SunTrac Design Team

Preliminary Proposal

Kadeja Alhossaini

Nathan Firor

Edwin Smith

Ethan Vieane

2019-2020

Project Sponsor: SunTrac USA

Sponsor Mentor: Stu Siebens

Instructor: Sarah Oman

DISCLAIMER

TABLE OF CONTENTS

1 BACKGROUND

1.1 Introduction

This capstone project consists of redesigning the braze welding jig that is currently in use at SunTrac USA. The objective of this project is to design a new braze welding jig that is compatible with SunTrac's 8', 6', and 4' product variants. This project is important to SunTrac because they are projected to grow exponentially in the next three years and need to be ready for the increase in demand for their products. This product solves issues relating to lean manufacturing and ensures that SunTrac is being as efficient as possible given the limited space in their manufacturing facility.

1.2 Project Description

Following is the original project description provided by the sponsor:

> The director of engineering for SunTrac USA (please see www.suntracusa.com) would like a capstone team to create a system to help with manufacturing. We manufacture a radiant solar panel that when coupled with variable speed or two speed Air Conditioning systems reduces the energy consumption of the AC system by up to 45 %.
>
> One of the key components of our system is a series of (6) 5/8" diameter copper tubes that must be brazed at both ends into a 1-1/8" copper tube. We call this a "copper manifold" and we make it in three different lengths (4 ft, 6 ft, and 8 ft).
>
> What I would like your team to do is design and build a brazing jig that would give us the flexibility to do any of the three lengths on the same jig. The function of the jig is to hold all the copper pipes in place while they are brazed together. SunTrac would provide all the materials at no cost to the students. What we would like is for your team to design the jig and draw up the parts needed to assemble the fixture. We would have the parts made to their drawings and they could assemble the finished product. We would like to extend an invitation to the team that will be working on this project to visit our facility in Tempe AZ. Seeing how we do things now would be a good start for the team to get the wheels turning [1].

1.3 Original System

This section outlines the original system provided through by Suntrac, then demonstrated in person during the benchmarking on-site visit. The original designs include an 8 and 6 foot jig.

1.3.1 Original System Structure

The original design for SunTrac's braze welding jig was constructed with ⅛" thick rectangular tubing that are 4"x3". The frame was constructed in an 'A' shape with horizontal tubing running across the floor that are bolted into the concrete. At the top of the 'A' structure it features a ball bearing that allows for 360 degree rotation in a vertical configuration. Figure 1 below shows the current state of the 8' braze welding jig. Other notable structural features include ⅛" plate mild steel on either end of the spinning subassembly of the braze welding jig to support additional hardware. The original design has limited moving parts and was designed to be operated by one person.

Figure 1. Original Braze Welding Jig

1.3.2 Original System Operation

The main operational system in the original design is a central pivoting point at the top of the 'A' shaped frame. The purpose of this design was to allow the supported copper manifold to to rotate with its axis of rotation perpendicular to the front plane. This rotation is needed for SunTrac manufacturing to allow easy access to all braze welded joints. The jig currently takes three pounds of force to begin rotation. Another operating system used in the original design is a locking mechanism to hold the jig in a stationary position. The original design had the option to lock in one of two locations as shown in the figure above. The last operational system was the clamps used to hold the horizontal pipes while braze welding them in place. These clamps were made of steel in order to ensure they were not deformed as the copper was heated up.

1.3.3 Original System Performance

The original design was completely human operated and required no power or electricity other than human energy. The original design is 12' tall and weighs approximately 300lbs. The brze welding jig is welded solid and therefore can hold the copper pipes with a tolerance ~0.5mm. The pivoting mechanism is nearly perfectly balanced and takes approximately 3lbf to begin rotation. This data was collected by visiting SunTrac's manufacturing facility in Tempe, Arizona and referring to the data that had already been done on the braze welding jig. The ball bearing is also kept clean so that little to no notable noise is noticed when rotating.

1.3.4 Original System Deficiencies

The original design met most customer needs with the main exception that each braze welding jig is specific to one product variant or size. The desired customer need is for one braze welding jig to be compatible with all three product variants. Another deficiency in the original design is that it was over designed to have heavier and more expensive materials then were required. Other deficiencies include that the original braze welding jig does not have an associated drawing and therefore cannot be easily recreated without spending excess time and money to create them.

2 REQUIREMENTS

The requirements that were set by SunTrac USA are listed in the customer needs and their resulting engineering requirements. These data sets are then further analyzed in a House of Quality to determine correlations in the data as well as ranking the engineering requirements. The highest priority customer requirements are safety, cost, and the ability for the welding jig to be compatible with all three product variants. This section expand further to the data listed above and provide data to support the decisions made in the concept evaluation.

2.1 Customer Requirements (CRs)

The customer needs are listed below with their associated weights.

1. Safe to Operate 5
2. Cost within budget 5
3. Can fit a 4', 6', and 8' copper manifold 5
4. Machinable parts 4
5. Fit within a 5'x5' square 3
6. Allow easy access to all copper joints 4
7. Jig can rotate and lock at various angles 3
8. Durable and Robust design 4
9. Reliable design 4

The weighting system used for the customer needs included a one to five ranking with five being the most important need for the client. The customer needs and weights were given to us from Suntrac directly. The first customer need is for the system to be safe to operate. This was given a high weight because safety is a priority that is stressed at SunTrac. The second customer need is for the system to be within budget. Ths was given a weight of five because Suntrac desires this to be a cheap and easily repeatable design. The third customer need is for the braze welding jig to be compatible with SunTracs 4', 6', and 8' product variants. This was given a weight of five because Suntrac wants this system to employ lean manufacturing principles and have multiple functions within the manufacturing facility.

The next set of customer needs were given a ranking of four given their high importance but lower priority than the other needs. These needs include that the system is made with standard parts to keep costs down. Suntrac also desires a braze welding configuration that allows easy access to all copper joints. This customer need specifies that the jig should allow access to the copper joints even from behind the jig. The last two customer needs that are given a weight of four are that the braze welding jig has a durable and robust design while also being reliable. This customer needs details how the jig should be strong enough to complete its designed task and continue to function optimally for many years into the future.

The last set of customer needs are given a weighting of three because they are still important but have the smallest priority. The first customer need in this category is that it fits within a 5'x5' square footprint. SunTrac specified that they prefer this customer need to be met but will accept designs with a larger footprints if all other needs are met. The last customer need is for the jig to be able to lock in many different configurations. This need was given a weight of three because the braze welding jig is still as functional as the original design as long as two locking positions are permitted.

2.2 Engineering Requirements (ERs)

The engineering requirements are listed below along with their target values.

1.	Melting Temperature (degrees Celsius)	1400 ± 300
2.	Force to Rotate (Newtons)	13 ± 3
3.	Cost (dollars)	1500 ± 300
4.	Versatile (number of compatible product variations)	3 ± 0
5.	Standardized Parts (dollars)	1500 ± 300
6.	Footprint (feet^2)	25 ± 5
7.	Degree of Rotation (Radians)	2pi ± 0
8.	Adaptable (Number of locking positions)	8 ± 2
9.	Durable (Years before repair)	20 ± 5
10.	Error (Difference in desired length) (in)	1/16" ± 1/32"

The first engineering requirement is melting temperature. The jig must have a high melting temperature so the braze welding process does not change the physical properties of the jig and therefore increase the error regarding the tolerances. Most mild steels with a melting temperature around 1400C or higher should suffice for this project. The second engineering requirement is for the force to rotate the subassembly to be within a range for ideal safety circumstances. A force approximately 13 ± 3 newtons is ideal because most people can exert that much force without struggle and it won't cause the jig to rotate at an unsafe speed. The third engineering requirement is the cost which has a target value of $1500 ± $300 as per SunTrac's specifications. The fourth requirement is to increase versatility by allowing all three product variations to be compatible with this jig. The requirement is derived directly from the clients needs. The fifth requirement is closely related to costs in that the jig be made of standard parts to keep costs low. Again this requirement states the total cost of the jig be around $1500 with a tolerance of ± $300.

Engineering requirement six states the footprint of the final braze welding jig be 25sqft ± 5sqft. This is not a critical engineering requirement but more so a guideline for the team to follow. Ideally the jig must fit within those dimensions but SunTrac stated that those dimensions could be larger if all customer needs are met. The seventh requirement is to allow a full 360 degree angle of rotation. This requirement quantifies the need for all copper joints to be easily accessible. The eighth engineering requirement detailed that a desirable number of locking positions would be eight or more. Additional locking positions allows the welder at SunTrac to lock the jig at their desired position to maximize production. The ninth requirement is that the jig lasts 20 years with minimal repairs or alterations. This requirement was derived directly from SunTrac's specifications. The last requirement is that the jig can hold each manifold to a tolerance of 1/16" ± 1/32". This requirement ensure all manifolds are consistent and repeatable.

2.3 House of Quality (HoQ)

The House of Quality detailed the correlation between the customer needs that were provided from SunTrac USA and the team derived engineering requirements. The completed House of Quality as well as the approvals are listed in appendix A1. The House of Quality helps in the design process by determining correlations between the engineering requirements, customer needs, and their associated weights. This helped the team by ensuring that all the customer needs that SunTrac specified were satisfied and quantifiable with related engineering requirements. The absolute and relative technical importance also helped the team by ensuring that all design concepts met the most important engineering requirements as a minimum. The House of Quality also provided a single document that all relevant data could populate following the in person meeting at SunTrac's manufacturing facility.

3 DESIGN SPACE RESEARCH

To effectively and informedly re-engineer SunTrac USA's current copper manifold production process in an ergonomic manner, the team has undergone a comprehensive research procedure. This section will outline the literature review process where each team member had established research material, benchmarking where the team visited Suntrac's manufacturing warehouse, as well as the functional decomposition in which the general and specific functions of the brazing jig are analyzed.

3.1 Literature Review

To gain an intensive understanding of the braze welding jig to be created, the design team created topics of research. Each team member was assigned a specific topic and generated five sources for it. The four topics of research are copper sweating and attributes, machining processes, jig material, and mechanical elements. The researching of copper sweating and attributes ensures a comprehensive understanding of the reactions in which the copper tubing may have during the brazing process, such as thermal expansion, which is a direct influence on the design of subsystem components. The study of machining process will ensure an efficient approach to design in regard to section assembly and allowing for a streamlined replication process. Understanding the mechanics and physics of materials will ensure a cost effective solution to what kind of steel the jig will be constructed out of. Researching resources relevant to mechanical components is essential in creating well operating and durable mechanical components such as the gear stopper and power screw.

3.1.1 Kadeja Alhossaini

The role of Kadeja within the team is to understand the fundamentals of different machining processes. Since this project is based on manufacturing, it is necessary to compare the machining processes available and which materials could be used in those processes. Moreover, the project's goal is to create a brazing jig and jigs are sensitive when it comes to dimensioning, therefore knowing how machining processes could alter the dimensions and tolerances is vital. In this section, five different sources on machining will be discussed in detail along with their relevance to the project.

The first source is a handbook called *Manufacturing Processes for Engineering Materials* which details common machining processes such as straight turning, cutting off, slab milling, end milling etc [2]. It also goes into typical production rates of some machining processes and their tool life. It also discusses the economics relating to machining and manufacturing. This information is valuable since it will help the team decide which process will reduce manufacturing costs in the long run since SunTrac wants to manufacture more jigs in the future.

The second source is also a handbook which is called *Fundamentals of Modern Manufacturing* [3]. This source contains content such as surface processing operations and different types of assembly processes. The information in this handbook is important as it provides an in depth understanding of how to assemble parts after they are machined which the team will need to take into consideration for the production of the jig.

The third source is a journal that discusses *Integrated Inspection and Machining for Maximum Conformance to Design Tolerances* [4]. This source is valuable as it represents a technical way to calculate systematic and nonsystematic errors found in machine tools. This information will be used to calculate tolerance errors that could possibly affect our design when machining.

The fourth source provides a summary on different manufacturing processes than are found in most machine shops [5]. This source provides a specific explanation on using CNC lathe. Since the University has CNC lathe in the machine shop, this source will be beneficial as it will help the team have a better grasp of using the device.

The final source is a journal that discusses the *Mechanical modelling of dry machining processes* [6]. This source is valuable as it provides a detailed description of the dry machining processes and how friction factors into those machines. This information is valuable as it will aid the team in estimating the wear factor that is caused by friction.

3.1.2 Nathan Firor

Nathan's primary role in this team is to study the mechanics of copper pipes. For this project, it is important to understand how copper formed into tubing can deflect with excessive heat applied, How that deflection may influence the performance of the jig or conversely how the jig may alter the copper manifold. The associated sources include copper tubing specialty handbooks and guides, websites with material properties, and chapters from textbooks. Brief summaries of these sources and their relevance are detailed here [7].

The first source associated with Nathan's role is Soldering and Brazing Copper Tubes and Fitting, by the Copper Development Association Inc.. This source is handbook containing tabulated information on the mechanics of copper when it is welded in a variety of ways. This is a guide which derives conclusions from empirically found data. This source is important for it details how copper under certain applied conditions [8].

The next source is Copper Tube Handbook by the Copper Development Association. This source is a handbook containing various tables and figures particularly around the mechanics and properties of copper formed into tubes of ASME standardized size. This source is important for it details copper behavior, qualities, and other useful information when it is formed into cylindrical tubing [9].

The third relevant source is Young's Modulus - Tensile and Yield Strength for Common Materials by Engineering Toolbox. This source is a website which contains known constants for properties of commonly used industrial materials. This project potentially allows some variety for applicable materials to be used because many sorts of steels or other metals can satisfy the engineering requirements detailed. This source is important for it is an index which can help the team in interpreting a proper material to use for a part [10].

This next source is *Shigley's Mechanical Engineering Design* by J.E. Shigley [11]. Chapter 13 of this textbook contains sets of tables, figures, and equations established by the American Society of Gear Manufacturers for spur gears. The final jig design is likely to contain a spur gear, and it is important that this gear is made of the proper material, and has the correct size and dimensions so it is guaranteed to perform correctly without fail. This chapter is important because it allows the team to conduct an in-depth engineering analysis of a spur gear.

The fifth source is *Statics and Mechanics of Materials* by R. C. Hibbeler. [12] Chapter 2 and 4 of this textbook contains approaches to analyzing the thermal expansion of materials. For this project it is important to analyze how much a material heated up to a high temperature would behave under certain conditions. Thermal expansion can induce high stresses on surrounding materials and potentially cause them to yield or fail. This source is important for the project because it allows extra insight on how to design in anticipation for thermally induced stresses.

3.1.3 Edwin Smith

The device to be created involves several mechanical features. The failure to properly analyze the physics behind each element of each mechanism allows for a high probability of overall device failure. Due to this logic, Edwin has researched the topic of mechanical elements in relation to the pivoting, clamping, and locking aspects of the device. The five relevant sources generated by this student are discussed in this section.

The first source in relation to the mechanical components of the design is *Shigley's Mechanical Engineering Design*, by J.E Shigley, Richard G. Budynas and J. Keith Nisbett [13]. In particular chapters 7, 8, 11, and 13 will be referenced during the design consideration of the mechanical elements of this brazing jig. Chapter 7 discusses shaft design for stress, critical speeds, limits and fits, and other significant design considerations. Chapter 8 relates to the proper designing of screw, fasteners and other non permanent joints, this will be referenced during the designing of the power screw mechanism which will clamp the horizontal manifold pipes. Chapter eleven relates to the designing of bearings, which will prove useful when creating our frame rotation design, and the study of chapter thirteen will ensure the proper gear usage.

The second source is *Mechanisms and Mechanical Devices* Sourcebook, by Neil Sclater and Nicholas Chironis [14]. The chapters to be used in particular are 6, 9, and 16. Chapter 6 delves into the topic of gears, how they affect speed ratios, equations for designing gears and overall usages of many gear types. Chapter 9 involves latching, fastening, and clamping, which will serve useful in creating the clamping system to secure the horizontal manifold pipes. Chapter 16 resources the topic of pneumatic and hydraulic systems. This is an ongoing consideration of the design team, to implement some sort of power system to relieve the user of much physical effort while maneuvering the frame. Although this is just a consideration, this chapter will serve useful in understanding the implementation of this idea.

The third source is *Design of Machine Elements* by V. B. Bhandari [15]. This textbook analyzes the design of machine elements and their ergonomic considerations, a significant and relevant topic to the design team as not only must a device be made that meets requirements, but one that does this ideally and most efficiently in relation to a user in the manufacturing workspace. Other relevant information presented in this book include stress, strain, modes of failure, axial loading, power screws, threaded joints, shafts, springs, bearings, and gears

The fourth source is *Mechanism Design: Visual and Programmable Approaches*, by Kevin Russell, Qiong Shen, and Raj S. Sodhi [16]. This textbook details the physics behind the movement of mechanisms, and kinematics during particular applications. This textbook can be resourced when considering the application of the mechanical devices to be constructed in the jig design; in understanding the movement of one component and how it will transfer to another.

The fifth source is *Mechanics*, by J. P. Den Hartog [17]. This textbook will serve useful to the design team as it describes the physics of a broad depth of topics in the realm of mechanics. Chapter 13 considers the equations governing the act of rotating about a fixed axis, being a major sub function of the reengineered device. The textbook discusses equations and applications equations of equilibrium which will certainly be applied to the design teams metal structure. It also delves into the physics of centers of gravity, beams, motion, angular momentum, and plane motion.

3.1.4 Ethan Vieane

The focus of Ethan's literature review was the study of materials and their associated properties. The goal of this research was to determine the ideal material in which to construct SunTrac's updated braze welding jig. Sources reviewed include textbooks, websites, and an interview with the head of engineering of SunTrac. All the references

The first source is a college level textbook titled 'Mechanics of Materials.' This textbook details different forms of axial loading, torsion, bending, and material property relationships including poisson's ratio and hooke's law. This textbook is useful when selecting SunTrac's brazing jig material because it details how different materials deform under various loads. The team will use this source to determine how different materials will deform under the forces present at SunTrac's manufacturing facility [18]

The second source is another college level textbook titled 'Mechanical Engineering Design.' This textbook details different mechanical processes and strengths associated with different forms of bonding. This knowledge is relevant to material selection because different materials have different available forms of bonding and only certain forms may have the strength required for this project. The team may use this source to determine the method of bonding that may be used on the final design [19]

The third source is an interview that took place September 30, 2019 when the team took a tour of SunTrac's manufacturing facility. Stu Siebens is the head of engineering at SunTrac and allowed the team to interview him regarding the ideal characteristics of a revised braze welding jig. He is a valuable source of information for material selection because he has knowledge regarding the daily heat and force requirements that are exerted on the braze welding jig per cycle [1]

The fourth source is a data sheet from McMaster-Carr listing the yield strength, hardness, and other specifications for low-carbon steel tubing. This is a relevant source for material selection because it has data on cost, tolerancing, sizes available, and material properties. The reason this source deals specifically with low carbon steel because it is the cheapest material that meets the minimum strength requirements set by SunTrac. It also comes in the most wide selection of sizes. This source will benefit the team by displaying the sizes of standardized parts and the strengths associated with different lengths and thickness of tubing [20]

The last source that Ethan researched was a college level textbook titles 'Theory and Design for Mechanical Measurements.' This textbook detailed methods of measuring system behavior. This is a useful source for material selection because it provides knowledge to test whether materials behave the way the team expects them to behave. The team will use this source to test samples of different materials to determine whether they pass the standards that were provided by SunTrac [21]

3.2 Benchmarking

The design team took a trip to the Suntrac USA manufacturing warehouse to establish a solid foundation of the original designs to be re-engineered, this section will outline the outcomes of this on-site visit. In arriving at the Suntrac facility, the team was briefed on the processes in which the business commercial operates by. This understanding of the application of Suntrac's product better equips the team with the ability to discern between a satisfactory and an ideal design. Further along this visit the team was introduced to the two original design as outlined in section 1.3, as well as a second jig which is entirely created to satisfy a necessary sub function of the to be reengineered design. The team was able to physically inspect these original designs as well as their specifications as outlined in section 1.2. As careful consideration was already applied to the specifications and images provided by the director of engineering at Suntrac, a rough idea of design solutions were generated well before the visit and these were able to be articulated and given direct feedback by Suntracs COO and director of engineering. This benchmarking process was especially beneficial as some of the ideas that were presented during the visit had not met requirements that weren't conceptualized until physically examining them. Discussions of aspects of the benchmarking method such as these will be illustrated below.

3.2.1 System Level Benchmarking

The design team has three existing designs to reference as this project is entailed within the protected manufacturing process of a commercial operation and will yield a proprietary product as a result. The three existing designs consist of the initial operation which Suntrac used to braze copper manifolds, followed by their systems to more efficiently achieve the same result. These designs are the brazing of copper manifolds on a flat table, as well as two vertical jigs of different sizes. The relation of requirement satisfaction of these existing designs relative to the design set forth by the design team will be analyzed in the sections below.

3.2.1.1 Existing Design #1: Horizontal Table

The horizontal table Is the process which Suntrac initially used to braze copper manifolds. This method falls short from the effectiveness of the product to be created by the design team, and even the other two vertically standing existing designs. This method was utilized during the initial startup of the company in which ideal dimensions of the copper manifold were yet to be realized and consequently rendering the investment of creating such a device useless. This rough design met the requirements of securing the vertical and horizontal pipes, although fell short of all other requirements. There was no ability to maneuver about any point to allow for ease of use, and consequently no locking mechanism was required. The method also created its own problems such as the hindrance of reaching across the table to certain parts of the manifold.

3.2.1.2 Existing Design #2: 6' Braze Welding Jig

The six foot vertically standing device was created to satisfy a requirement which the eight-foot jig could not, brazing of six-foot-long manifolds. This device can be seen in figure 2 below.

Figure 2. 6' Braze Welding Jig

Although this solution itself can only braze six-foot manifolds, meaning that it doesn't satisfy the requirement of allowing for variation of sizes. This device is more effective than the table brazing, although fall short of the reengineered device in many ways. The jig was created with a backing of solid metal, creating an impediment between the welder and the rear side of the manifold. The device also falls short in that its locking mechanism requires two components and has very few locking positions, compared to the design to be created. It has no allowance for multiple jig sizes and its locking of vertical pipes is more resource intensive. Also, the horizontal pipes require multiple clamps to be inserted and secured, when the updated design will consist of a built in clamping system.

3.2.1.3 Existing Design #3: 8' Braze Welding Jig

The eight-foot jig is currently Suntrac's most effective device which was created to reinvent the manifold brazing process. This design is illustrated in figure 3 below.

Figure 3. 8' Braze Welding Jig

This device has all the capabilities which the six-foot design has, although it is created with a skeleton frame. This allows for access to the back side of the copper manifolds, although in this design the vertical pipes are positioned directly on the skeletal beams which acts as a minor impediment. The reengineered design implements this effective skeleton frame but offsets the manifold placement to allow for the entire access of all brazing points. This eight-foot design is similar to the six foot in that it requires multiple components to lock the rotating frame and to clamp the horizontal pipes, and it does not allow for variation of manifold size.

3.2.2 Subsystem Level Benchmarking

The subsystem analysis of the team's final design can comprise of numerous processes such as frame maneuvering, locking of vertical pipes, locking of horizontal pipes, variable manifold sizing, base structure, frame locking, and bracket securing. This section will emphasize the subsystems of the base structure, frame configuration, and frame lock. The frame configuration is comprised of a skeleton structure, solid plate, and a wooden table. The base structure existing designs include a bent T, a rectangular beam, and a rectangular solid base. It's important to highlight that locking mechanism has only two existing designs as the horizontal table existing design had no ability to maneuver. Within this subsystem there is the locking by pin and swing arm.

3.2.2.1 Subsystem #1: Frame Roto-Locking

Maneuverability for ease of use is a key feature of the reengineered product, although this requires the ability to lock. The solution the team has come up with for maneuvering is to rotate about the centroidal axis, as is two of the existing designs. All locking mechanisms will be regarding the stopping of angular momentum of the skeleton frame design, these mechanisms being a pin and swing arm

3.2.2.1.1 Existing Design #1: Pin Lock

The method used in the eight foot existing design is to simply lodge a pin between the frame and the supporting stand behind. This design is simple to recreate, although greatly minimizes the number of locking positions and convenience of the welder. This method also requires having a separate component not connected to the jig itself, expanding on the inconvenience of the user.

3.2.2.1.2 Existing Design #2: Swing Arm lock

The locking mechanism utilized by the six-foot jig is a swing arm. Unlike the pin, this device is attached to the supporting structure. Although there is no detriment of an extra detached component, this design still has its shortcomings. This methods implementation on the six-foot jig does not have many locking positions. Although many can be achieved, but this would require much material to create contact beams. This expense is not worth the capability in comparison to the gear locking device where it will be costly, although result in great convenience.

3.2.2.2 Subsystem #2: Frame Configuration

The aspect of the apparatus which holds all the mechanisms that contacts the manifold is a critical design consideration. This part comprises of most of the entire jig, thus maximizing its effectiveness helps to ensure a successful design. The three existing designs to be discussed are the skeleton, solid, and table.

3.2.2.2.1 Existing Design #1: Skeleton Frame

The design proven to be most effective is the skeleton frame as it allows for the rear access of the copper manifold while still providing support to the vertical pipes. This design can be utilized in a couple of ways, six or five vertical beams. The existing eight-foot design uses six beams where each vertical manifold pipe is secured to a beam, this is effective although still acts as an impediment as stated in section 3.2.1.3. The designs teams device will use the skeleton frame with five beams because the manifold can be symmetrically offset and accessed from all directions.

3.2.2.2.2 Existing Design #2: Solid Plate Frame

The use of a solid frame can be seen through Its use in the six-foot jig. This method allows for great stability and tolerance assurance, although it acts as a considerable inconvenience to the welder as the rear side of the copper manifold cannot be accessed during brazing. This method is also resource intensive, and creates a great amount of inertia to overcome when rotating.

3.2.2.2.3 Existing Design #3: Wooden Table

The frame of the brazing process during Suntracs startup was simply a horizontal table. This frame design is evidently less effective than the others as the welder must move around the manifold to reach certain points. It is less than ideal to be required to navigate around the device with an oxyacetylene torch in one's hand. This design also comes with the problem of restricting access to the middle of the manifold.

3.2.2.3 Subsystem #3: Base Structure

The base structure is another critical subsystem which is important to design efficiently as it comprises of more than half of the mass of the system and provides support for all other components. The three existing designs used by Suntrac are a bent L, square beam, and a solid rectangle base.

3.2.2.3.1 Existing Design #1: Bent T Base

The bent T base configuration is utilized by the existing eight-foot design. It is called the bent T as from a side view it appears to be an upside-down bent T. This design is effective as it minimizes the warehouse floor space used by the jig with minimal material and has essentially set the requirement of a 5'x5' footprint.

3.2.2.3.2 Existing Design #2: Rectangular Beam Base

The rectangular beam base configuration is used by the six-foot design. This design effectively minimizes the floorspace of the jig, while employing very little resources. This method is also easy to manufacture and duplicate. This results in the device being a great consideration during the concept generation aspect of the design process.

3.2.2.3.3 Existing Design #3: Rectangular Solid Base

The rectangular solid base is employed by the initial method of brazing over a horizontal table. This table had a skeleton top section attached to a solid wooden foundation. This method ensures absolute stability as the foundation is excessively large and resource intensive. This relates to the requirements in that it does not allow for maneuvering of the manifold and doesn't satisfy the 5'x5' footprint restriction.

3.3 Functional Decomposition

The process of creating the functional decomposition began during the in-person visit to SunTrac's manufacturing facility. During the visit SunTrac gave the team a tour of the facility and detailed the braze welding process within the scope of this capstone project. One of the results of this meeting was the knowledge to create the hypothesized functional model for the new braze welding jig. SunTrac explained that the final result of this project must be able to support eight copper pipes and four brass standoffs in the correct orientations while maintaining tolerances during the braze welding process. The hypothesized material flows for this process are the components and human for inputs and the completed manifold and human for outputs. The hypothesized energy flows for this system include human and thermal input energies while just thermal energy remaining as an output. The signals used in this design include olfactory, visual, and auditory as both input and output flows. These signals are shown in the hypothesized functional model as sensory checks to ensure the braze welding process is being done correctly.

Notable subsystems that are listed in the hypothesized functional include adjust orientation, import components, position components, secure components, and join components. The scope of this project as detailed from SunTrac is to create a jig that has the capability of changing orientation while also securing all components in place. The other subsystems detail the process of building a copper manifold but fall outside the scope of this project. Due to the large quantity of parts and small degree of tolerance, many different systems must be employed to satisfy the one subsystem of Secure Components as seen in section four.

3.3.1 Black Box Model

Figure 4. Black Box Model

Figure 4 clearly shows the black box model for the teams hypothesized functional model. Notable features of this figure include that components enter the material flow and completed manifold exit the material flow. This is important because it shows the main purpose of this process. The black box model also states that "Support Components" is the main function that needs to be accounted for when designing this project. This model helps the team clarify our project by neglecting all details and stating the main purpose of the teams devise. This figure also helps the team refocus our efforts on satisfying the main goal instead of focusing on every insignificant detail.

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

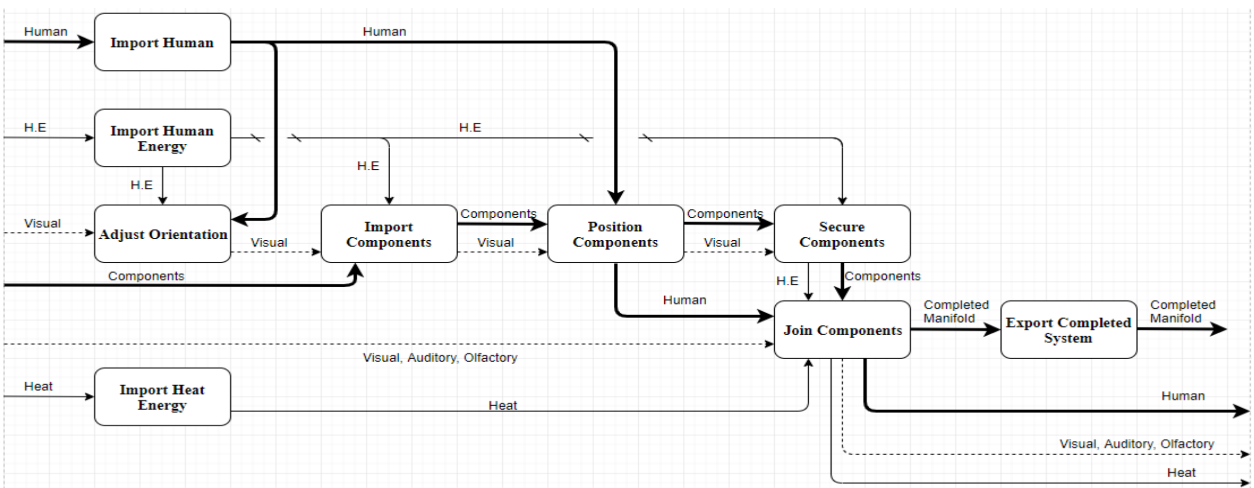

Figure 5. Hypothesized Functional Model

Figure 5 displays the teams hypothesized functional model for SunTrac's braze welding jig. This model helps visualize the project by detailing every subfunction that our team must design around. Whereas the black box model states the main function of the design, the hypothesized functional model details how that main function is achieved. This figure is important because it ensures every subfunction is accounted for in the design and the scope of the project is fully defined.

4 CONCEPT GENERATION

To generate concepts, the team utilized the gallery method to brainstorm ideas. First, the team generated seven concept variants from the Engineering Requirements. Next, each team member individually came up with two to three sketches for each sub-concept. After finishing the sketches, each team member presented the sketches created. Some concepts were adjusted and others were eliminated. This procedure to generate ideas is called the gallery method.

4.1 Full System Concepts

After generating ideas, the team produced seven full system concepts.These full system concepts were called design alternatives. The top three design alternatives were design alternative one, four, and six, therefore they will be discussed in detail in the following sections.

4.1.1 Full System Design #1: DA 1 with circular slides and swivel latches

The first design alternative that will be discussed uses circular pipes that are locked by pins to adjust the height of the jig. To rotate the jig, a foot pedal is connected to a gear that locks it into place. When the foot pedal is pressed, the gear is released thus causing rotation. To lock the jig in place, the base is being bolted to the ground. To keep the vertical pipes from moving, U-shaped brackets are used, and to keep the horizontal pipes from moving, swivel latches are used on either end. Finally, to keep the brass brackets locked, an indented surface is used with a slider that slips on top of the bracket thus keeping it in place. Figure 6 is a sketch of design alternative one.

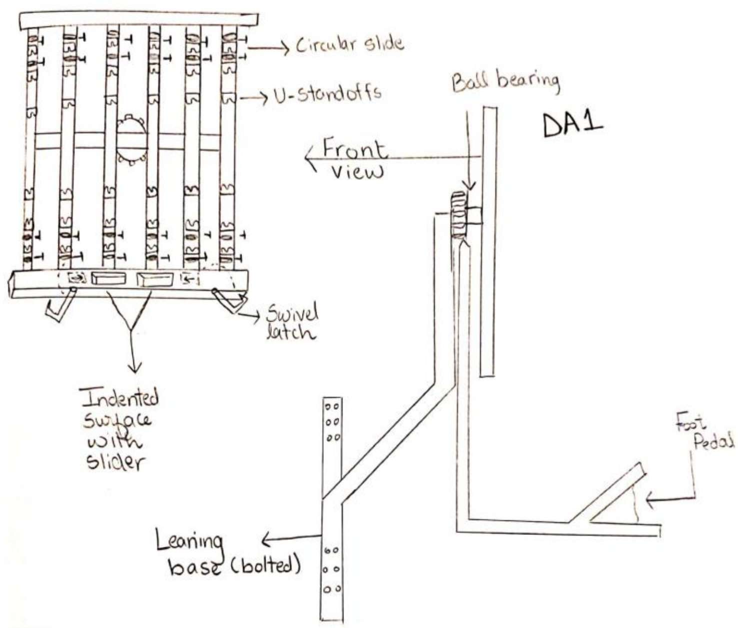

Figure 6. Design Alternative 1

As seen in Figure 6, the front view of the jig shows where the features discussed are being placed on the skeleton of the jig. It also shows the location of the foot pedal mechanism and where the device is being bolted to the ground. This design is beneficial as it will require a minimum amount of force to rotate and lock the jig in place. Another pro to using this design is that it uses round pipes for the skeleton which is easier to handle when assembling the jig. Although using round pipes is beneficial for assembly, it weakens the device making it less durable and stable thus allowing more space for error. Also, bolting the design to the ground requires more footprint than bolting it to the wall which is another con to this design.

4.1.2 Full System Design #2: DA 4 with rectangular slides and power screws

The second design alternative that will be discussed uses rectangular slides to adjust the height of the jig. Pins will be used to lock the apparatus from moving in the vertical direction. For rotation, the same concept will be used from design alternative one where a gear is being locked by a foot pedal which controls the rotation of the device. In this design, the jig will be bolted to the wall instead of the ground to lock it in place. Moreover, to keep the vertical pipes from moving, the same U-bracket standoffs are used and for locking the horizontal pipes, a pad is oriented at either end of the jig where a power screw locks it to keep the pipes in place. Lastly, for locking the brass brackets, the same idea is used from design alternative one by which an indented surface with a slider keeps the bracket in place. Figure 7 is a sketch of design alternative four.

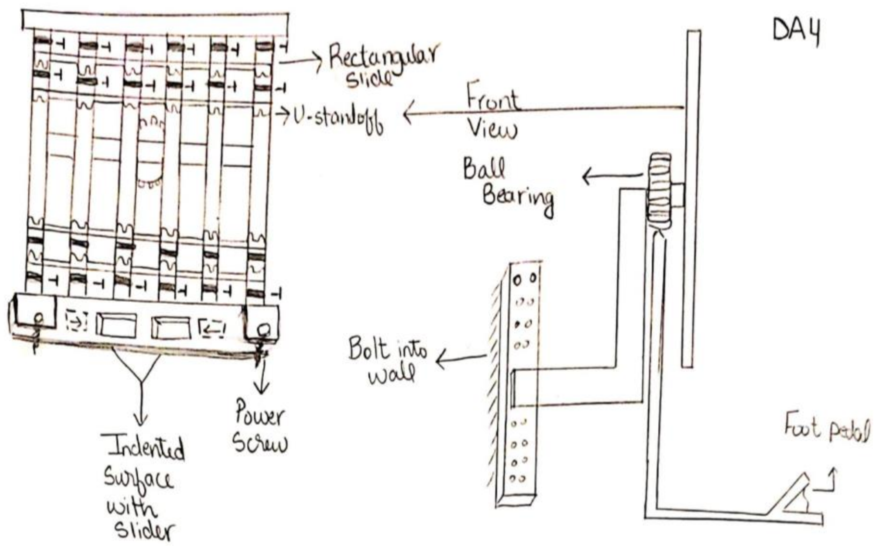

Figure 7. Design Alternative 4

Figure 7 shows design alternative four's sub-functions in a front view. It also shows a side view of the device representing the location of the foot pedal and where the device is bolted. The pros of using this device are less footprint space, minimum amount of force to rotate the device, and rectangular slides are rigid. This device takes less footprint space because it is bolted to the wall and since it uses the same pedal mechanism it will require a minimum amount of force to rotate and lock the jig. Also, since the skeleton of this design is rectangular and not circular, it will offer more stability and durability. On the other hand, rectangular slides require more effort to assemble than circular, and bolting the device to the wall restricts the client on where to place the device.

4.1.3 Full System Design #3: DA 6 with rectangular slides and swivel latches

The third design alternative that will be discussed also uses rectangular slides to vary the height of the jig and pins to lock the slides in place. For rotation, this design also uses the foot pedal mechanism and to lock the device in place, a base with the shape of the letter "n" is being bolted to the ground. In addition, this design uses v-bracket standoffs to keep the vertical pipes from moving and swivel latches for the horizontal pipes. The same indented surface with a slider will be used for locking the brass brackets as in the previous two designs. The sketch of design alternative six can be seen in Figure 8.

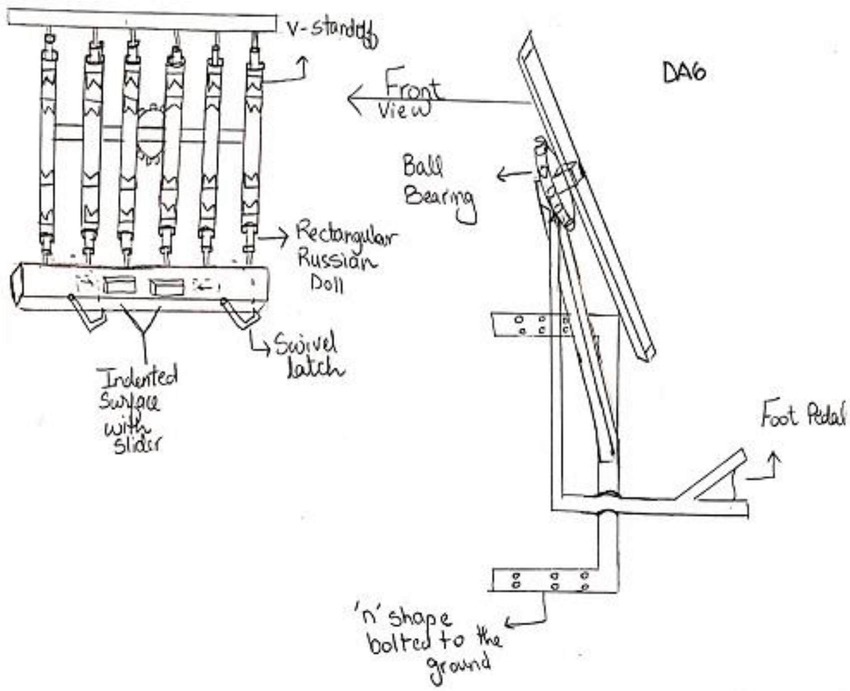

Figure 8. Design Alternative 6

From Figure 8, the features that make up design alternative six can be seen in a front and side view. This design is similar to design alternative four in Figure # with some minor changes. The pros to using this design are minimum amount of force to rotate, rectangular slides are rigid, and v-standoffs. The design requires a minimum amount of force due to the foot pedal mechanism and having rectangular slides make the device stable and durable. Moreover, using v-standoffs instead of u-standoffs is a pro since pipes expand while being welded and having the bracket shaped as a v will reduce the chance of the pipes sticking to the brackets. The cons to using this design is that it will require more footprint space as it will be bolted to the ground and the rectangular slides will take more effort to assemble.

4.2 Subsystem Concepts

The team had originally came up with seven different concept variants or subsystem concepts which are maneuvering the jig, locking jig, locking vertical pipes, locking horizontal pipes, adjusting size, standing upright, and locking brass brackets. After brainstorming ideas, the team combined the subsystems maneuvering the jig and locking the jig since they have to be used together.

4.2.1 Subsystem #1: Maneuvering and locking the jig

This subsystem combines maneuvering the jig and locking it because the design to maneuver the jig has to be compatible with the design to lock it. This subsystem satisfies the need to adjust orientation found in the functional decomposition in Figure #. It is also one of the major requirements the client discussed when benchmarking.

4.2.1.1 Design #1: Ball Bearing pivot to maneuver and foot pedal to lock

Design one utilizes a foot pedal to rotate the jig. When the pedal is pressed it releases a gear that is attached to a ball bearing. After the gear is released it will rotate until the pedal locks it again. This design will be attached to the skeleton of the gear.Figure 9 is a sketch of the foot pedal mechanism.

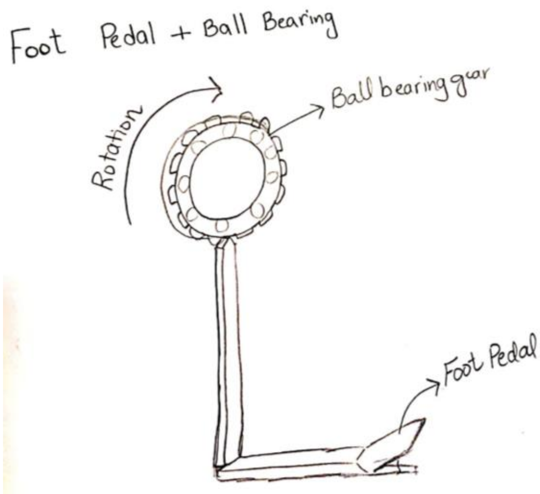

Figure 9. Foot pedal mechanism

The pros to the design in Figure 9 is that it is easy to use, does not require a great amount of force, and it only takes a few seconds to maneuver the jig. The only con to this design is that it might be a safety hazard since it is positioned on the ground and could cause tripping.

4.2.1.2 Design #2: Ball Bearing to maneuver and pull the handle to lock

This design is similar to design one in which it uses the idea of the ball bearing gear to rotate the jig. When the handle is pulled, the gear is released thus causing rotation. To lock the jig, the handle goes back to its original position. This design would be located behind the skeleton of the jig. Figure 10 is a sketch of the design.

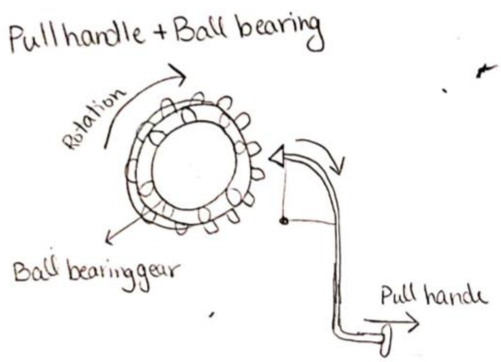

Figure 10. Pulling mechanism

Using the design in figure 10 has two pros, the first is that it is easy to handle and the second is that is does not require a huge amount of force to rotate the jig. A con to using this design is that it will require the user to move to the back of the jig to access the handle. Therefore, it will require more footprint space for each jig to account for the accessibility of the handle.

4.2.1.3 Design #3: Crank to maneuver and handle to lock

This design uses a crank and a handle to rotate the device. The crank will be located behind the skeleton of the jig. To use this design, the user will need to access the handle and spin it to cause rotation on the crank. The schematic of this design is found in Figure 11.

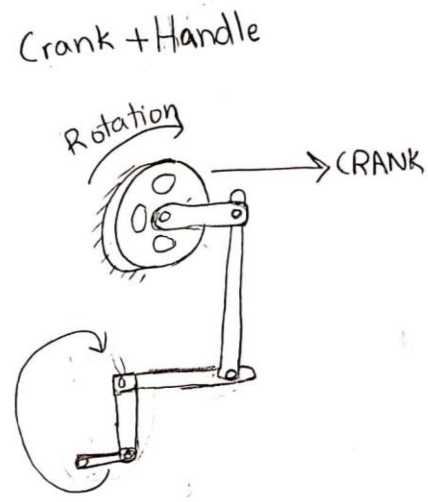

Figure 11. Crank mechanism

Figure 11 shows the crank mechanism of design three. The pro to using this design is that it is easy to handle since it only requires the handle to be spun. However, this design is poor because it will require a crank that can withstand a great amount of force to rotate the jig and since it is attached to a handle that is accessible from the back it will require more footprint space to account for the handle's accessibility.

4.2.2 Subsystem #2: Locking vertical pipes

This subsystem ensures the vertical pipes are locked in place while the manifold is being welded. The designs under this subsystem should keep the pipes from tilting left or right. Another use of this subsystem is to hold the teflon rings from moving while the manifold is being welded since they are attached to the vertical pipes. This subsystem satisfies the position and secure components in the functional decomposition.

4.2.2.1 Design #1: U-standoff

This design will be brazed on the skeleton of the jig to lock the vertical pipes in place. It will also keep the teflon rings from sliding to the bottom of the pipes where they are welded. Figure 12 is a sketch of u-standoff design.

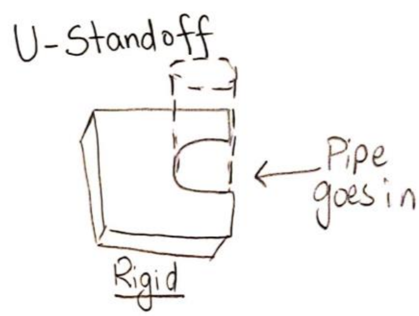

Figure 12. U-standoff

In Figure 12, the u-standoff sketch shows where the pipe will be positioned within the bracket. The pro to using this design is that it is a rigid piece so it will be easy to manufacture and the con is that the copper pipes could expand when they are being brazed and stick to the walls of the standoff.

4.2.2.2 Design #2: V-standoff

This design is very similar to design one except for the fact that it is shaped as a "v" instead of a "u". Therefore, it uses the same idea to lock the vertical pipes and the teflon rings in place. These brackets are positioned on the vertical bars of the jig. The sketch of this design can be seen in Figure 13.

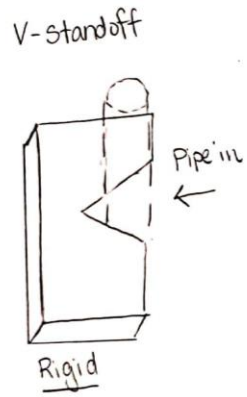

Figure 13. V-standoff

The v-standoff in Figure 13 is a rigid piece therefore one of its pros is that it is easy to manufacture. Another pro is that the v-shaped bracket minimizes the chance of the pipe sticking to the walls of the bracket when the pipes face heat expansion. The only con to using this design is that the pipes could not be secured properly if the bracket have a tolerance error from manufacturing.

4.2.2.3 Design #3: Latch

This design will be welded on the vertical bars of the jig. It has a latch that rotates and locks the vertical pipes in position. The latch design will also hold the teflon rings from sliding down the pipe frame. Figure 14 shows a sketch of the latch.

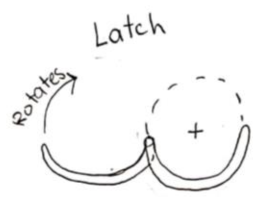

Figure 14. Latch

The latch design in Figure 14 secures the pipes in all positions which is one of its pros. It is also easy to use and handle. However, since the jig will require multiple latches on each vertical bar to hold the vertical pipes, it will require more time to release the manifold after it is brazed which is a downfall for this design.

4.2.3 Subsystem #3: Locking horizontal pipes

This subsystem is similar to subsystem two with the difference of locking the horizontal pipes instead of the vertical ones. The horizontal pipes will be welded to the vertical pipes on one side and two brass brackets will be welded on the other side, therefore the designs of this subsystem should ensure the pipes are held in position from all directions. This subsystem satisfies the position and secure components in the functional decomposition.

4.2.3.1 Design #1: Swivel latch

This design is similar to the latch design from subsystem two. The only difference is the location of the latch on the jig. This latch will be located on the horizontal bars of the jig. When the latch rotates it will lock in place thus securing the horizontal pipes. A sketch of the swivel latch is presented in Figure 15.

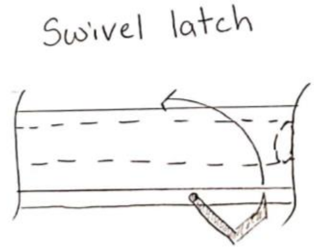

Figure 15. Swivel latch

A pro to using this design is that it is easy to handle and use since it has only one component that needs to rotate as seen in Figure 15. A con to using this design is that the latch could expand when the pipes are welded since its position is close to the welding area. When the latch expands it could be harder to release the pipes thus possibly damaging the manifold.

4.2.3.2 Design #2: Power screw

The power screw concept variant is intended to lock the horizontal pipes by clamping them using increased force output with a screw. This is seen in Figure 16.

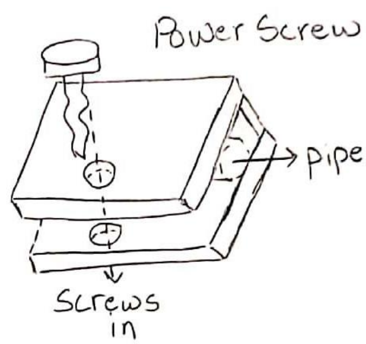

Figure 16. Power screw

This design is a relatively effective one. It is rugged and guaranteed the hold the copper pipes in place so the pipes falling out and being a safety hazard is not an issue. The con is that power screws open and close the apparatus slowly

4.2.3.3 Design #3: Simple Clamp

The simple clamp is intended to secure the horizontal copper pipes in place. this involves an external clamp that would be placed by the user and latched on. Figure 17 shows a sketch of the simple clamp.

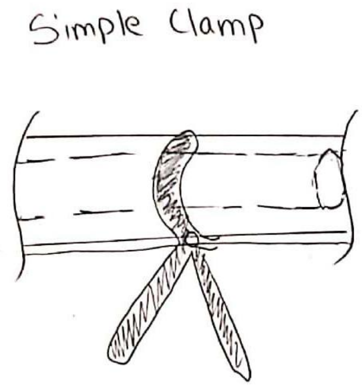

Figure 17. Simple clamp

The pro to this design is that it is quick and easy to use. While still being strong enough to hold on to the pipe. there are few cons though, This is a little more expensive than the other existing designs, Also since it is applied and removed quickly there may be some sacrifice of accuracy in the manifold. Finally it can be potentially knocked off while in use.

4.2.4 Subsystem #4: Adjusting size

This subsystem allows the client to adjust the height of the jig into three different sizes, a 4 foot, 6 foot, and 8 foot. The designs for this subsystem must be able to adjust the size of the jig within a maximum of one hour. Moreover, this subsystem satisfies one of the major goals of the project and benchmarking.

4.2.4.1 Design #1: Circular slides

This design utilizes circular pipes that slide on top of each other to adjust the jig height. The pipes are locked in the position needed by using pins. The sketch of the design is found in Figure 18. These elongations will be used on both ends of the skeleton frame.

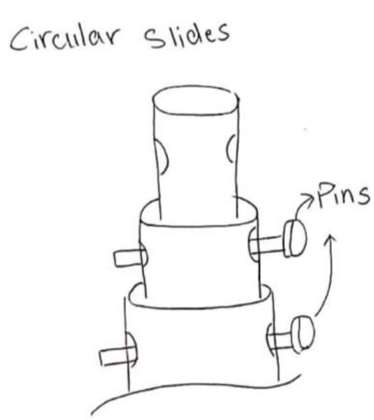

Figure 18. Circular slides

A pro to using the design in Figure 18 is that it is easy to assemble and lock and since it will be located on both ends of the jig instead of one it will reduce the chance of the slides tilting. A con to this design is its durability since the weight of the jig is only being held by the pins.

4.2.4.2 Design #2: Rectangular slides

This design utilizes rectangular collapsible pipes that will fit inside another to allow the three size manifold configuration. This design is seen in Figure 19. Like the circular slide these will also be locked in place using pins.

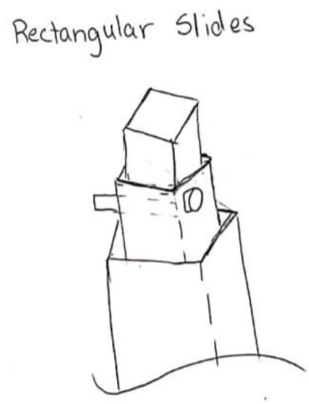

Figure 19. Rectangular slides

Some pros to this design or that the jig apparatus will be rigid and durable. However, the extra material will make the frame heavier and harder to manage, as well as increased raw material cost.

4.2.4.3 Design #3: Modular design

This very impractical design utilizes multiple compatible sections to be dismantled and installed during each manifold size variation. This is illustrated in figure 20 below.

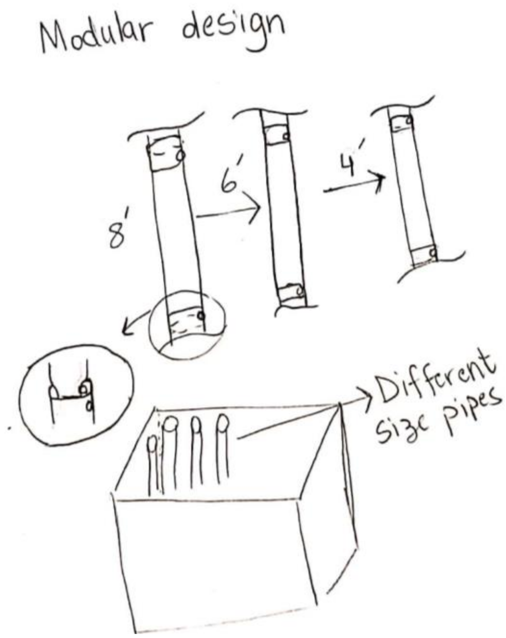

Figure 20. Modular design

The only pro for this design is that it does allow for manifold size variation. All together the design is very impractical and has many cons such as inconveniencing the user as it requires much physical effort. The dismantling of these product components creates an increased part count and uses more warehouse space.

4.2.5 Subsystem #5: Standing upright

This subsystem requires designs that help the jig stand upright thus producing the base of the jig. The designs created for this subsystem also account for footprint space since the jig will be bolted in SunTrac facilities.

4.2.5.1 Design #1: Leaning base bolted to the ground

This design uses a straight bar that is bolted to the ground. The frame of the jig will be attached to the straight base in an angle. Figure 21 shows the orientation of the base.

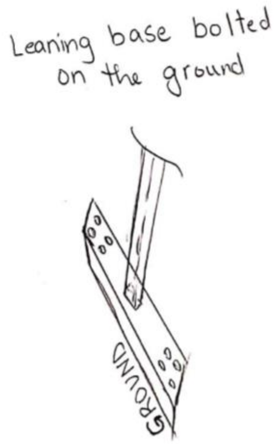

Figure 21**.** Leaning base bolted on the ground

The design in Figure 21 is basic therefore its only pro is that it is easy to bolt on the ground. The con to using this design is that it will require a wide space thus occupying more footprint.

4.2.5.2 Design #2: Bolted into the wall

This design is similar to design one however the difference is that it is being bolted to the wall. Likewise, the frame of the jig will also be attached to the base in an angle. Figure 22 provides a sketch of the design being bolted to the wall.

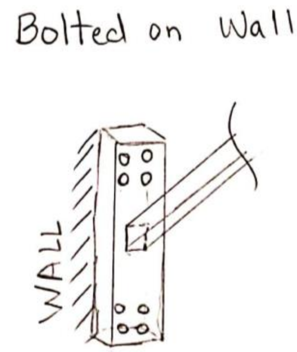

Figure 22. Bolted onto the wall

The design in Figure 22 has one pro, which is that it occupies less footprint space since it is bolted to the wall. The cons to using this design is that it will constrict the jigs to be placed on walls and it will require a great amount of effort to bolt the jig to the wall.

4.2.5.3 Design #3: "n" shape bolted to the ground

This design entails of an n shaped structure as a solid base from which all other components are supported. The design is to be bolted on the ground from the side farthest from the downward force to balance the jig. This is illustrated in Figure 23 below.

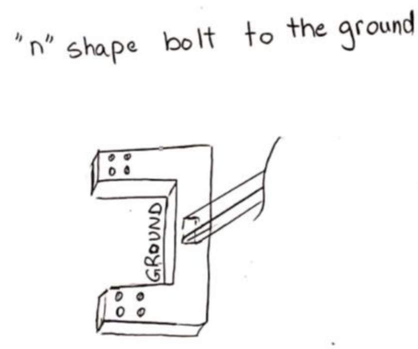

Figure 23. "n" shaped base bolted to the ground

The pros of this design is that it requires minimal floor space as the downward force is being balanced in two locations where the bolts are placed. This also doesn't act as an impediment to the user, the base is directly beneath the rear frame support structure where no welder will stand. The cons of this design are that the downward force is acting on the far side of this base, requiring maximum counter force to maintain stability.

4.2.6 Subsystem #6: Locking brass brackets

This subsystem locks the brass brackets in place to make sure that they are positioned accurately when they are welded onto the horizontal copper pipes. Since the designs in this subsystem takes care of locking and positioning, they satisfy the position component and secure component from the functional decomposition.

4.2.6.1 Design #1: Indented surface with a slider

This design will be located on the skeleton of the jig. It is made up of two parts, the first has an indented surface where the bracket goes in and the second has a slider which slides on top of the bracket to lock it into position. The sketch of the design is found in Figure #.

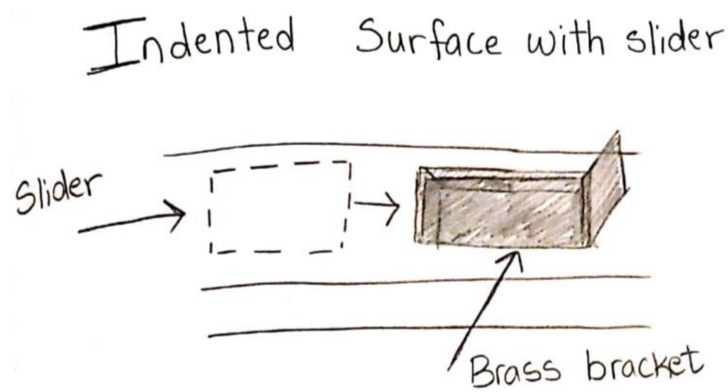

Figure 24. Indented surface with slider

The design in Figure # has two pros. The first pro is that the indented surface makes sure the bracket will have an accurate position when it is welded since it eliminates human errors that could be produced when measuring the distance by hand. The second pro is that it is easy to handle and does not require a large amount of time to place the brackets and secure them. The only con to this design is that the bracket could be stuck in the surface when it is brazed due to heat expansion.

4.2.6.2 Design #2: Built in clamp

This design consists of a bracket which is constructed with the skeleton frame of the jig. This clamp is a single unit with the jig and cannot separate, minimizing the inconvenience to the welder. This device can be seen in in Figure 25.

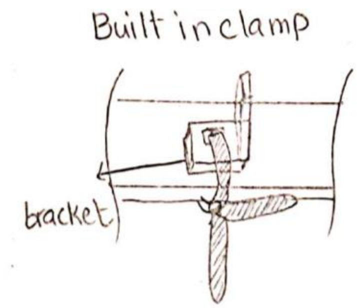

Figure 25**.** Built in clamp

The pros of this device include it minimizing part count by not acting as a separate component. Also with the clamp being built in the bracket which it secures will always be clamped with no possibility of human error of not clamping the bracket during brazing. The cons of this process are that it is not as accurate as say an indented surface as the bracket must still be secured on the horizontal plane. This design also doesn't ensure proper placement of the bracket as does the indented surface.

4.2.6.3 Design #3: Slides into place

This design is comprised of a bracket which is slid into a strap securing the bracket in both the horizontal and vertical directions. This is illustrated below in figure 26.

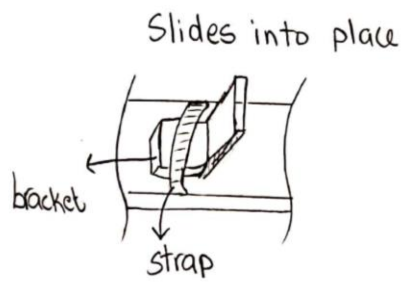

Figure 26. Bracket slide

The pros of this design are the effectiveness of securing the bracket, as this is securing in the horizontal and vertical directions as opposed to the built in clamps single direction. This design is easy to use by the brazer as it doesn't require much physical effort such as positioning and tightening a clamp. The cons are the lack of stability. The strap does restrict movement in both the vertical and horizontal directions, although not all horizontal movement as it can still slide out from where it is slid in.

5 DESIGNS SELECTED – First Semester

This section details the selected designs and the processes that were used to justify the results. This section begins by discussing the technical selection criteria that is used to compare the designs found in section four. The rationale for these choices are then discussed using a pugh chart paired with a decision matrix. This section concludes by providing the analytical analysis for the pugh chart and stating the best hypothesized concept variant.

5.1 Technical Selection Criteria

To Recall information from the project description and preliminary contact with the customer Suntrac USA. the team and they were able to devise nine customer requirements that were detailed earlier in this report. Of those nine, three of them were agreed upon to have the highest weight; first that the jig would be safe to operate, it would cost within the customers budget, and then it could fit a 4', 6', and 8' copper manifold. Subsequently after this meeting the team developed nine quantifiable engineering requirements, also earlier in this report, that we would need to reference as we implemented components into our design.

The most imperative customer need is that the jig is safe to operate. This from an engineering standpoint not only gives certain implications at the design needs but utter requirements. Firstly, this means that the jig as it is under operation must satisfy a factor of safety of at least 1.5. However, since the jig is anticipated to be a rigid steel structure under little load, a factor of safety of 4 or even 5 may be satisfied which qualifies it to be a below the hook loading frame [3].

Secondly The Jig needs to cause within Suntrac USA's budget. for any company satisfying the budget is an important thing. however Suntrac USA current circumstances dictate that the jig must be affordable. As a small company they already do not have a large budget to play around with. However they are projected to grow exponentially in the next 3 years; manufacturing many more jigs, hiring more employees, and purchasing more warehouse and factory floor space. A relatively cheap copper brazing jig could well ensure more effective growth.

And lastly when considering the most important customer requirements, the jig must adapt to manufacture a fit a 4', 6', and 8' manifold. This versatility has the potential to save SunTrac USA a lot of time, money, and physical space. In addition, they currently do not have a jig capable of supporting a 4-foot manifold. so the potential of placing all 3 configurations into one manifold is tremendous for them.

From the customer requirements the team was able to develop nine engineering requirements. In the what versus how room in the House of Quality (Appendix A) we could determine absolute and relative technical importance. The team came to determine that minimizing costs and maximizing durability are the two most important objectives. The cost is measured in dollars from how much it costs to purchase materials and manufacture the parts. The durability is measured in how many years the jig can go before it needs repair. These were the utmost considerations in our concept generation and selection portion. Note that the two of these engineering requirements may have some negative influence on another, such as using cheap materials may reduce the durability of the jig.

5.2 Rationale for Design Selection

This section details the bulk of our concept selection process and provides a rationale for the decisions that were made. The full system design alternatives were weighed against each other in our process of concept evaluation. The selection process began with the use of a Pugh Chart to eliminate weaker design alternatives. In this process, the seven first design alternatives were weighed with respect to the customer requirements to arrive at the top three choices. Then, a Decision Matrix was used to evaluate the top three DA's with respect to the team's found engineering requirements. The design with the highest weighted score was chosen as the final design.

5.2.1 Pugh Chart and Decision Matrix

The first thing needed to begin concept evaluation was to consider the customers needs and weights of important each need had. These needs were initially applied in developing concept variants, and are criteria to be fulfilled in selection. The Pugh Chart (Appendix B) is a means of weighing each design against each other on the basis of satisfying customer needs. The designs are rated qualitatively against the team's selected datum design, which is the design selected that most closely resembles the current jig used by SunTrac. If the team agreed that the design performed the customer need better then it was awarded a plus symbol for that need. Conversely if it doesn't meet up to the datum it was given a minus. If it can perform the requirement approximately as well as the datum, it was granted a 'S' for same.

Seen in the Pugh Chart Design Alternatives 1, 4, and 6 scored the highest net positive score. This initial portion of the design selection process proved rather tricky since most of the designs the team awarded positives to. When the team was going through the concept generation and design construction process, these customer requirements were held in mind when generating the design alternatives, they considered the datum to be the design that reflects what Suntrac currently employees at their facility. That signifies that this design isn't very satisfactory with respect to the customer needs since it doesn't employ a locking mechanism, is bulky, and doesn't allow easy access to the copper manifold. Each design alternative scored a plus in this category. However, because of each design alternatives possess increased versatility and adaptability compared to the datum, this means that each has more moving parts and dynamic mechanisms. Thus, the team associated more moving parts to have an inversely proportional relationship with durability, reliability, and accuracy; so some minuses and 'S's were awarded.

Design alternatives 1, 4, and 6 obtained the highest net positive score and are marked in green signifying that they move on to the Decision Matrix (Appendix C). The team gauged that these three designs in particular were just as or more versatile, accessible, safe, and adaptable in operation compared to the datum. Each of these three also utilized the gear foot stop locking mechanism which the team is fond of. They are now weighed against each other in the Decision Matrix. The Decision Matrix uses the teams determined engineering requirements and their associated weights to select one design alternative of the remaining three. The weighted score each engineering requirement was predetermined in the House of Quality (Appendix A).

Design alternative 4 came in first with design alternative 6 in a close second. There aren't many features that discern between these two but they are significant. The similarities between the two are the square collapsible tubes to adjust the frame size, the foot pedal gear stop, and rigid standoffs to hold the vertical copper pipes in place. The two also rotate about the vertical plane on a ball bearing for easy rotation, and use the square indented surface slider method to align and secure the brass brackets.

Design 4 utilizes a different frame shape, which allows for a tripod configuration or for the back part of the stand to be removed to allow it to be bolted into a wall. This enables some configuration possibilities and the ability to save floor space by reducing the footprint. Where on the factory floor these can be placed, bolted to the floor or wall is up to Suntrac's discretion. Design 4 also secures the horizontal pipes by clamping them with a power screw against the rigid frame. The team agreed that this is more rigid and reliable over the swivel clamp, which has the chance of falling out and releasing the manifold before it is done being assembled.

5.2.2 Analytical Analysis

The section details some analysis that was done to support the decisions that were made in the Decision Matrix. Three analyses on various components were completed. They are all computational and utilized constants and equations found in some of the referenced sources.

5.2.2.1 Analysis 1: Moment of Inertia

Some concern the team had was associated with the rigidity of the design. an analysis was performed to determine which shape of pipe would be more rigid and deflect less when under stress. The only major source of stress that can affect the jig Would be induced dresses that come from the thermal expansion of the copper pipes. These pipes can reach 800 degrees Celsius (1,450 degrees Fahrenheit) [1V]. To minimize the amount of dimensioning error that may happen when these pipes expand, the team determined it would be best to make the jig as rigid as possible. For this, the second moments of area for two of the collapsible tubes were calculated.

$$I_{square} = \frac{1}{12}((bh^3)_o - (bh^3)_i) = \frac{1}{12}((3\, in^4 - 2\, in^4)_o = 5.42\, in^4$$

$$I_{cylinder} = \frac{\pi}{4}({r_o}^4 - {r_i}^4) = \frac{\pi}{4}(3\, in^4 - 2\, in^4) = 3.19\, in^4$$

The cylindrical shape has a smaller moment of area. what this means is that the shape itself has a higher resistance to motion about the axis which it is taking respect to. this comes from the Parallel Axis Theorem and a higher number means a higher resistance to motion [16]. Fundamentally, in terms of the project this means that the square collapsible tubes will deflect less under the same load.

5.2.2.2 Analysis 2: Copper Pipe Thermal Expansion

When the copper tubes are heated up thermal expansion will occur in both the axial and radial directions. Depending on what the pipes are coincident with, this may induce very high stresses on the pipes and/or the pipe surroundings [Mech Mat]. Thermal expansion in the axial and radial directions were computed to provide some insight on this phenomenon.

$$Diameter + \delta_{rdial} = D_o\,(\Delta T(\alpha) + 1) = 5/8\, in\,(1375F\,(9.4 * 10^{-6} in/in * F) + 1)$$
$$= 0.633\, in$$

$$\delta_{axial} = \Delta T(\alpha)(L) = 1375F(9.4 * 10^{-6} in/in * F)(8ft * 12in/ft) = 1.24\, in$$

There are assumptions built into these computations. Both calculations assume that there are no external boundaries that would restrict this motion. They also assume that the heat distribution is uniform along the pipe, but this is not highly unrealistic given copper has excellent thermal conductivity.

5.2.2.3 Analysis 3: Force to Yield Gear Lock

The last analytical analysis performed revolves around the gear and how strong it is. For this analysis, assume the gear size, which is dimensioned according to the American Gear Manufacturers Association standards; the gear is 2.0 inches in diameter, has 20 triangular teeth, is 0.5 inches wide, has a geometrically standard 20 degree pressure angle, and is made of common stainless steel. Then the problem is if someone were to push at the bottom of the jig with some reasonable amount of force, would they break the gear? These next set of equations came from *Shigley's mechanical engineering design* [10] to evaluate the spur gear.

$$P = TPI\ (Threads\ Per\ Inch)$$
$$n = number\ of\ teeth$$
$$t = half\ tooth\ thickness$$
$$P = n/d = 20teeth/2in = 10\, TPI$$
$$t = \pi/(2 * 2 * P) = \pi/(2 * 10TPI) = 0.03925\, in$$

This portion of the analysis was to determine the cross-sectional area of the tooth. for the rest of the analysis, halfway up the triangular tooth is called the pitch diameter, the distance between the tooth tip and the root. The cross-sectional area of this part of the gear tooth may be used in transmitted force modeling for it is commonly a contact point at a 20 degree pressure angle gear. Next, the moment net sum about the pivot point is found to solve for the reaction force that the gear needs to give in order to maintain equilibrium, and this reaction force is found by dividing the yield strength of stainless steel (79,800 psi) [9] by the cross-sectional area of the half tooth thickness multiplied by the sin of the tooth angle.

$$\sum M = 0 = F * L - F_R * R_{gear} ==> F * L - A_c \sigma_y * sin(20) * R_{gear}$$
$$0 = F * 48\, in - 0.03925\, in\, (72{,}800\, Psi) * sin(20) * 2\, in$$
$$Solving\ for\ F\ gives\ F = 108.7\, lbf$$

So this shows that when the jig is in its eight foot long manifold configuration then if one were to apply 108.7 pounds of force then they would yield the gear. A force of this magnitude may be easily achieved through a small accident such as running a cart into the bottom of the Jig. To counteract this the team may design for a gear with a larger diameter and/or manufacture it out of stronger material.

5.2.3 Conclusion

The team is through the design evaluation process selected design alternative 4 (Figure 7) as the final design. This design utilizes square collapsible tubes to adjust the frame size, the foot pedal gear stop, rigid standoffs to hold the vertical copper pipes in place, pivots about on a ball bearing, and uses the square indented surface slider method to align and secure the brass brackets. The team agreed that the fundamental characteristics of this design would simultaneously meet or exceed the customer needs. Through some analytical analysis, the team was able to substantiate their decision with supporting engineering principles to possibly produce the most effective design.

6 REFERENCES

[1]S. Siebens, Interviewee, *Ideal Characteristics for Revised Braze Welding Jig.* [Interview]. 30September 2019

[2]S. Kalpakjian, K.-S. .., and S. R. Schmid, *Manufacturing processes for engineering materials*. Upper Saddle River, NJ: Prentice Hall, 2008.

[3]M. P. Groover, *Fundamentals of modern manufacturing: materials, processes, and systems*. Hoboken, NJ: John Wiley & Sons, Inc., 2013.

[4]H. Elmaraghy, A. Barari, and G. Knopf, “Integrated Inspection and Machining for Maximum Conformance to Design Tolerances,” *CIRP Annals*, vol. 53, no. 1, pp. 411–416, 2004.

[5]B. Grover, “Machining Processes Introduction of Machining Process,” Academia.edu. [Online]. Available: https://www.academia.edu/40169860/Machining_Processes_Introduction_of_Machining_Process. [Accessed: 19-Oct-2019].

[6]G. Varga, “Mechanical Modelling of Dry Machining Processes.”

[7]N Copper Development Association Inc. (CDA) (2005). *Soldering and Brazing Copper Tube and Fittings*. [online] New York: CDA, pp.1 - 8. Available at: https://www.copper.org/publications/pub_list/pdf/soldering_brazing_ads.pdf [Accessed 12 Sep. 2019].

[8]N Copper Development Association Inc. (CDA) (2019). *Copper Tube Handbook*. [online] New York: CDA, pp.1 - 96. Available at: https://www.copper.org/publications/pub_list/pdf/copper_tube_handbook.pdf [Accessed 12 Sep. 2019].

[9]N Engineering ToolBox, (2003). *Young's Modulus - Tensile and Yield Strength for common Materials*. [online] Available at: https://www.engineeringtoolbox.com/young-modulus-d_417.html [Accessed 17 Oct. 2019]

[10]R. G. Budynas, J. K. Nisbett, and J. E. Shigley, *Shigley's Mechanical Engineering Design*, Ch 13. 9th ed. New York, NY: McGraw-Hill Education, 2011.

[11]R. C. Hibbeler, *Statics and Mechanics of Materials*, Ch 2,4. 9th ed. Singapore: Pearson, 2014.

[12]N. Sclater and N. P. Chironis, *Mechanisms and mechanical devices sourcebook*. Ch 6,9,16. New York: McGraw-Hill, 2007.

[13]V. B. Bhandari, *Design of machine elements*. New Delhi: McGraw-Hill Education (India), 2017.

[14]K. Russell, Q. Shen, and R. S. Sodhi, *Mechanism design: visual and programmable approaches*. Boca Raton: CRC Press, 2014.

[15]J. P. den. Hartog, *Mechanics*. New York: Dover Publications, 1961.

[16]R. Hibbeler, Mechanics of Materials., Pearson Prentice Hall, 2014.

[17]R. G. Budynas and N. Keith, Mechanical Engineering Design, New York: McGraw-Hill, 2008.

[18]S. Siebens, Interviewee, *Ideal Characteristics for Revised Braze Welding Jig.* [Interview]. 30 September 2019.

[19]S McMaster-Carr, "Low-Carbon Steel Rectangular Tubes," [Online]. Available: https://www.mcmaster.com/rectangular-tubing. [Accessed 9 October 2019].

[20]R. S. Figliola and D. E. Beasley, Theory and Design for Mechanical Measurements, Hoboken: John Wiley & Sons, Inc., 2011.

7 APPENDICES

7.1 Appendix A: House of Quality

House of Quality (HoQ)

Customer Requirement	Weight	Engineering Requirement	Melting Temperature (degrees Celsius)	Force to Rotate (Newtons)	Cost (dollars)	Versatile (number of compatible product variations)	Standardized Parts (dollars)	Footprint (meters^2)	Degree of Rotation (Radians)	Adaptable (Number of locking positions)	Durable (Years before repair)	Error (Difference in desired length) (in)	
Desired Direction			^	v	v	^	v	v	^	^	^	v	
1. Safe to Operate	5		9	9	9				1	1	3		
2. Cost within budget	5		1	1	9	3	9			1	9	9	
3. Can fit a 4', 6', and 8' copper manifold	5				3	9		9	3			3	
4. Machinable parts	4				9		9						
5. Fit within a 5'x5' square	3					1		9	3				
6. Allow easy access to all copper joints	4			1		3		1	9	9			
7. Jig can rotate and lock at various angles	3			3	1	9			9	9		3	
8. Durable and Robust design	4		3	1	3	1	3				9		
9. Reliable design	4		3		3	1	1		1		3	9	
Absolute Technical Importance (ATI)			74	67	168	110	97	76	96	73	108	105	
Relative Technical Importance (RTI)			8	10	1	2	5	7	6	9	3	4	
Target ER values			1400	13	1500	3	1500	2.32	2*pi	8	20	1/16"	
Tolerances of Ers			300	3	500	0	500	0.5	0	2	5	1/32"	
			0.08	0.07	0.17	0.11	0.10	0.08	0.10	0.07	0.11	0.11	974

Approval (print name, sign, and date):

Team member 1: Edwin Smith 09/13/19

Team member 2: Ethan Vieane 09/13/19

Team member 3: Kadeja Alhossaini 09/13/19

Team member 4: Nathan Fior 09/13/19

Client Approval: Stu Siebens 09/14/19

7.2 Appendix B: Pugh Chart

Concept / Criteria	Datum	D.A. 1	D.A. 2	D.A. 3	D.A. 4	D.A. 5	D.A. 6
Safe To Operate	D	S	S	S	S	S	S
Cost Within Budget		S	-	-	S	-	S
Fit a 4', 6', 8' Manifold	A	+	+	+	+	+	+
Machinable Parts		S	S	S	S	S	S
Fits within 5'x5' square	T	+	+	+	+	+	+

Easy access to Copper		+	+	+	+	+	+
Rotate and Lock	U	+	S	+	+	+	+
Durable and Robust		-	S	-	S	S	+
Reliable	M	S	-	-	+	-	S
Σ+		4	3	4	5	3	5
Σ-		1	2	3	0	2	0
ΣS		4	4	2	4	4	4
ΣNet		3	1	1	5	1	5

7.3 Appendix C:Decision Matrix

Criterion	Weight	Design Alternatives (DA's)					
		DA1		DA4		DA6	
Melting Temperature	0.08	100	8	100	8	100	8
Force to Rotate	0.07	90	6.3	90	6.3	90	6.3
Cost	0.17	60	10.2	60	10.2	60	10.2
Versatility	0.11	100	11	100	11	100	11
Standardized Parts	0.1	100	10	100	10	100	10
Footprint	0.08	90	7.2	95	7.6	90	7.2
Degree of Rotation	0.1	100	10	100	10	100	10
Adaptability	0.07	100	7	100	7	100	7
Durability	0.11	80	8.8	85	9.35	85	9.35
Error	0.11	70	7.7	75	8.25	75	8.25
Totals	1	/	86.2	/	87.7	/	87.3
Relative Rank		3		1		2	