 - 5 Steps	4 - 6 Rev.	4.5 Sec.	.07 Min.	.0012 Hr.		10
16	6 - 9 Steps	7 - 11 Rev.	7.0 Sec.	.11 Min.	.0019 Hr.	Precision	16

M Push or Pull
Extended Values

Index	Steps
24	10 - 13
32	14 - 17
42	18 - 22
54	23 - 28
67	29 - 34

Crank
Extended Values

Index	Revs.
24	12 - 16
32	17 - 21
42	22 - 28
54	29 - 36

I Alignment of Machining Tools

Index	Align To
3	Workpiece
6	Scale Mark
10	Indicator Dial

Alignment of Non-typical Objects

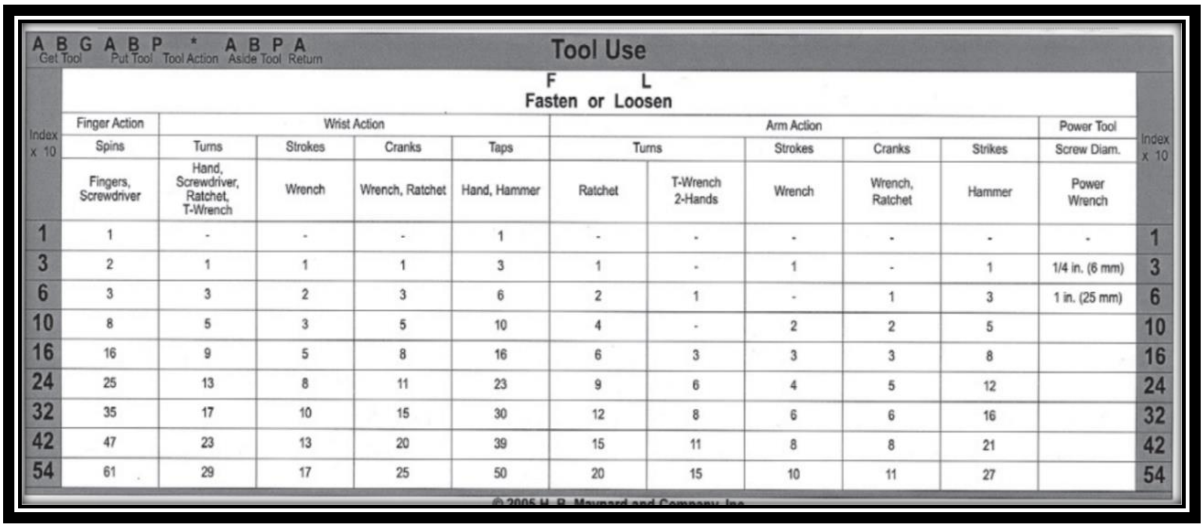
Index	Positioning Method
0	Against Stop(s)
3	1 Adjustment to Stop
6	2 Adjustments to Stop(s) 1 Adjustment to 2 Stops
10	3 Adjustments to Stop(s) 2 - 3 Adjustments to Linemark

Non-typical Object Characteristics

Flat, Large, Flimsy, Sharp, Difficult to handle

Figure 15

MOST Time Values for Tool Use (Fasten and Loosen)



A B G A B P * A B P A
Get Tool Put Tool Tool Action Aside Tool Return

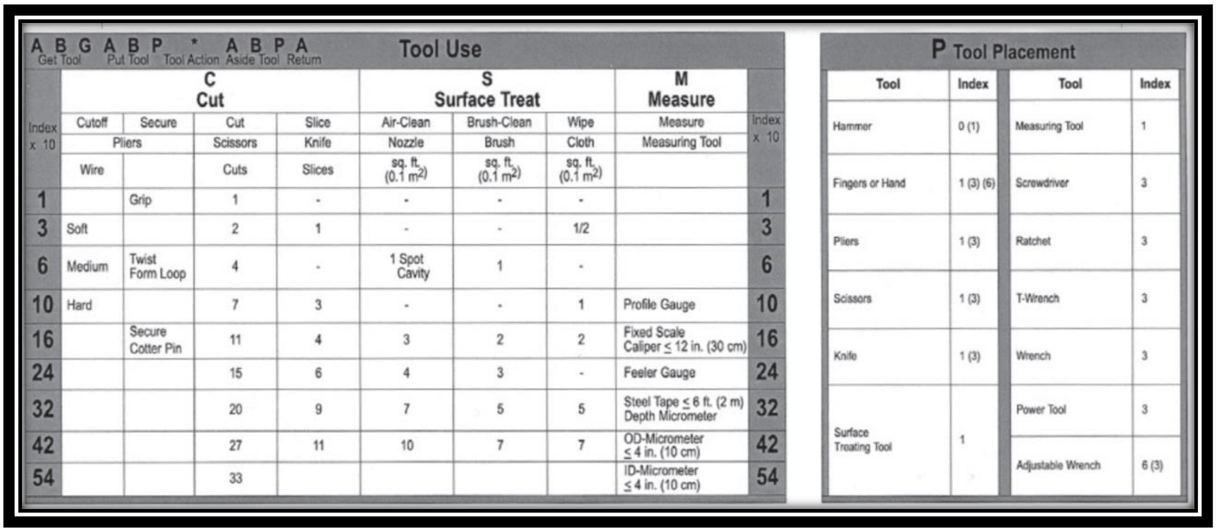
Tool Use

F L
Fasten or Loosen

Index x 10	Finger Action	Wrist Action				Arm Action					Power Tool	Index x 10
	Spins	Turns	Strokes	Cranks	Taps	Turns		Strokes	Cranks	Strikes	Screw Diam.	
	Fingers, Screwdriver	Hand, Screwdriver, Ratchet, T-Wrench	Wrench	Wrench, Ratchet	Hand, Hammer	Ratchet	T-Wrench 2-Hands	Wrench	Wrench, Ratchet	Hammer	Power Wrench	
1	1	-	-	-	1	-	-	-	-	-	-	1
3	2	1	1	1	3	1	-	1	-	1	1/4 in. (6 mm)	3
6	3	3	2	3	6	2	1	-	1	3	1 in. (25 mm)	6
10	8	5	3	5	10	4	-	2	2	5		10
16	16	9	5	8	16	6	3	3	3	8		16
24	25	13	8	11	23	9	6	4	5	12		24
32	35	17	10	15	30	12	8	6	6	16		32
42	47	23	13	20	39	15	11	8	8	21		42
54	61	29	17	25	50	20	15	10	11	27		54

Figure 16

MOST Time Values for Tool Use (Cut, Surface Treat, and Measure)



A B G A B P * A B P A
Get Tool Put Tool Tool Action Aside Tool Return

Tool Use

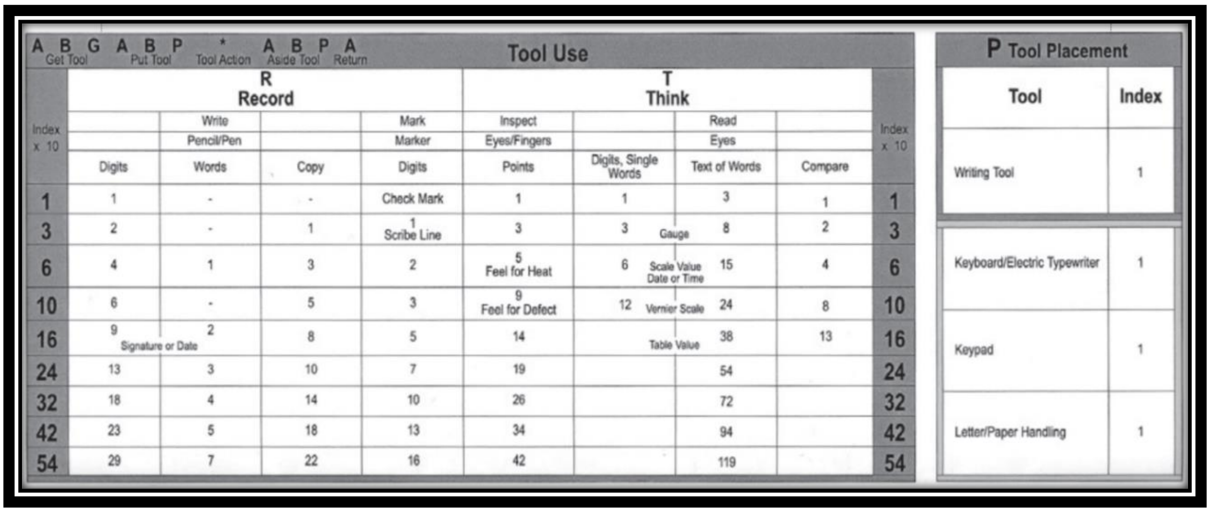
Index x 10	C Cut				S Surface Treat			M Measure	Index x 10
	Cutoff	Secure	Cut	Slice	Air-Clean	Brush-Clean	Wipe	Measure	
	Pliers		Scissors	Knife	Nozzle	Brush	Cloth	Measuring Tool	
	Wire		Cuts	Slices	sq. ft. (0.1 m²)	sq. ft. (0.1 m²)	sq. ft. (0.1 m²)		
1		Grip	1	-	-	-	-		1
3	Soft		2	1	-	-	1/2		3
6	Medium	Twist Form Loop	4	-	1 Spot Cavity	1	-		6
10	Hard		7	3	-	-	1	Profile Gauge	10
16		Secure Cotter Pin	11	4	3	2	2	Fixed Scale Caliper ≤ 12 in. (30 cm)	16
24			15	6	4	3	-	Feeler Gauge	24
32			20	9	7	5	5	Steel Tape ≤ 6 ft. (2 m) Depth Micrometer	32
42			27	11	10	7	7	OD-Micrometer ≤ 4 in. (10 cm)	42
54			33					ID-Micrometer ≤ 4 in. (10 cm)	54

P Tool Placement

Tool	Index	Tool	Index
Hammer	0 (1)	Measuring Tool	1
Fingers or Hand	1 (3) (6)	Screwdriver	3
Pliers	1 (3)	Ratchet	3
Scissors	1 (3)	T-Wrench	3
Knife	1 (3)	Wrench	3
Surface Treating Tool	1	Power Tool	3
		Adjustable Wrench	6 (3)

Figure 17

MOST Time Values for Tool Use (Record and Think)



A B G A B P * A B P A
Get Tool Put Tool Tool Action Aside Tool Return

Tool Use

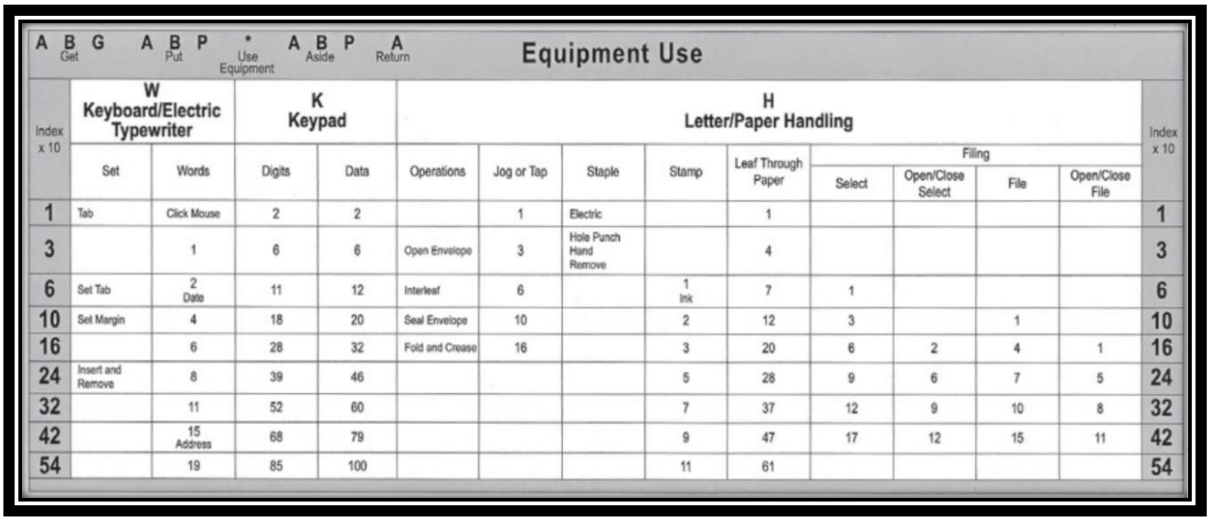
Index x 10	R Record				T Think				Index x 10
		Write		Mark	Inspect		Read		
		Pencil/Pen		Marker	Eyes/Fingers		Eyes		
	Digits	Words	Copy	Digits	Points	Digits, Single Words	Text of Words	Compare	
1	1	-	-	Check Mark	1	1	3	1	1
3	2	-	1	1 Scribe Line	3	3 Gauge	8	2	3
6	4	1	3	2	5 Feel for Heat	6 Scale Value Date or Time	15	4	6
10	6	-	5	3	9 Feel for Defect	12 Vernier Scale	24	8	10
16	9 Signature or Date	2	8	5	14	Table Value	38	13	16
24	13	3	10	7	19		54		24
32	18	4	14	10	26		72		32
42	23	5	18	13	34		94		42
54	29	7	22	16	42		119		54

P Tool Placement

Tool	Index
Writing Tool	1
Keyboard/Electric Typewriter	1
Keypad	1
Letter/Paper Handling	1

Figure 18

MOST Time Values for Equipment Use



A B G A B P * A B P A
Get Put Use Equipment Aside Return

Equipment Use

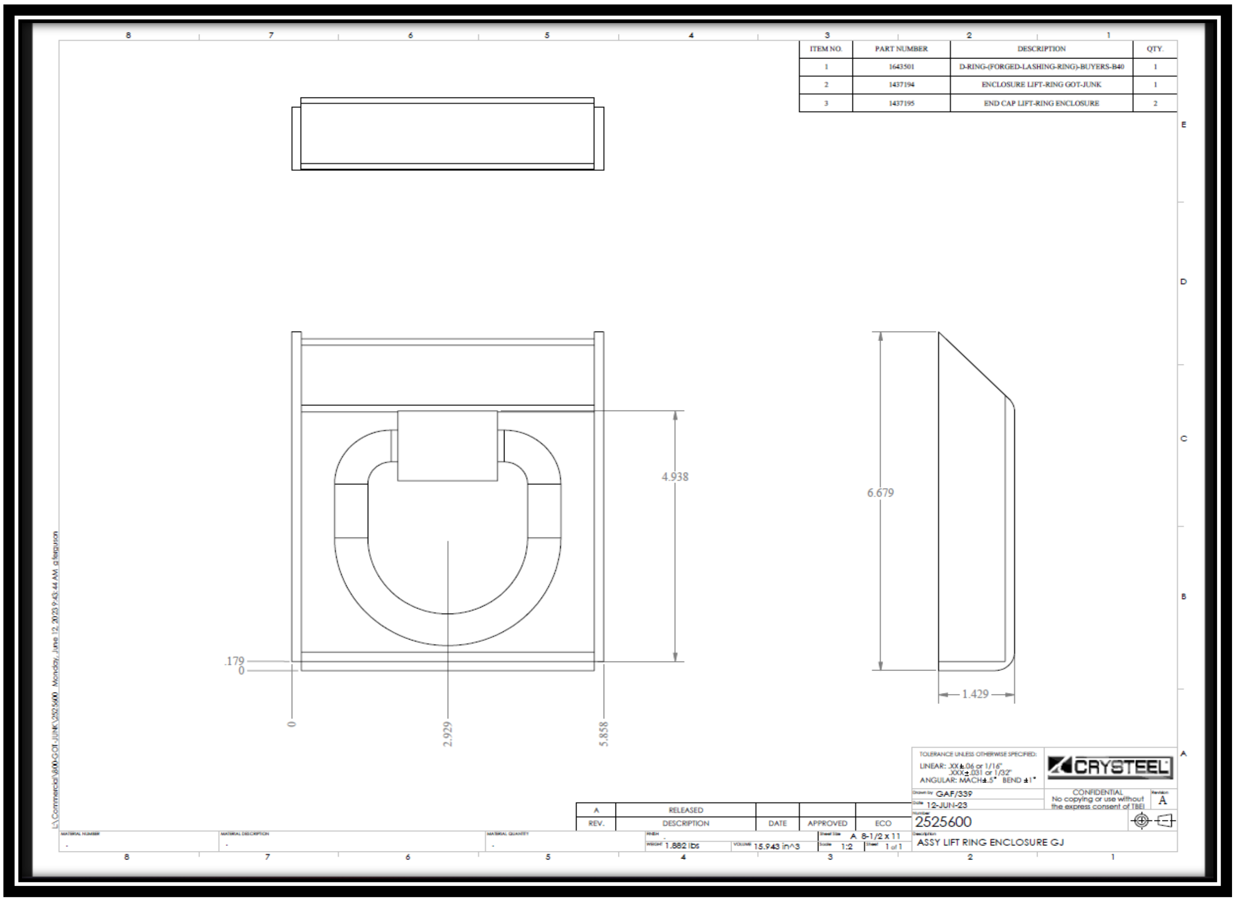
Index x 10	W Keyboard/Electric Typewriter		K Keypad		H Letter/Paper Handling									Index x 10
										Filing				
	Set	Words	Digits	Data	Operations	Jog or Tap	Staple	Stamp	Leaf Through Paper	Select	Open/Close Select	File	Open/Close File	
1	Tab	Click Mouse	2	2		1	Electric		1					1
3		1	6	6	Open Envelope	3	Hole Punch Hand Remove		4					3
6	Set Tab	2 Date	11	12	Interleaf	6		1 Ink	7	1				6
10	Set Margin	4	18	20	Seal Envelope	10		2	12	3		1		10
16		6	28	32	Fold and Crease	16		3	20	6	2	4	1	16
24	Insert and Remove	8	39	46				5	28	9	6	7	5	24
32		11	52	60				7	37	12	9	10	8	32
42		15 Address	68	79				9	47	17	12	15	11	42
54		19	85	100				11	61					54

Time Study Analysis:

Our study used the part assembly lift ring enclosure, specifically for items like a D-ring, enclosure lift ring, and end cap lift ring. These components are used within a larger assembly, potentially for applications that require secure latching or lifting.

Figure 19

CAD Drawing for assembly lift ring enclosure.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1643501	D-RING-(FORGED-LASHING-RING)-BUYERS-B40	1
2	1437194	ENCLOSURE LIFT-RING GOT-JUNK	1
3	1437195	END CAP LIFT-RING ENCLOSURE	2

Figure 20

Lift ring enclosure.

Figure 21

All part assembly.

Welding Time Study Engineering Analysis. We take several criteria into account when comparing the time efficiency of robotic and manual welding for these components:

- Complexity of the welds: The decision between robotic and manual welding may depend on the accessibility and intricacy of the welds needed to secure these components to their respective assemblies. Robotic welding may be more effective for simple, repeatable welds, but manual welding may be better for intricate, variable, or difficult-to-reach welds.
- Material Specifications: Welding parameters are affected by the materials specified for these components. Robotic welding systems can precisely maintain consistent welding settings for materials that need precision heat control.
- Considering the tolerances (.XX ±.06 or 1/16", XXX ±.031 or 1/32") and finish requirements, robotic welding may provide better consistency and quality control, particularly for components where surface finish or aesthetics are essential after welding.
- Production Volume: Due to its quicker changeover times and faster welding speeds than hand welding, robotic welding can decrease cycle times and significantly boost throughput in high-volume production.

Figure 22 Positioning of the workpiece.

Figure 23

Positioning of the workpiece.

Figure 24

Welding of the Specialized workpiece.

Manual Welding Analysis for the part.

MTM-1 Analysis (Maynard, H. B., & Stegemerten, M). The MTM-1 system was chosen for the manual welding operation analysis because it is the first and most comprehensive predetermined time system for time and motion studies. It is particularly well-suited for the in-depth analysis of labor-intensive manual occupations such as welding due to its comprehensive method of measuring human motions. The depth of MTM-1's analysis of fundamental motions allows for a sophisticated comprehension of the operation's time requirements, guaranteeing accurate temporal element measurement and analysis of the welding process. This decision demonstrates a dedication to using a strict process that accurately and carefully depicts the intricacy of manual welding.

A thorough observational study was used to document the intricate details of the process during the course of a Methods-Time Measurement (MTM) analysis of a hand welding process. The welding process was recorded on camera, creating a visual dataset for more in-depth analysis afterward. This recorded footage was carefully examined using a stopwatch, allowing the welding procedure to be divided into distinct steps. To help with the measurement of time values for standardized motions, each identified step was then cross-referenced against established normal time value tables. This approach is an essential part of the MTM methodology. The actual time spent on the welding operations was precisely recorded because of the unique nature of welding operations and the absence of specified time values within the standard MTM tables for the welding process itself. Since standard MTM time value tables do not address the welding process's particular needs and time requirements, this real-time measurement was essential. To ensure compliance with the MTM framework, the actual welding time was converted into Time Measurement Units (TMU), a standardized unit of measure in MTM analysis.

A total MTM time value for the whole welding operation was created by combining these TMU-converted welding timings with the MTM values obtained from the standardized motions. This complete TMU value provided a comprehensive time profile of the manual welding process by summing the distinctive welding times and the standardized motion timings. After calculating these MTM values, the welding processes' actual observed times were compared. The comparative examination showed that the values produced from the MTM Analysis were about 9% less than the real observed times.

MOST Analysis (Niebel, B. W., & Freivalds, A). We chose the Maynard Operation Sequence Technique (MOST) as our other technique for time and motion study analysis of a manual welding operation. This choice was made because MOST is one of the most advanced and effective work process analysis approaches available in industrial engineering. In this case, we applied the Basic MOST analysis option, which was thought to be most suitable considering how little time the welding job took—roughly three minutes per part.

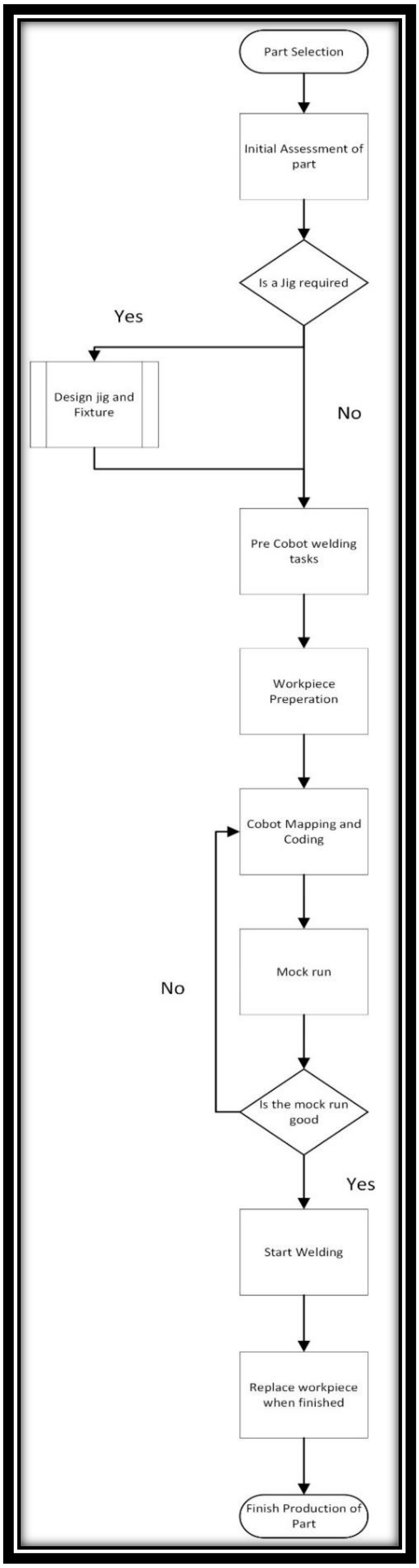
MOST is well known for its effectiveness, providing a far quicker analytical procedure than the conventional MTM-1 system. This efficiency gain—which is projected to be around five times larger—is especially beneficial in situations where quick assessments and iterative process adjustments are essential. In addition, the simplified methodology of Basic MOST, which is distinguished by a smaller count of motion types, makes the analysis more straightforward to understand and less complicated. This simplicity is beneficial when doing tasks involving basic movements, like manual welding procedures.

In our analysis, we used index values for motions taken from the MOST data card to calculate Time Measurement Units (TMU). Using this card as a guide, the measurement of motion times may be standardized, and every step of the welding process can be assessed in relation to a reliable and consistent standard. The accurate and objective measurement of work aspects made possible by the use of index values and the MOST data card structure enhances our time study's accuracy and dependability.

Robotic Welding analysis for the part. Robotic welding at TBEI utilizes cutting-edge automation with the VECTIS Automation UR10E Co-bot. It combines human experience with robotic precision to enhance welding efficiency and quality and improve worker safety. The workflow must be meticulously structured to integrate human and robotic capabilities seamlessly.

Figure 25

Robotic welding process.



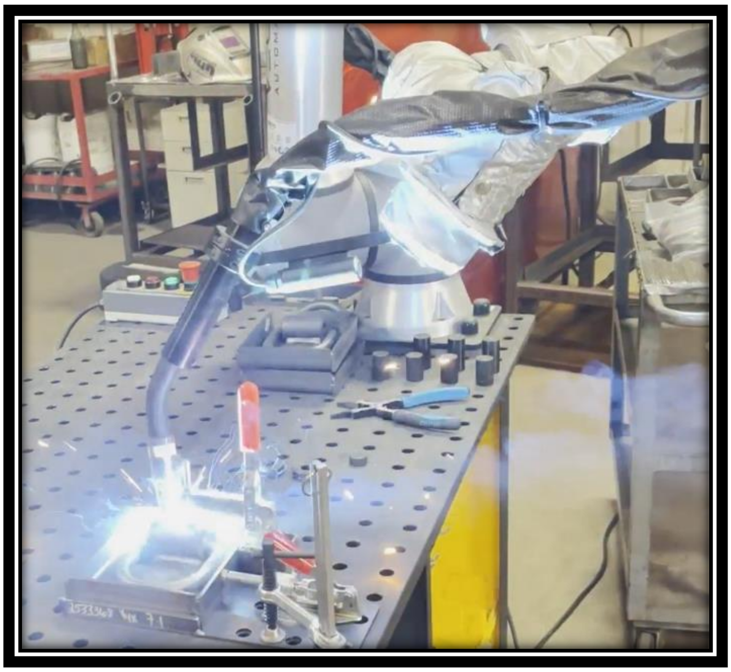
The process begins with a comprehensive evaluation of a part to determine its suitability for robotic welding. Subsequently, if necessary, the design and fabrication of fixtures and jigs are redesigned with precision to facilitate optimal positioning of the workpiece for both manual and co-bot welding ease.

Upon completion of the fixture preparation, human operators perform initial welding tasks such as tack welds, particularly for intricate components beyond the co-bot's current capabilities. Once these steps are done, the workpiece is securely clamped to the fixture.

The next stage is crucial and involves mapping and coding the welding path into the co-bot's system. This is achieved through point-by-point instructions by moving the co-bot’s welding arm through the start point of the weld multiple times between tracking points and the finishing point. A mock run is conducted to ascertain the coding accuracy and the anticipated welds' quality.

Figure 26

Robotic Welding.



Should any discrepancies arise during the mock run, the mapping and coding process is redone to revalidate, ensuring the precise execution of welding tasks. Only upon successful revalidation does the welding process start.

This systematic approach is replicated for subsequent welds, ensuring consistent quality throughout the manufacturing process.

MOST Analysis for Robotic Welding. We used both MTM and MOST predetermined time systems to calculate the theoretical time taken to weld the D ring. We wanted to compare the predetermined time system to see which was closest to the time to weld the part. It was determined that MTM1 was closer because it considered more intricate movements such as pressing the trigger, walking by the operator, precise positioning of the parts, movement of the parts, etc. MOST values were not as close because, to make the process more efficient, it does not consider the intricate details present in the welding process. The MOST predetermined time system was chosen to measure the theoretical time needed to weld the part using co-bots because, for the D ring, there is not much human-based welding expertise required for the welding process.

Figure 27

Robotic Fixtures

Cost Analysis:

Cost plays a major role in every industry, and in this scenario, it does, too. By including co-bots in the manufacturing process, the dependence on highly skilled operators is reduced; hence, the cost to employ a highly experienced operator can be optimized.

A few factors were considered while doing cost analysis, such as the hourly wage of highly skilled operators for manual welding, fixture cost (if - needed), design and material cost (if - needed), and coding costs for the co-bots.

Figure 28

Robotic Costing Factors

Fixture Costing	
Design (4 Hours @$50/hr)	$200
Material	$100
Fabrication	$100
Total	$400
Programming Time	
1 Hour @ $100/hr	$100

The cost analysis was done in the following steps:

- Calculating the average times:
    - Using time study, we are calculating the average times for both manual and robotic welding processes for the lift ring
- Considering welding costs:
    - We are assuming $60/hr. as a standard welding rate for our calculations.

- Establish price per part:
    - Divide the welding cost by the number of parts per hour.
- Optimization of robotic welding times:
    - Assume an improvement of robotic welding times by 5% &10% and calculate new costs.
- Creation of a price table:
    - Develop a table using the above calculations for quantities until we reach the breakeven point.
- Adding upfront costs of robot purchase design and programming:
    - Add the robot, fixtures, and coding costs to the equation to finally get the per-part price.

Conclusion:

Time Study Results:

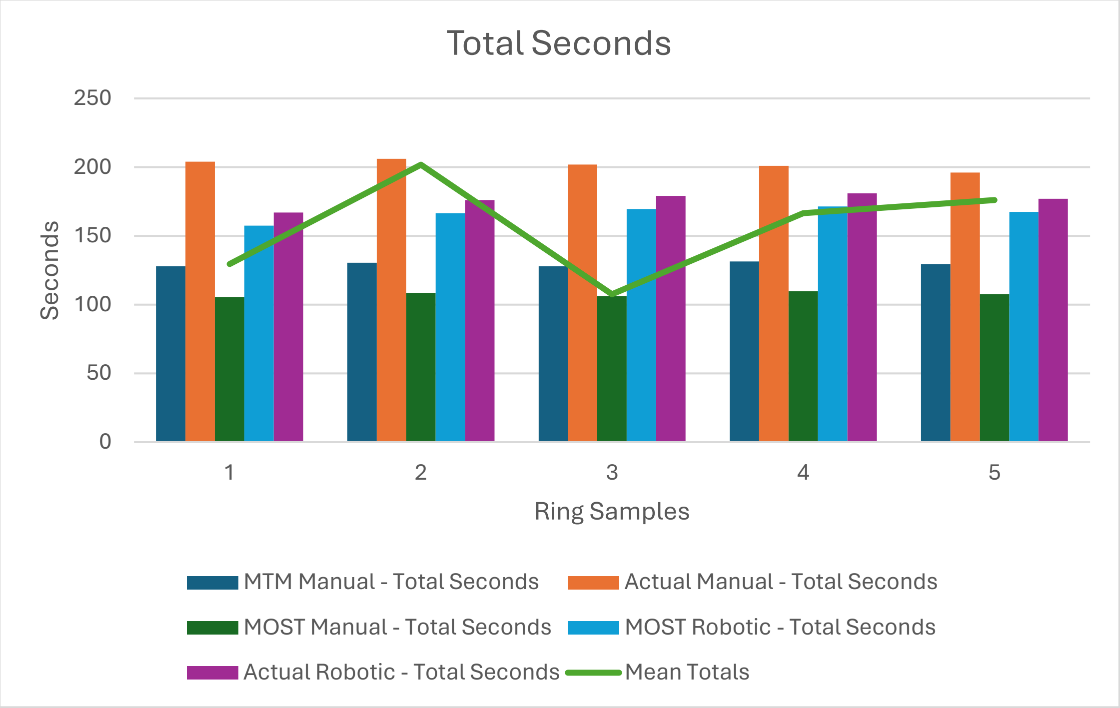
We executed three critical analyses with significant implications for manufacturing efficiency and labor dynamics during our study. First, we conducted a detailed comparative analysis between MTM 1 (Methods-Time Measurement) and MOST (Maynard Operation Sequence Technique), aiming to understand these time management frameworks' relative advantages and application contexts in streamlining manufacturing processes. This comparison was essential for identifying the most effective technique for enhancing operational throughput.

To validate the accuracy of predetermined time standards against real-world times, these methods' reliability can be assessed in predicting job completion times in a live production environment by applying predetermined time study techniques and actual time tracking on a single part across five samples.

We also explored the performance differential between a professional human welder and an automated robotic unit, utilizing the abovementioned time study methods.

Graph 1

Total Time Taken in Seconds

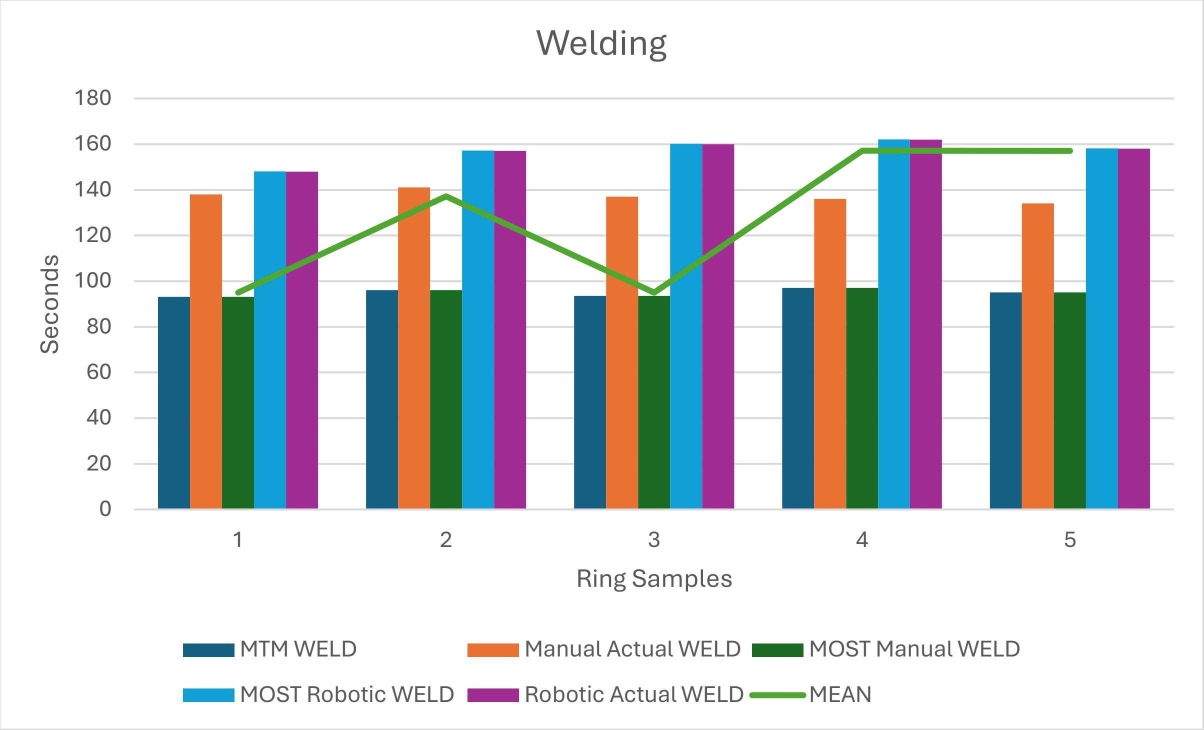


From the predetermined time studies and time and motion studies of both manual and robotic welding, we can see that for manual welding, there is a significant difference in time between the predetermined time systems and normal time study. For manual welding, the MTM time is 35% lower than the actual time taken, and MOST is 47% lower than the actual; when it comes to robotic welding, the difference between the predetermined time and the actual time is much closer as they are only 6% apart.

This is because when doing the predetermined time systems analysis of manual welding, there are a lot of precise, intricate movements made by the human to get the part, prep it, and weld it. The predetermined time systems don't accurately measure the time taken for the action to be completed. In robotic welding, the values are closer since there aren't many human movements to be done.

Graph 2

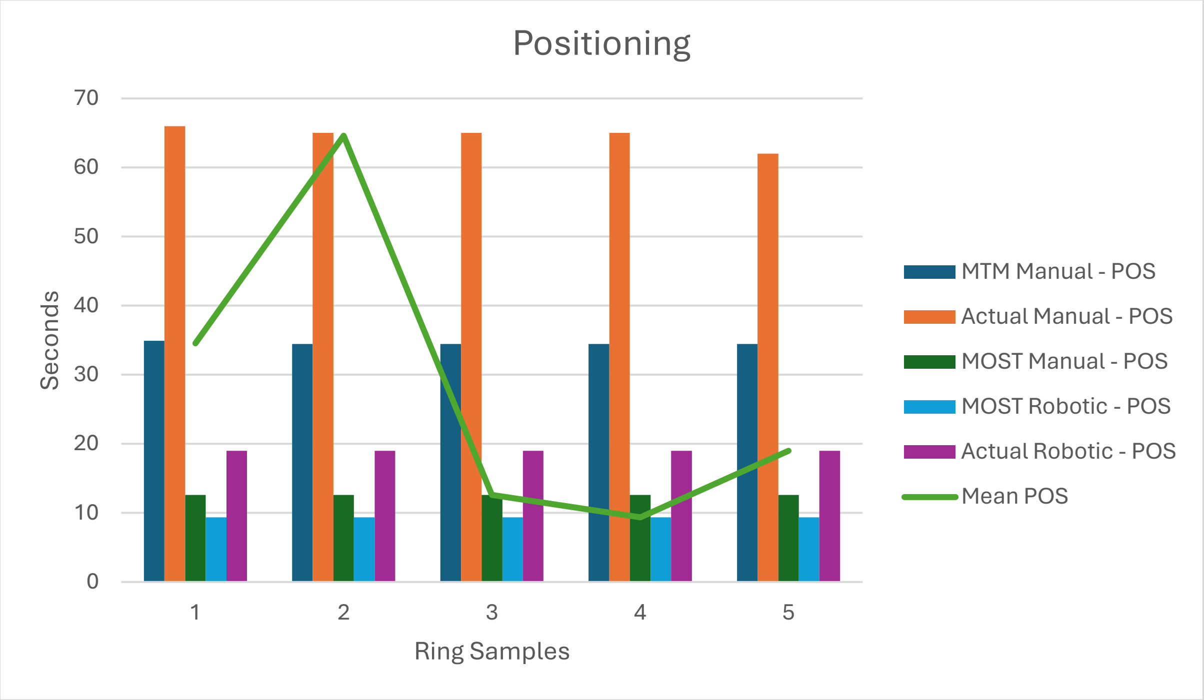
Welding Times in Seconds



As seen from the graph, it is seen that the actual weld values in MTM and Most analyses for manual welding are significantly lower than the actual welding time taken because in MTM and most, only the welding time was taken and noted down as in the actual measurement, even the movement of the hands and pressing of triggers, release of trigger and other small movements were counted too. And the result of that is that the MTM and most values are 30% lower than the actual value on average.

Graph 3

Positioning time in Seconds

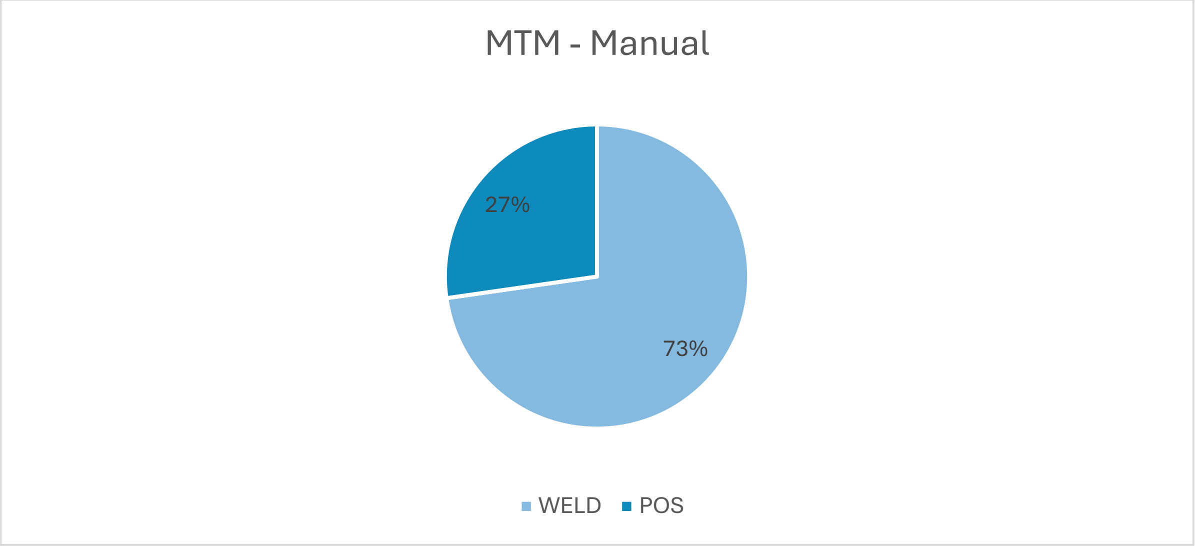


As seen from the separate positioning graph, MTM analysis has the closest value to the actual value compared to MOST because, as explained in the MTM analysis, the therbligs in MTM are more detailed. This leads to the difference between the MTM manual time and actual manual time, which is 45% on average, and between most manual time and actual time, which is 80% on average. The values are closer in robotic welding since there is not much manual positioning. The difference between robotic positioning time and MOST position time is 50% in this scenario. Still, the actual time difference between them is only 10 seconds when compared to MTM manual vs actual time, which is 30 seconds, and between MOST and actual time, which is 52 seconds.

The total process time was broken down into the positioning/preparation of the workpiece and the actual welding. Below is the positioning and welding breakdown established by the predetermined time systems and the normal time study.

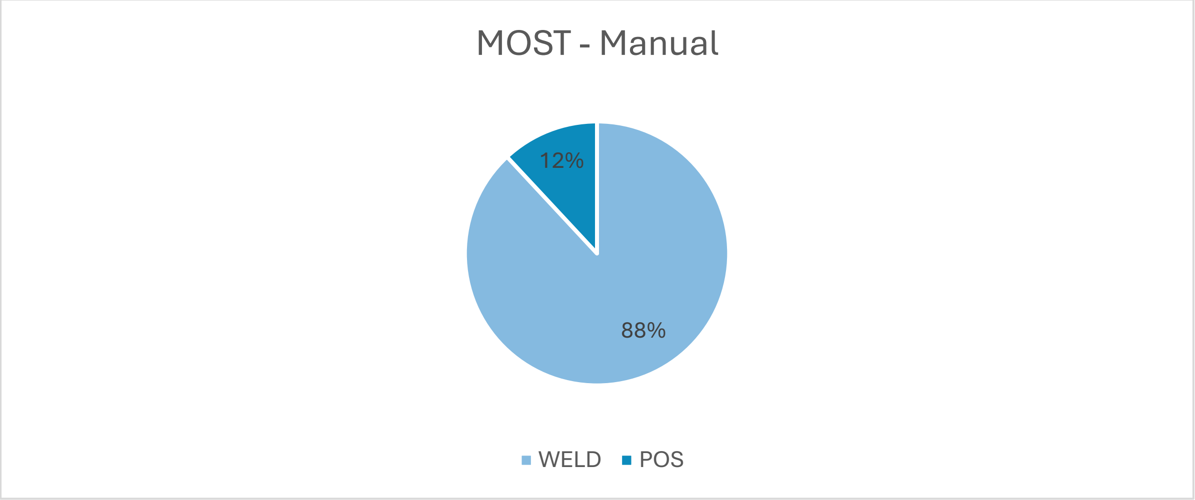
Graph 4

MTM Manual Breakdown



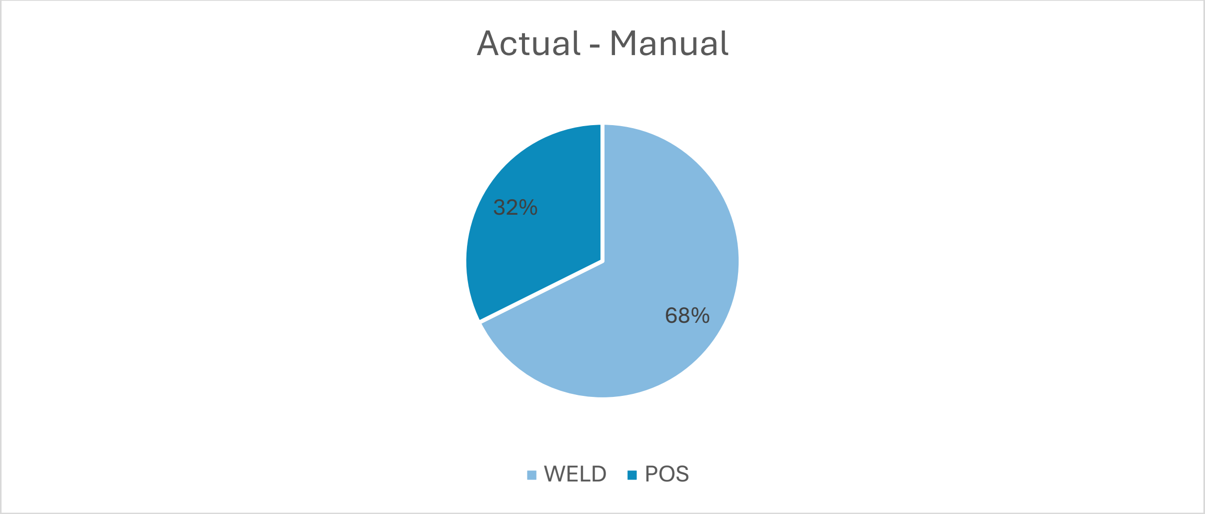
Graph 5

MOST Manual Breakdown



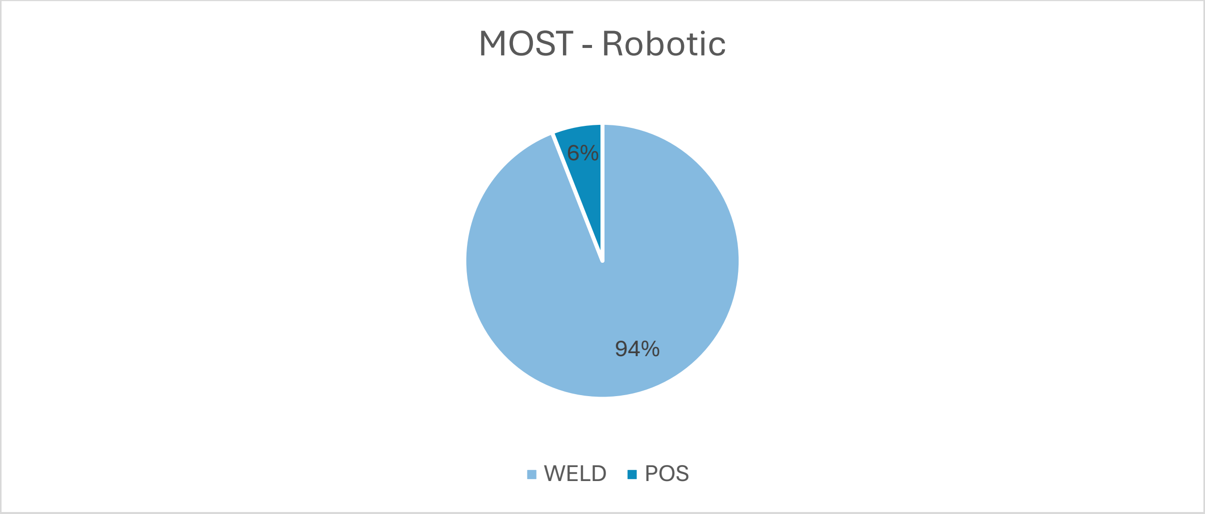
Graph 6

Actual Manual Breakdown



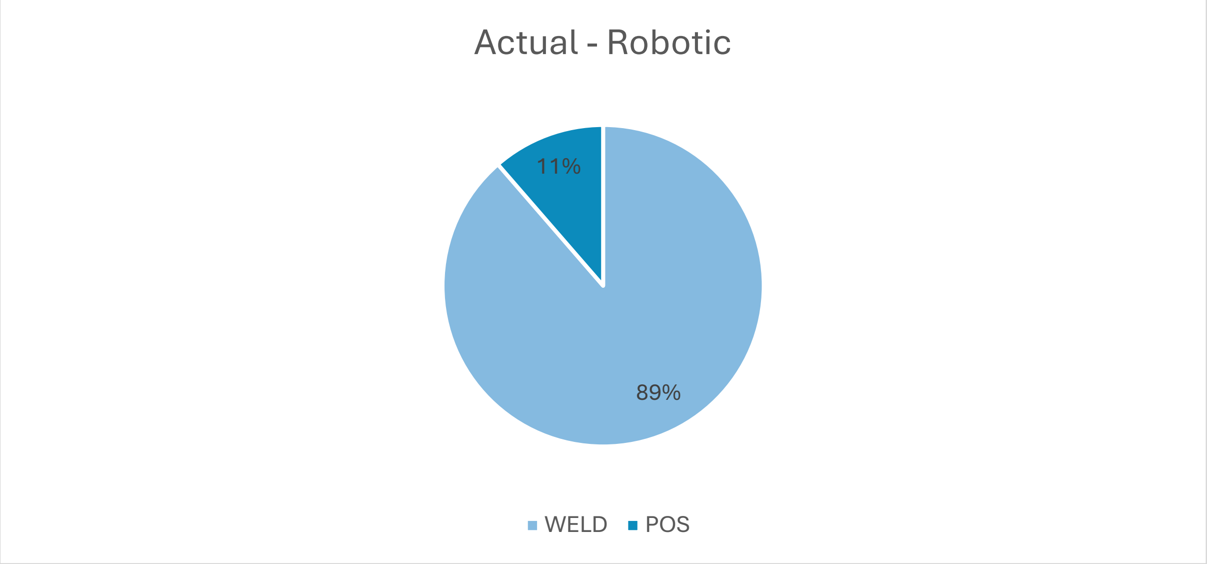
Graph 7

MOST Robotic Breakdown



Graph 8

Actual Robotic Breakdown



As seen from the pie charts above, welding takes a significant amount of time throughout the process, and the positioning prep time in the manual is 70% quicker for this specific part.

The benefit of using robotic welding over manual welding is that in manual welding, the time taken to position is, on average, 34 seconds or 32% of the total process time. In robotic welding, the time taken to position is, on average, 9 seconds, or just 11% of the total process time.

The overall process time for robotic welding is 13% faster than manual welding. That means that for this specific part, there need not be a highly experienced welder working on this part, and a less experienced welder can assist the robot by positioning, placing the workpiece on the fixture, and changing the workpiece when the weld is finished.

Cost analysis results:

The thorough investigation undertaken for this work leads to some significant findings about the comparison of robotic and manual welding procedures. First of all, robotic welding routinely beats manual welding in terms of time efficiency in a variety of situations.

Robotic welding requires a much shorter average time, translating into increased production, throughput, and consequent cost savings. For example, robotic welding takes an average of 176 seconds, while manual welding takes an average of 191.2 seconds. Even if the hourly labor cost for both robotic and manual welding is the same, the impact of this cost is better managed with robotic welding because of how quickly tasks are completed. Robotic welding maximizes labor resource efficiency by minimizing overall labor expenses per item produced, even with a fixed labor cost.

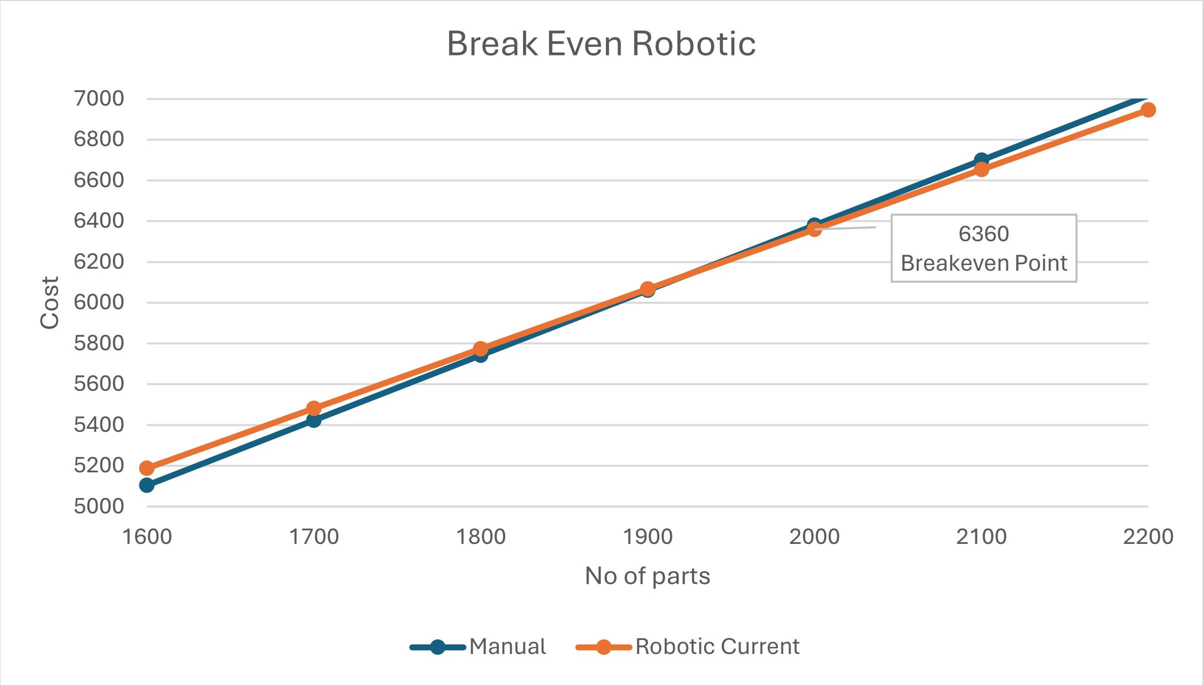
Furthermore, robotic welding shows better cost-effectiveness than hand welding when comparing welding cost per part. Robotic welding's cost per part drops as optimization levels rise, underscoring the system's financial benefits even more. For example, robotic welding reaches a cost per component as low as $2.64 at optimization levels of 10%, while the most significant cost per part for manual welding is $3.19. The thorough research concludes by highlighting the economic advantages of robotic welding over manual welding. Investing in robotic welding technology significantly reduces costs and increases productivity and throughput. Therefore, switching to robotic welding is a wise financial and strategic move for companies looking to streamline their welding procedures and increase cost-effectiveness.

To calculate the breakeven points between robotic and manual welding procedures, we now need to find the point at which the total cost of each approach equals one. This happens when the total cost of employing robotic welding and manual welding adds up to the same amount. By scrutinizing the gathered data, we were able to evaluate the breakeven points for varying quantities of parts manufactured.

Breakeven Analysis:

Graph 9

Breakeven Robotic

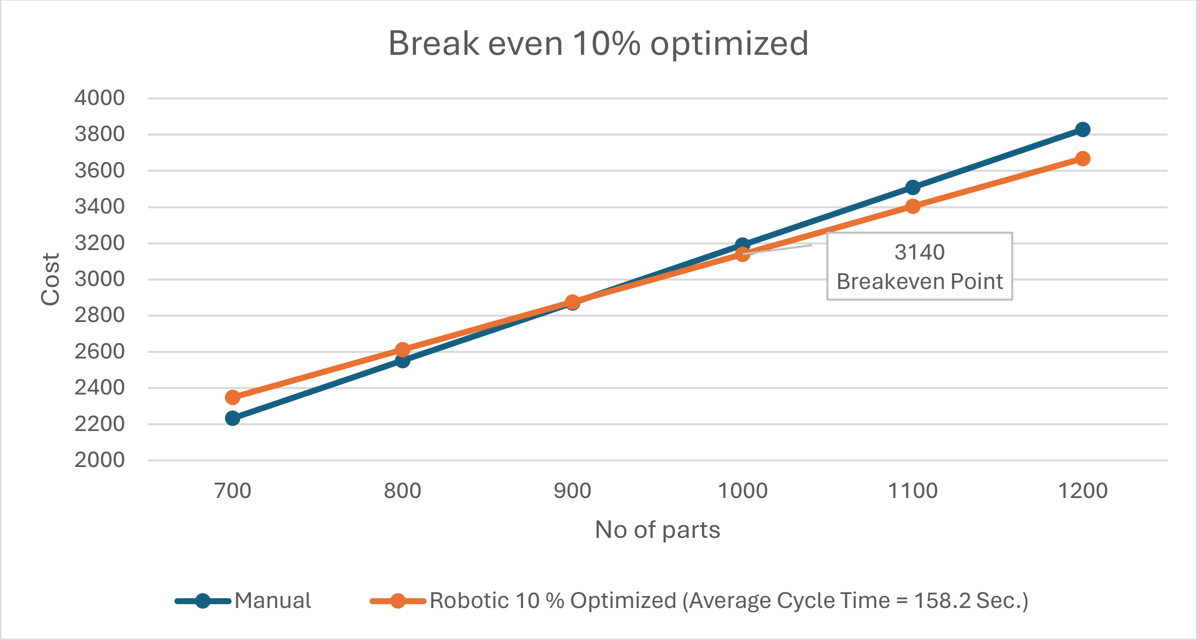


When a cost analysis is run, it is seen that robotic welding will break even with manual welding at 1930 parts, at which point robotic welding will cost $6154.9 and manual welding will cost $6156.7.

With the average welding times and a workday of 6 hours each, including breaks for the operator and some leeway, the robot will break even and be more efficient in 15.8 working days. (122 parts per day and at breakeven at 1930 parts)

Graph 10

10% Optimization of Robotic

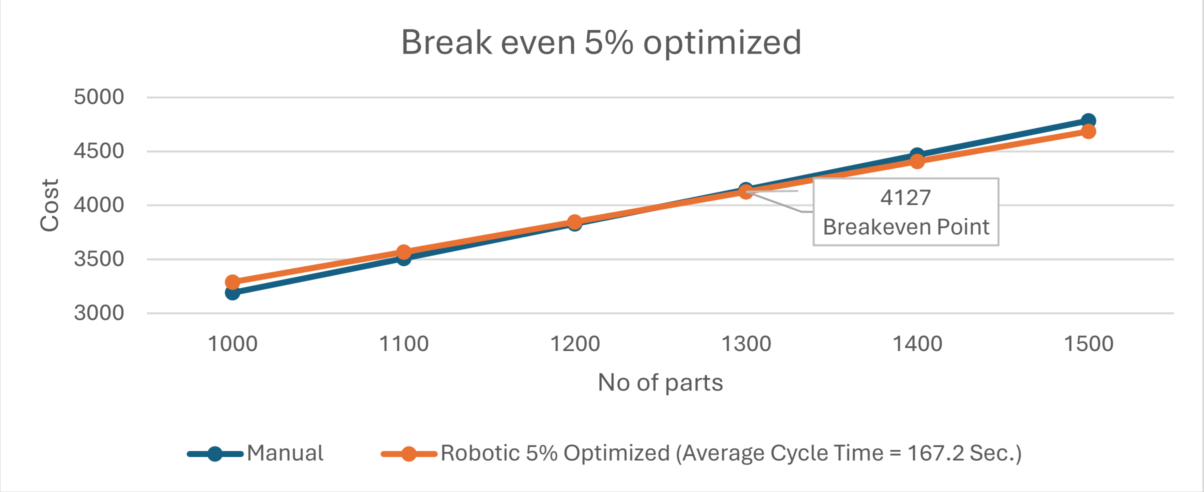


If the robotic welding is optimized by 10%, then it will break even with the manual welding cost at 910 parts, at which the robotic welding will cost $2902.4, and the manual welding will cost $2902.9.

With the average welding time and a workday of 6 hours each, including breaks for the operator and some leeway, the robot will break even and be more efficient in 6.7 working days (136 parts per day and at breakeven at 910 parts).

Graph 11

5% Optimization of Robotic



If the robotic welding is optimized at 5%, it will break even with the manual welding cost at 1260 parts, at which the robotic welding will cost $4015.4, and the manual will cost $4019.4.

With the average welding times and a workday of 6 hours each, including breaks for the operator and some leeway, the robot will break even and be more efficient in 9.7 working days (129 parts per day and at break-even at 1260 parts)

According to the break-even analysis, manual welding can be more economical when producing lower quantities of parts. However, the benefits of robotic welding become more evident with an increase in the number of parts, which lowers overall costs. The efficiency and optimization of robotic welding are key factors in reaching breakeven points at increasing production volumes. Therefore, switching to robotic welding becomes more advantageous for long-term cost reductions and efficiency, especially for large-scale manufacturing operations.

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Appendix

Table 4

MTM analysis of Manual Ring sample -1

MTM Manual 1								
SL No	**Left-hand description**	**LH motion**	**TMU**	**RH motion**	**Right-hand description**	**Body Motion**	**Body Description**	**Actual time taken**
1			37.2			TBC2	Operator turned 90	4
2			37.2			TBC2	Operator turned 90	
3			15.9			W3FT	The operator moved to the parts table.	
4	Grasp the base	G1A	2	G1A	Grasp the plates			
5			37.2			TBC2	Operator turned 90	
6			37.2			TBC2	Operator turned 90	
7			15.9			W3FT	The operator moved to the worktable.	
8			2	RL1	Release the base			
9			47.8	P3NS	Positioning the plate			28
10	Grab plate from right hand	G1A	5.6	G3	Transfer one plate to left hand			
11	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
12			2	G1A	Grab welding gun			8
13			13.5	M10C	Move gun to part			
14			10.6	APA	Press the trigger			
15			27.8		Tack Weld			
16			2	RL1	Release trigger			
17			9.2	M5C	Move the gun to next position			
18			10.6	APA	Press the trigger			

19			27.8		Tack Weld			
20			2	RL1	Release trigger			
21			13.5	M10C	Move gun to holder			
22			2	RL1	Release gun into holder			
23	Turn base	T290	5.4					11
24			2	G1A	Grab Plate			
25	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
26			7.3	R10HA	Move hand to gun			7
27			2	G1A	Grab welding gun			
28			13.5	M10C	Move gun to part			
29			10.6	APA	Press the trigger			
30			27.8		Tack Weld			
31			2	RL1	Release trigger			
32			9.2	M5C	Move the gun to next position			
33			10.6	APA	Press the trigger			
34			27.8		Tack Weld			
35			2	RL1	Release trigger			
36			13.5	M10C	Move gun to holder			
37			2	RL1	Release gun into holder			
38			7.3	R10HA	Move hand to Part			2
39	Flip Part	TS180	9.4	TS180	Flip Part			
40			7.3	R10HA	Move hand to gun			7
41			2	G1A	Grab welding gun			
42			13.5	M10C	Move gun to part			
43			10.6	APA	Press the trigger			
44			111.2		Weld 2 inches			

45			2	RL1	Release trigger			
46	Turn base	T290	9.2	M5C	Move the gun to next position			3
47			10.6	APA	Press the trigger			
48			83.4		Weld 1 inches			
49			2	RL1	Release trigger			
50			10.6	APA	Press the trigger			14
51			361.4		Weld 5 inches			
52			2	RL1	Release trigger			
53	Turn base	T290	5.4					8
54			11.1	M7C	Move the gun to next position			
55			83.4		Weld 1 inches			
56			2	RL1	Release trigger			
57			9.2	M5C	Move the gun to next position			5
58			10.6	APA	Press the trigger			
59			139		Weld 2 inches			
60			2	RL1	Release trigger			
61			10.6	APA	Press the trigger			19
62			444.8		Weld 5 inches			
63			2	RL1	Release trigger			
64	Turn base	T290	5.4					2
65			13.5	M10C	Move gun to holder			
66			2	RL1	Release gun into holder			
67			37.2			TBC2	Operator turned 90	4
68			37.2			TBC2	Operator turned 90	

69			15.9			W3FT	The operator moved to parts table	
70	Grasp the ring	G1A	2	G1A	Grasp the sleeve			14
71	Position the Ring	P3NS	47.8					
72			47.8	P3NS	Positioning the sleeve			
73			7.3	R10HA	Move hand to gun			8
74			2	G1A	Grab welding gun			
75			13.5	M10C	Move gun to part			
76			10.6	APA	Press the trigger			
77			27.8		Tack Weld			
78			2	RL1	Release trigger			
79			5.2	M2C	Move the gun to next position			
80			10.6	APA	Press the trigger			
81			27.8		Tack Weld			
82			2	RL1	Release trigger			
83			10.6	APA	Press the trigger			16
84			305.8		Weld 2 inches sleeve base			
85			2	RL1	Release trigger			
86			5.2	M2C	Move the gun to next position			11
87			10.6	APA	Press the trigger			
88			222.4		Weld 2 inches sleeve top			
89			2	RL1	Release trigger			
90			8	M4C	Move the gun to next position			15

91			10.6	APA	Press the trigger			
92			305.8		Reweld the sleeve base			
93			2	RL1	Release trigger			
94			7.4	TS135	Turn Part 135			17
95			5.2	M2C	Move the gun to next position			
96			10.6	APA	Press the trigger			
97			361.4		Reweld the loop Top			
98			2	RL1	Release trigger			

Table 5

MTM analysis for manual Ring sample-2

MTM Manual 2								
SL No	**Left hand description**	**LH motion**	**TMU**	**RH motion**	**Right hand description**	**Body Motion**	**Body Description**	**Actual time taken**
1			37.2			TBC2	Operator turned 90	4
2			37.2			TBC2	Operator turned 90	
3			15.9			W3FT	The operator moved to parts table	
4	Grasp the base	G1A	2	G1A	Grasp the plates			
5			37.2			TBC2	Operator turned 90	
6			37.2			TBC2	Operator turned 90	
7			15.9			W3FT	Operator moved to the worktable	
8			2	RL1	Release the base			

9			47.8	P3NS	Positioning the plate			26
10	Grab plate from right hand	G1A	5.6	G3	Transfer one plate to left hand			
11	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
12			2	G1A	Grab welding gun			9
13			13.5	M10C	Move gun to part			
14			10.6	APA	Press the trigger			
15			27.8		Tack Weld			
16			2	RL1	Release trigger			
17			9.2	M5C	Move the gun to next position			
18			10.6	APA	Press the trigger			
19			27.8		Tack Weld			
20			2	RL1	Release trigger			
21			13.5	M10C	Move gun to holder			
22			2	RL1	Release gun into holder			
23	Turn base	T290	5.4					11
24			2	G1A	Grab Plate			
25	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
26			7.3	R10HA	Move hand to gun			8
27			2	G1A	Grab welding gun			
28			13.5	M10C	Move gun to part			
29			10.6	APA	Press the trigger			
30			27.8		Tack Weld			

31			2	RL1	Release trigger			
32			9.2	M5C	Move the gun to next position			
33			10.6	APA	Press the trigger			
34			27.8		Tack Weld			
35			2	RL1	Release trigger			
36			13.5	M10C	Move gun to holder			
37			2	RL1	Release gun into holder			
38			7.3	R10HA	Move hand to Part			3
39	Flip Part	TS180	9.4	TS180	Flip Part			
40			7.3	R10HA	Move hand to gun			9
41			2	G1A	Grab welding gun			
42			13.5	M10C	Move gun to part			
43			10.6	APA	Press the trigger			
44			111		Weld 2 inches			
45			2	RL1	Release trigger			
46	Turn base	T290	9.2	M5C	Move the gun to next position			3
47			10.6	APA	Press the trigger			
48			83.4		Weld 1 inches			
49			2	RL1	Release trigger			
50			10.6	APA	Press the trigger			14
51			361		Weld 5 inches			
52			2	RL1	Release trigger			
53	Turn base	T290	5.4					7

54			11.1	M7C	Move the gun to next position			
55			83.4		Weld 1 inches			
56			2	RL1	Release trigger			
57			9.2	M5C	Move the gun to next position			6
58			10.6	APA	Press the trigger			
59			139		Weld 2 inches			
60			2	RL1	Release trigger			
61			10.6	APA	Press the trigger			16
62			445		Weld 5 inches			
63			2	RL1	Release trigger			
64	Turn base	T290	5.4					2
65			13.5	M10C	Move gun to holder			
66			2	RL1	Release gun into holder			
67			37.2			TBC2	Operator turned 90	5
68			37.2			TBC2	Operator turned 90	
69			15.9			W3FT	The operator moved to parts table	
70	Grasp the ring	G1A	2	G1A	Grasp the sleeve			14
71	Position the Ring	P3NS	47.8					
72			47.8	P3NS	Positioning the sleeve			
73			7.3	R10HA	Move hand to gun			10

74			2	G1A	Grab welding gun			
75			13.5	M10C	Move gun to part			
76			10.6	APA	Press the trigger			
77			27.8		Tack Weld			
78			2	RL1	Release trigger			
79			5.2	M2C	Move the gun to next position			
80			10.6	APA	Press the trigger			
81			27.8		Tack Weld			
82			2	RL1	Release trigger			
83			10.6	APA	Press the trigger			14
84			306		Weld 2 inches sleeve base			
85			2	RL1	Release trigger			
86			5.2	M2C	Move the gun to next position			10
87			10.6	APA	Press the trigger			
88			222		Weld 2 inches sleeve top			
89			2	RL1	Release trigger			
90			8	M4C	Move the gun to next position			16
91			10.6	APA	Press the trigger			
92			334		Reweld the sleeve base			
93			2	RL1	Release trigger			
94			7.4	TS135	Turn Part 135			19

95			5.2	M2C	Move the gun to next position			
96			10.6	APA	Press the trigger			
97			417		Reweld the loop Top			
98			2	RL1	Release trigger			

Table 6

MTM analysis for manual Ring sample 3

MTM Manual 3								
SL No	**Left hand description**	**LH motion**	**TMU**	**RH motion**	**Right hand description**	**Body Motion**	**Body Description**	**Actual time taken**
1			37.2			TBC2	Operator turned 90	4
2			37.2			TBC2	Operator turned 90	
3			15.9			W3FT	The operator moved to parts table	
4	Grasp the base	G1A	2	G1A	Grasp the plates			
5			37.2			TBC2	Operator turned 90	
6			37.2			TBC2	Operator turned 90	
7			15.9			W3FT	Operator moved to the worktable	
8			2	RL1	Release the base			
9			47.8	P3NS	Positioning the plate			26
10	Grab plate from right hand	G1A	5.6	G3	Transfer one plate to left hand			
11	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
12			2	G1A	Grab welding gun			9
13			13.5	M10C	Move gun to part			
14			10.6	APA	Press the trigger			

15			27.8		Tack Weld			
16			2	RL1	Release trigger			
17			9.2	M5C	Move the gun to next position			
18			10.6	APA	Press the trigger			
19			27.8		Tack Weld			
20			2	RL1	Release trigger			
21			13.5	M10C	Move gun to holder			
22			2	RL1	Release gun into holder			
23	Turn base	T290	5.4					11
24			2	G1A	Grab Plate			
25	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
26			7.3	R10HA	Move hand to gun			8
27			2	G1A	Grab welding gun			
28			13.5	M10C	Move gun to part			
29			10.6	APA	Press the trigger			
30			27.8		Tack Weld			
31			2	RL1	Release trigger			
32			9.2	M5C	Move the gun to next position			
33			10.6	APA	Press the trigger			
34			27.8		Tack Weld			
35			2	RL1	Release trigger			
36			13.5	M10C	Move gun to holder			
37			2	RL1	Release gun into holder			
38			7.3	R10HA	Move hand to Part			3
39	Flip Part	TS180	9.4	TS180	Flip Part			
40			7.3	R10HA	Move hand to gun			10
41			2	G1A	Grab welding gun			

42			13.5	M10C	Move gun to part			
43			10.6	APA	Press the trigger			
44			125		Weld 2 inches			
45			2	RL1	Release trigger			
46	Turn base	T290	9.2	M5C	Move the gun to next position			3
47			10.6	APA	Press the trigger			
48			83.4		Weld 1 inches			
49			2	RL1	Release trigger			
50			10.6	APA	Press the trigger			16
51			417		Weld 5 inches			
52			2	RL1	Release trigger			
53	Turn base	T290	5.4					7
54			11.1	M7C	Move the gun to next position			
55			55.6		Weld 1 inches			
56			2	RL1	Release trigger			
57			9.2	M5C	Move the gun to next position			7
58			10.6	APA	Press the trigger			
59			167		Weld 2 inches			
60			2	RL1	Release trigger			
61			10.6	APA	Press the trigger			15
62			389		Weld 5 inches			
63			2	RL1	Release trigger			
64	Turn base	T290	5.4					2
65			13.5	M10C	Move gun to holder			
66			2	RL1	Release gun into holder			
67			37.2			TBC2	Operator turned 90	5

68			37.2			TBC2	Operator turned 90	
69			15.9			W3FT	The operator moved to parts table	
70	Grasp the ring	G1A	2	G1A	Grasp the sleeve			14
71	Position the Ring	P3NS	47.8					
72			47.8	P3NS	Positioning the sleeve			
73			7.3	R10HA	Move hand to gun			10
74			2	G1A	Grab welding gun			
75			13.5	M10C	Move gun to part			
76			10.6	APA	Press the trigger			
77			27.8		Tack Weld			
78			2	RL1	Release trigger			
79			5.2	M2C	Move the gun to next position			
80			10.6	APA	Press the trigger			
81			27.8		Tack Weld			
82			2	RL1	Release trigger			
83			10.6	APA	Press the trigger			12
84			334		Weld 2 inches sleeve base			
85			2	RL1	Release trigger			
86			5.2	M2C	Move the gun to next position			9
87			10.6	APA	Press the trigger			
88			222		Weld 2 inches sleeve top			
89			2	RL1	Release trigger			
90			8	M4C	Move the gun to next position			13
91			10.6	APA	Press the trigger			

92			278		Reweld the sleeve base			
93			2	RL1	Release trigger			
94			7.4	TS135	Turn Part 135			18
95			5.2	M2C	Move the gun to next position			
96			10.6	APA	Press the trigger			
97			361		Reweld the loop Top			
98			2	RL1	Release trigger			

Table 7

MTM analysis for manual Ring sample 4

MTM Manual 4								
SL No	**Left hand description**	**LH motion**	**TMU**	**RH motion**	**Right hand description**	**Body Motion**	**Body Description**	**Actual time taken**
1			37.2			TBC2	Operator turned 90	4
2			37.2			TBC2	Operator turned 90	
3			15.9			W3FT	The operator moved to parts table	
4	Grasp the base	G1A	2	G1A	Grasp the plates			
5			37.2			TBC2	Operator turned 90	
6			37.2			TBC2	Operator turned 90	
7			15.9			W3FT	Operator moved to the worktable	
8			2	RL1	Release the base			
9			47.8	P3NS	Positioning the plate			26
10	Grab plate from right hand	G1A	5.6	G3	Transfer one plate to left hand			
11	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
12			2	G1A	Grab welding gun			9

13			13.5	M10C	Move gun to part			
14			10.6	APA	Press the trigger			
15			27.8		Tack Weld			
16			2	RL1	Release trigger			
17			9.2	M5C	Move the gun to next position			
18			10.6	APA	Press the trigger			
19			27.8		Tack Weld			
20			2	RL1	Release trigger			
21			13.5	M10C	Move gun to holder			
22			2	RL1	Release gun into holder			
23	Turn base	T290	5.4					11
24			2	G1A	Grab Plate			
25	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
26			7.3	R10HA	Move hand to gun			8
27			2	G1A	Grab welding gun			
28			13.5	M10C	Move gun to part			
29			10.6	APA	Press the trigger			
30			27.8		Tack Weld			
31			2	RL1	Release trigger			
32			9.2	M5C	Move the gun to next position			
33			10.6	APA	Press the trigger			
34			27.8		Tack Weld			
35			2	RL1	Release trigger			
36			13.5	M10C	Move gun to holder			
37			2	RL1	Release gun into holder			
38			7.3	R10HA	Move hand to Part			3
39	Flip Part	TS180	9.4	TS180	Flip Part			
40			7.3	R10HA	Move hand to gun			8
41			2	G1A	Grab welding gun			

42			13.5	M10C	Move gun to part			
43			10.6	APA	Press the trigger			
44			111		Weld 2 inches			
45			2	RL1	Release trigger			
46	Turn base	T290	9.2	M5C	Move the gun to next position			4
47			10.6	APA	Press the trigger			
48			83.4		Weld 1 inches			
49			2	RL1	Release trigger			
50			10.6	APA	Press the trigger			17
51			445		Weld 5 inches			
52			2	RL1	Release trigger			
53	Turn base	T290	5.4					5
54			11.1	M7C	Move the gun to next position			
55			55.6		Weld 1 inches			
56			2	RL1	Release trigger			
57			9.2	M5C	Move the gun to next position			8
58			10.6	APA	Press the trigger			
59			195		Weld 2 inches			
60			2	RL1	Release trigger			
61			10.6	APA	Press the trigger			15
62			389		Weld 5 inches			
63			2	RL1	Release trigger			
64	Turn base	T290	5.4					2
65			13.5	M10C	Move gun to holder			
66			2	RL1	Release gun into holder			
67			37.2			TBC2	Operator turned 90	5
68			37.2			TBC2	Operator turned 90	

69			15.9			W3FT	The operator moved to parts table	
70	Grasp the ring	G1A	2	G1A	Grasp the sleeve			14
71	Position the Ring	P3NS	47.8					
72			47.8	P3NS	Positioning the sleeve			
73			7.3	R10HA	Move hand to gun			10
74			2	G1A	Grab welding gun			
75			13.5	M10C	Move gun to part			
76			10.6	APA	Press the trigger			
77			27.8		Tack Weld			
78			2	RL1	Release trigger			
79			5.2	M2C	Move the gun to next position			
80			10.6	APA	Press the trigger			
81			27.8		Tack Weld			
82			2	RL1	Release trigger			
83			10.6	APA	Press the trigger			12
84			278		Weld 2 inches sleeve base			
85			2	RL1	Release trigger			
86			5.2	M2C	Move the gun to next position			10
87			10.6	APA	Press the trigger			
88			250		Weld 2 inches sleeve top			
89			2	RL1	Release trigger			
90			8	M4C	Move the gun to next position			13
91			10.6	APA	Press the trigger			
92			361		Reweld the sleeve base			
93			2	RL1	Release trigger			

94			7.4	TS135	Turn Part 135			17
95			5.2	M2C	Move the gun to next position			
96			10.6	APA	Press the trigger			
97			361		Reweld the loop Top			
98			2	RL1	Release trigger			

Table 8

MTM analysis for manual Ring sample 5

MTM Manual 5								
SL No	**Left hand description**	**LH motion**	**TMU**	**RH motion**	**Right hand description**	**Body Motion**	**Body Description**	**Actual time taken**
1			37.2			TBC2	Operator turned 90	4
2			37.2			TBC2	Operator turned 90	
3			15.9			W3FT	The operator moved to parts table	
4	Grasp the base	G1A	2	G1A	Grasp the plates			
5			37.2			TBC2	Operator turned 90	
6			37.2			TBC2	Operator turned 90	
7			15.9			W3FT	Operator moved to the worktable	
8			2	RL1	Release the base			
9			47.8	P3NS	Positioning the plate			26
10	Grab plate from right hand	G1A	5.6	G3	Transfer one plate to left hand			
11	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
12			2	G1A	Grab welding gun			9
13			13.5	M10C	Move gun to part			
14			10.6	APA	Press the trigger			
15			27.8		Tack Weld			
16			2	RL1	Release trigger			

17			9.2	M5C	Move the gun to next position			
18			10.6	APA	Press the trigger			
19			27.8		Tack Weld			
20			2	RL1	Release trigger			
21			13.5	M10C	Move gun to holder			
22			2	RL1	Release gun into holder			
23	Turn base	T290	5.4					11
24			2	G1A	Grab Plate			
25	Positioning the plate	P3NS	47.8	P3NS	Positioning the plate			
26			7.3	R10HA	Move hand to gun			8
27			2	G1A	Grab welding gun			
28			13.5	M10C	Move gun to part			
29			10.6	APA	Press the trigger			
30			27.8		Tack Weld			
31			2	RL1	Release trigger			
32			9.2	M5C	Move the gun to next position			
33			10.6	APA	Press the trigger			
34			27.8		Tack Weld			
35			2	RL1	Release trigger			
36			13.5	M10C	Move gun to holder			
37			2	RL1	Release gun into holder			
38			7.3	R10HA	Move hand to Part			3
39	Flip Part	TS180	9.4	TS180	Flip Part			
40			7.3	R10HA	Move hand to gun			9
41			2	G1A	Grab welding gun			
42			13.5	M10C	Move gun to part			
43			10.6	APA	Press the trigger			
44			167		Weld 2 inches			

45			2	RL1	Release trigger			
46	Turn base	T290	9.2	M5C	Move the gun to next position			2
47			10.6	APA	Press the trigger			
48			55.6		Weld 1 inches			
49			2	RL1	Release trigger			
50			10.6	APA	Press the trigger			14
51			389		Weld 5 inches			
52			2	RL1	Release trigger			
53	Turn base	T290	5.4					5
54			11.1	M7C	Move the gun to next position			
55			55.6		Weld 1 inches			
56			2	RL1	Release trigger			
57			9.2	M5C	Move the gun to next position			6
58			10.6	APA	Press the trigger			
59			139		Weld 2 inches			
60			2	RL1	Release trigger			
61			10.6	APA	Press the trigger			14
62			361		Weld 5 inches			
63			2	RL1	Release trigger			
64	Turn base	T290	5.4					2
65			13.5	M10C	Move gun to holder			
66			2	RL1	Release gun into holder			
67			37.2			TBC2	Operator turned 90	4
68			37.2			TBC2	Operator turned 90	
69			15.9			W3FT	The operator moved to parts table	
70	Grasp the ring	G1A	2	G1A	Grasp the sleeve			12

71	Position the Ring	P3NS	47.8					
72			47.8	P3NS	Positioning the sleeve			
73			7.3	R10HA	Move hand to gun			10
74			2	G1A	Grab welding gun			
75			13.5	M10C	Move gun to part			
76			10.6	APA	Press the trigger			
77			27.8		Tack Weld			
78			2	RL1	Release trigger			
79			5.2	M2C	Move the gun to next position			
80			10.6	APA	Press the trigger			
81			27.8		Tack Weld			
82			2	RL1	Release trigger			
83			10.6	APA	Press the trigger			15
84			389		Weld 2 inches sleeve base			
85			2	RL1	Release trigger			
86			5.2	M2C	Move the gun to next position			10
87			10.6	APA	Press the trigger			
88			278		Weld 2 inches sleeve top			
89			2	RL1	Release trigger			
90			8	M4C	Move the gun to next position			13
91			10.6	APA	Press the trigger			
92			278		Reweld the sleeve base			
93			2	RL1	Release trigger			
94			7.4	TS135	Turn Part 135			19
95			5.2	M2C	Move the gun to next position			

96			10.6	APA	Press the trigger			
97			361		Reweld the loop Top			
98			2	RL1	Release trigger			

Table 9

MOST analysis of manual ring sample – 1

MOST Manual 1										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding Tacks								0	55.6
3	positioning the part	1	0	1	1	0	6	0	9	90
4	Welding Tacks								0	55.6
5	Turns part								0	0
6	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	861.8
7	Moves part around								0	0
8	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	973
9	Getting a part	3	0	3	1	0	6	0	13	130
10	Welding Tacks								0	222.4
11	Welding(4*2 inch welds)								0	1223.2

Table 10

MOST analysis of manual ring sample – 2

MOST Manual 2										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding Tacks								0	55.6
3	positioning the part	1	0	1	1	0	6	0	9	90
4	Welding Tacks								0	55.6
5	Turns part								0	0
6	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	556

7	Moves part around								0	
8	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	667.2
9	Getting a part	3	0	3	1	0	6	0	13	130
10	Welding Tacks								0	55.6
11	Welding(4*2 inch welds)								0	1278.8

Table 11

MOST analysis of manual ring sample – 3

MOST Manual 3										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding Tacks								0	55.6
3	positioning the part	1	0	1	1	0	6	0	9	90
4	Welding Tacks								0	55.6
5	Turns part								0	0
6	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	625.5
7	Moves part around								0	
8	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	611.6
9	Getting a part	3	0	3	1	0	6	0	13	130
10	Welding Tacks								0	55.6
11	Welding(4*2 inch welds)								0	1195.4

Table 12

MOST analysis of manual ring sample – 4

MOST Manual 4										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding Tacks								0	55.6
3	positioning the part	1	0	1	1	0	6	0	9	90
4	Welding Tacks								0	55.6
5	Turns part								0	0

6	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	639.4
7	Moves part around								0	
8	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	639.4
9	Getting a part	3	0	3	1	0	6	0	13	130
10	Welding Tacks								0	55.6
11	Welding(4*2 inch welds)								0	1251

Table 13

MOST analysis of manual ring sample – 5

MOST Manual 5										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding Tacks								0	55.6
3	positioning the part	1	0	1	1	0	6	0	9	90
4	Welding Tacks								0	55.6
5	Turns part								0	0
6	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	611.6
7	Moves part around								0	
8	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	556
9	Getting a part	3	0	3	1	0	6	0	13	130
10	Welding Tacks								0	55.6
11	Welding(4*2 inch welds)								0	1306.6

Table 14

MOST analysis of robotic ring sample – 1

MOST ROBOTIC 1										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
3	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
4	Getting a part	3	0	3	1	0	6	0	13	130
5	Welding(6*2 inch welds)								0	0

Table 15

MOST analysis of robotic ring sample – 2

MOST ROBOTIC 2										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
3	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
4	Getting a part	3	0	3	1	0	6	0	13	130
5	Welding(6*2 inch welds)								0	0

Table 16

MOST analysis of robotic ring sample – 3

MOST ROBOTIC 3										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
3	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
4	Getting a part	3	0	3	1	0	6	0	13	130
5	Welding(6*2 inch welds)								0	0

Table 17

MOST analysis of robotic ring sample – 4

MOST ROBOTIC 4										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
3	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
4	Getting a part	3	0	3	1	0	6	0	13	130
5	Welding(6*2 inch welds)								0	0

Table 18

MOST analysis of robotic ring sample – 5

MOST ROBOTIC 5										
Sl No.			**Get**			**Put**		**Return**	**Index**	**TMU**
	General move	A	B	G	A	B	P	A		
1	Getting parts to the work area	3	0	3	1	0	6	0	13	130
2	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
3	Welding(2 inch weld, 1 inch weld, 5 inch weld)								0	0
4	Getting a part	3	0	3	1	0	6	0	13	130
5	Welding(6*2 inch welds)								0	0

Table 19

Time analysis of robotic ring sample – 1

Robotic Actual Time 1		
SL No.	**Action**	**Time**
1	Move base and 2 sides to welding fixture	8
2	Clamp the fixture	3
3	Weld plate 1	34
4	Weld plate 2	36
5	Position ring and sleeve	8
6	Weld sleeve on the bottom (pass 1)	10
7	Weld sleeve on the top (pass 1)	13
8	Weld sleeve on the bottom (pass 2)	13
9	Weld sleeve on the top (pass 2)	15
10	Weld sleeve on the bottom (pass 3)	13
11	Weld sleeve on the top (pass 3)	14

Table 20

Time analysis of robotic ring sample – 2

Robotic Actual Time 2		
SL No.	**Action**	**Time**
1	Move base and 2 sides to welding fixture	8
2	Clamp the fixture	3
3	Weld plate 1	38
4	Weld plate 2	39
5	Position ring and sleeve	8
6	Weld sleeve on the bottom (pass 1)	10
7	Weld sleeve on the top (pass 1)	14
8	Weld sleeve on the bottom (pass 2)	13
9	Weld sleeve on the top (pass 2)	15
10	Weld sleeve on the bottom (pass 3)	14
11	Weld sleeve on the top (pass 3)	14

Table 21

Time analysis of robotic ring sample – 3

Robotic Actual Time 3		
SL No.	**Action**	**Time**
1	Move base and 2 sides to welding fixture	8
2	Clamp the fixture	3
3	Weld plate 1	39
4	Weld plate 2	39
5	Position ring and sleeve	8
6	Weld sleeve on the bottom (pass 1)	11
7	Weld sleeve on the top (pass 1)	15
8	Weld sleeve on the bottom (pass 2)	12
9	Weld sleeve on the top (pass 2)	14
10	Weld sleeve on the bottom (pass 3)	15
11	Weld sleeve on the top (pass 3)	15

Table 22

Time analysis of robotic ring sample – 4

Robotic Actual Time 4

SL No.	**Action**	**Time**
1	Move base and 2 sides to welding fixture	8
2	Clamp the fixture	3
3	Weld plate 1	40
4	Weld plate 2	40
5	Position ring and sleeve	8
6	Weld sleeve on the bottom (pass 1)	10
7	Weld sleeve on the top (pass 1)	15
8	Weld sleeve on the bottom (pass 2)	13
9	Weld sleeve on the top (pass 2)	15
10	Weld sleeve on the bottom (pass 3)	14
11	Weld sleeve on the top (pass 3)	15

Table 23

Time analysis of robotic ring sample – 5

Robotic Actual Time 5		
SL No.	**Action**	**Time**
1	Move base and 2 sides to welding fixture	8
2	Clamp the fixture	3
3	Weld plate 1	39
4	Weld plate 2	39
5	Position ring and sleeve	8
6	Weld sleeve on the bottom (pass 1)	11
7	Weld sleeve on the top (pass 1)	14
8	Weld sleeve on the bottom (pass 2)	12
9	Weld sleeve on the top (pass 2)	14
10	Weld sleeve on the bottom (pass 3)	15
11	Weld sleeve on the top (pass 3)	14

Table 24

Cost Analysis

Number of Parts	**Manual**	**Robotic Current**	**Robotic Optimized (Average Cycle Time = 158.2 Sec.)**	**Robotic Optimized (Average Cycle Time = 167.2 Sec.)**

1	3.19	502.93	502.64	502.79
2	6.38	505.86	505.28	505.58
3	9.57	508.79	507.92	508.37
4	12.76	511.72	510.56	511.16
5	15.95	514.65	513.2	513.95
6	19.14	517.58	515.84	516.74
7	22.33	520.51	518.48	519.53
8	25.52	523.44	521.12	522.32
9	28.71	526.37	523.76	525.11
10	31.9	529.3	526.4	527.9
11	35.09	532.23	529.04	530.69
12	38.28	535.16	531.68	533.48
13	41.47	538.09	534.32	536.27
14	44.66	541.02	536.96	539.06
15	47.85	543.95	539.6	541.85
16	51.04	546.88	542.24	544.64
17	54.23	549.81	544.88	547.43
18	57.42	552.74	547.52	550.22
19	60.61	555.67	550.16	553.01
20	63.8	558.6	552.8	555.8
21	66.99	561.53	555.44	558.59
22	70.18	564.46	558.08	561.38
23	73.37	567.39	560.72	564.17
24	76.56	570.32	563.36	566.96
25	79.75	573.25	566	569.75
26	82.94	576.18	568.64	572.54
27	86.13	579.11	571.28	575.33
28	89.32	582.04	573.92	578.12
29	92.51	584.97	576.56	580.91
30	95.7	587.9	579.2	583.7
31	98.89	590.83	581.84	586.49
32	102.08	593.76	584.48	589.28
33	105.27	596.69	587.12	592.07
34	108.46	599.62	589.76	594.86
35	111.65	602.55	592.4	597.65
36	114.84	605.48	595.04	600.44
37	118.03	608.41	597.68	603.23
38	121.22	611.34	600.32	606.02
39	124.41	614.27	602.96	608.81
40	127.6	617.2	605.6	611.6
50	159.5	646.5	632	639.5
100	319	793	764	779
150	478.5	939.5	896	918.5

200	638	1086	1028	1058
300	957	1379	1292	1337
400	1276	1672	1556	1616
500	1595	1965	1820	1895
600	1914	2258	2084	2174
700	2233	2551	2348	2453
800	2552	2844	2612	2732
900	2871	3137	2876	3011
1000	3190	3430	3140	3290
1100	3509	3723	3404	3569
1200	3828	4016	3668	3848
1300	4147	4309	3932	4127
1400	4466	4602	4196	4406
1500	4785	4895	4460	4685
1600	5104	5188	4724	4964
1700	5423	5481	4988	5243
1800	5742	5774	5252	5522
1900	6061	6067	5516	5801
2000	6380	6360	5780	6080
2100	6699	6653	6044	6359
2200	7018	6946	6308	6638
2300	7337	7239	6572	6917
2400	7656	7532	6836	7196
2500	7975	7825	7100	7475
2600	8294	8118	7364	7754
2700	8613	8411	7628	8033
2800	8932	8704	7892	8312
2900	9251	8997	8156	8591
3000	9570	9290	8420	8870