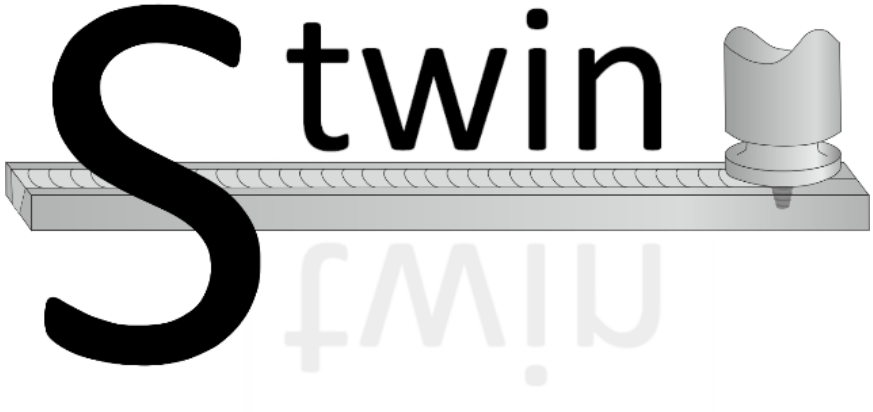
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# Advanced, non-destructive technologies to improve friction stir welding of steel through artificial intelligence and smart digital twins (Acronym: STWIN)



Research Fund for Coal and Steel
Grant Agreement Number 101112504

## Deliverable 1.2: Comprehensive overview of STWIN

Project with funding from the European Union's Horizon Europe research and innovation programme (Research Fund for Coal and Steel; RFCS) under grant agreement No. 101112504.

## Project & Deliverable Information Sheet

| | | | |
|---|---|---|---|
| **Grant Agreement No** | 101112504 | **Acronym** | STWIN |
| **Project Full Title** | Advanced, non-destructive technologies to improve friction stir welding of steel through artificial intelligence and smart digital twins | | |
| **Project Website** | Link | | |
| **Coordinator** | CIDAUT (Spain) | | |
| **Start Date** | 01/07/2023 | **Duration** | 36 months |
| **Deliverable** | 1.2 | **Work Package** | WP 1 |
| **Document Type** | Report | **Dissemination Level** | PU |
| **Lead beneficiary** | CIDAUT | | |
| **Responsible author** | Javier Romo (CIDAUT) | | |
| **Contractual due date** | 31/12/2023 | **Actual submission date** | 15/01/2025 |

## Document Control Sheet

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| Revision Table | | |
|---|---|---|
| **Version** | **Date** | **Modified sections - Details** |
| 0.1 | 25/10/2023 | Initial ToC |
| 0.2 | 16/05/2024 | First consolidated version |
| 0.3 | 14/01/2025 | Full draft |
| 1.0 | 15/01/2025 | Final version for submission |

## Executive summary

The STWIN project, funded under the Research Fund for Coal and Steel (RFCS), is aimed at developing a flexible friction stir welding (FSW) system, capable of automatically fabricating complex 3D structures including different joint configurations between steels of dissimilar grades and thicknesses. All this by applying AI. By means of this action, the project seeks to improve the productivity of the metal processing sector and the working conditions of welders and operators. For that purpose, it relies on the knowledge and experience of 10 partners from 5 different European countries.

This document summarises and illustrates the project concept and the way in which it will be managed. Thus, it begins by describing the objectives and the problem from which the project arises. Following that, it exposes the state of the art of the techniques and technologies that will be used to address the defined objectives, the methodology and the expected results. The report continues by describing how risk management will be addressed, explaining the specific strategy to be followed to identify risks and the measures to be adopted to minimise their effects and, finally, the management strategy.

All information that appears in the document is based on the terms and conditions established in the Grant Agreement. Furthermore, the deliverable has been designed as a reference guide to assess the proper performance of the project over time.

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# 1 Introduction

## 1.1 Project Summary

STWIN is an initiative whose objective is to develop a flexible friction stir welding (FSW) system, capable of automatically fabricating complex 3D structures including different joint configurations between steels of dissimilar grades and thicknesses. All this by applying an artificial intelligence-based real-time monitoring system of the welding process.

From this approach, the project aims to address the need to improve productivity in the metal processing sectors; specifically in the automotive, transport and loader crane sectors, while improving the working conditions of welders and operators. To this end, it will exploit the advantages of friction stir welding, in combination with a real-time quality control system that will perform the adaptive control of welding parameters based on non-destructive testing methods and the combination of artificial intelligence techniques.

The project will result in a new three-dimensional friction stir welding method based on the use of kinematic robots. In fact, much of the efforts will be focused on the design and development of the robot and the welding head. The integration of both innovations together with the monitoring system of the joining process will be evaluated and validated through 3 innovative use cases:

- welding and bending of dissimilar joints (dissimilar materials and thicknesses), for its application in strategic reinforcements of loader cranes.
- welding between high strength steel and cast iron with curved weld paths to produce automotive sub-assemblies.
- welding of aluminium-steel for its application in trailers.

Under this framework, the STWIN project has gathered a high qualified consortium composed of 10 members of different nationalities from all over Europe. Specifically, the consortium is made up of experts in welding (BWI, STIRWELD, E6), robotics (TRICYLON), steel production (SSAB), non-destructive testing methods (BWI, ISEND), artificial intelligence (CIDAUT), dissemination (CIDAUT, BWI) and industrial manufacturing of steel products (HIAB, HORSE and GRANALU, as representatives for the targeted sectors).

## 1.2 STWIN Main objectives

In general terms, STWIN aims to develop a flexible friction stir welding (FSW) system, capable of automatically fabricating complex 3D structures, and with which zero defects are achieved; all this on the basis of the concepts of digital twin and artificial intelligence. It thereby seeks to drastically improve productivity in the metalworking sector and the working conditions of welders and operators.

In order to achieve this general objective, the project has been subdivided into several specific objectives, which are detailed below:

1. **Development of a friction stir welding tooling oriented towards three-dimensional joints.**

   This first objective focuses on producing a translational parallel kinematic robot with 6 degrees of freedom (DOF), able to perform 3D friction stir welds. The starting point will be the MONARCH robot of TRICYLON, the FSW head of STIRWELD and some of E6 tools and solutions.

2. **Optimisations of friction stir welding process parameters in 3D joints between high strength steels and for dissimilar joints (steel-aluminium and sheets with different thicknesses).**

   The second objective seeks to achieve defect-free welds through the optimisation of welding parameters (forces, tool rotation speed, etc). To this end STWIN will explore various non-destructive testing methods, combined with artificial intelligence techniques. This dual approach will result in a real-time monitoring system of the joining process, based on the concept of Digital Twin.

3. **Demonstration of the techno-economic advantages of the system developed using demonstrators. In particular, by applying the technology developed in loader cranes, vehicle differentials and a transport trailer.**

   The third objective is to verify that the parts manufactured by FSW comply with the specifications set by the applicable standards and the end user requirements. This approach, in addition to ensuring that the final product manufactured meets the minimum quality requirements, will be used to validate the proper functioning of the developments.

4. **Real-time weld quality prediction using AI models, based on real measurements data and innovative non-destructive testing.**

   Objective four, for its part, involves using AI algorithms to analyse and interpret the data obtained from non-destructive testing and, based on the results, adjust the process parameters in real time. This approach will allow establishing the causal links between the process parameters and the occurrence of defects.

5. **Validation of the applicability of the concepts of digital twin and artificial intelligence to FSW under real workshop circumstances.**

   Objective five focuses on demonstrating the capabilities of the developed quality monitoring system in 3D FSW applications and under real circumstances, specifically by developing the planned use cases. In this way, the applicability of the concepts of digital twin and artificial intelligence to FSW process are validated.

6. **Demonstration of the environmental benefits of using a real-time quality monitoring system, based on the concept of Digital Twin, in friction stir welding.**

   Finally, the objective six involves a comprehensive environmental assessment of the FSW process in combination with the monitoring system. By analysing the quantity of heat needed and rate of defective weld, STWIN seeks to demonstrate that the application of the project results more sustainable than its current counterparts (fusion welding techniques).

Overall, STWIN's objectives represent a balanced combination of research, innovation and practical applications, all of them aimed at transforming the landscape of metalworking sector. In fact, the objectives do not solely focus on the target sectors but go beyond them.

# 2 Problem Description

The metalworking sector, and particularly the welding industry, face a myriad of challenges and adversities that demand attention and innovative solutions. Specifically

in recent years, the welding industry has had to cope with the pandemic, inflation and soaring energy costs, which have had a negative impact on productivity. In parallel, the aging workforce and a shortage of skilled welders pose significant challenges to the industry's future sustainability.

A study done by the company Sait Abrasives UK (1) points out that one of the key issues negatively impacting productivity and directly affecting the lack of talent attraction is the sector's failure to embrace new technologies. In the same vein, the study also highlights the industry's inability to retain staff and blames the lack of innovation for this. This problem is of concern to the European Commission which, as such, among its objectives includes addressing the skills gap, especially in relation to the 'digital and green transition'.

In this scenario, STWIN emerges as an initiative aiming to improve productivity in the metal processing sectors; specifically in the automotive, transport and loader crane sectors, and bridge the skills gap, improving the working conditions of welders. Thus, it contributes to achieving objectives five, six and seven of the Research Fund for Coal and Steel (RFCS) Programme's, which seek to ensure a resilient and prosperous future for the metals industry. Indeed, STWIN's approach is holistic, encompassing not only the technological side, but also addressing societal and environmental dimensions. By focusing on three specific industries, STWIN ensures that its impact is felt in some of the most relevant industries in the metals sector.

In short, the issue at hand is threefold: (1) ensuring technological evolution, (2) boosting workforce development and (3) mitigating environmental impact. STWIN stands at the crossroads of this scenario, embodying the objectives of the RFCS Programme and serving as beacon for growth and innovation in the welding sector.

# 3 State of the Art

## 3.1 AI-based Quality Control

### *3.1.1 AI-supported Real Time Quality Monitoring*

The influence of many welding parameters and conditions on the FSW process, along with the complexity of the underlying thermo-mechanical phenomenon often makes the modelling of the FSW process a cumbersome problem (2). Moreover, the thermo-mechanical properties of tool/sheet materials, and current limitations of plasticity theories may hinder the analytical modelling of FSW process. Hence, Machine Learning (ML) approaches can be employed to develop data-driven models of FSW due to their excellent ability to **establish relationships between the process parameters and monitoring variables (inputs) and the outcomes of the welding process (outputs)**. The main advantages of ML compared to conventional (analytic) approaches are its capability to figure out non-linear relationships between features, and its high generalization capabilities.

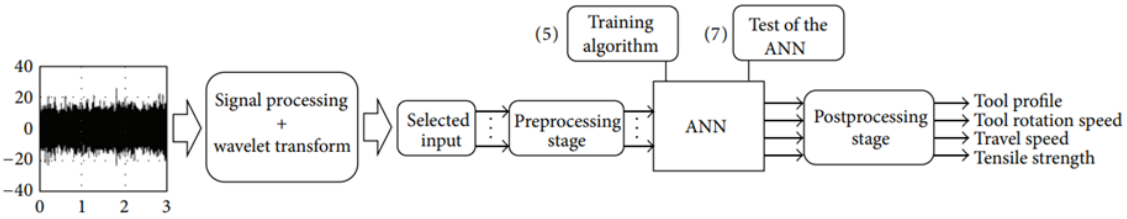



*FIGURE 1. USE OF ML TO FIND RELATIONSHIPS BETWEEN INPUT AND OUTPUT VARIABLES OF THE FSW PROCESS. SOURCE:* (3)

Another potential field of application of ML in FSW processing is the **monitoring and control of the welding process**. The need to deliver high quality FSW joints with minimum costs has raised the need for developing and implementing efficient on-line techniques to monitor and control the welding process. These methodologies make use of different signals measured during the welding process such as force, temperature, acoustics, vibrations, currents, power, and torque, to derive aspects related with the quality of the FSW joint. In this context, all those signals could be collected using sensors attached to the welding machine and then analysed using ML techniques to verify in **real time** that the FSW outcome is meeting the expected quality.

Artificial Intelligence (AI) can also be employed to develop **predictive maintenance** solutions in FSW. In this sense, the most promising field of work is the diagnosis of the state and **wear of the FSW tools and the prediction of their lifetime**. As FSW tools are subjective to intense fluctuating tensile and compressive loads, fatigue failure of the FSW tool may occur. Also, plastic deformation of the FSW tool may also occur under high welding loads and temperature, as the yield strength of some tool materials dramatically decreases at high temperature. Moreover, it has been reported that some alloying elements may be transferred from the base materials to the tool at high temperatures. These diffused elements tend to form brittle intermetallic compounds, which usually affects the tool strength.

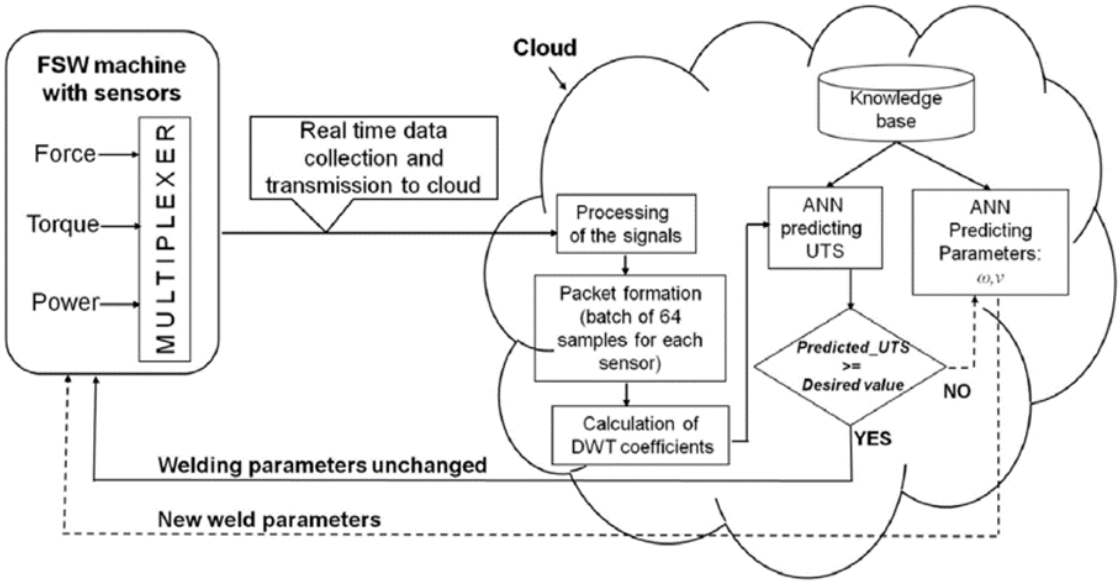



*FIGURE 2. SYSTEM ARCHITECTURE OF A SOLUTION ENABLING REAL-TIME MONITORING OF FSW PROCESSES. SOURCE:* (4)

Finally, the **integration of AI with other digital tools such as Finite Element Methods (FEM)** can help to build synergies between them and to provide higher quality FSW joints as a result. In such scenario, AI methodologies are used either to predict the adjustable

parameters that are used to correlate FEM simulations to real-world FSW processes, or to act as a virtual machine to generate a greater dataset to strengthen data analysis performance.

Several research works have investigated the application of AI methodologies and techniques to the FSW process. In general terms, the available literature can be classified in two main groups, according to the type of algorithms employed:

- Research works that employ **regression algorithms** to predict the performance of the FSW joint (for instance, tensile strength estimation). These algorithms, that can belong to the machine learning (5) (e.g Support Vector Machines, multi-linear regression, etc.) or to the deep learning (6) (e.g Artificial Neural Networks) domains, aim to find relationships between the values of a set of input variables, and one or more output variables, as schematised in the following Figure 3.
- Research works that employ **classification algorithms** to detect and identify anomalies in the FSW process such as defects.

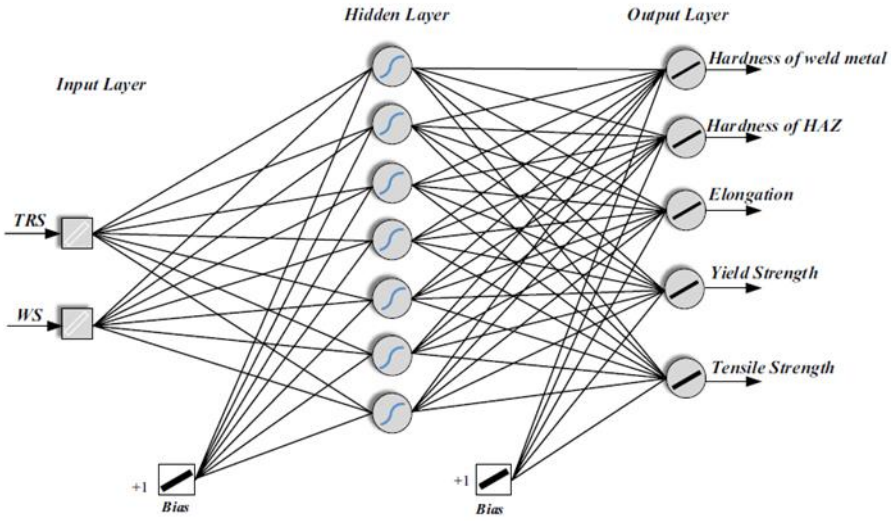



*FIGURE 3. SCHEME OF AN ARTIFICIAL NEURAL NETWORK APPLIED TO THE FSW PROCESS TO PREDICT OUTPUT VARIABLES. SOURCE:* (6)

Considering the scope of STWIN, the latter works are of special interest. There are several approaches to this challenge in what concerns the type and number of variables employed to feed the AI algorithms. Also, in some works raw input data are used as inputs, while in others a data pre-processing stage takes place in order to extract representative features of the measured signals. This stage is particularly explored in research dealing with acoustic emission data, or force and acceleration measurements over time.

Amongst all the available literature on the subject, there are some works that are especially relevant for the purpose of STWIN. Du et al. (7) investigated the conditions for void formation using a decision tree and a Bayesian neural network in aluminium-aluminium FSW joints, using 108 sets of unprocessed welding parameters and computed variables obtained from analytical and numerical models. They found that temperature and maximum shear stress had the maximum influence on void formation and were able to predict void formation with >83.3% accuracy. Hartl et al. (8) explored whether Convolutional Neural Networks were suitable for identifying surface and internal weld defects in FSW joints, using a set of 120 welds analysed with ultrasonic testing. They found that, if a proper labelling method and neural network combination is found, the presence of defects can be predicted with up to 98,5% accuracy. Dahmene et al. (9)

investigated the performance of a process monitoring method (defect detection and tool state estimation) based on the application of AI to acoustic emission signals. They found that, in their case, the K-nearest neighbours (KNN) and Support Vector Machine (SVM) algorithms performed the best as binary classifiers (defect/no defect) with similar performance. Instead, when a multi-class classification (type of defect) was pursued, KNN outperformed SVM. Guan et al. (10) studied the response of the welding force signal in FSW. Assisted by machine learning techniques, they found that some detailed characteristics of the force waveform can reflect the characteristics of defect formation. As a result, they mapped the relations between some force signal features and the presence and characteristics of defects. Finally, Rabe et al. (11) employed raw recorded force data together with other FSW parameters (workpiece geometry, gap tolerance, etc.) to train different Convolutional Neural Networks (CNN), achieving a rate of correct void defect classification of around 93%. They highlighted that the CNN training is a critical stage, because if a small dataset and many input features are employed, there is an increased risk of overfitting.

### *3.1.2 Multi-Sensor Monitoring Systems – Sensor Fusion*

The implementation of automated workplaces is an important step towards the factories of the future because of the efficiency and flexibility gains it entails. The practical realization of automated processes depends heavily on the development of reliable and robust monitoring systems, which are used in the online and off-line monitoring of critical machining processes (12). In a multi-sensor monitoring system, each sensor can measure a certain parameter independently, and then some kind of signal-processing algorithm is employed to combine all the independent measurements into a complete measurement result. Compared with single sensor setups, integrated and fused multi-sensor systems provide abundant, complementary, real-time and low-cost information. The sensor-based monitoring and subsequent control can reduce manual contribution, make the manufacturing process more maintainable, flexible, error-free and cost-effective

Several multi-sensor monitoring solutions have been reported in literature, specifically designed for welding process control purposes. Lee et al. (13) proposed a system for the quality inspection of welding bead quality that combines sensor-based measurements (current, voltage, gas data) with 2D images. The authors claim that through that integration, they could overcome the limitations of an only-sensors system such as difficulty in determining welding locations, and the accuracy and speed issues of 2D image inspection. Thanks to the combination of both techniques, the classification accuracy of the system improved. Zeng et al. (14) modified a robotic arc welding facility to implement a multi-sensor sensing system in order to improve the quality, stability and reliability of the welding process. The intelligent sensing system (Figure 4) counted with high-performance high-speed camera, vibration sensors, and current Hall sensors that allowed collecting in real-time images of the welding dynamic molten pool, vibration signals, and current parameters. The measurements were then used as inputs for a SVM algorithm that was used to classify welds as good or defective welds.

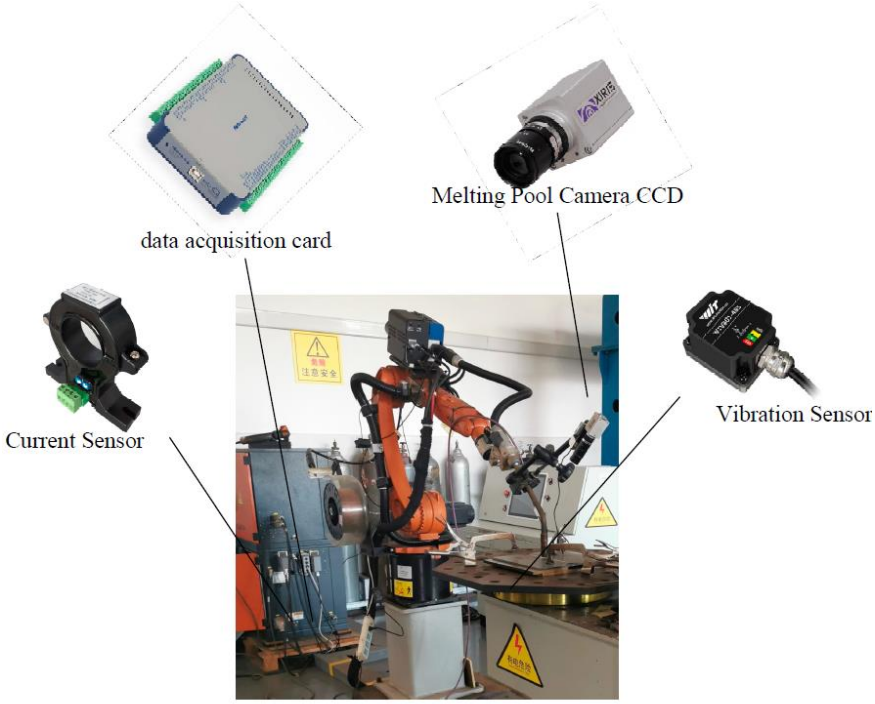



*FIGURE 4. MULTI-SENSOR MEASURED SYSTEM EMPLOYED BY ZENG ET AL.*

A similar approach was followed by Xu et al. (15) to investigate the double-sided double arc welded T-joints. In this case, Hall sensors, microphones, and a camera were added to the robotic welding system (Figure 5) to record voltage, sound signals, and weld pool images. The information collected by the multi-source system was them processed to extract main features of each variable and combine them to create a model able to characterise the quality of the welds.

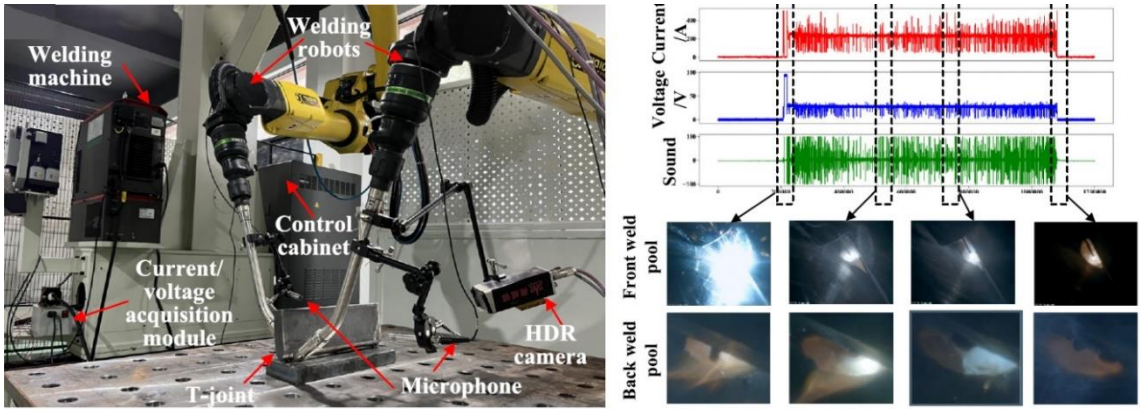



*FIGURE 5. MULTI-SENSOR SYSTEM PROPOSED BY XU ET AL (LEFT) AND ASSOCIATED MEASUREMENTS (RIGHT)*

There are also some research works that have aimed to develop multi-sensor setups for the monitoring and control of friction stir welding processes. In a review authored by Babalola et al. (16), they identified temperature, force, current, power, process images and acoustic emission as the most important process elements to be measured and combined in FSW. In many cases, these signals are post-processed to extract relevant statistical features such as root mean square, kurtosis, or variance. Besides, the combination of multi-sensor measurements with AI techniques commonly leads to the best outcomes of the monitoring process.

For example, Mishra et al (4) proposed a novel cloud-based remote and real time monitoring and control system for FSW processes to avoid the occurrence of weld defects. The control scheme proposes to acquire data from several sensors linked to the FSW machine (rotational speed, displacement speed, force sensor, torque sensor, power sensor) and transmits them to the cloud by using the TCP/IP protocol, where they are processed and analysed. The authors of the research claim that by using cloud computation together with a multi-sensor approach, the FSW process can be more efficient, reliable, and cost-effective. Also, the system is flexible, meaning that more sensors can be added if needed. Sahu et al. (17) developed a multi-sensor strategy to predict of the outcome of the FSW process when applied to polycarbonate sheets. The monitoring system (Figure 6) counted with the following sensors: thermocouples (in the advancing and retreating sides), rotational speed sensor, torque sensor, force sensor, and linear speed sensor. In their work, all the data collected was employed to develop second order regression models that allowed a satisfactory prediction of the ultimate tensile strength of the welded joints.

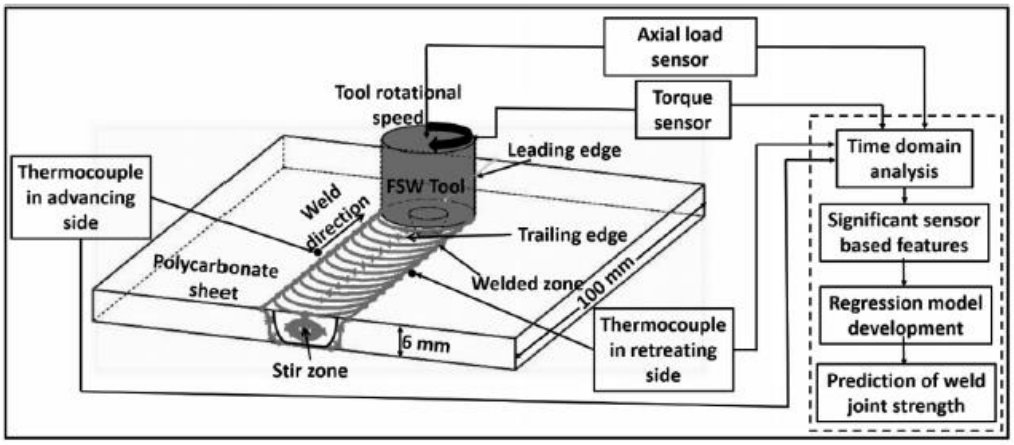



*FIGURE 6. MULTI-SENSOR MONITORING SYSTEM PROPOSED BY SAHU ET AL.*

Goswami et al. (18) employed measurements from force and torque sensors to monitor the quality of dissimilar Al6061-polycarbonate friction stir welded joints in lap configuration. In that work, the measurements were used to feed a model aiming to predict the tensile shear strength and fracture elongation of the dissimilar lap welds. Das et al. (19) developed a sensor fusion-based model for the identification of tunnel defects in friction stir welding samples. For that purpose, real-time signal information obtained from different sensors (force, speed, current) was fused to estimate a quantitative indicator for defect detection within the welded samples. The main statistical features of the signals were extracted as intermediate step.

### *3.1.3 Digital Twin*

A Digital Twin (DT) can be defined as the virtual copy of any real-world thing, system or process. This approach is based on the fusion of the digital world with the physical world, which when applied to industrial processes is associated with improved productivity. The virtual commissioning of any digital twin enables the possibility to monitor and evaluate the behaviour of physical elements and thereby predict errors and defects that will occur in the real world (20). This feature makes this technology a fundamental tool within smart manufacturing. The prediction of defects thanks to the use of the technology allows much faster adjustments to be made to prevent them, thus achieving an improvement in the performance of production processes, among other benefits.

In the field of welding, the friction stir welding has been one of the latest methods to join this trend. This is reflected in the study done by Roy et al. (21). Motivated by the absence of a comprehensive framework to oversee the FSW procedure in conjunction with the equipment, Roy et al. have created a Digital Twin to supervise the process. The developed technology processes and analyses real-time data form various sensors and extracts relevant information about the machine and the process evolution. In particular, the information includes predictions of weld quality, machine health and proposals for corrective actions. The proposals suggested by the twin are transmitted back in real-time to the FSW machine, which helps to achieve the 'zero defects' goal. The designed DT's workflow can be seen in Figure 7.

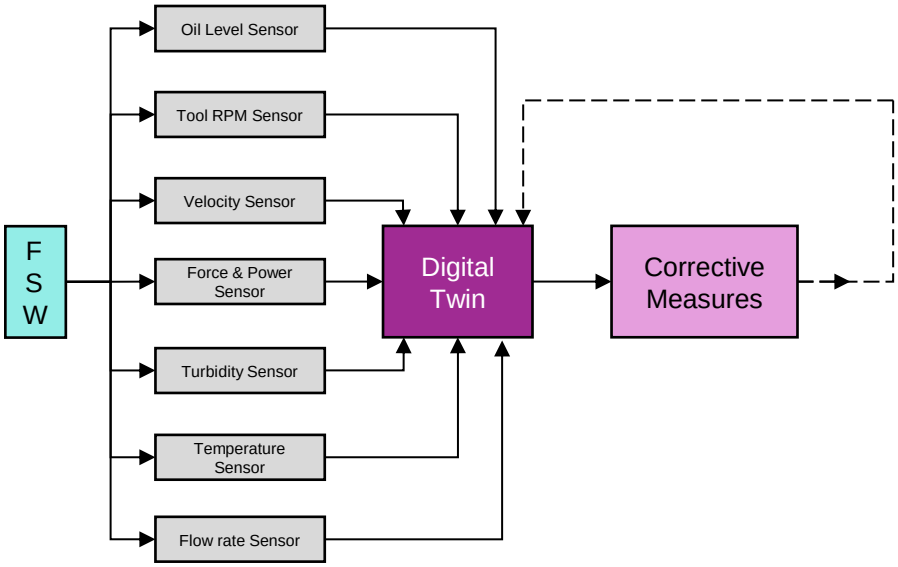



*FIGURE 7. DEVELOPED DT WORKFLOW FOR FSW* (21)

Looking at other research initiatives, most of them focus on identifying defects (22–24), classifying welds (25) and monitoring process changes (26). Outside of this interest, the studies that go beyond dynamics are few. Among these, the investigations carried out by Chen et al. (27) and Chen et al. (28) stand out. Propelled by improving the accuracy and efficiency of friction stir welding, Chen et al. and Chen et al. have developed two independent models that are fed with process data. In the first case (27), the model allows the weld quality to be evaluated and optimise the process parameters, based on robot position and applied force data. With them, the model is able to predict deviations in real time. From another approach, Chen et al. (28) have focused on modelling the temperature field of the materials during welding, based on sensor data. For that purpose, they rely on a three-dimensional numerical model that predicts the temperature distribution. In both cases, the results achieved demonstrate that it is feasible to control the physical process through numerical simulations, confirming the potential of cyber-physical systems to monitor the FSW process.

In other areas, such as laser welding, the digital twin technology has been further explored. This is reflected in the study done by Franciosa et al. (29), who focused on the remote laser welding (RLW) technique. Due to the advance of new technologies (Internet of Things (IoT), Big Data and Cloud Computing, among others) that allow the intelligent management of information, the concept of Digital Twin is expanding at great speed. In particular, their research introduces the technology and explains its development process in three stages: concept stage (S1), scale-up stage (S2) and production pilot stage (S3). Although the study focuses on a field of research different form that of STWIN, it describes a general structure for the digital twin applicable to the project, based

on two main streams: process monitoring (forward process) and process control and adjustment (feedback process).

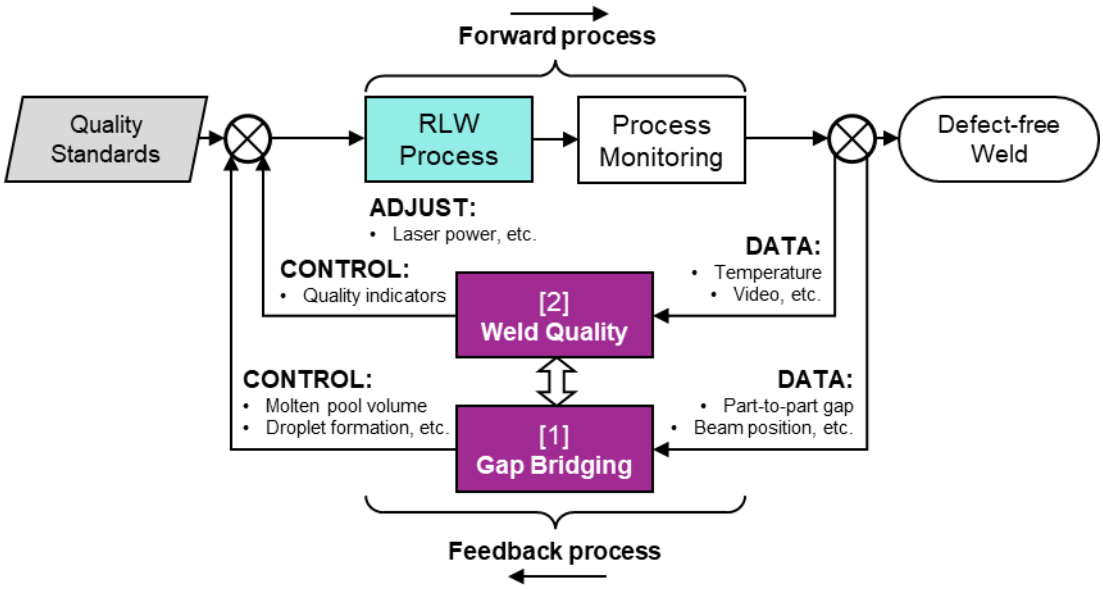



*FIGURE 8. DIGITAL TWIN STRUCTURE FOR REMOTE LASER WELDING (RLW) PROCESS* (29)

In view of the concept of structure in Figure 8, it was validated and successfully applied to the laser welding process virtually, obtaining an improvement in the performance and efficiency of the production process, as well as a reduction in downtime and idle time, among many other benefits.

## 3.2 Friction Stir Welding

### *3.2.1 Friction Stir Welding of Steel*

Besides conventional construction steels, the weldability has been demonstrated for various steels, like low carbon, dual phase and stainless steels. The sheet thicknesses that can be welded amount to up to 20 mm in a single layer (30–32), however with a considerable tool wear.

During FSW of steel, the tool is subjected to extremely high temperatures of approximately 1200°C and corrosive and abrasive wear.

The current standard practice for FSW tools is the use of PCBN materials (polycrystalline cubic boron nitride), which has a very high hardness and excellent wear resistance (33–35).

Investigations were carried out in the EU project SOLVSTIR (36) to increase the tool lifetime by local preheating. In the project (37), a new composite tool material (WC-$ZrO_2$) was developed that has outstanding properties and consequently can be classified as very promising. Depending on the potential purchase quantity, costs per metre of the weld can be realised that corresponds to those of conventional processes (38).

The EU project RESURGAM (39) investigated FSW of steels for marine applications. Element Six developed a PCBN-based tool with a higher durability (40).

### 3.2.2 Friction Stir Welding of Steel-Aluminium Dissimilar Joints

FSW is a solid-state welding process where no melting is involved, making it suitable for dissimilar joints (41–48). Although the combination of steel and aluminium is ideal and the development of such a joining technology is highly desirable, it is difficult to obtain a sound steel/aluminium joint by means of the usual fusion welding processes. This is because hard and brittle intermetallic compounds (IMCs) are formed at the joint interface due to mutual diffusion during welding.

Continuous and spot FSW is more efficient in cost and time, effectively weld various plate thicknesses with different joint configurations, and the process generates lower heat input compared to fusion welding methods which produce thinner IMC at the Al-to-steel interface.

Several studies have explored the joining of aluminium and steel using FSW (44,47–50). Uzun et al. (44) investigated the microstructure, hardness, and fatigue properties of friction stir butt welds between 4 mm thick aluminium alloy 6013-T4 and X5CrNi18-10 stainless steel. While they successfully achieved sound joints and characterized the microstructure of the dissimilar weld zones (heat-affected zone and thermo-mechanically affected zone) in both base metals, the influence of the process parameters on the tensile properties of the joints wasn't explored.

Watanabe et al. (47) focused on the impact of tool rotation speed and pin position on the tensile strength of joints formed between 2 mm thick aluminium alloy 5083 and mild steel sheets. Their joints exhibited up to 86% of the ultimate tensile strength of the aluminium base alloy. Tanaka et al. (48) analysed the effect of the rotation speed on temperature rise and joint strength of aluminium alloy 7075-T65 and mild steel under a constant welding speed and pin position. This study investigated how heat input affects the formation of intermetallic compounds (IMCs) and the resulting tensile strength. Chen and Kovacevic (49) reported on the effects of pin position on temperature distribution and the microstructure of the weld zone in Al 6061 to AISI 1018 steel joints, using constant tool rotation and traverse speeds. Lee et al. (50) examined the types of IMCs produced in the reaction layer between friction stir welds of Al 6056-T4 and 304 austenitic stainless steel.

In dissimilar welds, controlling IMC formation is crucial due to the high reactivity between aluminium and iron. Studies have shown that appropriate selection of welding parameters, particularly tool rotation speed, traverse speed, and tool design, can influence heat input and, consequently, the joint's microstructure (51).

### 3.2.3 3D Friction Stir Welding of Steel

Today, the typical industrial FSW application is a flat 2D weld in aluminium with thicknesses between 2 and 7 mm, carried out on a C-shape or Gantry type FSW machine. Nowadays, 3D-structures become more and more common in industrial applications. Therefore, instead of 2D joints, 3D-structure welds are unavoidable in industrial applications. For example, in automotive, the body of the automobile has an extremely complex geometry. Robots are a versatile and flexible solution to implement and integrate FSW for 3D applications.

Friction stir welding has emerged as a promising joining technique for steel, offering advantages like minimal distortion, solid-state welding (reducing liquification and porosity issues), and excellent joint strength. However, integrating FSW with robots (RFSW) for steel presents unique challenges compared to traditional aluminium applications.

- Steel's higher strength and lower thermal conductivity compared to aluminium necessitate significant forces and heat generation during FSW.

- Standard industrial robots often lack the stiffness and force capacity required for stable RFSW of steel (52).
- Tool wear is a significant concern due to the abrasive nature of steel.
- Precise control of process parameters (rotation speed, travel speed, plunge depth, etc.) is crucial for achieving defect-free welds (53).

Research is ongoing for developing robust robotic systems with enhanced stiffness and force capabilities specifically designed for FSW of steel (52). Novel tool designs with wear-resistant materials and optimized geometries are being explored to improve tool life (53). Advanced process control strategies like force feedback and sensor-based monitoring are being implemented to ensure consistent weld quality (54).

### *3.2.4 Post-processing of welded parts*

Unlike aluminium, FSW of steels typically doesn't require extensive post-processing due to the solid-state nature of the joining process. However, in some cases, post-processing techniques might be employed to achieve specific goals:

- **Surface finishing**: The weld area on the steel parts might exhibit discoloration or a slightly rough texture due to the high temperatures involved during FSW. Depending on the application's aesthetic or functional requirements, post-processing techniques like grinding, machining or wire brushing might be used to achieve a smoother or cleaner surface finish.
- **Stress relief**: In some high-strength steel applications, the residual stresses introduced during FSW could be a concern. Post-weld heat treatment (PWHT) at a controlled temperature and time can help alleviate these stresses and improve the overall toughness of the joint.
- **Tailoring mechanical properties**: For certain steels, especially those with a specific heat treatment history, a post-weld heat treatment might be employed to achieve desired mechanical properties in the weld zone. This can involve specific temperature and time profiles to influence grain structure and achieve the required strength or ductility.

The post-processing of FSW joints, either aluminium to steel or steel to steel, also includes subjecting the welded blanks to forming processes to produce semi-finished products or final components, depending on the targeted application. In STWIN, the main mechanical post-processing method that will be explored is bending, as it is closely related to HIAB's demonstrator. From a technical perspective, for the different material combinations and formats (mainly thicknesses) that will be investigated, it must be assessed which the acceptable limits of the bending process are, considering quality and performance requirements. The knowledge that will be generated in this investigation will be then employed during the demonstrator design and execution stage of the project. Regarding the bending process characterisation, the following aspects will be covered for the different welds:

- Determination of the bending strength and flexural modulus of the welded samples compared to the properties of the parent materials. This will allow evaluating the material consolidation, the ductility of the welds, and the bond strength under tensile loads. It is relevant to mention also that, according to the available literature, it may happen that for the case of dissimilar welds, the formability behaviour of the TWBs is different depending on the relative orientation of the specimens with respect to the weld seam (55,56). Furthermore,

in the case of defective welds, it will also be possible to assess the performance loss due to their presence, and also to which extent defects can alter the failure mechanisms of the joint.

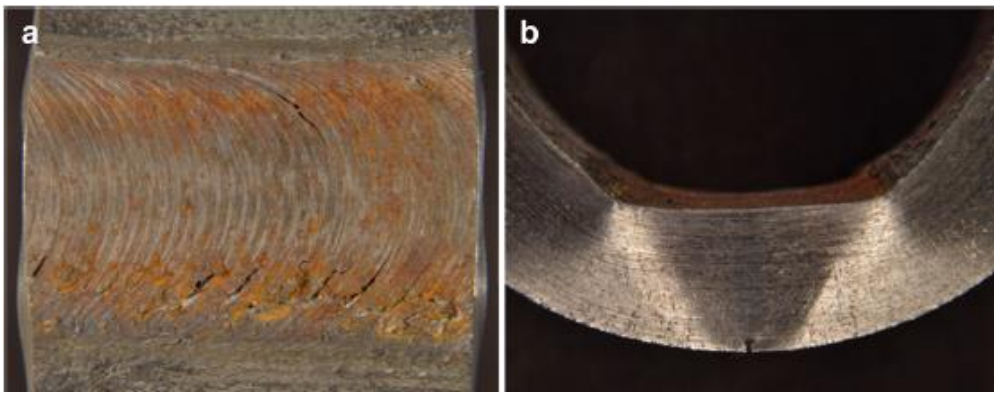



*FIGURE 9. EXAMPLE OF AN AS-WELDED BENDING TEST SPECIMEN, FACE (LEFT) AND ROOT (RIGHT) SIDES* (57)

- Determination of the impact that the FSW process has on the fatigue performance of the resulting blank, especially in what concerns crack growth resistance.
- Determination of the influence of the forming process parameters on the springback performance of FSW TWBs (58), as this phenomenon must be counteracted during the bending stage to meet the dimensional requirements of the demonstrator.

# 4 Proposed Approach

For its practical implementation, the STWIN project is structured around six carefully designed work packages (WPs): four technical WPs, one dedicated to management and one focused on exploitation and dissemination results. This structured approach ensures that all facets of the project are aligned with the objectives described in section 1.2.

The interdependencies between work packages can be seen schematically in Figure 10.

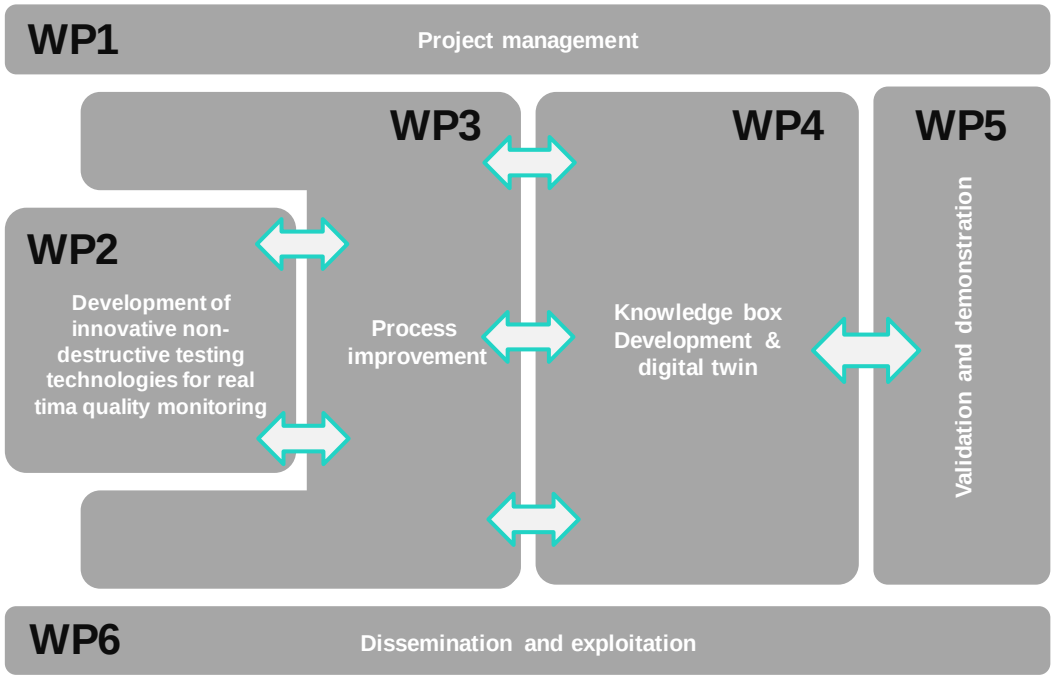



*FIGURE 10. STWIN WORK PACKAGE INTERRELATIONS*

The WP1 (led by CIDAUT) monitors the overall project progress, including the management of costs and time. The WP2 (led by BWI) investigates the connections between process parameters and weld defects, through non-destructive testing. The WP3 (led by TRICYLON) is focused on the design of tools for FSW and the exploration of a novel robot concept capable of realising complex joints. The WP4 (led by CIDAUT) addresses the development of a Digital Twin for the FSW process. The WP5 (led by HIAB) demonstrates the feasibility of applying the developed DT under three industrial use cases: a loader crane, a vehicle powertrain application and a transport trailer. Finally, all work packages feed WP6 (led by BWI) for the Dissemination and Communication activities and to promote the use of high-strength steel among the industry.

The duration of each work package is shown in Figure 11. Note that the project duration will be 36 months.

| ACTIVITY | YEAR 1 | | | | YEAR 2 | | | | YEAR 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| WP1 – Project management | | | | | | | | | | | | |
| WP2 – Development of innovative non-destructive testing technologies for real time quality monitoring | | | | | | | | | | | | |
| WP3 – Process improvement | | | | | | | | | | | | |
| WP4 – Knowledge box development & digital twin | | | | | | | | | | | | |
| WP5 – Validation and demonstration | | | | | | | | | | | | |
| WP6 – Dissemination and exploitation | | | | | | | | | | | | |

*FIGURE 11. GANTT CHART OF THE PROJECT*

In the following sections, the challenges that the Consortium will have to face during the execution of the technical packages to achieve the success of the project are described.

## 4.1 Real Time Quality Monitoring for Friction Stir Welding

**Eddy Currents and Magnetic Field Leakage monitoring**

ISEND, with the support of BWI, will develop the application of Eddy Currents and Magnetic Field Leakage monitoring. In essence, this is a challenge because the irregular weld surface will affect the behaviour of the eddy currents. The challenge will be especially interesting when dealing with dissimilar welds, as in the case of the GRANALU demonstrator (WP5), where stainless steel and aluminium sheets are combined, whereby the weld will present an irregular mixture of both materials. The great difference between the electromagnetic behaviour of aluminium and stainless steel is an added challenge when it comes to the application and processing of the signals obtained. Figure 12, this phenomenon can be observed.

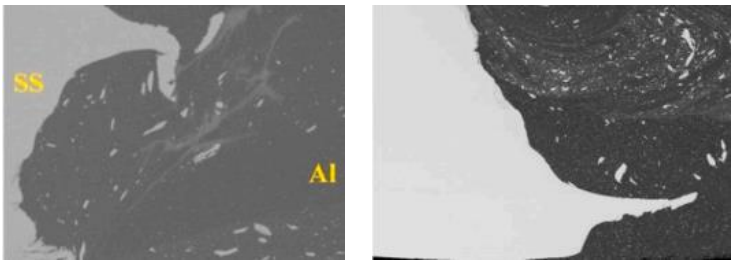



*FIGURE 12. DETAIL OF SEM MICROGRAPHIES OF STAINLESS STEEL (LEFT SIDE) AND ALUMINIUM AL2024 (RIGHT SIDE) FRICTION-STIR WELDING* (59)

The HORSE demonstrator presents a comparable situation, albeit less severe. Here, welding of high hardenability steel to cast iron will create similar variations in the electromagnetic feedback. Lastly, the biggest challenge for NDT inspections using the ISEND technology for the HIAB demonstrator will be the curved surfaces. These variations in geometry can affect the distance between the probe and the material, which is crucial for accurate signal interpretation. Real-time signal corrections will be necessary to address this challenge. At this point, we have the great advantage that the probes will be coupled to the MONARCH robot of the partner TRYCILON, which with its high precision positioning capacity, will be able to maintain a constant distance between the probe (in our case, magnetizer and sensor are combined in the same probe) and the inspection material.

The image below (Figure 13) shows how as the distance between probe and material moves away (either decreasing or increasing) from the optimal inspection distance, the signal drops significantly in amplitude, and therefore the system will lose sensitivity.

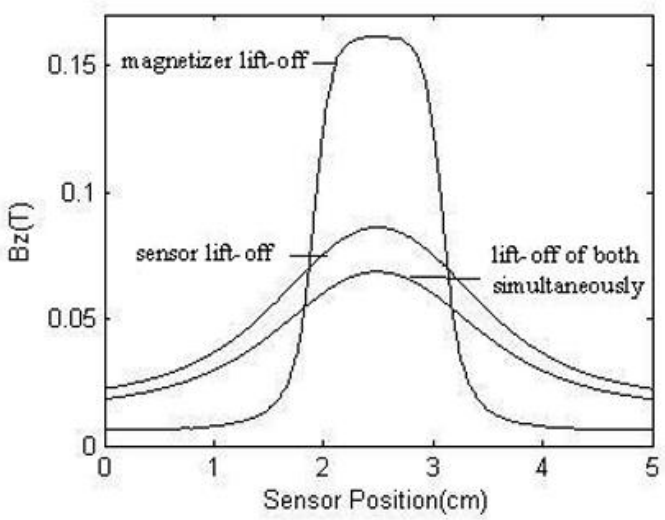



*FIGURE 13. EFFECT OF LIFT-OFF VARIATION BETWEEN THE MATERIAL TO BE INSPECTED AND MFL MAGNETIZER AND SENSOR* (60)

An added problem in the planning and preliminary development and testing phase (WP2) has been the substitution of partners in the early stages of the project and the consequent modifications of the demonstrators, from the point of view of the NDT application.

Initially, eddy current monitoring was an optimal method for inspection, as all demonstrators included paramagnetic stainless steel. These adaptations necessitated the addition of a new NDT inspection method, magnetic flux leakage. Magnetic flux leakage is better suited than eddy currents for inspecting the steels chosen for the HIAB and HORSE demonstrators due to its material properties. To sum up, the NDT solution that ISEND will develop for each demonstrator is as follows (Table 1):

*TABLE 1. NDT SOLUTION TO BE DEVELOPED PER DEMONSTRATOR*

| Demonstrator case | Material A | Material B | Proposed NDT |
|---|---|---|---|
| HIAB | High-strength steel | High-strength steel | **Magnetic flux leakage** |
| HORSE | High hardenability steel | Cast iron | **Magnetic flux leakage** |
| GRANALU | Stainless Steel | Aluminium | **Eddy Currents** |

**Acoustic emission monitoring and thermography**

Besides magnetic flux leakage and Eddy current monitoring, also acoustic emission monitoring and thermography will be used by BWI.

Acoustic emission quality monitoring (AEM) as a non-destructive test method has been developed based on the principle that every material exhibits natural vibrations, and that machines and processes emit sounds. The main goal of acoustic emission monitoring is to survey industrial processes or structures in a non-destructive way (crack detection, vessel inspection, leak detection). In case of welding processes, the formation of weld defects can be monitored.

The sensors to perform the AE measurements have been defined, both for the structure-borne as for the air-borne sound signals. A critical part of the AEM process is the selection of the suitable frequency range of the sensors for detection and signal processing. Both contactless sensors and sensors in contact with the plates to be welded will be used.

In a first phase, the feasibility of AEM for friction stir welding will be investigated using the STIRWELD welding equipment. The materials to be used for this investigated will be oriented towards the GRANALU demonstrator (aluminium to stainless steel).

Thermography is the 2nd method to be used by BWI. Infrared sensors and cameras can detect the infrared radiation emitted by the material during welding. Therefore, these are useful for monitoring of welding processes, which are inherently thermal processes. These methods are non-contact, which allows for in-line defect detection. This technique will be particularly useful for FSW of dissimilar materials, which are difficult to execute and more prone to defect formation.

The BWI thermal camera will be used to capture temperature data during FSW, using the STIRWELD welding setup. Values for the emissivity and reflectivity will be determined by experiments, and used to pre-process the thermal data, and to calculate temperatures. The software will be set up to capture the thermal images, pre-process them and deliver it for further evaluation (AI).

Phase 1: Generic investigation of AEM and thermography for monitoring of FSW

To use AEM and thermography for defect detection for FSW, it shall be demonstrated that it can detect the predefined relevant defects. Instrumented welding experiments will be performed with the STIRWELD equipment to assess the detection capabilities. Samples with artificial defects or welded with non-optimised parameters will be used for the evaluation. Subsequent destructive testing will demonstrate the reliability, detection and sizing capability of the measurement techniques.

Therefore, a selection of conditions obtained during optimisation of the parameters will be inspected using AEM and thermography:

- conditions for the desired or optimum joint quality, to serve as reference,
- conditions which produce particular defects and indications, in order to optimise the detection capability and procedures,
- conditions for establishing relationships between the measured signals and the destructive or metallographic test results,

All sensor signals and process parameters will be recorded simultaneously during the welding trials. This enables the highest possible amount of information, and as this data is saved, it can be evaluated afterwards from various perspectives.

Workplan

The applicability of acoustic emission monitoring (AEM) and thermography for monitoring of FSW will be assessed on the STIRWELD equipment, with a particular focus on dissimilar welds (aluminium to stainless steel).

*I. Acoustic Emission Monitoring (AEM) investigations*

The first phase will involve selecting appropriate sensors for capturing both structure-borne and air-borne sound signals emitted during FSW. Experiments will be conducted to identify the optimal frequency range for these sensors to effectively detect and process AEM signatures associated with defect formation in dissimilar welds.

Following sensor selection and frequency range determination, a feasibility study will be carried out using the STIRWELD equipment. The STIRWELD setup will be configured for FSW of aluminium to stainless steel plates. The chosen AEM sensors will be integrated with the setup, ensuring optimal placement for signal acquisition (both contact and contactless). A series of FSW trials will be conducted while simultaneously monitoring AEM signals. The collected data will be analysed to assess its effectiveness for detecting signatures indicative for defects during FSW.

*II. Thermography Investigations*

The thermography investigation will begin with emissivity and reflectivity calibration. Experiments will be designed to determine these coefficients for the aluminium and stainless steel materials to be used in the FSW trials. Accurate temperature calculations from the thermal camera data rely on these coefficients.

Next, we will focus on thermal data acquisition and processing. The BWI thermal camera will be set up to capture temperature data using the FSW equipment at STIRWELD. A software routine will be developed to automate the thermal image capture, pre-processing, and delivery for further analysis using AI techniques by CIDAUT. Finally, the acquired thermal data will be analysed to identify any temperature variations that might correlate with defect formation in the dissimilar welds.

Destructive testing methods (metallographic examination, mechanical testing) will be performed on the welded samples to assess the quality and identify any defects. The acquired AE and thermal data will be correlated with the observed weld defects to establish relationships between specific AE signatures and defect types.

This workplan serves as a starting point, and further refinements will be made based on the initial findings and ongoing discussions. After the execution and analysis of this first series of experiments, a 2$^{nd}$ series will be prepared and planned.

<u>Phase 2: Investigation of AEM and thermography for monitoring of FSW with the TRICYLON robot</u>

The second phase of the investigation focuses on integrating and optimizing Acoustic Emission Monitoring (AEM) and thermography for quality monitoring of Friction Stir Welding (FSW) using the TRICYLON welding robot. This phase aims to enhance the defect detection capabilities established in phase 1, adapting the methodologies to a robotic welding environment, and ensuring scalability and robustness for industrial applications.

In this phase, the TRICYLON welding robot will be employed to perform FSW on steel and dissimilar materials, utilising AEM and thermography for real-time quality monitoring. The findings from phase 1 will guide the sensor placement, frequency range selection, and data acquisition techniques. The primary goal is to validate the effectiveness of these monitoring techniques in a robotic setup and to refine the processes based on the feedback from the TRICYLON system.

The workplan for phase 2 will be composed based on the findings and insights gained from Phase 1. This will ensure that the strategies and techniques developed for AEM and thermography are effectively adapted and optimized for the TRICYLON welding robot.

## 4.2 Development of AI Models and Digital Twin

The overall monitoring of the FSW process including the welding quality assessment proposed in STWIN relies on the digitalization of the FSW operations. This includes mainly two main tasks: the application of AI-based models to the data collected during the welding process, and the development of a Digital Twin of the FSW process able to monitor the process and provide corrective suggestions (adaptive features) in case a potential risk of lack of quality of the welding is predicted. One example of the steps involved in the development of a Digital Twin of a manufacturing process are presented in Figure 14.

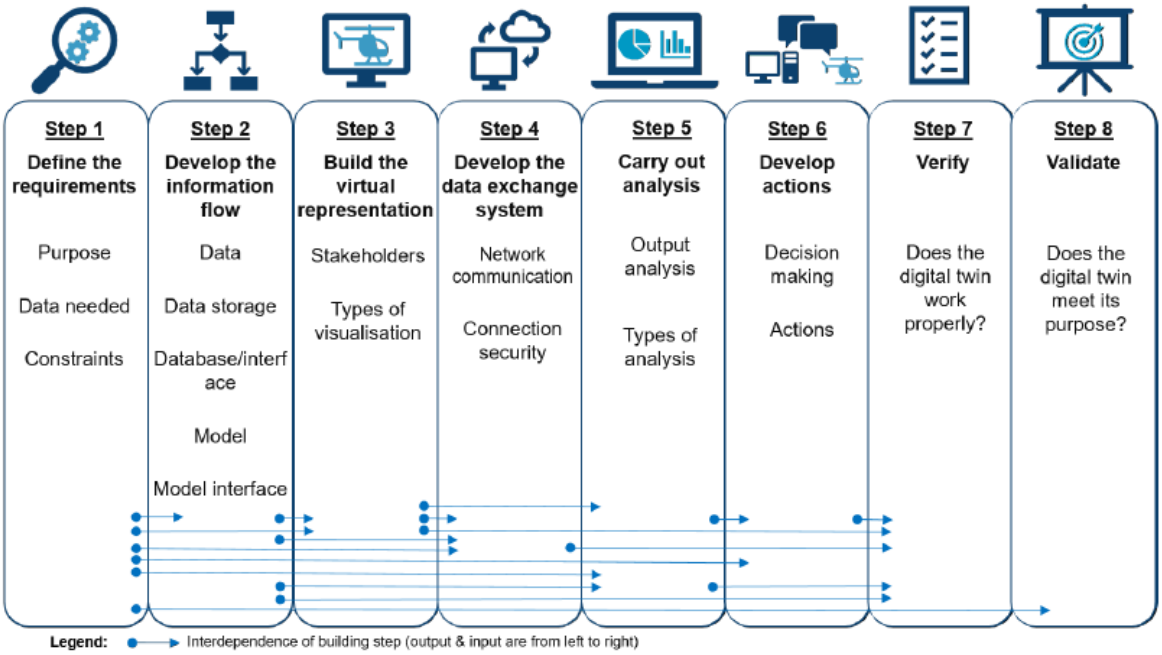



*FIGURE 14. STEP-BY-STEP PROCESS OF DEVELOPING A DIGITAL TWIN. SOURCE:* (61)

To reach this goal, an approach based on five major phases has been envisioned, which are briefly described below:

### PHASE 1: Investigation of AI algorithms applied to FSW

Sensors' data can provide deep insights into the friction stir welding process. To make the most of the data gathered, AI algorithms can be used. Hence, the first phase of the process consists of exploring the different AI algorithms, considering their nature (regression vs classification), level of complexity (machine learning and deep learning), as well as data requirements, advantages and disadvantages of all of them. Once this knowledge is gained, a set of algorithms will be selected using available data from literature. This will allow determining which the strong points of each one of them are, and how they can complement each other to obtain as much information as possible from the welding monitoring setup.

### PHASE 2: Model selection, training and evaluation using ad-hoc data

The second phase in the process entails the final selection of AI algorithms to be applied to the FSW process considering the different data types that will be available (images, signals, discrete data, etc.), as well as the combination of some of them if deemed appropriate. This will provide the Consortium a clear scheme of how the input data will be processed to get automated conclusions about the performance in terms of quality of the FSW process. To maximise the accuracy of the algorithms, they will be trained with

specific data corresponing to both OK and not OK welds, and their performance will be evaluated and documented following best practices known by the partners.

### PHASE 3: Definition of the Digital Twin architecture and requirements

In this phase, the high level architecture of the Digital Twin will be defined. It is expected to consist of four main building blocks:

- Data collection layer: cost-effective Internet-of-Things (IoT) devices such as Arduino, Raspberry Pi or alike will be used to interface with the welding system (machine + monitoring devices) to collect data from the welding process, in such a way that the data collection is machine agnostic.
- Data transmission layer: the data collected by the IoT device(s) is sent to a server or cloud platform located elsewhere for its processing and visualization, using standard communication protocols such as MQTT or HTTP.
- Data storage and processing layer: this layer contains all the different services that the Digital Twin will provide. In this sense, it will count with the software infrastructure to store the data, the underlying platform to manage the overall status of the Digital Twin, and the AI models that will be used to analyse the data to provide insights to the welders and corrective actions when necessary.
- Visualization layer: a web-based or desktop Graphical User Interface (GUI) will be developed to visualise data in real time, allowing users to interact easily with the Digital Twin.

For each layer, open access tools will be employed when feasible. Also, the functional and non-functional requirements for the Digital Twin will be determined in agreement between the partners to meet all expectations.

An example of the high-level structure of the Digital Twin, extracted from the scientific literature, is shown in Figure 15.

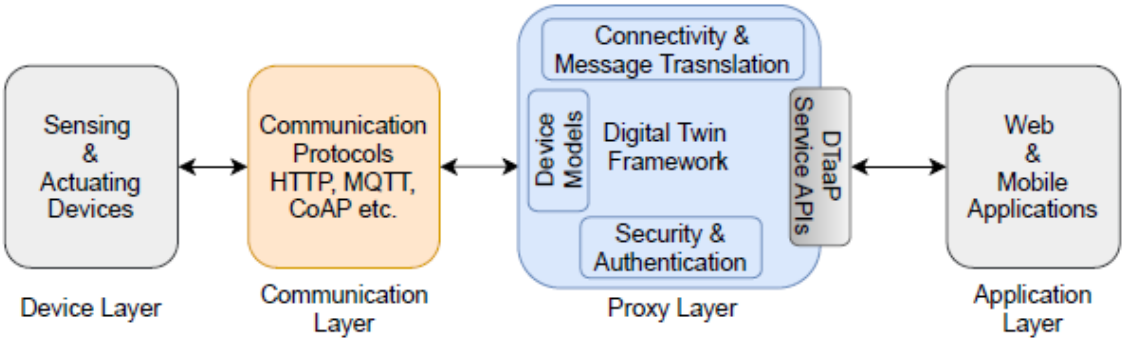



*FIGURE 15.HIGH-LEVEL STRUCTURE OF THE DIGITAL TWIN, EXAMPLE EXTRACTED FROM* (62)

### PHASE 4: Development of the Digital Twin modules and integration with the welding machine

In this phase, the different modules and functionalities of the Digital Twin will be developed and put together, also considering the different interfaces that need to be developed to connect the modules between them, and with the welding machine.

### PHASE 5: Deployment, testing, and optimisation

Once the beta version of the Digital Twin is ready, it will be deployed in a real manufacturing scenario. From that point onwards, it will be subjected to a continuous enhancement and optimisation process that will pursue i) a better performance (accuracy and speed) of the system, and ii) adapting its functionalities or add new ones to meet the

expectations from the end users. Also, the next steps to ensure scalability and allow its implementation in an industrial environment will be defined.

### 4.3 Manufacturing Processes Optimisation

**Process development for friction stir welding of steels and dissimilar joints**

Specific objectives:

- Development of FSW for joining high strength steels, dissimilar materials and sheets with dissimilar thicknesses and for joining of large thickness plates.
- Better understanding of the metallurgical and mechanical characteristics of FSW joints of steels, high strength steels and dissimilar joints (dissimilar materials and thicknesses).

A flexible and low-cost method for friction stir welding of steels and joints with dissimilar materials and thicknesses will be developed. The materials and material combinations present in the demonstrators will be welded:

- the high strength steels of interest for the end users HIAB and HORSE,
- sheets with dissimilar thicknesses, of interest for GRANALU and HIAB,
- dissimilar materials (aluminium-steel), of interest for GRANALU,
- dissimilar materials (cast iron-steel), of interest for HORSE,
- and dissimilar materials present in TWBs, more specific aluminium and steel, and dissimilar steel combinations.

For welding of aluminium to steel, the friction stir tool profile will be optimised in terms of geometry. For friction stir welding of steels, also tools with improved materials will be used.

A cost-effective solution will be obtained by the use of a specially designed FSW head to produce the welds, which will be mounted on the TRICYLON Monarch robot, allowing to create 3D friction stir welds for the intended applications.

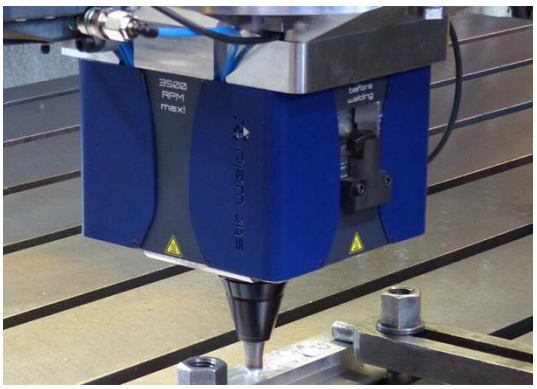


*FIGURE 16. FSW HEAD CONCEPT OF STIRWELD*



*FIGURE 17. MONARCH ROBOT CONCEPT*

FSW tool design

Specific objectives:

Design of FSW tools for:

- FSW of tailored blanks made of high strength steels, sheets with dissimilar thicknesses and dissimilar materials,

- FSW of cast iron to high strength steel parts,
- FSW of steels with large thicknesses (>6 mm, double-sided weld).

Weld quality and tool wear are two important considerations for the selection of tool materials, whose properties which may affect the weld quality by influencing the heat generation and dissipation. The tool geometry affects the heat generation rate, traverse force, torque and the thermomechanical environment experienced by the tool. The flow of plasticised material in the workpiece is affected by the tool geometry as well as the linear and rotational motion of the tool. Important factors are the shoulder diameter, shoulder surface angle, pin geometry including its shape and size, and the nature of the tool surfaces.

Tools for FSW of the above-mentioned materials and material combinations will be designed and produced by Element 6.

Weldability investigations

Specific objectives:

- Investigation of the influence of the FSW process parameters on the joint quality.
- Determination of the process parameters to create high quality welds, maximising the travel speed (and the subsequent forming behaviour for the TWBs),
- Generation of knowledge concerning the joint properties (mechanical properties, quality, metallographic structure, hardness, etc.), also to be used later as basis for FSW real time quality monitoring.

FSW will be used for joining the materials and sheet thicknesses defined by the end users HIAB, GRANALU and HORSE. Element 6 will provide input about the FSW tools to be used and guidance about the FSW process parameters. SSAB will support this task with its expertise about the steel behaviour during and after welding. SSAB will also provide the high strength steels to be welded. For the execution of the experiments of the experimental matrix, several optimisation steps will be conducted. During optimisation, the process parameters will be varied for optimum joint quality and optimal bending behaviour (for the TWB). The parameter measurements during the optimisation steps will be used for evaluating the impact of the parameters on the joint properties. The required number of optimisation steps depends on for example the joint type, the material combination, etc.

The joint properties will be investigated as a function of the process parameters, in order to evaluate the technical feasibility of FSW to join the selected materials, material combinations and thickness combinations. Tables will be prepared with the optimal parameter settings to be used for creating joints with optimal quality and optimal forming (bending) behaviour. For each material, material combination and sheet thickness combination, the “window” of operational parameters will be determined for achieving defect-free joints.

Weld quality assessment will be used to define the response variables (such as weld efficiency, weld properties etc.) and to evaluate the weld quality. The statistical methodology shall finally be used to identify how a particular process parameter affects the weld performance and which interactions between process parameters occur. The parameter measurements during the optimisation steps will be used for evaluating the impact of the parameters on the joint properties.

The welding trials will be subdivided between BWI and STIRWELD. STIRWELD will focus on the material combination stainless steel-aluminium and will use its FSW

equipment. BWI will focus on FSW of steels, high strength steels and on dissimilar steel combinations.

The work will be subdivided in the following subtasks:

- Parameter optimisation of FSW of steel-aluminium joints [STIRWELD]
- Parameter optimisation of FSW of high strength steel [BWI]
- Parameter optimisation of FSW of steels with dissimilar thicknesses [BWI]
- Parameter optimisation of FSW of steel with large thickness [BWI]

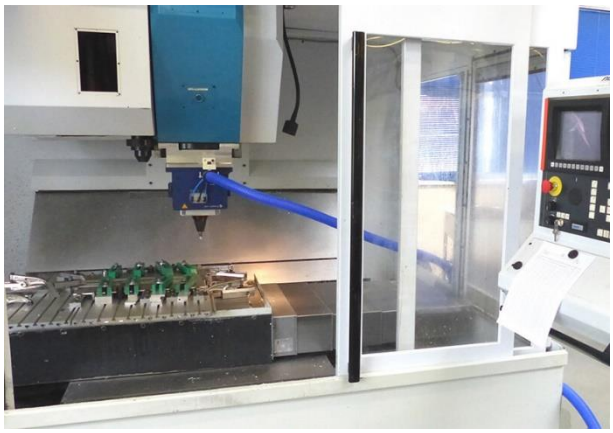


*FIGURE 18. STIRWELD FSW EQUIPMENT*

Optimisation of the forming process for tailored blanks welded by FSW

Specific objectives:

- Optimisation of the forming process of the tailored welded blanks for the highest performance during and after bending, for the specified applications (HIAB's demonstrator).
- Numerical model of the bending process able to predict the tailored welded blank's mechanical performance and to reduce the amount of experimental testing.
- Optimize material properties through complex welding paths taking into account subsequent manufacturing operations such as bending.

The range of benefits of tailor welded blanks includes better use of the material in load bearing structures as well as weight reduction through the possibility to use sheets with different thicknesses and materials. Furthermore, TWB provides greater flexibility for component designers. However, this has the major disadvantage that forming these TWBs. The forming behaviour of TWBs is critically influenced by different parameters:

- thickness and material combinations of the blanks welded,
- weld configuration, such as the weld orientation,
- weld location in the part,
- weld properties, represented by for example the stress-strain curve.

The impact of the above-mentioned parameters on the tensile and forming behaviour of TWBs, more specific the stress-strain curve, the fatigue behaviour, face-bending vs back-bending asymmetry, and weld line movement, has been studied by different authors. Major efforts have to be undertaken to improve the failure prediction, since

computer simulation allows to ensure a successful forming process. By managing the positions and the joint properties by controlling the FSW parameters, a new generation of TWBs can be created, leading to more lightweight components.

Through a proper combination of sheets with different thicknesses and materials like aluminium-steel, a better material usage efficiency can be obtained and the structural performance of the TWB structure can be improved considerably, and the number of structural components can be thus reduced. In this regard, the relatively new FSW joining technology offers interesting opportunities to improve TWBs. Besides the environmental advantages of this process, it also allows joining of dissimilar materials.

*Optimisation of the formability*

In order to evaluate the feasibility of FSW for TWBs, the forming behaviour during forming (bending) will be examined using different joint orientations related to the test setup. The bending process of the TWBs will be optimised for the highest performance and will consider the potential placement of the welded joint in the final application. Therefore, specimens in which tension will be introduced at the bottom and at the top of the weld will be manufactured. Static and dynamic (fatigue) behaviour of the resulting TWB will be studied in bending mode. As a result, the optimal weld line locations and orientations will be determined. Tooling will be designed, to ensure that the final parts can be safely bended without failure. Since the TWBs can consist of sheets of different thicknesses and materials, a method will be developed to compensate for these differences during the forming process. This will be achieved by the creation of a numerical model of the stamping process, able to predict the TWB's bending behaviour with a high level of detail. This methodology will be effective to improve the overall performance of multi-material TWB structures and provides useful guidance for the structural design in industrial engineering.

*Numerical simulation of the forming process*

In order to reduce trial-and-error experimental work and costs, simulation of the forming process of TWBs will be performed, which will include a feasible methodology or theory for evaluating the bending characteristics of TWBs. In the simulation, the weld characterisation will support the modelling, in order to obtain an accurate prediction of the strain behaviour of the weld seam.

The numerical model will be also correlated with the information related to the strain limits and failure behaviour of the lab-scale samples, allowing to deal with complex-shaped parts. Furthermore, this will allow assisting the definition of the tooling for the bending trials. The obtained physics-based models will be used for the definition of relevant demonstrators that implement friction stir welded TWBs in real applications in the heavy machinery industry.

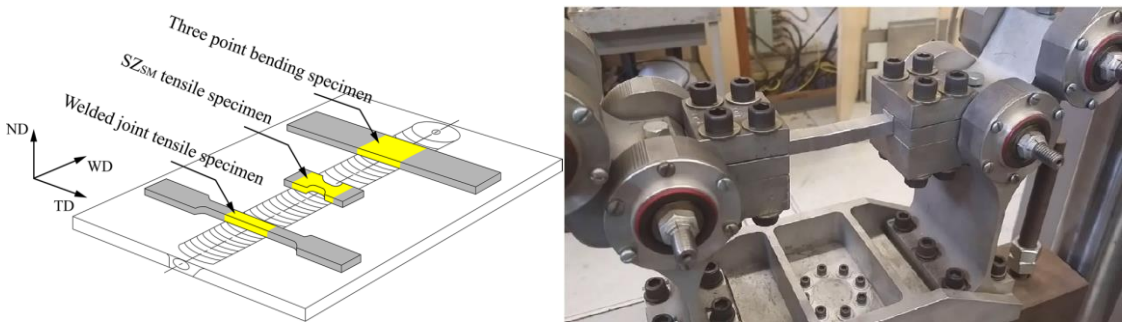



*FIGURE 19. PROCESS FOR THE LAB SCALE OPTIMISATION OF THE FORMABILITY OF FRICTION STIR WELDED BLANKS WILL INCLUDE DEDICATED COUPON DESIGN (LEFT) AND BENDING TESTS (RIGHT)*

*Experimental trials and bending process optimisation*

The experimental results will be used to calibrate the model. To investigate the influence of different weld orientations, weld positions and different mechanical properties of the welds in the final parts, bending tests with the previously will be performed by CIDAUT and HIAB. The data obtained will make it possible to refine the simulation model using a greater variability of cases. The goal is to determine the optimal FSW parameters regarding the forming behaviour.

# 5 Demonstrators

To recapitulate, STWIN addresses three industrial sectors of large importance within the steel industry: automotive, transport and loader cranes. Under this umbrella the project sets out a strategy based on automation and digitalisation of the friction stir welding process to be applied to three specific products of the above-mentioned sectors. These three applications cases will be represented in the project through the following demonstrators:

## 5.1 Loader Cranes

STWIN will focus on exploring the feasibility of applying friction stir welding in the manufacture of HIAB loader cranes, specifically on 1) the backside joint of the column (detail: see Figure 20) and 2) the joint between the reinforcement plate and the crane arm (detail: see Figure 21). In general terms, HIAB cranes are characterised by the fact that they are made of high-strength steel, in particular S700, and are constructed from tubular profiles.

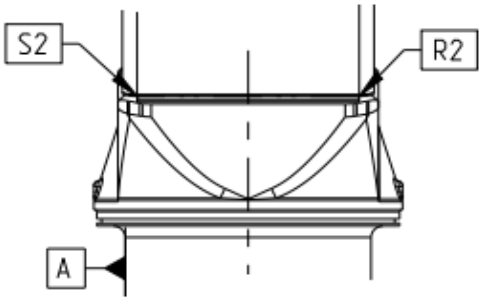



*FIGURE 20. DEMONSTRATOR 1*

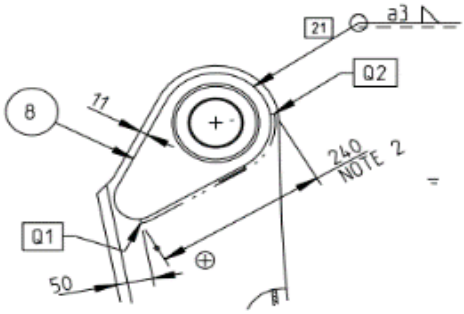



*FIGURE 21. DEMONSTRATOR 2*

In view of the details and particularities of the demonstrator, the difficulty of getting it done lies in the FSW tool being in continuous contact with the materials to be welded. Since the 3D profiles are extremely tight and with small radii, there is a risk of a lack of physical touch between the FSW tools and the parts to be welded. STWIN will meet this challenge with an investigation that explores the possibilities of the FSW process, considering the profiles used, the capabilities of the FSW machine and the tools to be used. Under this approach the methodology to be followed will be divided into two axes:

- On the one hand, the minimum radius that can be welded by FSW will be investigated using bent plates representative of the crane column profile. This work will be carried out in the framework of demonstrator 1.

- On the other hand, several butt-welding test will be carried out between plate of different thicknesses using the FSW process. These tests will be executed as part of demonstrator 2.

In parallel to all this, specific acceptance criteria will be specified for the FSW process in high-strength steel. As there is no EN ISO standard describing them, a set of criteria will be established on the basis of the results obtained in the investigation. For this, HIAB will be supported by SSAB and E6.

## 5.2 Automotive assembly (vehicle differential)

In this demonstrator, STWIN will apply the FSW process to an automotive component, in particular, a differential gear. The differential is a mechanical component located in the drive axle of most vehicles that essentially transmits torque to the wheels. In the case that applies to the project, the differential is made up of a cast iron housing and a carburized steel crown wheel. The integration of the two parts is now done by laser welding, replacing the bolts and nuts that were used in the past (see Figure 22). STWIN will go one step further and apply the FSW process to join the two components.

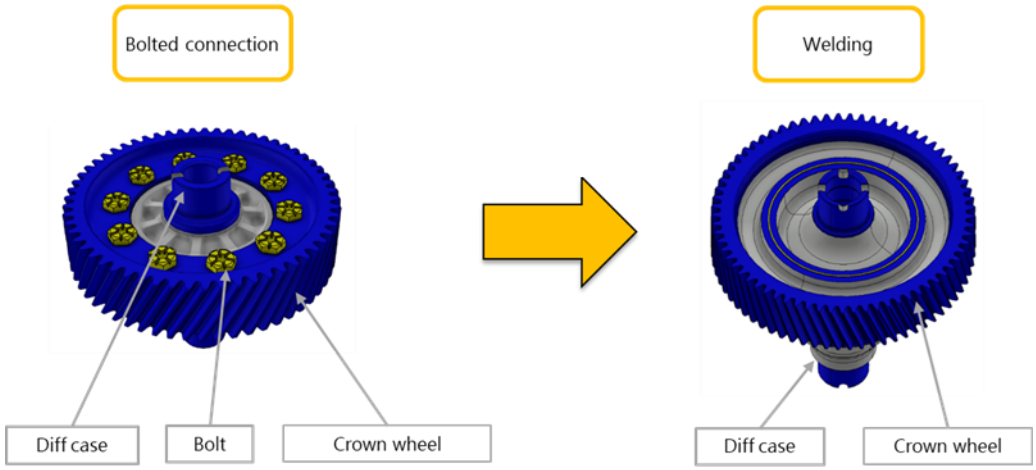



*FIGURE 22. DIFFERENTIAL GEAR DEMONSTRATOR. PREVIOUS (LEFT) AND CURRENT (RIGHT) CONFIGURATION*

STWIN will address the challenge of welding cast iron due to the presence of graphite in its microstructure, that hinder the generation of frictional heat for a successful weld, with an investigation of the process. Broadly speaking, the graphite flakes present in the microstructure of the cast iron act as internal lubricants during the FSW process, reducing frictional heat generation. STWIN will dive into the parameters and procedure to be executed for a more reliable application of the FSW process to cast iron welding. Given the known challenges of welding cast iron, an alternative demonstrator has already been planned, consisting also in the substitution of laser welding by FSW. In this case, a rotor shaft weld would be targeted, joining hot rolled steel (SP221P) to carbonitrided steel (27MnCr5) in butt configuration, as shown in Figure 23.

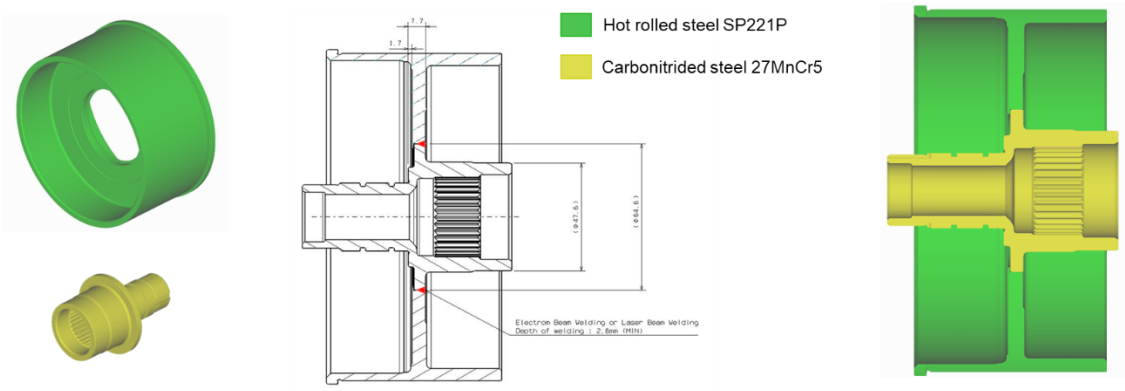
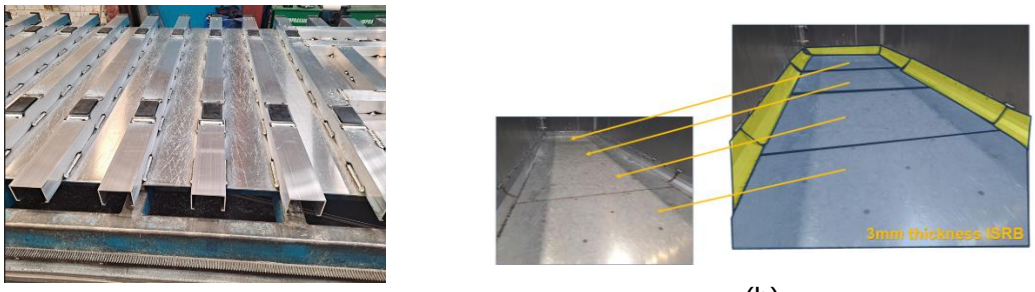



*FIGURE 23. ALTERNATIVE HORSE DEMONSTRATOR.*

## 5.3 Multi-metal Trailer

STWIN will also investigate the feasibility of joining dissimilar materials, particularly inox steel and aluminium of different thicknesses, by friction stir welding. In doing so it will be used an aluminium semi-trailer reinforced with inox steel plates on the floor. At present, the semi-trailer configuration offered by GRANALU to its customers integrates the steel reinforcement to the aluminium structure with bolts. This reinforcement is bolted both to the floor, in order to fix their position, and to the sidewalls of the semi-trailer as shown in Figure 24, therefore there is a double opportunity for the assembly process improvement thanks to FSW. For this purpose, a pilot configuration will be developed with the Monarch robot, the STIRWELD head and E6 tools.




(a) (b)

*FIGURE 24. CURRENT CONFIGURATION OF THE MULTI-METAL TRAILER DEMONSTRATOR. (A) VIEW OF THE FLOOR, (B) VIEW OF THE SIDEWALLS*

The different mechanical properties and melting temperatures of aluminium and steel will be considered in an experimental investigation with field work and simulations.



*FIGURE 25. GENERAL VIEW OF THE TRAILER DEMONSTRATOR*

# 6 Risks Identification and Contingency Plan

Broadly speaking, the risk management is based on maximising the chances of project success by identifying risks and planning how to manage them. To better understand how these steps will be addressed in STWIN, here is explained the strategy that will be followed to identify risks, and then the measures that will be taken to minimise their effects.

## 6.1 Risk assessment. Preliminary risk identification

Risks arise in projects due to various reasons, e.g. excessive schedule pressure, poor communication etc. Addressing risks is crucial to guarantee the success of the project, and this is where risk assessment comes into play.

In a brief way, in STWIN the risk assessment process will be carried out sequentially according to the following phases:

- **Risk identification**: The analysis of the possible risks that could affect the progress of the project will be the first step to be done. To this end, it will be taken into account that risks can be internal or external and positive or negative. CIDAUT, as coordinator, will promote workshops to exchange ideas and detect risks at key dates of the project. To serve as guide, this activity has already carried out during the proposal, and resulted in a number of risks related to the method and impact, among others (see Table 2).
- **Risk rating**: It is the second step and involves evaluating the risks that have been identified and prioritizing them based on their probability and impact. To do this, it is defined to use a qualitative approach (high, medium, low) in order to facilitate the execution of this practise. Indicatively, the order of priority will work as follow:
    - **High (H)**: These will be critical risks that may affect the success of the project, or at least a combination of WPs. These risks will be managed by the Coordinator.
    - **Medium (M)**: These risks will have medium consequences and may affect a specific WP. WPLs will manage these risks after informing the PC.
    - **Low (L)**: These risks will only affect the outcomes of a particular task. Tasks leaders will manage these risks after reporting them to the WP leader.
- **Risk mitigation**: In broad terms, mitigation implies developing and implementing strategies and actions to reduce or eliminate the probability and impact of the risks. Within this phase, for each risk, it is established to identify the best mitigation strategy, the responsible partner and the expected outcomes. The results of this activity will be discussed with the entire consortium in different events.
- **Risk monitoring and review**: This is the last step and consists in reviewing the risks throughout the project. In short, monitoring and review involves collecting and analysing data and information on the status of the risks, and comparing them to a baseline and expectations. This activity will help identify any deviations or changes in the risk environment, and adjust mitigation plans accordingly.

Finally, if after complying with the proceeding it is detected that there is a high probability that a certain risk will materialise, the contingency plan associated with the risk will be

implemented. This will imply a greater workload for the Coordinator, as he will be responsible for monitoring whether the measures are effective. If the Coordinator determines that the plan fails to mitigate the risk, then the consortium will need to make adjustment to the plan.

*TABLE 2 RISKS IDENTIFIED DURING THE PROPOSAL*

| # | Type | Description | WP(s) | P | I | Mitigation Strategy |
|---|---|---|---|---|---|---|
| 1 | ADO | Inability of partner to commit required resources and time to the project. | WP1 | L | M | All partners are fully committed. If a partner fails to respond according to the plan, there will be alternatives e.g., the use of alternative project resources. |
| 2 | ADO | Delay of work plan execution. | WP1 | M | M | Regular meeting will be held to enhance the sound communications and the continuity of the project among the partners. In case of failure in the expected actions, the project management procedures will be reassessed. |
| 3 | TEC | Difficulties to monitor the weld quality in real-time using defined NDT methods. | WP2 | L | H | Increasing efforts in the instrument settings definition and the required conditions in order to ensure real time monitoring of the welded joints. |
| 4 | TEC | Dissimilarity between the NDT measurements and the destructive tests results. | WP2 | M | M | A redefinition of test methods will be considered. However, the expertise of both industrial and research partners ensure that the test will be carried out correctly. |
| 5 | TEC | Failure of welded joints according to the specifications set. | WP3 | L | M | If the welded joints do not perform well according to the established specifications, a redefinition of materials to be joined, thicknesses, surface properties... will be considered. |
| 6 | TEC | Welding tools not available, causing delay in deliverables. | WP3 | M | M | Propose re-planning of activities whenever necessary. Additionally, external datasets will be considered to start building the Digital Twin. |
| 7 | TEC | Data required to feed Digital Twin is not available, insufficient or incomplete. | WP4 | L | H | In the absence of data, external datasets, such as Open Data sources, will be used and processed to build the Digital Twin. |
| 8 | TEC | The available data is insufficient to build accurate Digital Twin models. | WP4 | H | M | In case of insufficient property datasets, missing data can be estimated exploring patterns exhibited by available data. |
| 9 | TEC | Lack of correlation between simulation and the part forming behaviour. | WP4 | M | H | This risk will be addressed by collecting more experimental data and re-feeding simulations. Also, deviations between parts and simulations behaviour can be reduced by parameter fitting. |
| 10 | TEC | Poor demonstrators' behaviour due to failures in the prototyping phase. | WP5 | M | H | Establishing a redundant verification system during the prototype manufacturing to ensure the conformity of the parts with the high quality of the manufacturing process. |
| 11 | TEC | Advanced joints result in too expensive demonstrators. | WP5 | M | M | Industrial partners will start manufacturing the demonstrators as soon as the process specification are defined, giving feedback to research partners to optimise the parameters and reduce the cost associated, proposing alternatives. |
| 12 | ADO | Failure to engage external interest to the STWIN | WP6 | L | M | The industrial partners are already engaged in the consortium and will act as multipliers |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | activities. Failure to establish links with the industry. | | | | of innovation. In addition, STWIN will further strengthen dissemination efforts by the organization of events. |
| 13 | TEC | Market competition emerges before exploitation. | WP6 | L | M | On-going assessment of potential competitors throughout the project. |
| 14 | ADO | Confidentiality issues prevent the creation of a credible decision support platform. | WP3, WP4, WP2 | L | M | The consortium agreement will include a section dedicated to handle data where it will be considered confidential. |
| 15 | TEC | Availability of other/new technologies that may make the quality monitoring system developed obsolete. | ALL | L | M | The coordinator will constantly monitor other monitoring technologies and on-going projects addressing similar problems. Additional quality monitoring technologies will be adopted to build the DT platform, when possible. |

### 6.2 Amendment to the GA

While the fundamental objective of risk assessment is to mitigate potential risks, everyone is aware that innovative activities have a high component of uncertainty. As a consequence of this factor, it is sometimes necessary to amend the GA as the project implementation plan is affected. In this sense, the departures of CLN and VERWATER from the consortium have been a good example of this.

As a result of the decision of these two partners to decline their participation in the project, it was necessary to introduce an amendment which modified part of the original agreement. In particular, the tasks associated with CLN and VERWATER were amended according to the main activities and interests of the new partners who joined to the consortium (HIAB, E6, SSAB and HORSE). In addition, the excellence and impact sections were adapted to meet the requirements of the original template. These changes were incorporated into the original agreement with track changes, as directed by the European Commission.

In essence, this deliverable is a summary of the amended text in which all changes made in the research and reflected in the amendment are integrated. Thus, both the changes in the consortium and the new agreed demonstrators are taken into account. Note that, as a result of the changes in the partners, only the trailer demonstrator has been maintained. Both the new demonstrators and the new project approach following the amendment are described here.

For more details, see deliverable D1.1, which explains the procedure followed to request the modifications described above.

## 7 STWIN Management Plan

### 7.1 STWIN Project Organization

As the introduction previewed, STWIN has a working group made up of 10 partners of different nationalities from all over Europe. All partners were selected on the basis of the expertise required to fulfil the objectives set, as well as their influence within the metal industry (see Table 3 for more details).

*TABLE 3 STWIN CONSORTIUM COMPOSITION*

| Participant No. | Participant organisation name | Short name | Country |
|---|---|---|---|
| 1 (Coordinator) | FUNDACION CIDAUT | CIDAUT | Spain |
| 2 | HIAB | HIAB | Sweden |
| 3 | ELEMENT SIX | E6 | Ireland |
| 4 | SVENSKT STÅL AB | SSAB | Sweden |
| 5 | BELGISCH INSTITUUT VOOR LASTECHNIEK VZM | BWI | Belgium |
| 6 | INGENIERA Y SISTEMAS DE ENSAYOS NODESTRUCTIVOS SA | ISEND | Spain |
| 7 | STIRWELD | STIRWELD | France |
| 8 | HORSE | HORSE | Spain |
| 9 | TRICYLON ROBOTICS AB | TRICYLON | Sweden |
| 10 | GRANALU TRANSFORMACIONES SL | GRANALU | Spain |

While the heterogeneity of the consortium is a positive point, it can also lead to conflicts. With the purpose of ensuring that all the beneficiaries are on the same page regarding responsibilities and expectations, the following describes the contracts signed and the organisational structure to be followed.

### *7.1.1 Documentation*

The STWIN project is based on two contracts: the Grant Agreement and the Consortium Agreement. Whereas the Grant Agreement defines the rights and obligations related to the project, of the beneficiaries on one side and the EC on the other side, the Consortium Agreement deals with the rights and obligations between the beneficiaries themselves with regard to the execution of the project. That said, both documents serve as a framework for the development of the project.

In the project environment, the Grant Agreement defines the activities to be undertaken, the project duration, overall budget, rates and costs, the EU budget's contribution and all rights and obligations. Generally, this document is divided into 5 annexes among which the above information is distributed:

- Annex 1 – Description of Action (DoA)
- Annex 2 – Estimated budget of the action
- Annex 3 – Accession Forms
- Annex 4 – Model for the financial statement
- Annex 5 – Specific rules

The Project Coordinator is responsible for transforming the proposal into the technical annex (Annex 1). In fact, this section is the most important and is organised as follow:

- **Part A**: contains the workplan tables.

- **Part B**: is based on Part B of the application form and comprises the technical description of the project.

On the other hand, the Consortium Agreement is a contractual document approved by all beneficiaries. It regulates the commitments and obligations of the partners, the organisation and coordination, the internal operation of the project and the management of the results generated.

Far from being a mere formality, the Consortium Agreement is of great significance and can be of great use, especially when problems arise during or after project implementation. In essence, this contract aims to help to minimise risks and thus to achieve the project's objectives.

In the Consortium Agreement we find different parts and clauses that regulate such diverse aspects as:

- **General provisions**: identification of the partners, purpose and duration of the contract.
- **Responsibilities**: technical obligations, management of the results...
- **Organisational structure**: meeting, voting system, decision-making...
- **Economic provisions**: budget distribution, payment terms...
- **Ownership of results**: ownership, management.
- ...

### *7.1.2 STWIN Management Structure*

To sum up, the management structure is based on the following key pillars:

- Ensure that the project's contractual obligations are met.
- Ensure that the project management decisions comply with the project's priorities.
- Make easier to deliver high-quality research and innovation. For this purpose, the coordination of the technical tasks and the integration of their results are critical.
- Ensure and validate the project impact on both industry and the research community.

With that in mind, the organizational structure of the consortium comprises the following Bodies:

- The **General Assembly** (GA): is responsible for making strategic decisions, following project progress, initiating corrections and resolving conflicts. It is led by CIDAUT and represented by Mr. Javier Romo (project coordinator). Additionally, it has one representative from each entity in the consortium.
- The **Coordinator**: is the person who serves as liaison between the project and the European Commission. Among his functions are to ensure the punctual delivery of reports and deliverables, coordinate the consortium and perform risk management. In STWIN, Mr. Javier Romo (CIDAUT) assumes the role of Project Coordinator (PC).
- The **Work Package Leaders** (WPLs): are the people in charge of the coordination of the work packages. Basically, their responsibilities are to: (1) monitor the progress of the WP; (2) ensure that the WP is aligned with the general

budget; (3) meet milestones and deliverables and (4) alert the coordinator in case of any delay.

- The **Task Leaders** (TLs): are responsible for coordinating activities within their respective tasks. In addition, it is up to them to ensure that the deliverables are submitted on time. In STWIN, each task leader is obliged to report on progress and risks of the task to his/her WPL.

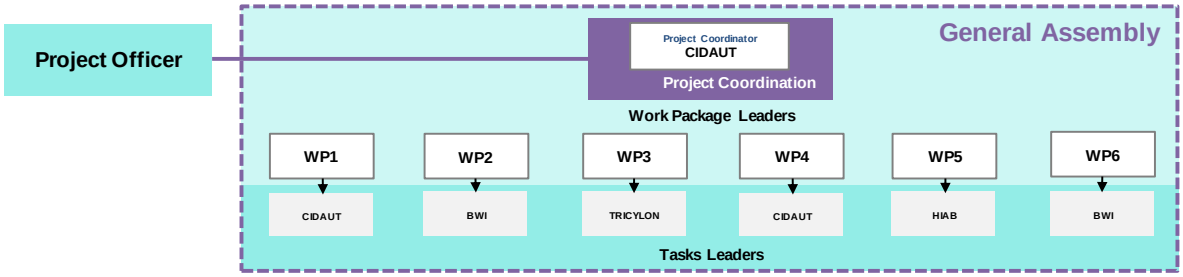



*FIGURE 26 STWIN MANAGEMENT STRUCTURE*

## 7.2 Project Meetings

In general terms, communication is critical to ensure the success of the project; that is why it is the responsibility of the coordinator to organise regular follow-up meetings. Basically, in these meetings the status of the project will be discussed from the point of view of schedule, scope, budget and risks. The information will always be presented in summary form, without going into detail, in order to give a quick overview of the most critical points. In addition, whenever feasible and appropriate, online meetings will be encouraged. This will ensure that all beneficiaries can attend.

At a high level, these ones are the meetings planned throughout the project (Table 4):

*TABLE 4 OVERVIEW OF STWIN'S MEETINGS*

| Meeting | Frequency | Participants | Objectives |
|---|---|---|---|
| Kick off | 2 days F2F meeting at the beginning | All partners | Launch project administration and financial matters. Review and confirm the work plan and timing. |
| General Assembly | 3 (F2F) meetings every 6 months.<br>Each one will have a duration of 2 days. | All partners | Follow up of the project development |
| Periodic review meetings | Follow up meeting every 6 weeks | All partners' representatives | Revision and discussion of the technical activities and results. Coordination among WPs. Review of budgetary issues. |
| WP & Task meetings | Varying frequency | WP/Task leader and participants | Technical aspects, procedures, technical results, progress in each task, inputs received from other WPs, etc. – referring the WP/Task. |
| Final meeting | 2 days F2F meeting at the end of the project | All partners | Revision of the project achievement and last Milestone. |

| | | | |
|---|---|---|---|
| | | | Agreement on the strategy to provide continuity of the project results. |

It shall be the responsibility of the attendees to actively participate in these encounters. In addition, the organiser of the meeting has the obligations to (i) plan and coordinate the agenda, (ii) steer the discussions and (iii) create an environment in which all attendees feel comfortable. On the other hand, the organising entity will be responsible for recording key points discussed during the meeting and distributing the notes to the entire consortium. The performance of these functions will ensure that the sessions are effective and that everything runs smoothly.

## 7.3 Project Repository

With a view to making it easier for beneficiaries to exchange information, the Coordinator has enabled a collaborative workspace in MS Teams. The members invited to this workspace can use the web interface or the desktop application to download and upload documents, as well as to edit files directly in the Teams area. In fact, the tool allows several team members to work simultaneously on the same document.

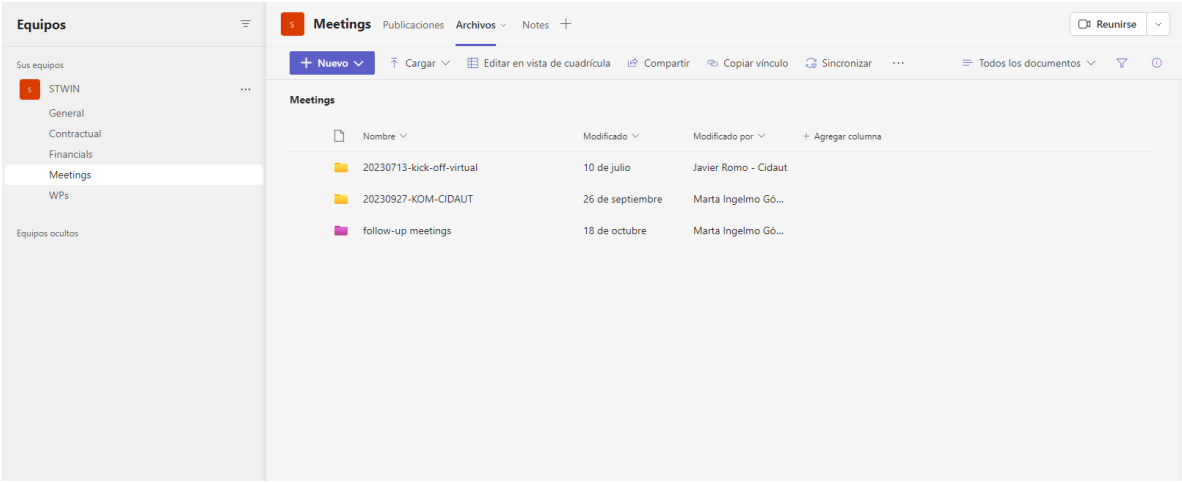



*FIGURE 27 MS TEAMS AREA*

In relation with the structure, the space has different channels where member can generate posts and comment on them, specifically the following:

*TABLE 5 MS TEAMS CHANNELS*

| Channel Name | Description | Primary audience | Access rights |
|---|---|---|---|
| General | General files for all Consortium | All team members | All team members |
| Contractual | Contractual documents (GA, CA and amendment) | All team members | All team members |
| Financials | Project Financials | Financial Officers | All team members |
| Meetings | Overview of the project meetings, presentations, agendas and minutes | All team members | All team members |

| | | | |
|---|---|---|---|
| WPs | All WPs deliverables, shared documents, meeting related files, planning information and posts related to the progress of WPs should be included here. | Partners collaborating with the WPs | All team members |

Only the Coordinator has the power to create new channel or delete the existing ones. In case a partner requires the creation of a new channel, he/she must inform the Coordinator.

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