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Cádiz IQP

NAVIGATING THE FURTURE OF REPAIR:

ASSESSING THE FEASIBILITY OF WIRE ARC ADDITIVE MANUFACTURING FOR SHIP REPAIR IN ALGECIRAS

Navigating the Future of Repair: Assessing the Feasibility of Wire Arc Additive Manufacturing for Ship Repair in Algeciras

An Interactive Qualifying Project Report
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE

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Degree of Bachelor of Science
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IQP D-Term 2024

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Abstract

The Port of Algeciras, Spain, draws in a high volume of ship traffic in need of repairs. The goal of this project, sponsored by the University of Cádiz, was to assess the feasibility of Wire Arc Additive Manufacturing (WAAM) for the repair of ship parts to provide a sustainable solution to improve the efficiency of port operations. Through interviews, site tours, and a life-cycle assessment, our team determined that WAAM offers a compelling solution for time and material savings.

Acknowledgments

We would like to begin by thanking our sponsor, The University of Cádiz, for giving us the opportunity to collaborate with them on this project. We would specifically like to thank Professor David Sales Lérida, Professor Nuria Baladés Ruiz, PhD Candidate Luis Segovia Guerrero, and Research Technician Juan José Gallardo Galán for supporting our project decisions, getting us in contact with stakeholders, and for showing us around the city of Algeciras. We would also like to acknowledge the contributions of UCA students Paula Guerrero Martín, Álvaro Sánchez Gutiérrez, Antonio Muñoz Pizarro, and Francisco Jose Gutierrez Villalba, who performed a life cycle assessment on a ship part that we selected for analysis, providing valuable data used in our report. We would like to thank all of the individuals and companies who gave us interviews and site tours of their facilities, including Sean Kelly from Solvus Global; Diran Apellian from the Metals Processing Institute; Ángel Pinillas Álvarez from the Algeciras Bay Port Authority; Enrique Pérez, Eduardo Ruiz Álvarez, and Jesús Burgos Arlandi from Cernaval Shipyards; Gonzalo Miranda from Surmeyca; Alejandro Sánchez García from Projekt Firmen Gruppe; Alberto from Crisnaval; Javier Vázquez from Algeciras City Hall; and Jesús Rodríguez and Bruno Campos from Kalmar Global. Finally, we would like to thank our advisors from Worcester Polytechnic Institute, Professors Svetlana Nikitina and Kira Kovnat for their efforts in coordinating the new project center and providing feedback on our report. We would also like to thank our ID2050 professor, Robert Hersh, who helped guide our project in the right direction during its initial stages.

Authorship

This project represents a combined effort by all members of the Circular Economy IQP Team: Ava Dickman, Jackie Edwards, Thomas Joyner, and Edward Stump. Through regular meetings, distributed asynchronous work, and rotating roles for interviews and communication, our group divided up the work of this project as evenly as possible. It would be nearly impossible to list in detail who worked on and edited each section as it was entirely a collaborative effort.

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1. Introduction: The Challenges Facing the Port of Algeciras

The maritime shipping industry is crucial for global trade as it is responsible for transporting approximately 90% of the world's goods. Given its size, the industry is a significant contributor to many environmental and economic issues. Some of the environmental concerns include greenhouse gas emissions, pollution, and other ecological issues (Orb, 2023). On the economic side, inefficient management of resources can lead to delays and potential supply chain disruptions. One potential cause of these concerns is the frequent need for ships to be docked, either for routine maintenance or emergency repairs. The manufacturing of new parts wastes material, uses the planet's limited natural resources, consumes significant energy, incurs high costs for all parties involved, and tends to produce delays that can cause unprofitable downtime for ships as they only make money while at sea (E Pérez, personal communication, April 3, 2024). Spain's Algeciras Port is not immune to these issues, and its sustainability practices could be improved. The contributions to climate change made by the activities of the Port of Algeciras could be reduced by the implementation of technologies that improve upon the sustainability of current manufacturing and repair processes.

Manufacturing technologies that are currently used to produce and repair ship parts are expensive and result in long downtimes for ship owners and operators (Agarwala, 2023). Consequently, many choose to replace these parts instead of repairing them. This leads to unnecessary waste as well as excess energy wasted by inefficient manufacturing processes. Not only is this inefficient, it does not align with Spain and Europe's current sustainability and circular economy goals (Bobba et al., 2018). Wire Arc Additive Manufacturing (WAAM) offers a potential solution to this issue. It has been introduced in many areas as a sustainable development technique because it is more efficient and effective than the current practices. The use of this technology mitigates the effects of climate change and conserves the lifespan of the planet's limited resources. However, as this technology is very new, effort is needed to build trust in both ship owners and manufacturing companies that repair ship parts in its efficiency and reliability. More research is needed to understand the barriers that currently obstruct the wider implementation of WAAM in Algeciras.

Our sponsor, Professor David Sales Lérida, is the research coordinator of the Smart Manufacturing Lab at the University of Cádiz (UCA). The team, also consisting of Professor Nuria Baladés Ruiz, Luis Segovia Guerrero, and Juan José Gallardo Galán, has been conducting experiments with WAAM, specifically analyzing the cost, energy consumption, and feasibility of this new technology for manufacturing. The lab is now looking to implement this manufacturing method into the maritime industry. To better understand opportunities for the adoption of WAAM in the maritime shipping industry, the lab needed to assess the perspectives of local shipping and ship repair companies. Before our project, the lab had not undertaken market research on the applicability of WAAM in the shipping industry. Our project is designed to bridge that gap.

The goal of this project was to assess the feasibility of the transition to WAAM for ship repairs in Algeciras. Both the constraints and opportunities for the adoption of this technology were identified and analyzed. Repair companies operating in Algeciras and officials in the Port were interviewed to learn about current manufacturing processes, focusing on the problems of expensive, slow, and unsustainable repair methods. We also worked in conjunction with master's students from the University of Cádiz, analyzing the sustainability and material usage of WAAM through a life cycle assessment. We have created a report that analyzes the economic and sustainability impact of WAAM with the goal of introducing this new repair technology to local companies, which would reduce repair times and costs while contributing towards modern sustainability goals.

2. Background: A Possible Solution to the Port's Issues

2.1 The Shipping Industry and Its Concerns

A report published by the European Commission under the Circular Economy Action Plan in 2018 defines a circular economy as one in which "the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized" (Bobba et al., 2018). This is crucial in the European Union's (EU) efforts towards a sustainable, low-carbon, resource-efficient, and competitive economy. The Sustainable Development Goals (SDGs) were established by the United Nations (UN) in 2015 as part of the UN 2030 Agenda for Sustainable Development. The ninth SDG calls for building resilient infrastructure, and the promotion of inclusive and sustainable industrialization (United Nations, n.d.). Efforts towards a circular economy are essential for reaching the UN's SDGs for inclusive and sustainable development, and reducing waste of raw materials would contribute towards this goal.

One aspect of sustainable development is the management of Critical Raw Materials. Critical Raw Materials (CRMs) have been defined by the European Commission as valuable raw materials that are particularly important for high-tech products and emerging innovations that are crucial for the European economy (Bobba et al., 2018). Parts manufactured for the maritime shipping industry often include these CRMs, such as stainless steel and titanium, and it requires additional raw material usage to repair these parts. The improvement of current manufacturing and repair processes would be beneficial, as inefficiency in these processes results in unnecessary amounts of CRMs being used, and increased costs for the manufacturers, who must purchase more materials than necessary. Common subtractive manufacturing techniques that produce parts by removing metal from a large piece of material generate much more waste than newer, less commonly used additive manufacturing methods, which work in tandem with subtractive manufacturing to minimize material waste. With waste minimization being a key factor in establishing a circular economy, the necessity of finding more efficient methods becomes increasingly important.

The maritime shipping industry has already adopted some aspects of the circular economy including "shipbreaking for recycling, emission control through decarbonization, and some reuse of materials" (Agarwala, 2023). However, the establishment of a circular economy has been impeded by issues such as high costs of part repair and disparity of information amongst suppliers (Agarwala, 2023). Currently, maritime equipment repairs are most commonly addressed through replacement due to the high costs associated with downtime and relatively low spare part costs. Even though cost-benefit analysis of repaired engines has shown that the acquisition cost of repaired engines is nearly half the cost of purchasing a new engine (Smith & Keoleian, 2008), repair has not become an industry norm to date. More efforts are needed to promote the widespread use of the technology, as in many cases this could both save money for the ship owners and reduce raw material consumption (Agarwala, 2023). The promotion of newer and more efficient manufacturing strategies among ship repair companies could help address this issue. An opportunity to mitigate and reduce the steep expenses and extended repair times can be found in additive manufacturing.

2.2 The Potential for Wire Arc Additive Manufacturing (WAAM)

Figure 1: WAAM Machine in the Smart Manufacturing Lab at the University of Cádiz

Economic Impacts

As far as repair and manufacturing technologies go, Wire Arc Additive Manufacturing (WAAM) is extremely new. Despite the method's development in the early 1900s, the technology has only recently seen significant research and development (Wu et al., 2018). Instead of traditional manufacturing methods for metal which involve casting or milling from a larger block, this method builds up the part over time by welding a continuous metal wire feedstock onto the surface of the part in layers, similar to a traditional 3D printer of plastic (see Figure 2). Then, the surface is finished through milling (Kumar et al., 2022).

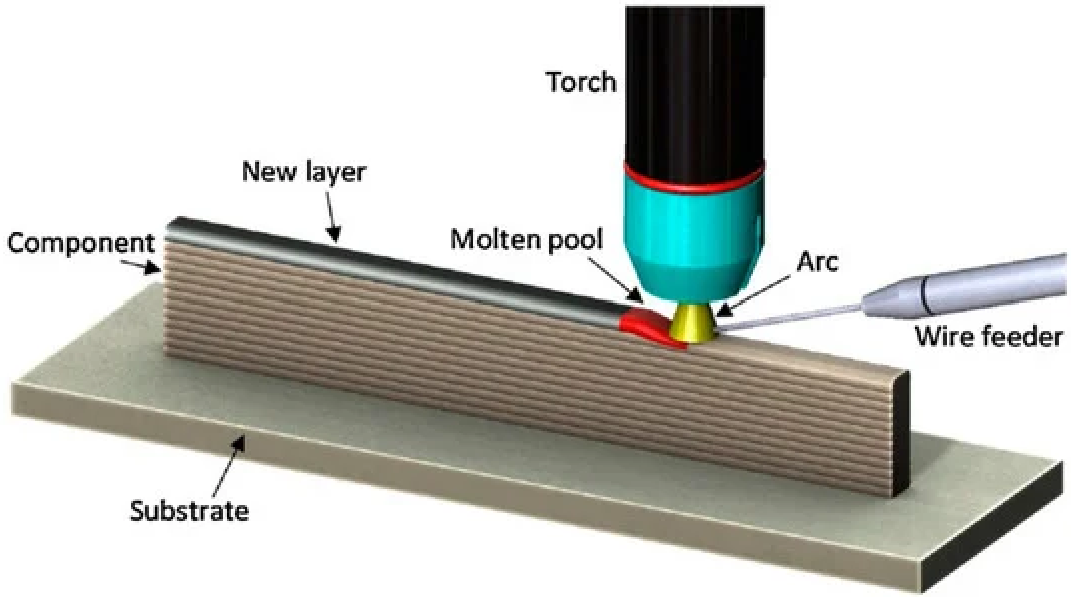

Figure 2: A diagram of wire arc additive manufacturing, (Jin W et al., 2020)

The differences WAAM has from other metal manufacturing methods currently used in factories also give it economic advantages. WAAM uses much less material than subtractive methods of manufacturing, such as CNC milling, because there is a significant amount of excess metal wasted. Figure 3, below, shows three stages of the creation of a part using WAAM. The only wasted material is the relatively small portion of the part milled away between the first and second phases of the process. In contrast, when a part is created through milling a block from the beginning, a considerable percentage of the initial mass is removed. In addition, additive manufacturing can also be far more energy efficient, depending on the shape of the part (Watson & Taminger, 2018). This reduction in metal and energy usage means that the finished part is cheaper to manufacture, translating to cheaper repair costs for shipowners. Even other metal additive manufacturing methods, such as powder additive manufacturing, are much pricier. The metal powder feedstock is between 2-50 times more expensive than the wire alternative, depending on the type of metal used (Derekar, 2018).

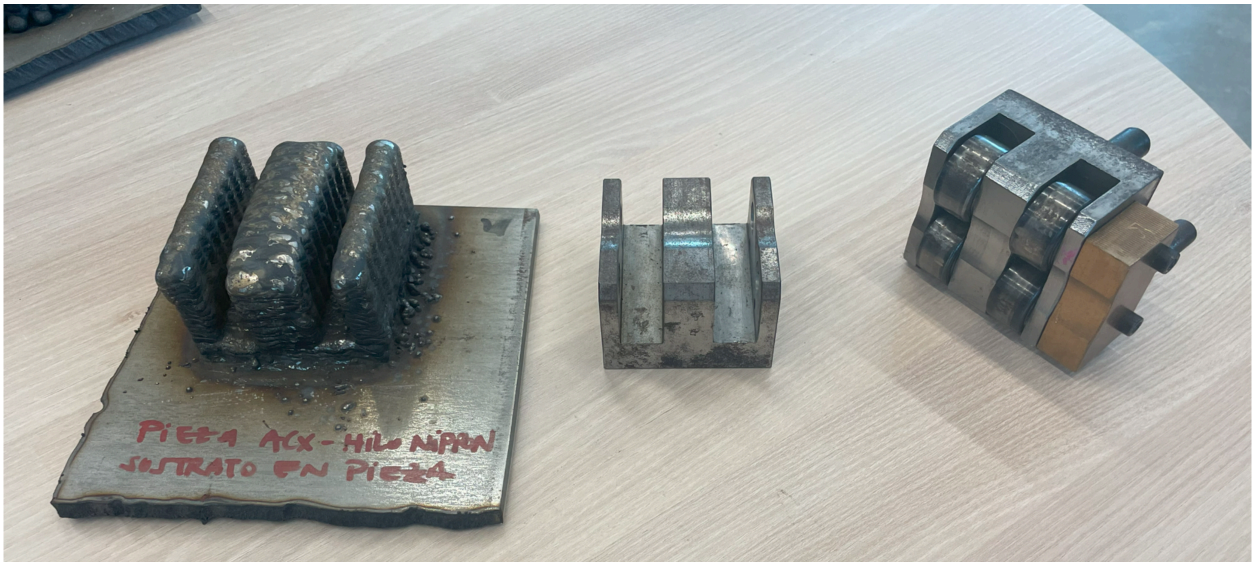

Figure 3: Part created using WAAM during three stages: deposition, milling, and installation in the University of Cádiz Smart Manufacturing Lab

While metal parts manufactured using wire arc additive manufacturing can be cheaper than those manufactured through subtractive manufacturing due to less material used, the economic benefits extend beyond the affordability of the manufactured or repaired parts. The cost to the end user of these parts is further reduced by the speed at which parts can be produced by this method. This is especially true of the potential consumers of this new technology: ship owners. Every hour that a ship spends in port waiting for repairs is an hour that could be spent in transit to the next port delivering goods. This means that the longer a repair takes, the more expensive it is for the ship owner. In an interview with Enrique Pérez, the commercial director of Cernaval Shipyards, a ship repair company operating in the Algeciras Bay, we were informed that “Ships only make money while at sea” (personal communication, April 3, 2024).

When compared to other additive manufacturing methods, wire arc additive manufacturing has a significantly higher deposition rate, meaning more metal is added to the piece in a shorter time (Williams et al., 2016). WAAM also cuts down on post-manufacturing machining time compared to other methods (Kumar et al., 2022). These time savings make WAAM a promising solution even when compared to other similar metal additive manufacturing methods. Below, in Figure 4, is a graph showing the deposition rate of material, in kg/hr, of various metal additive manufacturing methods compared to wire arc additive manufacturing

(Kumar et al., 2022). WAAM has the highest deposition rate by far and therefore can produce parts faster than other technologies.

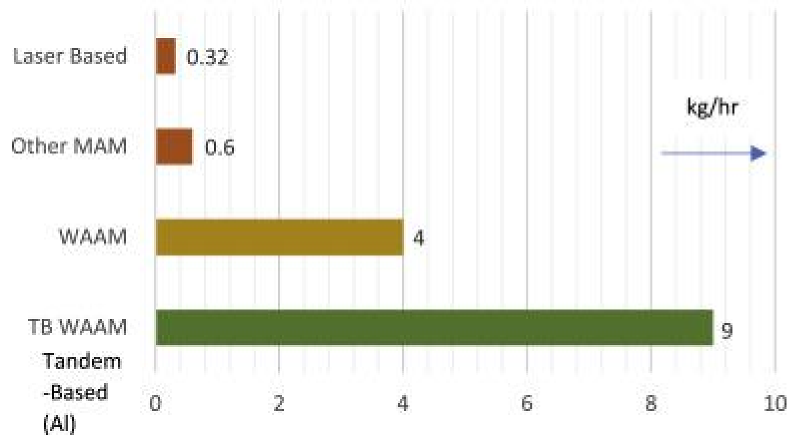

Figure 4: Direct Energy Deposition (DED) rate of various manufacturing methods, (Kumar et al., 2022)

Another advantage of WAAM is the ability to produce parts of diverse shapes and specifications as needed. In an interview with Solvus Global, a manufacturing company local to the Worcester area, we were informed by Co-founder Sean Kelly that a major advantage of WAAM is its versatility (S. Kelly, personal communication, February 20, 2024). This versatility also reduces the number of machines required to create a diverse selection of parts. This is not the only benefit that comes with being able to produce parts on demand. With traditional manufacturing methods, parts are manufactured in bulk in advance and sit in warehouses until they are required. For businesses, this means capital is tied up in warehouses and cannot be invested or used as free cash. Additive manufacturing methods, on the other hand, make it easy to create parts as needed (Ford & Despeisse, 2016). Due to the novelty of this technology, however, large-scale investment has been limited so far. At this point, WAAM has been a subject of research and testing by metals labs all over the world and is currently being used in a few niche manufacturing industries. As this section has proven, research on wire arc additive manufacturing has shown it to be a fast and inexpensive method of manufacturing that holds promise for the manufacturing industry.

Sustainability Impacts

Sustainability is an integral factor in deciding to utilize WAAM as an alternative manufacturing method compared to other computer numerical control (CNC) manufacturing methods, which rely solely on subtractive manufacturing methods. In contrast to subtractive manufacturing, WAAM provides numerous benefits including machine optimization, reduced material waste, and reusing recycled materials created from waste made during the WAAM manufacturing process. These benefits of additive manufacturing, specifically WAAM, further the cycle of the circular economy as it enables parts to be produced more quickly and sustainably.

Material consumption savings is one of the biggest considerations when choosing WAAM over other manufacturing methods, including milling. These manufacturing companies also have the ability to automate this process, allowing them to produce more parts in a shorter amount of time (Wahan & Azman, 2019). While automation is important for certain industries where mass production is important, WAAM is a much more cost-efficient method because its production process focuses on material optimization. The additive manufacturing procedure involves obtaining a three-dimensional CAD model which is used as a guideline for the manufacturing equipment (Volonghi et al., 2018). The part is then sent to the wire arc 3D printer, where the part is created using metal wiring with electric arc technology (see Figure 2). This machine produces a crude part, which then needs to be finalized in a CNC mill (Kumar et al., 2022). This method of manufacturing allows for large, complex parts to be created from the bottom up, optimizing and limiting the amount of material needed for the production process.

The WAAM process also produces a lot less waste than CNC milling. This is a major reason why WAAM is much more beneficial in establishing a circular economy. Spain is currently facing material shortage issues, which have been harmful to the economy. An article by Pedro Alvarez Ondina, an economist expert with a master’s degree from the University of Oviedo, analyzes the recovery of Spain's manufacturing industry. The study evaluated the availability of materials, assessing the cost increase over the past 20 years. The models created within the study show the importance that materials play in the manufacturing industry, highlighting the need for new and sustainable manufacturing methods that use fewer materials. It emphasized that the need for raw materials was increased by the COVID-19 pandemic, causing prices of aluminum, copper, and nickel to rise to levels never seen before (Ondina, 2022). This study was conducted just before the war between Russia and Ukraine broke out, where it was predicted that these prices would be driven even higher. In 2022 approximately 30% of manufacturing companies located in Spain reported material shortages with machinery repair, installation, and metal product manufacturing being two of the most impacted industries (Ondina, 2022). This highlights the importance of adopting WAAM as a primary manufacturing method to reduce waste and optimize the use of limited materials.

In addition to material optimization and waste reduction, WAAM has the potential for recycling the particles and shavings created during the subtractive process, often referred to as swarf material, and reusing it in the additive process. A research study conducted by Anas Ullah Khan and Yuvraj K. Madhukar explored the use of these particles with three different manufacturing processes. The article concluded that the use of swarf materials had no impact on the structural integrity of the manufactured part, performed well with WAAM, and was used to manufacture complex parts such as wheels and springs (Khan & Madhukar, 2022). The adoption of this recycling process in WAAM greatly contributes to the goal of a circular economy.

University of Cádiz - Smart Manufacturing Lab

To further the goal of promoting the widespread use of WAAM, the University of Cádiz (UCA) created the Smart Manufacturing Lab (see Figure 5). This lab specializes in additive manufacturing with a focus on WAAM technology and is researching its applications and benefits. The lab communicates with companies interested in the technology, using the lab space to demonstrate its applications and garner interest. Due to its proximity to the Port of Algeciras, the lab is mainly interested in researching applications of WAAM concerning the shipping industry, which is the topic this project aims to address.

Currently, the lab is using the new WAAM equipment to create parts that could be used in the real world. These parts are then examined for structural strength and used to determine how they hold up compared to parts manufactured through other methods. A master's student at the university, in collaboration with the lab, completed a master's thesis on the economic feasibility of WAAM (Martinez Dominguez, 2020). This study looked at the energy and material efficiencies as well as the strengths of the finished products. It also drew conclusions about the costs of WAAM, its advantages and disadvantages, and its best use cases. However, this study was purely lab-based and lacked the perspective of the end users of the technology and their concerns.

Figure 5: Our research group and sponsors in the Smart Manufacturing Lab

2.3 The Port of Algeciras and Sustainability Efforts

The Algeciras Port ranks as Spain's largest port and is among Europe's most important (Usero et al., 2016). Located within the Strait of Gibraltar, the port is at a gateway to the Mediterranean Sea between Europe and Africa. (Algeciras: Intelligent City Transformation Overview, 2022) (see Figures 6 & 7). The strategic location of the bay provides a place for ships to seek refuge from strong winds and currents, attracting a substantial number of ships seeking repair and maintenance services (The Algeciras Port Authority, 2022). According to the Vessel Operations Manager of the Algeciras Bay Port Authority (APBA), Ángel Pinillas Álvarez, roughly 120,000 vessels pass through the Strait of Gibraltar, and approximately 30,000 use port services. Out of those 30,000, more than 10% need repair. The port has the capacity for ships to be repaired in approximately 8-9 berths, a floating dock, a dry dock, and spots for anchorage. According to port regulations, ships are only allowed 10 days for repairs, however, approximately 20% of ships require more time.

Figure 6: Algeciras, Spain, (Google Maps, 2024)

Figure 7: The Algeciras Port, (Medports, 2023)

The Algeciras Bay is not only known for its significant naval traffic, but it is also home to major industrial facilities including power plants, manufacturing companies, refineries, and a biofuel production plant. Industrialized areas, especially those with heavy marine traffic, often face challenges related to environmental degradation and pollution (Usero et al., 2016). These impacts are not just from pollutants emitted by ships, but also from the activities ships engage in while at the port, such as manufacturing new parts for repair. To address these issues, ports are starting to implement sustainable practices and technologies.

The APBA holds sustainability as one of its core values (The Algeciras Port Authority, 2022). Some of the current sustainability and circular economy efforts of the bay include the use of biofuels and alternative energy sources (Usero et al., 2016). The port has been primarily concerned with air and water pollution from the marine vessels themselves, but not with the activities they engage in while at port. Manufacturing contributes to negative environmental effects through material waste, consumption of energy, and the release of greenhouse gasses (Priarone et al., 2021). This emphasizes the importance of considering the environmental effects of ship repairs.

Current repair processes carry both environmental and economic ramifications. The large parts needed by the maritime industry undergo prolonged fabrication periods. This delay is significant for the ship and its crew as vessels typically incur financial losses while docked because they are not operating. Consequently, this predicament may lead to the potential abandonment of ships. Although this problem is rare, cheaper repair methods could reduce the occurrence even further, benefiting both the port and ship owners (Á. Pinillas, personal communication, March 20, 2024). The main reason behind the abandonment was due to ship owners experiencing economic hardship and the inability to afford the costs and fees associated with operating the vessel. If ships sit unattended for too long, it can lead to irreparable damages, corrosion, pollution, value loss, and loss of crucial space for functional ships (Arranz et al., 2019). This leaves Algeciras with the decision of whether to repair these ships, auction them off, or transport them elsewhere.

The port provides a range of services for boats, ships, and cargoes. There are hundreds of service companies highlighted on their website for easy customer access, 79 of which are ship repair and waste management companies. The port has fostered strong relationships with several companies that are dedicated to ensuring effective waste management practices. These collaborative efforts represent the port's primary circular economy considerations as it remains committed to sustainability and responsible resource utilization (Medports, 2023). Their partnership with the repair companies helps satisfy the needs of the high volume of ships seeking repair. These ship repair companies offer a wide range of repair services from cleaning and painting to metal works and engineering (The Algeciras Port Authority, 2022). The use of additive manufacturing, specifically WAAM, has been explored in aerospace and wind turbine industries (Williams et al., 2016; O'Neill & Mehmanparast, 2024), however, the specific application of WAAM in the shipbuilding sector is still a nascent technology.

Additive manufacturing as a whole, however, has seen widespread use in the maritime sector in recent years. For example, plastic 3D printing is used in all kinds of manufacturing and repair to replace numerous other processes that were used before (Mélanie, 2022). These new parts can be manufactured quicker and without the need for molds, reducing waste and decreasing cost. For larger boats, additive manufacturing is being used to skip trips to port for repair. Researchers at UConn have developed a way for ships to manufacture replacement parts while at sea using additive manufacturing of ceramics and metals (Full Speed Ahead: Using Additive Manufacturing to Repair Ships at Sea, 2017). This demonstrates the versatility of additive manufacturing. With one machine they can repair numerous boat parts, eliminating the need for storage of replacement parts on the ship.

2.4 Conclusion

Our research on the shipping industry, wire arc additive manufacturing, and the Port of Algeciras provided necessary knowledge of how usage of WAAM can directly address some of the port and Spain's major problems. From this research, it is evident that there is a need for faster and more sustainable manufacturing technology in the Port of Algeciras. It is also clear that WAAM is a technology that can fill this gap, as it is faster and more sustainable than many common manufacturing methods. Throughout our report, this information is used to inform our methods, providing the baseline for our interviews as well as the starting point of our recommendations.

3. Methodology: Exploring WAAM in the Shipping Industry

The goal of this project is to assess the feasibility of the adoption of Wire Arc Additive Manufacturing (WAAM) for ship repairs in Algeciras and to determine its benefits over current repair methods. Our team interviewed repair companies and the port authority and compiled research to identify barriers preventing these companies from adopting WAAM in manufacturing in the Port of Algeciras. This chapter will provide an in-depth description of the methods we have implemented to achieve these objectives and through them, our project goal. Figure 8 details our group's project plan with our goals, objectives, and methods.

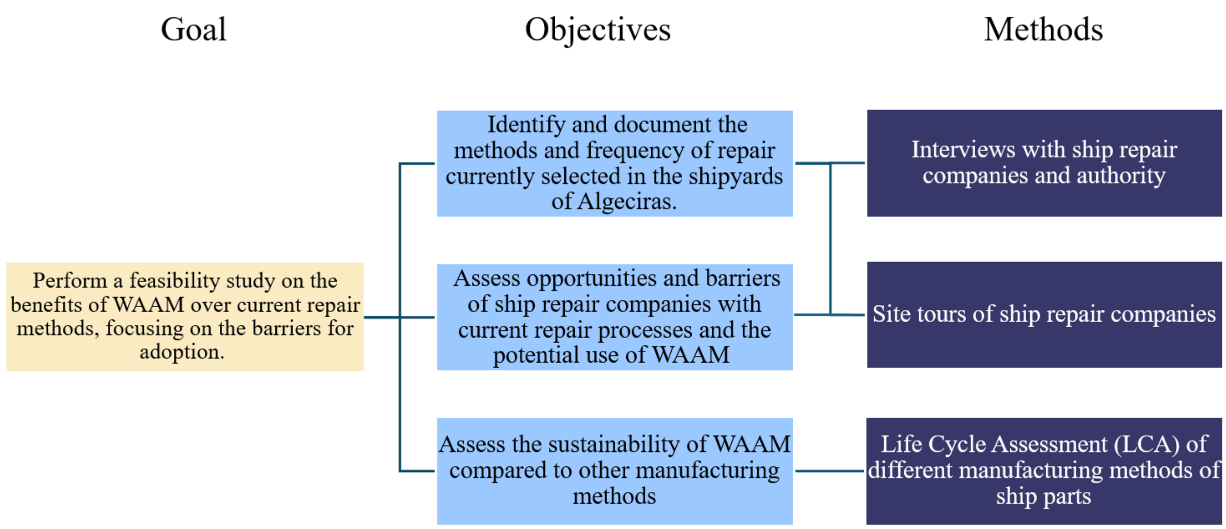

Figure 8: Project Plan

3.1 Stakeholder Interviews

To work towards these objectives, we conducted interviews with project stakeholders, including companies that manufacture ship parts, repair companies, the APBA, and a city hall manager. Before arriving in Spain, our interview questions and strategy were approved by the Institutional Review Board (IRB) at Worcester Polytechnic Institute (WPI) to ensure that all aspects of this project were ethical. Interviews were arranged through emailing and calling potential stakeholders and informing them of the purpose of our research. Stakeholders were conveniently sampled based on location around the Algeciras Port, willingness to participate in our study, and availability for our interview. We conducted semi-structured interviews to obtain stakeholder perspectives in a flexible, open-ended conversation (Berg & Lune, 2017). This indicates that interview questions were adjusted or additional information was introduced as the interview progressed based on the ongoing discussions. During each interview, there was a lead interviewer, a supporting interviewer, and two individuals tasked with taking notes.

Before arriving in Spain, we interviewed local experts on WAAM to gain an understanding of the process and to formulate our project goals. We first met with Sean Kelly, the co-founder of Solvus Global, a company focused on providing technological solutions specializing in additive manufacturing. The purpose of this interview was to gain knowledge on the applications of WAAM in the shipping industry, background information, and some of the benefits of this technology compared to others. We then interviewed Diran Apelian, founding director of the Metals Processing Institute (MPI) at WPI, to learn more about the technology from an industry expert.

Upon arriving in Spain, interviews focused on identifying and analyzing the problems stakeholders are facing with current ship repair methods, determining interest in the adoption of WAAM, and stakeholder familiarity with the technology. We began by interviewing the APBA staff to learn about the port operations and relationships. Information was collected from the APBA regarding the current costs of repairs, delays due to repair times, sustainability practices, and which companies and organizations repair ship parts. The questions in the Appendix address these goals and were used during the interview with the APBA.

Interviews with manufacturing and repair companies were used to gather information regarding the frequency of repair, delays caused by repair times, and the consequences of slow repairs and delays for both ship owners and repair companies. We also obtained additional information from these interviews, including where replacement parts come from, how long they typically take to arrive, and which manufacturing technologies are utilized to repair parts (see Appendix A for interview questions). These interviews sought to identify the perspectives of repair companies and shipowners about the potential opportunity to use WAAM repair methods. By investigating the barriers that exist against the adoption of WAAM, our team was able to write effective recommendations to further the widespread use of the technology.

Figure 9: The team interviewing with Cernaval Shipyards

3.2 Site Visits

To further our understanding of WAAM and the current practices of repair companies and the Port of Algeciras, site visits were conducted that were relevant to our research. These visits included research facilities that currently use WAAM for manufacturing, ship repair companies operating in Algeciras, and the Algeciras Port Authority. These visits served to further our background research, deepen our knowledge of WAAM, and better understand the problems facing the Port of Algeciras and repair companies that serve its ships.

The first set of stakeholders that we visited were two labs currently doing research with WAAM, working to learn about the fabrication process of various parts. In addition to this, these labs are researching the technology's benefits, drawbacks, and details about energy and raw material usage. This information is vital to our project, and visiting these labs to ask questions and see the WAAM machines in person has allowed us to learn significantly more about the technology than we would have learned through solely conducting interviews and research. The first of these locations visited was Solvus Global, a company that partially specializes in metal additive manufacturing and is currently testing and researching the use of WAAM to create metal parts. We also toured the Smart Manufacturing Lab, a metals research lab at UCA. As both of these labs extensively utilize WAAM, it was especially beneficial to our project to have the information that we have gathered regarding WAAM put into context, so that we can better understand the capabilities and potential applications of this technology.

Upon our arrival in Algeciras, we began touring repair facilities that specialize in working with the maritime shipping industry. Tours of repair companies allowed us both to ascertain the critical issues that repair companies and shipowners are having and to learn how WAAM could be applied as a solution to some of these major problems. These site visits allowed us to see in person the issues that were described in our interviews with various repair companies, and to observe the daily operations of these companies and their repair processes.

Table 1: Stakeholders Interviewed & Site Tours

Company	Type of Company	Name of Interviewee	Type	Date
Solvus Global	Technology Research	Sean Kelly	Interview	2/20/24
MPI	Research Lab	Diran Apelian	Interview	2/23/24
Solvus Global	Technology Research	Sean Kelly	Site Tour	3/1/24
Smart Manufacturing Lab	Research Lab	Luis Segovia	Site Tour	3/19/24
APBA	Port Authority	Ángel Pinillas Alvarez	Interview	3/20/24
Cernaval	Ship Repair	Enrique Pérez	Interview	4/3/24
Surmeyca	Ship Repair	Gonzalo Miranda	Interview	4/3/24
Projekt Firmengruppe	Wind Energy	Alejandro Sanchez	Interview	4/8/24
Crisnaval	Ship Repair	Alberto	Both	4/8/24
Algeciras City Hall	City Hall	Javier Vazquez	Interview	4/9/24
Kalmar	Port Equipment	Jesus Rodriguez and Bruno Campos	Both	4/9/24

3.3 Life Cycle Assessment

An important component of our research is the analysis of WAAM compared to current repair and manufacturing methods. Some of this information was gathered through background research, interviews, and site tours with facilities that currently operate WAAM machines. However, in order to get more specific data we had to use a different method.

To accomplish this, we worked in conjunction with students from UCA to perform a Life Cycle Assessment (LCA) on a boat rudder. This part was selected for the LCA due to its common manufacturing methods of sand casting or milling. The LCA utilized a cradle-to-gate assessment, which analyzes the manufacturing of a part from resource extraction to the time the manufacturing is finished, without considering its reuse (Kokare et al, 2023). It was important to only focus on cradle to gate as it is too difficult to predict exactly how the material will be used after leaving the manufacturing facility, and would not give an accurate assessment of material waste, and environmental pollution. By focusing only on the manufacturing process in this assessment, the importance of minimizing material waste is highlighted.

We provided the files and material specifications to the students, who then performed the assessment on SimaPro. WAAM was compared to CNC milling using this assessment, focusing on the 15 aspects of an LCA. These aspects focus on Global Warming, Stratospheric Ozone Depletion, Ionizing Radiation, Ozone Formation - Human Health, Fine Particulate Matter, Ozone Formation - Terrestrial Ecosystems, Terrestrial Acidification, Freshwater Eutrophication, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Human Carcinogenic Toxicity, Human Non-Carcinogenic Toxicity, Land Use, Mineral Resource Scarcity, Fossil Resource Scarcity, and Water Consumption. Each of these categories are defined in Table 2 below. This assessment allowed us to produce charts and figures comparing the different manufacturing methods. These results are presented and discussed in the results and discussion section below.

Table 2: Environmental Impacts (Hillege, n.d.)

Abbr.	Impact Category/Indicator	Unit	Description
GW	Global Warming	kg CO_2 eq	Indicator of potential global warming due to emissions of greenhouse gasses to the air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources, and (3) land use change.
SOD	Stratospheric Ozone Depletion	kg CFC11 eq	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer
IR	Ionizing Radiation	kBq Co-60 eq	Damage to human health and ecosystems linked to the emissions of radionuclides
OFHH	Ozone Formation - Human Health	kg NOx eq	Indicators of emissions of gasses that affect the creation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight
FPMF	Fine Particulate Matter Formulation	kg PM2.5 eq	Indicator of the potential incidence of disease due to particulate matter emissions
OFTE	Ozone Formation - Terrestrial Ecosystems	kg NOx eq	Indicators of emissions of gasses that affect the creation of photochemical ozone in the lower atmosphere (smog) catalyzed by sunlight
TA	Terrestrial Acidification	kg SO_2 eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.
FEU	Freshwater Eutrophication	kg P eq	Indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphorus-containing compounds
TE	Terrestrial Ecotoxicity	kg 1,4-DCB e	Impact on terrestrial organisms of toxic substances emitted to the environment.
FEC	Freshwater Ecotoxicity	kg 1,4-DCB e	Impact on freshwater organisms of toxic substances emitted to the environment.
ME	Marine Ecotoxicity	kg 1,4-DBC e	Indicator of the depletion of natural non-fossil resources.

HCT	Human Carcinogenic Toxicity	kg 1,4-DBC e	Impact on humans of toxic substances emitted to the environment, cancer-related toxic substances.
HNCT	Human Non-Carcinogenic Toxicity	kg 1,4-DBC e	Impact on humans of toxic substances emitted to the environment, non-cancerous toxic substances.
LU	Land Use	m2a crop eq	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration)
MRS	Mineral Resource Scarcity	kg Cu eq	Indicator of the depletion of natural non-fossil resources.
FRS	Fossil Resource Scarcity	kg oil eq	Indicator of the depletion of natural fossil fuel resources
WC	Water Consumption	m3	Indicator of the relative amount of water used, based on regionalized water scarcity factors.

4: Results

Throughout this project, our goal was to assess the feasibility of the adoption of WAAM for ship repair in Algeciras. Through interviews and site tours with local repair companies, research labs, and relevant governing bodies, we researched opportunities and barriers to the adoption of this technology. We were able to divide the findings of our methods into several themes: the need for fast and frequent repairs, delays relating to repairs, knowledge of WAAM, and legal barriers. Additionally, a life cycle assessment was conducted by master's students from the University of Cádiz for the purpose of this project, focusing on comparing WAAM to CNC milling. The findings of this assessment were compiled and analyzed below.

4.1: Need for fast and frequent repairs

In order to learn more about the regulations and procedures surrounding repairs for large ships, companies involved in these repairs at various levels were interviewed. In an interview with Cernaval Shipyards, a major shipyard in the bay of Algeciras, Enrique Pérez said that international standards and regulations for large vessels require dry-docking once every five years. This is a procedure in which the boat is removed from the water to undergo inspections and repairs. Ships are sand-blasted, repainted, repaired, and inspected for all manner of problems that are impossible to find while a large portion of the ship is underwater. The managers of the shipyard expressed that unexpected issues are commonly revealed once ships are removed from the water, further increasing repair needs (personal communication, April 3, 2024).

Miscellaneous routine maintenance is also a frequent occurrence. Based on regulations or manufacturers' specifications, machinery must be inspected or even replaced on a regular basis. Additionally, International Maritime Organization (IMO) regulations push for ships to be continuously upgraded (E. Pérez, personal communication, April 3, 2024). Since it is a financial burden for the vessel and its crew to be docked, ships often try to undergo repairs and upgrades at the same time, creating more of a need for vessels to seek repair. Also according to Enrique Pérez, Commercial Director of Cernaval Shipyards, ship owners often have a backup supply of parts available for repairs onboard at all times. These parts are then given to the repair crew to perform the needed maintenance. Even when parts are not available on board, ships coordinate to have replacement parts ready at the port by the time they get there. Despite these measures, he emphasized that one of the company's biggest challenges was the coordination between all of the parties involved in a repair. One reason for these challenges is emergency repairs. Emergency repairs include sudden failures of machinery or routine inspections that expose an issue that must be resurrected immediately. When this happens, it is much less likely that parts will be available onsite, leading to longer delays. As will be discussed further (see Section 4.2, “Results”, and Section 5, “Recommendations”), this is another application that is especially suited to the use of WAAM. Due to maintenance being frequent and causing significant delays, there is an opportunity for the implementation of WAAM to reduce the severity of these delays through its benefit of increased manufacturing speed.

The repair needs of ships are diverse and numerous. According to data provided to us by the APBA (see Table 3), 4,036 ships were repaired in 2023 in the port, in addition to the 117 vessels repaired at Cernaval Shipyards, a private shipyard in the bay. This marks a 9.2% increase in the number of repairs at the port since 2022. This also means that more than 10% of the approximately 30,000 ships that enter the bay are repaired there (Á. Pinillas, personal communication, April 15, 2024).

Table 3: Comparing the number of repairs in 2022 and 2023 by month in the Port of Algeciras (Á. Pinillas, personal communication, April 15, 2024)

Month	# Of Repairs 2022	# Of Repairs 2023	% Variation
January	204	305	49.51
February	269	284	5.58
March	277	343	23.83
April	317	289	-8.83
May	353	319	-9.63
June	345	362	4.93
July	349	373	6.88
August	303	304	0.33
September	336	393	16.96
October	337	351	4.15

November	311	378	21.54
December	295	335	13.56
Totals	3,696	4,036	9.20

Another key finding of our interviews was the importance of the speed at which repairs could be completed. In nearly every interview with those involved in repair processes, it was made clear to us that the desire of shipowners, repair companies, and the Port Authority was to have ships repaired as quickly as possible. The significance of repair speed is especially relevant to this project, as WAAM is a technology that is well suited to address this issue for the port, improving the speed at which certain repairs can be completed (see Section 2, “Background: A Possible Solution to the Port’s Issues”).

4.2: Delays relating to repairs

The majority of companies that were interviewed could speak to delays caused by waiting for parts to be delivered. These and other delays in the ship repair process can significantly increase costs, as ships cannot earn money while they are in the port (E. Pérez, personal communication, April 3, 2024). Oftentimes ships may have replacement parts on board. On occasion, however, unexpected issues occur and repairs are needed. In some instances, all of the space designated for repair in the port is occupied and the ship must wait for an extended period to dock and be repaired, raising repair costs even further. While undergoing repairs, ships incur double the losses, including both the cost of the repair and the profits lost while not at sea. Aggregating all of these factors, it is evident that there would be great benefit in decreasing the amount of time that repairs take for all parties involved. This is a clear opportunity for the introduction of WAAM, a technology that, as discussed in the background section, has many advantages related to speed.

Another cause for delay is due to the requirement of representatives for the repair of selected ship parts. According to Enrique Perez, Commercial Director of Cernaval Shipyards, even though a ship may have a spare part onboard that is needed for repair, the ship owner would need to call a supervisor from the company that manufactures that part to watch over its installation. The purpose of this is to avoid any legal issues that may arise from the repair (personal communication, April 3, 2024). Waiting for a representative can cause significant delays for ship repairs, as these companies are not located close to the port, and can take days for the representative to arrive. Most of the time, the ship operator will call ahead for the representative to be at the port when the ship arrives. This, however, is not possible in the case of an emergency.

One avenue explored in these interviews was the issue of ship abandonment in the port. Initially, we believed that these ships could either have their broken parts repaired with WAAM or that possibly the ships could be scrapped and used for repairing other ships. In our interview with Ángel Pinillas, the Vessel Operations Manager from the APBA, it was discovered that approximately three ships were abandoned in the port last year for various reasons. The main reason behind the abandonment was due to ship owners experiencing economic hardship and the inability to afford the costs and fees associated with operating the vessel. There is rarely a case where a repair of the ship is not possible and it is forced to be put out of commission. To get these abandoned ships out of the port, the APBA auctions off these boats to various companies. These auctions sell the vessel as a whole, not for individual parts of the ship. The buyer then has 30 days to move the ship out of the port (Á. Pinillas, personal communication, March 20, 2024). This eliminates the possibility of using abandoned ship parts for maintenance on other vessels, highlighting another opportunity for alternative repair methods such as WAAM.

4.3: Knowledge of Wire Arc Additive Manufacturing

Our interviews began with Sean Kelly, Co-Founder and Chief Operating Officer of Solvus Global. Solvus Global is a technology research and development company that focuses on a wide range of manufacturing techniques. The company has a subdivision called Mammoth Metalworks, which focuses on manufacturing unique parts by selecting the most optimal and sustainable technique. This “combines subtractive manufacturing with large additive manufacturing techniques such as Wire Arc Additive Manufacturing, Plasma Arc Additive Manufacturing, Cold Spray, and Friction Stir Additive Manufacturing to provide cost-effective production of large parts…” (Mammoth Metalworks, 2024). Specifically looking at WAAM, it is already being used in the aerospace and maritime industries. Sean highlighted that this technology is extremely versatile, and is great for making unique parts. He also recommended that the best solution for the integration of this technology into the Maritime industry would be to have one of these machines located directly on the vessel (personal communication, February 20, 2024). Even if the part created on the vessel is not exactly up to standards, it can be used as a temporary fix until the ship reaches its destination, thereby reducing the need to dock for repairs. We also interviewed Co-Founder Diran Apellian, who reiterated the versatility and impact this technology can have (personal communication, February 23, 2024).

Through our interviews with the local repair companies and the APBA, it became evident that very few had heard of WAAM. Alongside the lack of knowledge of WAAM among company representatives, none of the repair companies currently use the manufacturing method. These barriers made it very difficult to assess the willingness of these companies for the adoption of WAAM. This also made it difficult to assess current repair and manufacturing methods because most of the manufacturing was done offsite. After explaining the WAAM process to each of these companies, they seemed to be open to any change that reduces wait times for parts and decreases costs.

4.4: Legal Barriers to the Use of WAAM

The ocean is an environment with harsh conditions that could damage a ship while at sea. On a large vessel, there are countless parts that, if manufactured poorly, would put the entire ship in danger. To reduce risk, most repair companies are not allowed to manufacture these critical parts onsite. This is done at their main facility, where the part must undergo a thorough quality inspection by the supplier. To ensure the reliability of these critical parts, strict regulations specifying the exact manufacturing process and manufacturers have been put in place. During an interview with Kalmar, a local repair company, we were informed that they are unable to manufacture most parts at their facility due to these regulations (Jesús Rodríguez, personal communication, April 9, 2024). This kind of regulation is a direct barrier against the use of WAAM, as it is best used to manufacture parts on-site as needed. Such regulations reduce the possibility of on-site manufacturing, reducing the possible uses of WAAM. In addition, given that WAAM is a relatively new technology, there may be some hesitancy to use it to manufacture critical parts.

As it exists in its current state, this manufacturing method would be best implemented solely for non-critical use cases. This avoids the issues discussed above and gives time for trust to be built in the technology. Hopefully, after some time, enough research will be done to ensure the reliability of WAAM for critical applications and the industry can take advantage of the technology's benefits.

4.5: Life Cycle Assessment Results

The life cycle assessment (see Section 3, "Methodology: Exploring WAAM in the Shipping Industry") focused on comparing WAAM to CNC milling of a stainless steel boat rudder (see Appendix B). The assessment was performed on SimaPro, a simulation software commonly used for life cycle assessments. Three different graphs were generated from the simulation data. Figure 10 shows the comparison of the environmental impacts of WAAM vs. CNC milling, Figure 11 depicts a specified breakdown of the environmental impacts of WAAM, and Figure 12 shows a specified breakdown of the environmental impacts of CNC Milling. Looking at Figure 13, it is clear that WAAM outperforms milling in 15/17 categories, consequently causing less environmental damage. The category with the most significant discrepancy was Mineral Resource Scarcity (MRS), where WAAM had 56% of the environmental impact that milling did. It is a major advantage that WAAM uses fewer Critical Raw Materials, as sustainability is a high-priority issue for the industry and Spain as a whole. The two categories in which milling outperformed WAAM are Ionizing Radiation (IR) and Land Usage (LU). One theory for how this is possible is that the electricity consumption needed to perform WAAM is higher than that of milling. This high electricity usage is highlighted in Figure 11, as it is the second highest impact category in the manufacturing process. Regardless of this, milling only slightly out-performs WAAM in these categories.

Figures 11 and 12 provide detailed insights into specific aspects of the manufacturing processes, comparing WAAM to CNC milling. This allows for a complete understanding of the environmental implications associated with each material used throughout the process. Looking at Figure 11, it is clear that the use of steel is the primary concern throughout all of the environmental impact categories. In Figure 12, however, it is evident that the addition of steel and removal of steel are of equal significance. This emphasizes the environmental issue surrounding the waste of material during the CNC milling manufacturing process.

These results show that WAAM is much more environmentally safe when compared to milling for a stainless steel boat rudder. The main factors contributing to WAAM's better performance are due to its material efficiency and minimal waste generation. These findings highlight the potential of WAAM as a more sustainable manufacturing method and show that the adoption of WAAM could lead to significant environmental benefits in manufacturing processes.

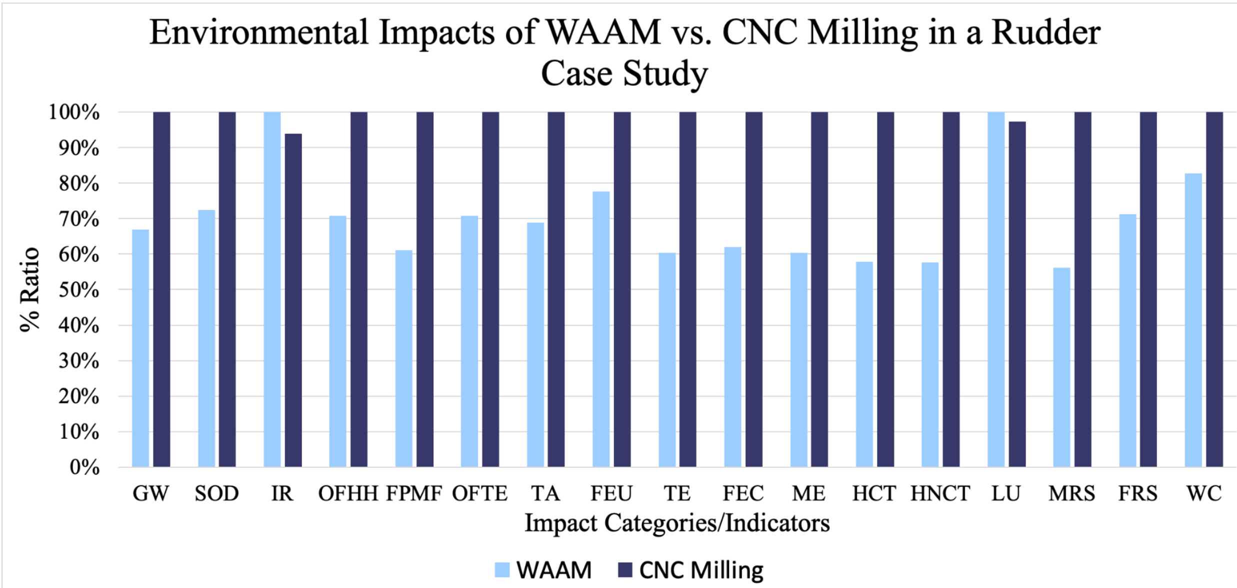

Figure 10: Environmental Impacts of WAAM vs. CNC Milling in a Rudder Case Study

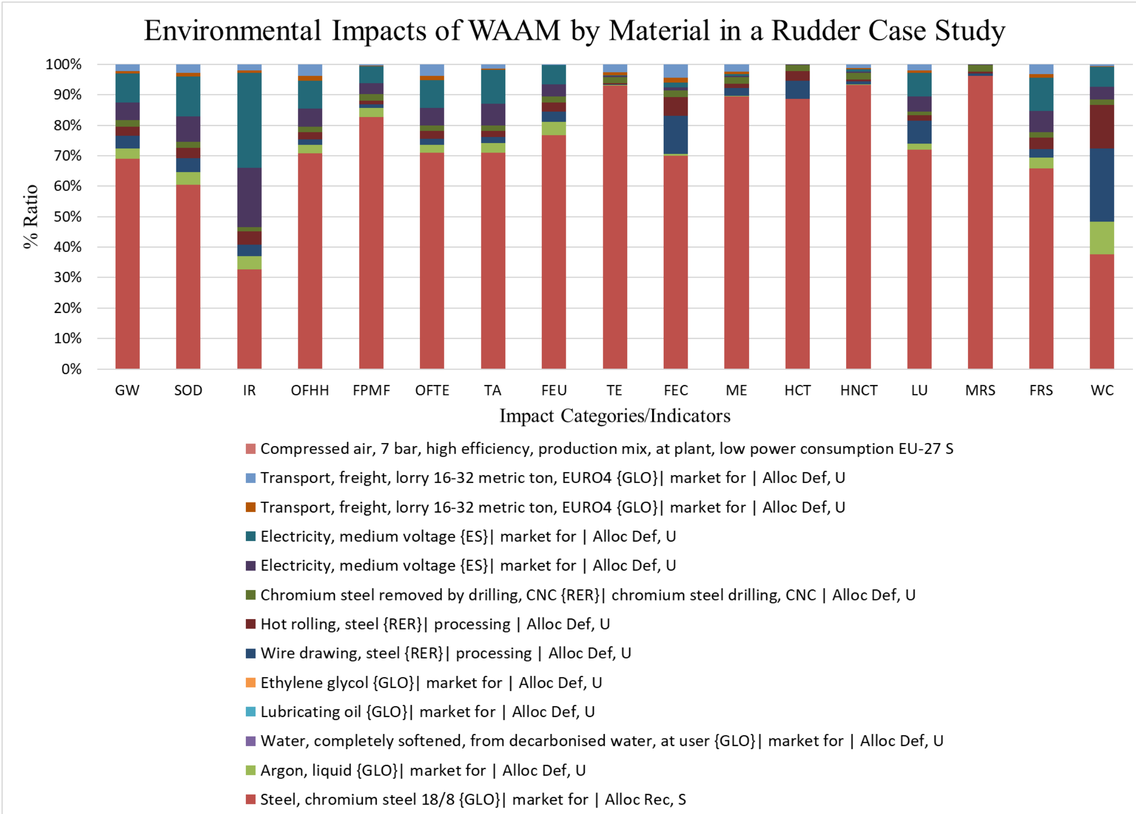

Figure 11: Environmental Impacts of WAAM by Material in a Rudder Case Study

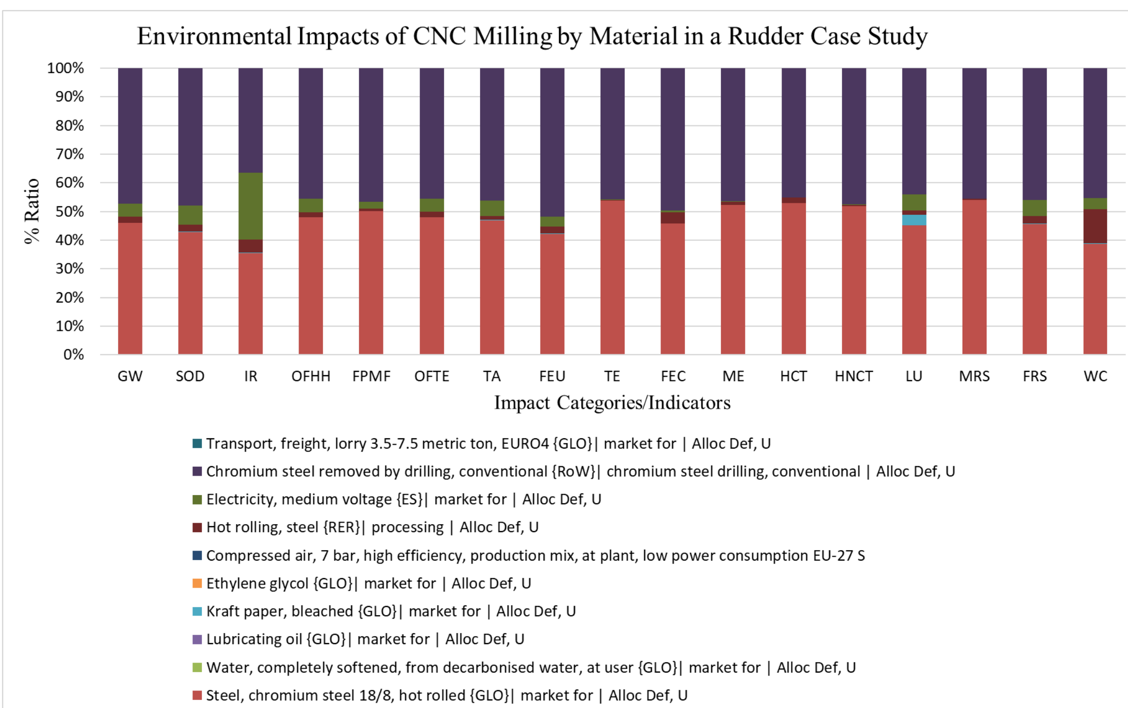

Figure 12: Environmental Impacts of CNC Milling by Material in a Rudder Case Study

4.6: Research Limitations

This report would be incomplete without acknowledging the limitations of the study. The project was limited by only having a total duration of 14 weeks, seven of which were in Spain and only five of which were in Algeciras, the location of the port that is the focus of our project as well as the repair companies we sought to interview. This short period of time in Algeciras made it difficult to accomplish all of our planned methods. In addition, the second week upon arriving in Algeciras was La Semana Santa, also known as Holy Week. During this week, most offices and businesses were closed and were not available for interviews or email responses. Our response rate over email was another challenge. The team reached out to roughly 30 companies via email with the intent of scheduling interviews or asking questions but received no responses. Calling companies was a far more effective method of soliciting responses, which allowed us to schedule interviews and site tours. Before coming to Spain, our initial plan was to interview Acerinox, a stainless steel manufacturing company that works closely with the University of Cádiz. However, this company was unfortunately on strike for the duration of our IQP, so an interview with them was not possible. We were also unable to interview a traditional manufacturing company, as opposed to repair companies that order replacement parts from various suppliers around the world. Additionally, while the majority of representatives that were interviewed spoke English, the language barrier still presented an issue. In some cases, this led to having a more generalized conversation in which we were unable to get the specific information that was needed.

5: Recommendations & Conclusions

The results displayed above serve as evidence that WAAM is a sustainable technology that is ready to be implemented in the maritime shipping industry. This section details the recommendations that our team has aggregated for the implementation of this technology, and what the next steps are for continuing this project in the future. These recommendations take into consideration all of the results analyzed above based on the strengths and limitations of this technology.

5.1: Recommendation 1: Research and Testing in Industry Applications

Due to the novelty of the technology, there is still much to learn about how best to use it. For WAAM to be fully integrated as a manufacturing or repair method into the well-established shipping industry, more research and testing are required. Our first recommendation concerns the best ways to further this research with the goals of using WAAM more frequently while collaborating with repair companies, increasing the general knowledge and acceptance of the technology for stakeholders, and using WAAM in applications where its strengths are best demonstrated.

WAAM is already used in some industries, especially the space and aircraft industries. In addition, companies like Solvus Global and research labs like the Smart Manufacturing Lab are working to expand the areas in which this technology is used. Before any technology sees widespread use, it must have widespread attention. An important finding of our interviews was that there is currently little awareness of WAAM at all, let alone its benefits for the repair of ship parts. Only one repair company representative that was interviewed had heard of WAAM, and no one that we interviewed used WAAM in their current operations. Reaching out to possible future users of the technology to get them interested and show them the benefits and use cases would accelerate the timeline of the introduction of this technology. For example, while we interviewed Kalmar, our sponsor took from the workshop, with permission, a broken bolt. Once back in the lab, our sponsor said that they could use milling and WAAM to repair the bolt, demonstrating its applications. This kind of real-world test not only served to help our sponsors understand the technology better but also showed a repair company how the technology could be used.

5.2: Recommendation 2: WAAM On-Board Ships

A possibility for the adoption of WAAM would be to install the machine on the ship itself. This idea was initially posed through our interview with Sean Kelly from Solvus Global, who emphasized the portability and versatility of this technology (personal communication, February 20, 2024). Having the machine on the ship would allow the vessel to manufacture spare parts on demand. The part would then be ready to be installed once the vessel is docked, eliminating the potential cause for delay from waiting for parts to arrive. This advantage would also apply in an emergency repair situation as the vessel would still need time to arrive at port. Additionally, the technician who manufactured the part using WAAM would already be on-board, eliminating the need to wait for a specific representative. This would not take away business from ship repair companies, as their crew can carry out the repairs with the representative as normal. It would solely eliminate the wait times for spare parts to arrive as well as the specific representative who manufactured the part, in order to manage the repair. Not only would this solution benefit the ship's efficiency but also port operations, directly addressing their goals. However, for this to be an effective solution, the costs saved by the addition of the WAAM machine onboard this ship would need to outweigh the cost of having the technician on board the ship. Further investigation would be needed to evaluate the advantages and drawbacks of this potential usage of WAAM.

5.3: Recommendation 3: WAAM Workshops

Lack of knowledge about the technology and its benefits is a significant barrier against the use of WAAM for industrial applications. A potential solution to increase awareness of WAAM would be to host educational and informational workshops for repair company representatives to attend and learn about WAAM and its benefits. These workshops would discuss the details of the technology, including how it works and its best use cases. Most importantly, the workshop would inform these stakeholders of the benefits of WAAM, including sustainability, lower costs for parts, and faster manufacturing times. It would also discuss the benefits of the technology's versatility and the prospect of reducing the need to wait for parts to ship from far-away suppliers. Repair companies would then be able to make the informed decision whether or not to add WAAM to their repair practices.

5.4: Future Work

In the future, this project could be taken in a multitude of directions. The first potential continuation of this project could be to focus on education and awareness about the benefits of WAAM among repair companies, ship owners, and other organizations that operate in the port. This could include focusing on a case study where a ship part is repaired in the Smart Manufacturing Lab using WAAM and repaired using the existing manufacturing method. This comparison would then be used as the main argument for adopting WAAM. This information could then be organized and presented to repair companies, in an attempt to get them to switch to WAAM. This would be a great addition to the LCA performed during this project, as this would show the cost savings, as well as a final product made using WAAM. Alternatively, the project could also shift focus to center on repairing a part given to the Smart Manufacturing Lab by a local repair company. The students would document the entire process, as well as participate in the creation of the new WAAM part. A project such as this one would allow the University of Cádiz to build a good working relationship with a local manufacturing company, allowing further future collaboration.

5.5: Conclusion

Ultimately, the findings presented in this report highlight the potential of Wire Arc Additive Manufacturing (WAAM) as a sustainable and efficient solution for the maritime shipping industry. Looking forward, efforts should focus on raising awareness about the benefits of WAAM and exploring the evolving technology's capabilities in repairing ship components. These efforts will, given enough time, help drive the adoption of WAAM across various industries. It is clear that WAAM technology addresses critical pain points of the Port of Algeciras, the maritime shipping industry, the Spanish economy, and the world's sustainability goals by speeding up repairs, reducing costs, and reducing material and energy waste.

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Appendix A: Interview Protocol

Considerations

- We will ask the questions listed below in an open-ended manner, asking for clarification and elaboration where necessary. We will not force any interviewee to go into more detail.
- We will ensure the interviewees know that them and their companies/organizations will be kept anonymous in both our feasibility study and our final report.
- We will keep in mind that English may not be a first language for the interviewees, and be careful to be clear in our wording.
- If the interviewee appears uncomfortable responding to any question, we will move on and not pry.

Verbal Consent

(Verbal consent may be appropriate when research presents minimal to no risk to a participant, for example, non-sensitive and no identifying information is collected)

Hello ______,

Our names are ______ and we are American students from Worcester Polytechnic Institute in Massachusetts. We are researching Wire Arc Additive Manufacturing (WAAM) and how it can be applied in the shipping industry in Algeciras. We are working with the Metals Additive Manufacturing Lab at the University of Cádiz. We would like to interview you to gain insight on current ship repair processes, opportunities for the adoption of WAAM, and any concerns you may have about the process with the ultimate goal of improving sustainability and cost.

Participation in this interview is completely voluntary and you may withdraw at any time. The data obtained from this interview will be kept completely confidential. Your name will not be used in our report without your permission. Only our team and the lab will have access to your responses, and all data will be stored in a secure folder. By verbally consenting, you acknowledge that you have been fully informed and agree to participate in the study described above.

Written Consent

(Written consent may be appropriate when research presents minimal risk to a participant, for example, identifying information is collected and/or interview is recorded)

Date: ____

Time: ____

Location: ____

Interviewers: ______________________________________

Interviewees: ______________________________________

Interviewee Role: ___________________________________

Hello ______,

Our names are ______ and we are American students from Worcester Polytechnic Institute in Massachusetts. We are researching Wire Arc Additive Manufacturing (WAAM) and how it can be applied in the shipping industry in Algeciras. We are working with the Metals Additive Manufacturing Lab at the University of Cádiz. We would like to interview you to gain insight on current ship repair processes, opportunities for the adoption of WAAM, and any concerns you may have about the process with the ultimate goal of improving sustainability and cost.

Participation in this interview is completely voluntary and you may withdraw at any time. The data obtained from this interview will be kept completely confidential. Your name will not be used in our report without your permission. Only our team and the lab will have access to your responses, and all data will be stored in a secure folder. By signing below, you acknowledge that you have been fully informed and agree to participate in the study described above.

I agree to participate in the interview: Printed name: ______________________________

Signature: ______________________________

Please initial for permission to record: ______________________________

Please initial for permission to be identified: ______________________________

(Este consentimiento puede ser apropiado cuando la investigación tiene un riesgo mínimo para el participante, por ejemplo, cuando se recopilan datos de identificación y/o se graba la entrevista)

Fecha: ____

Hora: ____

Ubicación: ____

Entrevistadores: ____

Entrevistados: ____

Rol (Posición) del Entrevistado: ______________________________

Hola ______,

Nuestros nombres son ______ y somos estudiantes estadounidenses del Instituto Politécnico de Worcester en Massachusetts. Estamos investigando sobre la fabricación aditiva mediante arco e hilo (WAAM) y cómo se puede aplicar en la industria naviera en Algeciras. Estamos trabajando con el Laboratorio de Fabricación Aditiva de Metales de la Universidad de Cádiz. Nos gustaría entrevistarle a usted para obtener información sobre los procesos actuales de reparación de barcos, las oportunidades para la adopción de WAAM y cualquier preocupación que pueda usted tener sobre el proceso, con el objetivo de aportar a la sostenibilidad y la reducción de costo.

La participación en esta entrevista es completamente voluntaria y usted puede cesarla en cualquier momento. Los datos obtenidos de esta entrevista se mantendrán completamente confidenciales. Su nombre no se utilizará en nuestro informe sin su permiso. Solo nuestro equipo y el laboratorio tendrán acceso a las respuestas suyas, y todos los datos se guardarán en una carpeta segura. Al firmar a continuación, se reconoce haber sido completamente informado y se consiente participar en el estudio descrito anteriormente.

Otorgo el consentimiento de participar en la entrevista:

Nombre en (letra de imprenta): ______________________________

Firma: ____

Por favor, ponga sus iniciales para dar permiso para grabar: ______________________________

Por favor, ponga sus iniciales para dar permiso para ser identificado:______________________

Interview Questions

The questions we ask certain stakeholders are marked with an X under their respective boxes.

P = Algeciras Bay Port Authority; O = Shipowners; R = Repair/manufacturing companies

Interview Questions:	P	O	R
We were wondering if we could record this interview to ensure that we capture everything you tell us? If not, that is completely fine and we will just take notes.	X	X	X
Are you willing to be identified in our report or would you prefer to remain anonymous?	X	X	X
How are ships repaired while in port in Algeciras? What companies or organizations typically do these repairs?	X	X	X
What types of repair work are most common, how often do new metal parts have to be ordered?	X	X	X
How often are ships delayed due to repairs and how long can they be delayed for?	X	X	
Are any parts manufactured directly at the port for repairs? Why or why not?	X		
What is the average cost of repairs?		X	X
How are replacement parts obtained for ships?	X	X	
How often are parts repaired, manufactured, or ordered from suppliers?	X		X
What methods are used for repair and manufacturing?			X
Have you ever heard of WAAM?	X	X	X
What is the process for notifying the port about repairs? Do you need to call ahead for parts to be shipped to the port?	X	X	
What concerns would you have about using WAAM?	X	X	X
Are there any difficulties switching to a new repair technology such as WAAM? What are they?			X

Conclusion

Thank you for talking with us today. Was there anything in the interview that you think we missed or wish we would have talked about more? Would you like to review our notes or transcript of the interview? Thank you so much for your time. If you have anything else to add you can reach us at our email gr-Cadiz_24_Circular_Economy@wpi.edu or our sponsor, Professor David Sales Lérida, from the Smart Manufacturing Lab at david.sales@uca.es.

Interview Email Template

Estimado/a (fem) (Nombre si es disponible): (this sign is used in Spanish correspondence after the name) // If the name is not available: Estimados Sres.:

Somos un grupo estudiantil de investigación de los Estados Unidos. Estamos colaborando con la Universidad de Cádiz en la investigación de métodos y prácticas de reparación de barcos en la zona de Algeciras.

Le quedaríamos sumamente agradecidos si usted nos concediera tiempo para una breve entrevista en persona para responder algunas de nuestras preguntas. En caso de que no le convenga, también estaríamos encantados de enviarle algunas preguntas a responderlas por correo electrónico.

Apreciamos mucho su ayuda,
Eddie Stump, Ava Dickman, Thomas Joyner, Jackie Edwards

Las preguntas de entrevista:

1. ¿Estaría usted dispuesto a ser identificado en nuestro informe o preferiría permanecer en el anonimato?
2. ¿Qué tipos de reparaciones son más comunes y con qué frecuencia se tienen que ordenar nuevos repuestos de metal?
3. ¿Con qué frecuencia se retrasan los buques debido a reparaciones y cuánto tiempo pueden estar retrasados?
4. ¿Puede darnos un ejemplo de una ocasión en la que un barco tuvo que necesitar un tiempo extraordinariamente largo para realizar reparaciones?
5. ¿Alguna pieza se fabrica directamente en sus instalaciones? ¿Qué método de fabricación se utiliza?
6. ¿Cómo se suministran repuestos para los buques?
7. ¿Con qué frecuencia se reparan, fabrican o piden repuestos a los proveedores?
8. ¿Ha escuchado alguna vez sobre Wire Arc Additive Manufacturing (WAAM)?
9. Si has oído hablar de WAAM,
    a. ¿Tendría Ud. algunas preocupaciones sobre el uso de WAAM para manufacturar los repuestos para los buques?
    b. ¿Existen dificultades al cambiar a una nueva tecnología de reparación como WAAM? ¿Cuáles éstas son?

Hello [Name if available],

We are a student research group from the United States. We are working with the University of Cádiz researching repair methods and practices on ships in the Algeciras area.

Would you be available for a short interview in person to answer some of our questions? If not, we would also be happy to send you a few questions to answer via email.

Thank you for your help,
Eddie Stump, Ava Dickman, Thomas Joyner, Jackie Edwards

Interview Questions:

1. Are you willing to be identified in our report or would you prefer to remain anonymous?
2. What types of repair work are most common, how often do new metal parts have to be ordered?
3. How often are ships delayed due to repairs and how long can they be delayed for?
4. Can you provide an example of a time a ship had to want an extraordinarily long time for repairs?
5. Are any parts manufactured directly at your facility? What manufacturing method is used?
6. How are spare parts supplied to ships?
7. How often are parts repaired, manufactured, or ordered from suppliers?
8. Have you ever heard of Wire Arc Additive Manufacturing (WAAM)?
9. If you have heard of WAAM,
    a. Would you have any concerns about using WAAM to manufacture vessel spare parts?
    b. Are there any difficulties switching to a new repair technology such as WAAM? What are they?

Non-Interview Email Template

Estimado/a (fem) (Nombre si es disponible): (this sign is used in Spanish correspondence after the name) // If the name is not available: Estimados Sres.:

Somos un grupo estudiantil de investigación de los Estados Unidos. Estamos colaborando con la Universidad de Cádiz en la investigación de métodos y prácticas de reparación de barcos en la zona de Algeciras.

Le quedaríamos sumamente agradecidos si usted nos responde algunas de nuestras preguntas a responderlas por correo electrónico.

Apreciamos mucho su ayuda,
Eddie Stump, Ava Dickman, Thomas Joyner, Jackie Edwards

Las preguntas:

1. ¿Estaría usted dispuesto a ser identificado en nuestro informe o preferiría permanecer en el anonimato?
2. ¿Qué tipos de reparaciones tienen los buques mientras están en puerto en Algeciras? ¿Qué empresas u organizaciones suelen realizar estas reparaciones?
3. ¿Qué tipos de reparaciones son más comunes y con qué frecuencia se tienen que ordenar nuevos repuestos de metal?
4. ¿Con qué frecuencia se retrasan los buques debido a reparaciones y cuánto tiempo pueden estar retrasados?
5. ¿Puede darnos un ejemplo de una ocasión en la que un barco tuvo que necesitar un tiempo extraordinariamente largo para realizar reparaciones?
6. ¿Hay repuestos que se fabrican directamente en el puerto para las reparaciones? ¿Por qué sí o por qué no?
7. ¿Cuál es el costo promedio de las reparaciones por hora o por día para los buques en general en Algeciras?
8. ¿Cómo se suministran repuestos para los buques?
9. ¿Con qué frecuencia se reparan, fabrican o piden repuestos a los proveedores?
10. ¿Ha escuchado alguna vez sobre Wire Arc Additive Manufacturing (WAAM)?
11. Si has oído hablar de WAAM,
    a. ¿Tendría Ud. algunas preocupaciones sobre el uso de WAAM para manufacturar los repuestos para los buques?
    b. ¿Existen dificultades al cambiar a una nueva tecnología de reparación como WAAM? ¿Cuáles éstas son?

Hello [Name if available],

We are a student research group from the United States. We are working with the University of Cádiz researching repair methods and practices on ships in the Algeciras area.

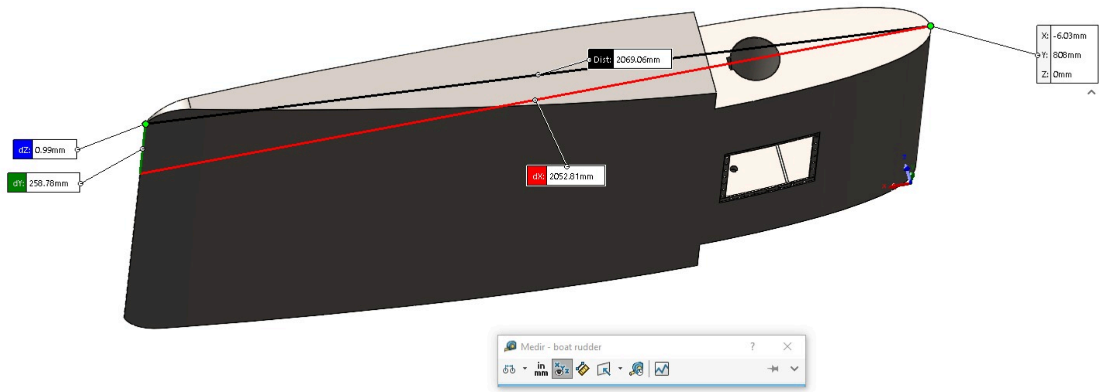
Would you be willing to answer a few questions via email?

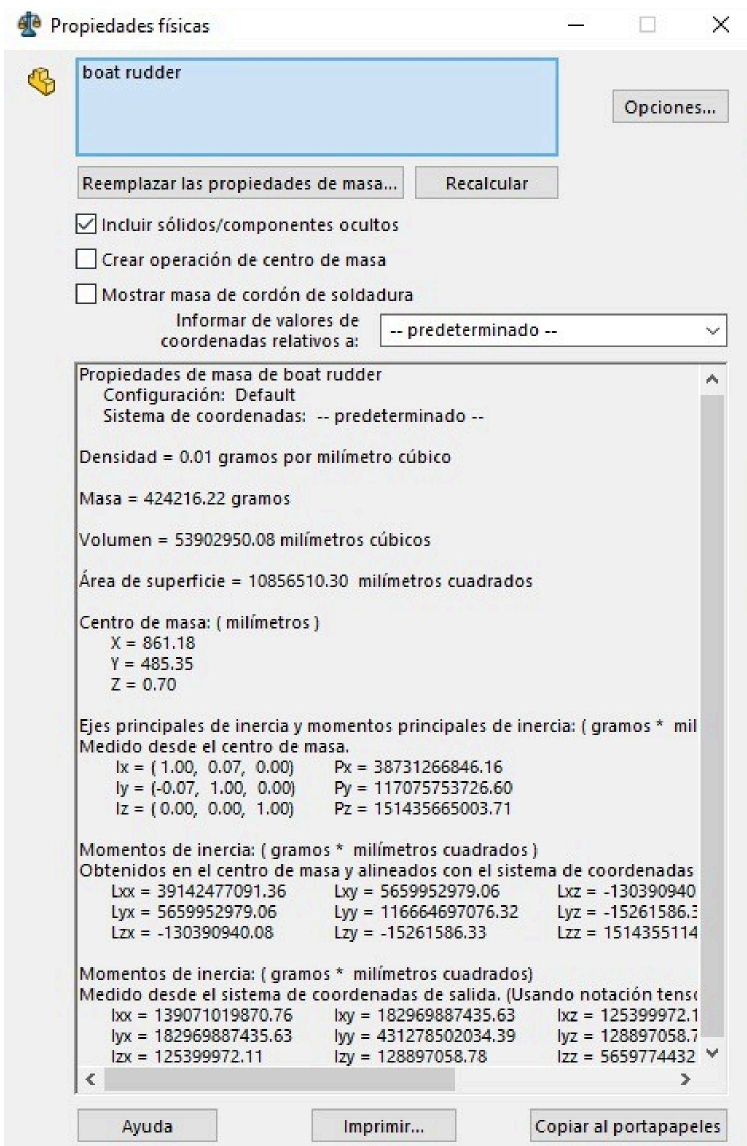
Thank you for your help,
Eddie Stump, Ava Dickman, Thomas Joyner, Jackie Edwards

Questions:

1. Are you willing to be identified in our report or would you prefer to remain anonymous?
2. How are ships repaired while in port in Algeciras? What companies or organizations typically do these repairs?
3. What types of repair work are most common, how often do new metal parts have to be ordered?
4. How often are ships delayed due to repairs and how long can they be delayed for?
5. Can you provide an example of a time a ship had to want an extraordinarily long time for repairs?
6. Are any parts manufactured directly at the port for repairs? Why or why not?
7. What is the cost of repairing ships per hour or per day for vessels in general in Algeciras?
8. How are spare parts supplied to ships?
9. How often are parts repaired, manufactured, or ordered from suppliers?
10. Have you ever heard of Wire Arc Additive Manufacturing (WAAM)?
11. If you have heard of WAAM,
    a. Would you have any concerns about using WAAM to manufacture vessel spare parts?
    b. Are there any difficulties switching to a new repair technology such as WAAM? What are they?

Appendix B: LCA Part Details





Appendix C: Timeline