# 5G Enabled Manufacturing
# 5GEM

# Final Report

Consortium:

Ford – Vodafone – VFE – TWI – ATS – HSSMI – TMForum – Lancaster University

Date: October 2022

# Foreword

As part of the UK's 5G test bed and trials program, 5GEM has provided Ford, it's partners and the wider UK 5G community with valuable insight into the application of 5G within the manufacturing environment.

As we progress on our Industry 4.0 journey, managing and then transferring the ever-increasing amount of crucial manufacturing data becomes significantly more challenging. Whilst the challenges of technology to collect and organise our shopfloor data are the primary focus, it's also critical to consider how best to transmit this data, as it grows in volume. The 5GEM pilot has highlighted key areas in which 5G supports the manufacturing environment, where manufacturing differs from other 5G use cases and where attention must be paid to develop 5G for widespread industrial application.

The use cases are early indicators of the power of being able to move data around the shopfloor so effectively. These are critical to the growth of Industry 4.0 and from a Ford perspective, facilities that can accelerate the electrification of our products

I would like to take this opportunity to thank the Ford team, our consortium partners and the team at DCMS for their support. This project would not have been possible without the wider team. The findings and insights are much richer as a result of the consortium-based approach.

Thank you.

Lee Turner

Powertrain Manufacturing Engineering Director

Ford Motor Company.

# Executive Summary

The team began designing and constructing the Ford and VFE Mobile private network in 2019.

Telecommunications and manufacturing experts across the project soon came to realise how much they needed to learn from each other. The expectations and assumptions took some considerable time to align, and our first recommendation would be not to underestimate this.

Despite these early incompatibilities and the pandemic, the team made excellent progress in installing a fully operational network in two manufacturing environments. Again, both sides learnt that (presently) this takes considerably more effort than commonplace WiFi solutions. The technology must evolve to become more shopfloor hardened, modular/preassembled and reconfigurable around the flexible manufacturing environment.

Considerable attention must be paid to network requirements and design. The manufacturing teams soon understood that 'wireless' systems must become wired at some point and detailed analysis of the use cases will avoid costly network mistakes or deficiencies. Having the 5G split across two distant sites was particularly challenging- especially as the Dunton site did not have an existing network connection,

Once live, the network was assessed from a safety perspective. Mindful of negative 5G publicity, the team worked to ensure those whose workplace was involved, understood the technology and the assessments that were made to confirm zero risk. By immediately briefing teams and working to address concerns, the facility switch-on was well understood and welcomed by those who worked around it.

The Ford use cases were heavily related to the production of electric vehicles. These applications are 'data-hungry' but it is true of all manufacturing applications, as we migrate to the 'factory of tomorrow'. Welding continues to be a central challenge in making e-drives and batteries. Solutions to handle the data involved will be key. 5G proved itself capable of that challenge, but it should also be stated that other technologies are more industrialised and economical. It remains to be seen, how quickly the technologies demonstrated her (Vision, AR etc) spread within industry and whether existing data management solutions can keep pace. Throughout the project, the market has developed in terms of 5G devices, networks and protocols 5G may well begin to challenge our traditional methods to connect the shop floor. VFE's use cases demonstrated that equipment suppliers can play a part in this transition by finding new offering in terms of supporting customers.

Partners were heavily engaged in understanding security and standards for moving industrial data around the factory safely and efficiently. TM Forum identified the need for standard for this data transfer. Ford has chosen to develop internal standards, rather than drive a global industrial standard. This is perhaps understandable, given the lead-time required to driving towards an industrial standard. The project has demonstrated the need for such a standard, going forward. Without this, integrating our solutions has been challenging and inconsistent.

The use of AR to supply remote expert assistance clearly took a step forward with the use of 5G. This is another area where compatible devices were problematical at first. However, the trials that were carried out have demonstrated capability of such systems. Events such as the pandemic and the war in Ukraine have highlighted how having experts present on the shopfloor will not always be possible.

In summary, Ford was looking to assess how well 5G might address some key needs within the business and this is summarised in the table below:

| Current State | Future State | Conclusion |
|---|---|---|
| Fixed connections take too long to complete, maintain and validate | Safer, faster connections that can be validated prior to delivery | The project team experienced connection issues, but once solved, SIM provisioning was relatively straightforward.<br>However, this process is still only possible to validate once the equipment is on-site. It is not possible to test the equipment's connectivity unless a duplicate MPN is set up. |
| Equipment cannot be easily reconfigured or moved during production | Reconfigurations without network updates, constant data from moving equipment | Demonstrated that the network would not need updating if the machine/device moved locations in an area covered by the MPN. Portable devices were successfully deployed. |
| Remote expert access is only possible via the Ford network-cyber security risk | Equipment communication with manufacturers and experts | The security work package warned of the MPN being considered as a security panacea. The project team held several discussions with Vodafone and other parties about the opportunities for well-designed network management tools. The most significant challenge remains in allowing suppliers to access their equipment and not the equipment of other suppliers on the same network. |
| Data connections, decision making and analysis is dispersed across the shop floor based computers | Provide more robust and manageable centralised remote computing | The project successfully moved data to the ATS Cloud for Lancaster Uni to access and process. This suggests the hardware could support removing the shopfloor computers. The greater challenge appears to be managing such data effectively. |
| Physical limitations on the amount of data that can be transferred and stored | New and increased amounts of data traffic accommodated | Data transfer was demonstrated, but projections showed that significantly more upload was required than download, which was opposite to most 5G uses cases and the MPN configuration. |

Overall, the testbed demonstrated the differences between the industrial environment and some of the other applications of 5G. Vodafone have learnt a significant amount about the needs of an industrial customer, and this will shape future 5G offerings.

# CONTENTS

# 1.0 Introduction

## 1.1 5GEM Consortium

The 5GEM project and consortium was initiated following discussions between Ford and Vodafone regards the benefits of 5G networks. This discussion grew to include HSSMI[1], a long-term innovation partner of Ford in the UK. Ford and HSSMI had been talking about a Laser Application Network of Excellence (LANE) for Electric Vehicles and applying to the APC[2] for funding of research. This then brought The Welding Institute (TWI) and their partnership with Lancaster University, known as the Joining 4.0 Innovation Centre (J4IC), into the discussions.

Parallel conversations with Digital Catapult and the opportunity for funding from the Department of Digital Culture Media and Sport (DCMS) resulted in forming a consortium of eight companies. The members of the consortium are listed below.

**Ford Motor Company Ltd.** An automotive manufacturer;

**Vodafone** a mobile network operator and provider;

**Vacuum Furnace Engineering (VFE)** a market-leading provider of maintenance servicing for heat treatment industry equipment including vacuum furnaces, pumps and autoclaves;

**ATS Global** specialists in digital transformation using software design, agile development, and lean methodology to produce continuous, sustainable improvement;

**TM Forum** a telecoms and technology companies association focusing on collaboration, collective problem solving and innovation;

**HSSMI** a sustainable manufacturing consultancy specialising in scale up, digitalisation and circular economy;

**TWI** experts in joining technology and non-destructive testing (NDT)

**Lancaster University** have expertise in data structure, processing, security and management through the J4IC.

## 1.2 5GEM Objectives

The 5GEM project was focused on two, high-level industrial use-cases:

1. the E:PriME Electrification pilot plant based at Ford's Dunton Campus and specifically the laser welding processes;

2. a vacuum furnace facility at TWI near Cambridge supported by VFE.

Figure 1 shows the five areas of technology the 5GEM project would tackle in the use-cases.

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[1] HSSMI = High Speed Sustainable Manufacturing Institute
[2] APC = Advanced Propulsion Centre

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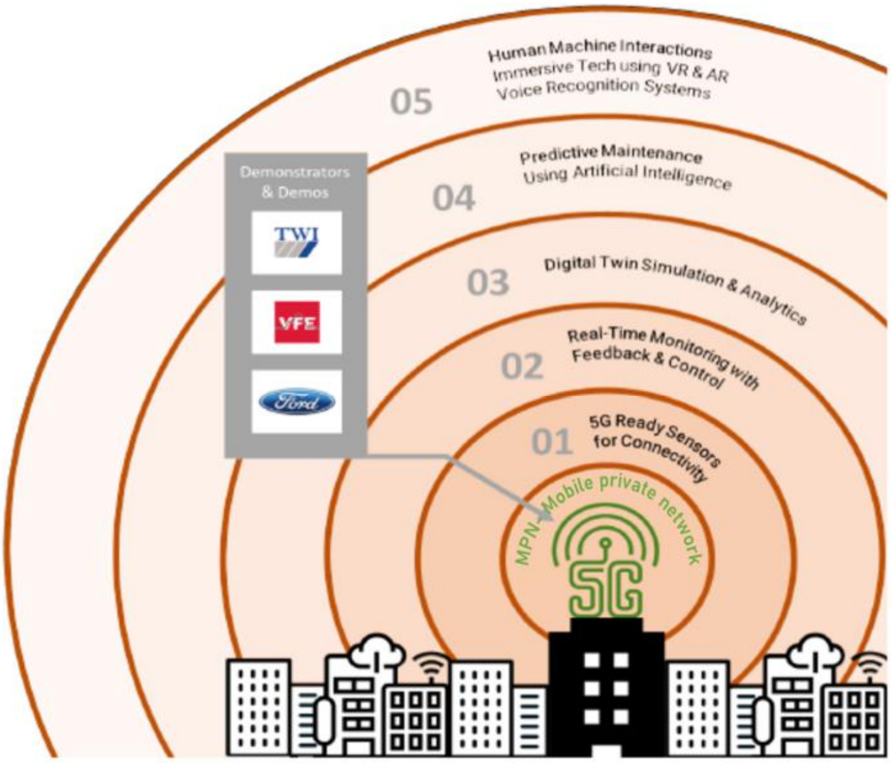



*Figure 1: Five use-cases of 5GEM project*

### 1.2.1 Ford objectives

Figure 2 below is taken from the original business case presentation and describes the benefits which were envisaged at the start of the project.

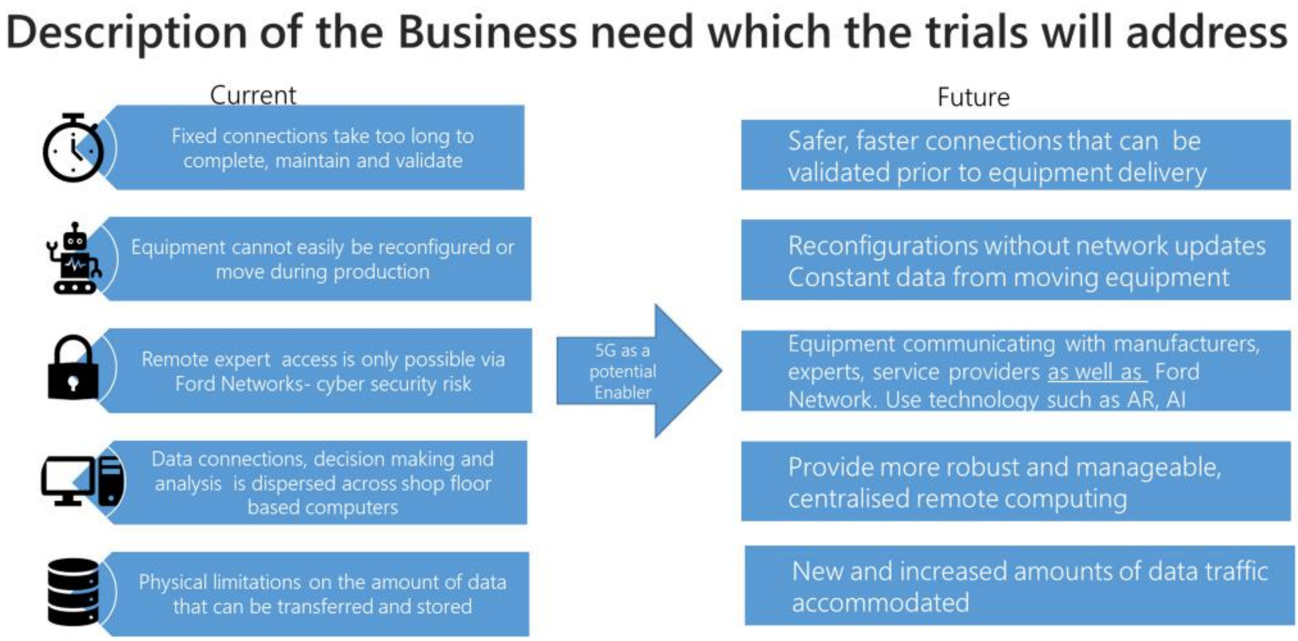



*Figure 2: Business case*

Ford's interest in laser applications meant that the use-cases for the E:PriME pilot plant would be focussed on it's laser welding machines. One machine is used for welding together the tabs of the battery cells in a battery module assembly line. This is described in more detail in section 2.2.3.

The other welding machine joins the "hairpins" in the stator of an electric motor. Once joined, the hairpins form the copper conductor of the stator coil (often known as the "winding"). More details on this process can be found in section 2.2.5.

A summary of the expected benefits the 5GEM project could bring to the laser welding process are shown in the figure below.

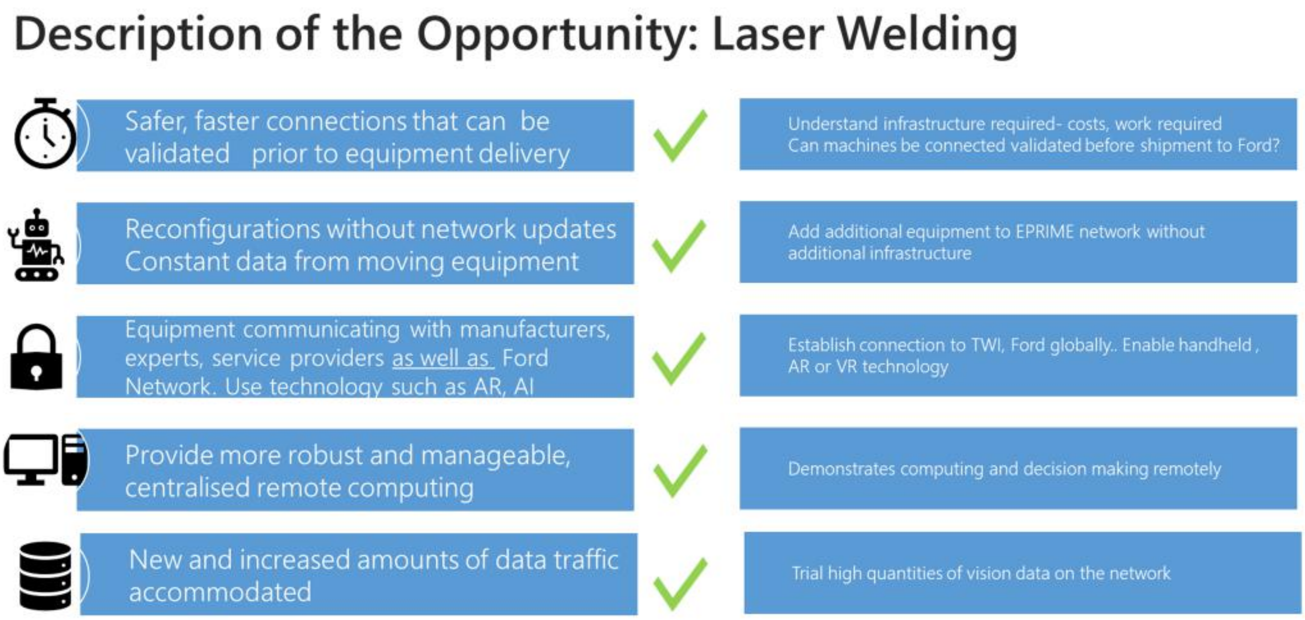



*Figure 3: Opportunity summary*

### 1.2.2 VFE Objectives

In figure 4 below the data flows in the VFE use case are shown.

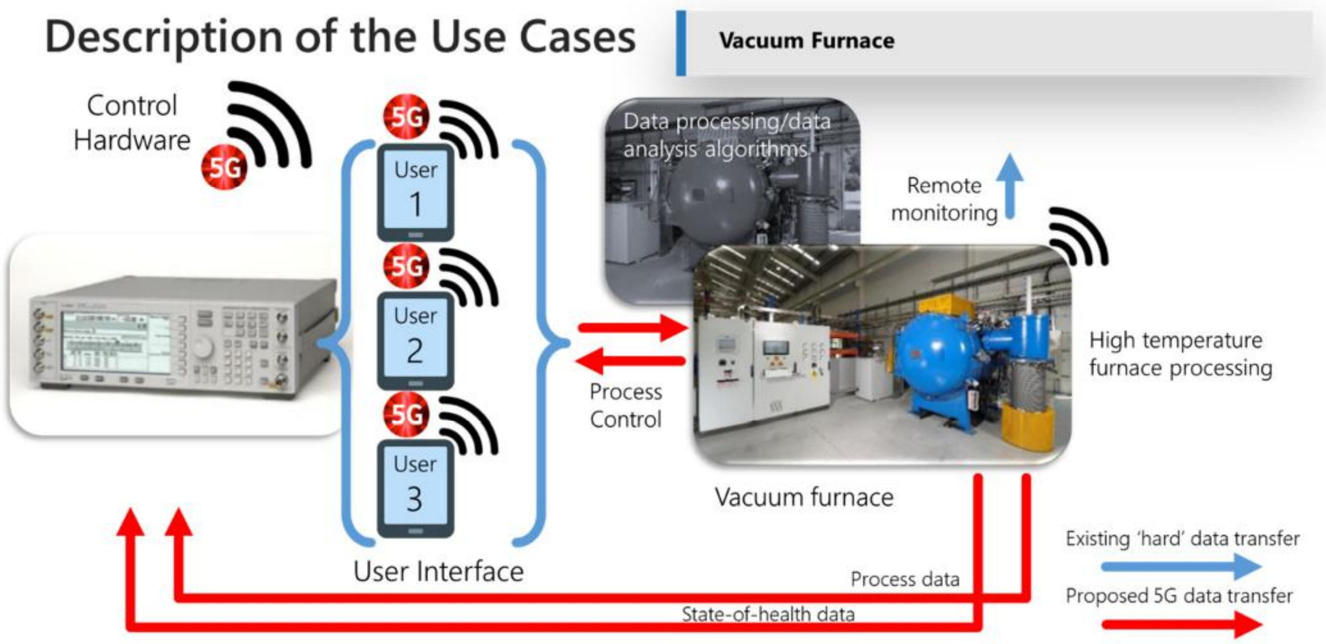



*Figure 4: VFE data flow*

The 5G solution proposed ultimately supports productivity enhancing services for our customers and will create a methodology for future adoption of the core technology for other advanced manufacturing capabilities:

Key Benefits:

- Enabling real-time monitoring, off-site engineering and support
  - Quicker troubleshooting and improved diagnostics
  - Better planning of service delivery – reduced business costs through travel and resource optimisation
  - Reduce downtime - Save £1000's/day to £100,000's/day depending on application
- Automated maintenance scheduling, enabled by new sensors, artificial intelligence and machine-to machine (M2M) communications, will reduce disruptions to production caused by breakdowns.
  - Move to intelligent maintenance
- Reduced cost of hardware - physical wiring and installation requirements by 50%
- Provide productivity enhancing services
  - Reduced downtime from faults
  - Reduced downtime with servicing
- Reducing the lead-time to launch or reconfigure facilities by eliminating the lead time to install and validate fixed data connections by 20%
  - Particularly relevant to sale, installation and servicing of second-hand furnace units.

# 2.0 Work Carried Out

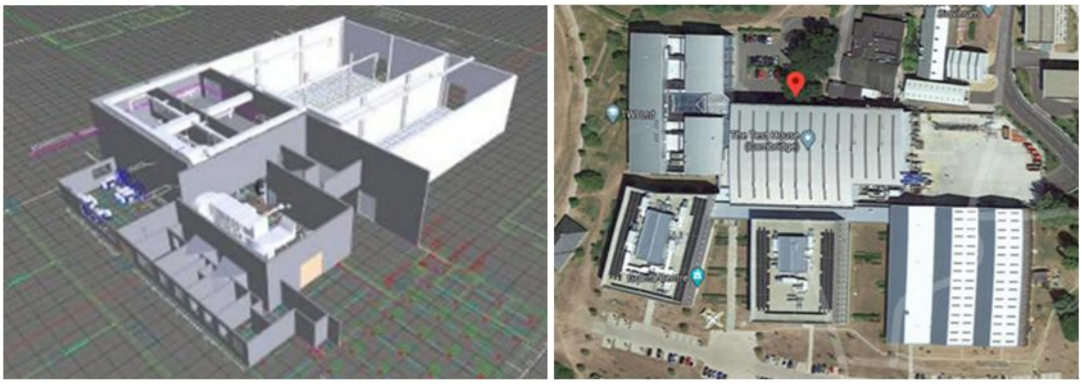
## 2.1 Network (Vodafone)

The first stage of the project was to build a private 5G network – also known as a Mobile Private Network (MPN) – at the two project locations:

- Site 1: Ford Motor Company – Dunton Campus, Essex
- Site 2: The Welding Institute – Granta Park, Cambridge

Vodafone constructed the MPN using 5G equipment supplied by Ericsson – comprising a 5G Non-Standalone Core (located at the Ford site) and 5G New Radio "dot" antennas installed at both locations (Ford and TWI). The two sites (50 miles apart) were connected via an IP-VPN link such that they both used the same 5G Core – resulting in a single 5G network (the same "logical" network) existing at two different "physical" locations, 50 miles apart.

This was the first time such a "multi-site" solution (a Mobile Private Network providing 5G coverage at two different locations) had ever been done. See figures 5 & 6 for site images and layouts.



**Site 1: Ford Motor Company** **Site 2: The Welding Institute**

*Figure 5: images of the sites*

Vodafone provided licensed radio spectrum: 20MHz Band 38 (2600MHz TDD) and 40 MHz Band N78 (3.5GHz TDD) at each location.

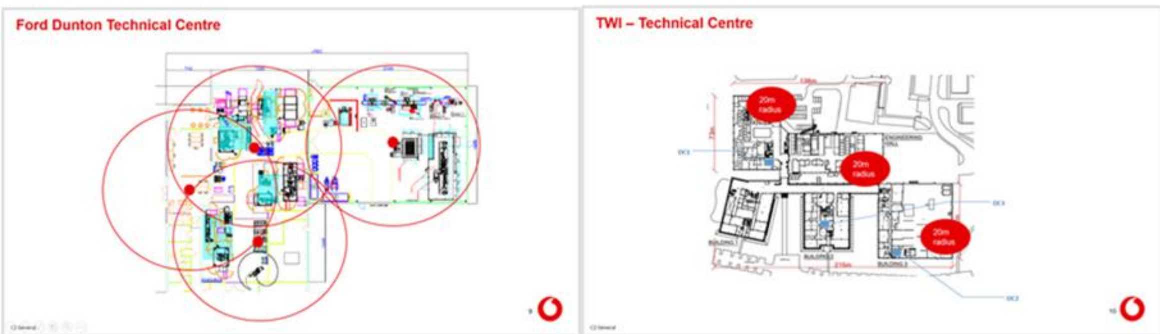



*Figure 6: Site layouts*

Vodafone provided private SIM cards for use with the Mobile Private Network. The SIMs used a private IMSI range and the network broadcast a private PLMN ID.

Figure 7 below describes how the two site networks come together and the unique elements of the network.

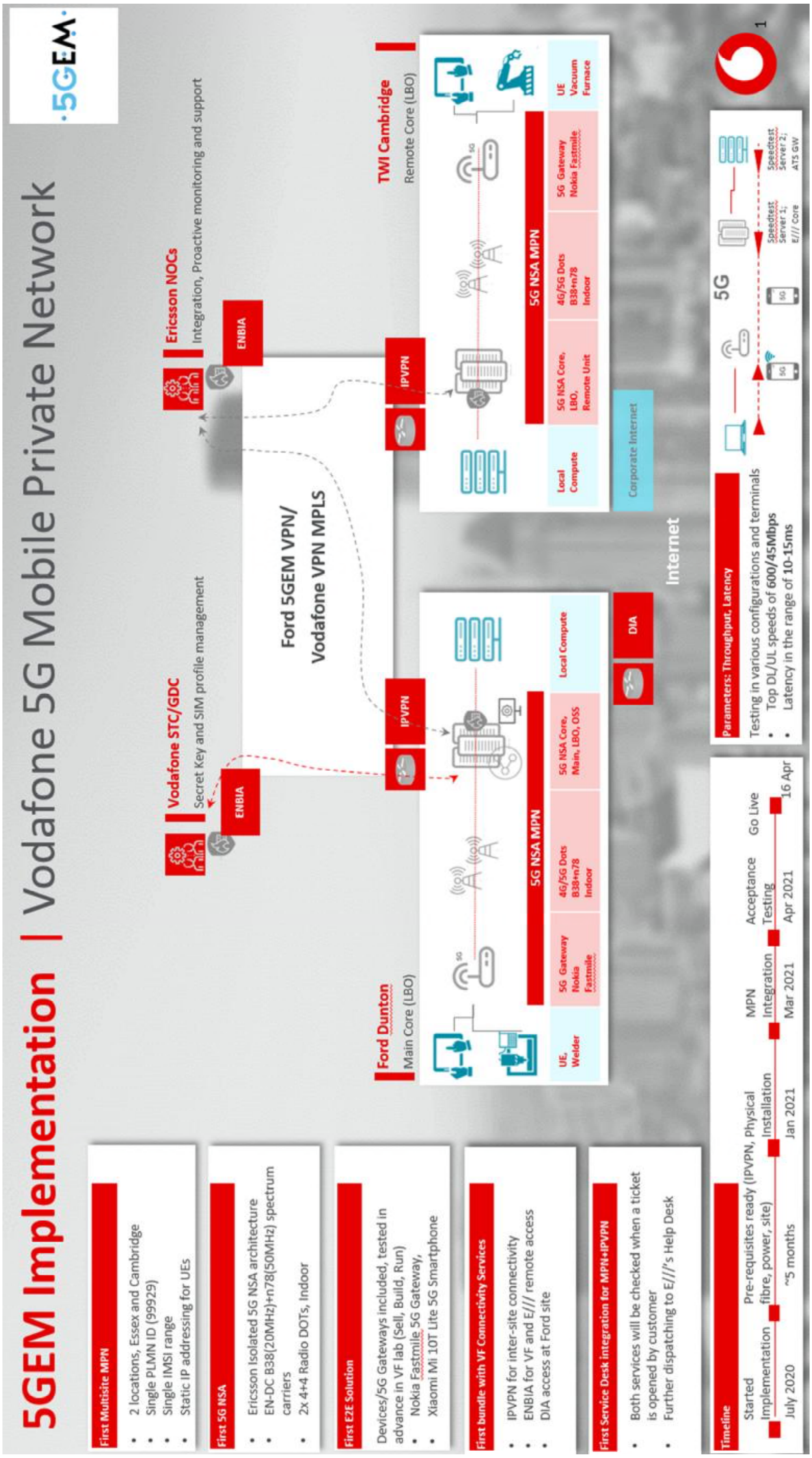



*Figure 7: summary of two site networks*

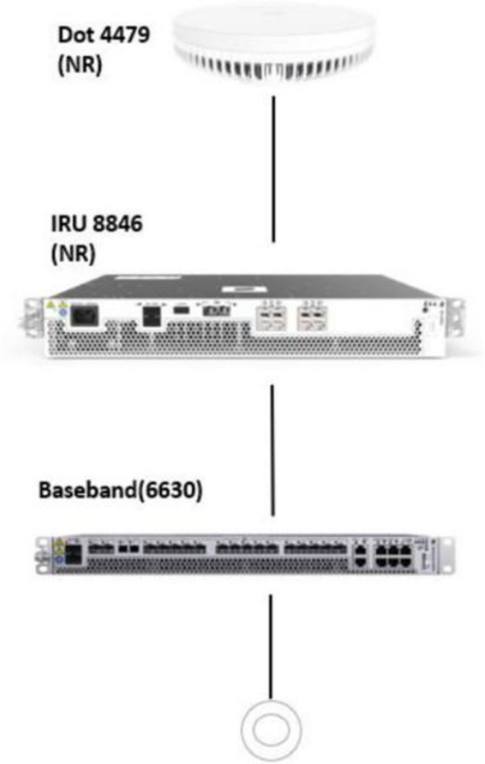



Figure 8: network hardware

Figure 9: comms cabinet on Ford shopfloor.

## 2.2 Ford Use cases

The following sections describe in detail the Ford based use-cases. Additionally, these four articles were published on TM Forum Inform and UK5G websites:

- Real-time process analysis & control: By analysing data in real time from 5G-enabled sensors, Ford is able to monitor the production process and make rapid adjustments automatically in response to changes in environment, input materials and other factors.
- Intelligent maintenance: Ford is using AI-based predictive maintenance to avoid unnecessary downtime on the production line, using data collected from 5G sensors. They are also exploring assisted maintenance using 5G-enabled AR, whereby an engineer follows instructions visually overlayed on the machine, or with real-time support from a remotely located expert using AR/VR to view the machine
- 5G and hybrid cloud: Ford is testing how 5G-connected sensors, edge computing and the hybrid cloud can help optimize productivity by converting vast quantities of data from machines on the production line into actionable insights in real time.
- 5G-enabled manufacturing: Realizing Industry 4.0: How 5G, mobile private networks, MEC, IoT, big data, cloud, AI will deliver Industry 4.0 and the factory of the future.

### 2.2.0 Data management (ATS)

To enable the use-cases a data management solution was required. The ATS Atlas solution deployed for the 5GEM Project is a data and system agnostic solution, allowing a large number of generic activities to be performed and support all Project Use Cases, along with some specific activities to support the specific Ford E:PriME and TWI-VFE Use Cases.

For the Ford case study, the following activities were performed:

- Development of an overall Architecture Document – D2.4 System Architecture Specification
- Development and enhancement of the existing Atlas Play and Boost products with the capabilities to support:
    - File Uploads from the Edge to the Atlas Cloud environment
    - Deployment of third party algorithms within the Atlas Cloud
    - Extraction of data from the Atlas Cloud Database into .csv format files
- Development of the core Atlas Edge Solution with the capabilities to support:
    - File Uploads from the Edge to the Atlas Cloud environment
    - Real Time data capture from devices via standard interfaces (MQTT (MQ Telemetry Transport))
    - Security via standard Azure Edge Security
    - Deployment of third party Algorithms for execution on the Edge
    - Data translation to a standard format, (Atlas Data Model), irrespective of the input data source and format (Data Mapping capability)
    - Data manipulation and enhancement, e.g. labelling of data with Process context i.e. Unit ID / Weld Id
    - A Rules Engine to make simple decisions based upon data values captured at the Edge
    - Changes to the Azure default Edge messaging solution to allow for the transfer of image file data between Edge modules
- Creation of the Atlas Cloud Environments to support the Ford use case https://ford.uat-5gem.weareatlas.com/
- Initial Capture of the Business Processes for the Use Cases within Atlas Play, to support both a clearer understanding of the Business Processes in place, and to help drive further clarity regarding data inputs and outputs associated to the Business Processes.
- Development of specific Edge Solution Interface Capabilities
    - MQTT Interface capability (MQTT Broker and Client)
    - MQTT message embedded File extract capability
- Configuration and Deployment of the Core Edge Devices at Ford's prime facility
- Configuration and Deployment of the MQTT Interfaces required for the Ford Use Cases
- Connectivity via MQTT to support data collection from shop floor devices: Hairpin Machine, Battery Machine and Sensors
- Data Interpretation/Translation of data from the Ford CDM (common data model) to the Atlas Internal Data Model to support visualisation
- Development of dashboards including the ability to define threshold limits, e.g. vibration sensor limits
- Deployment of the Lancaster University supplied LDD analysis algorithm to the Atlas Cloud and presentation of results via a report
- Edge Security and product compatibility testing with Atlas Edge and McAfee Solidcore

- Maintaining a consistent time signal across shopfloor devices via an NTP(Network Time Protocol) Server deployment onto the Atlas Edge hardware

### 2.2.1 Factory monitoring

Currently in Ford's PowerTrain Plants data is collected via a cable connection to a server where it is processed by the Factory Information System (FIS) application and then the data is presented via Ford's Intranet for interested parties to monitor. This requires a data cable connection to be set up when equipment is first installed and results in the use of elevated work platforms and "working at height" to run the cable at high level through the Plant. This carries a safety risk, cost and is a slow and inflexible installation process. Having reliable 5G wireless connectivity will mean connection can be made quicker, without the safety risk nor the cost of cable pulling. It also means that data verification can begin sooner and we have flexibility should equipment need to be moved within the factory in the future to meet changing customer needs or product demand.

The plan for this use case was to connect to the machine control systems in the hairpin and battery tab welding machines and extract the same information our existing (cable connected) FIS application does to demonstrate that the 5G MPN can provide reliable connection and, using the Atlas Cloud solution, we can share that data securely and process it without the need for bespoke systems like Ford FIS.

The diagram below explains the end to end data flow and connections

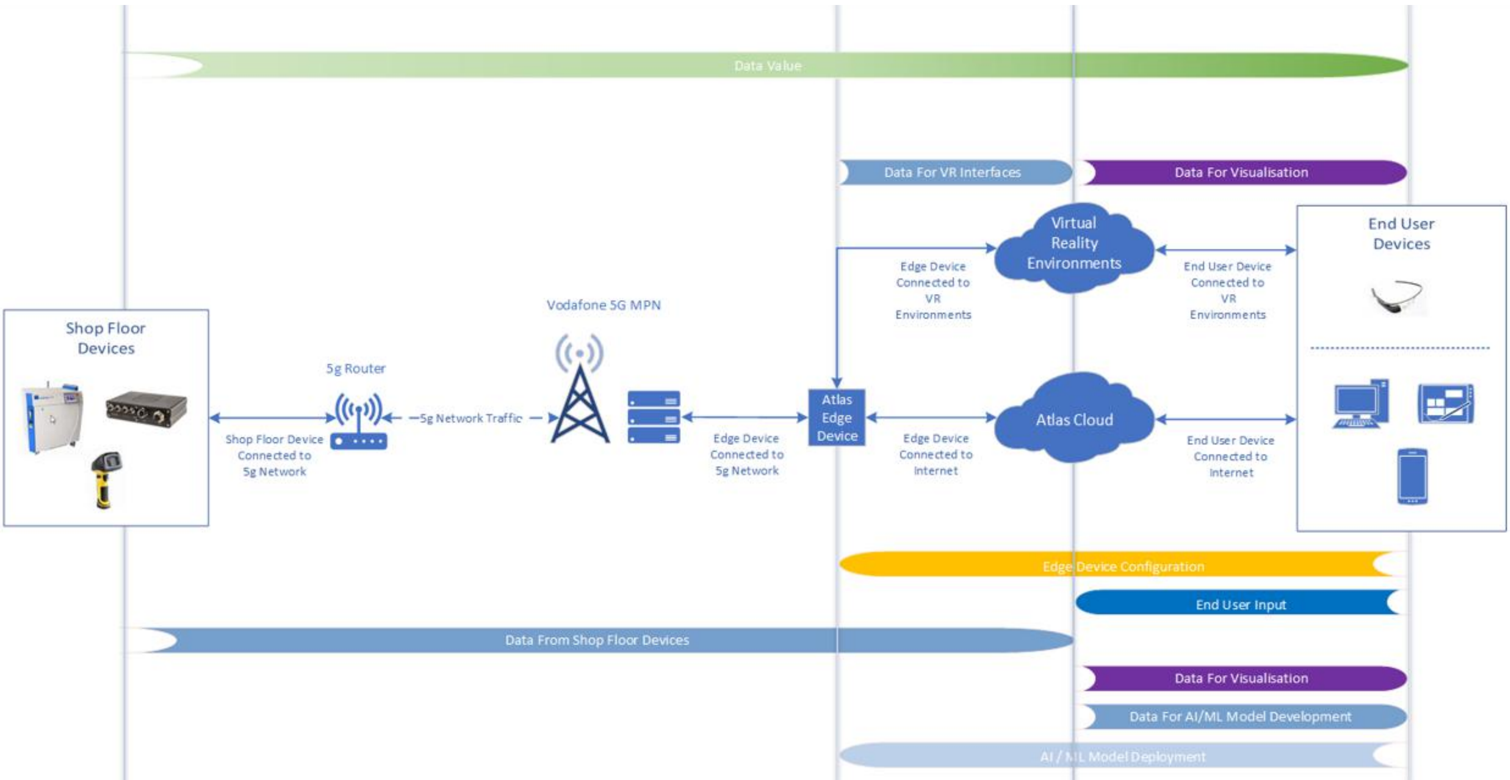



*Figure 10: data flow and connections diagram*

To collect the data the Nokia Fastmile router was connected to either the PC or Programmable Logic Controller (PLC) in the control cabinet of each of the laser welders which were being used in this use case.

The Ford standard for data transmission like this is the Message Queue Telemetry Transport (MQTT) protocol using JavaScript Object Notation (JSON) data format. MQTT is used because it is bandwidth efficient and well suited to small, status messages and JSON has a simple, human readable data structure. This data was then mapped (translated) into a data structure that could be displayed in the Atlas cloud application. The mapping process was actually quite labour intensive and repetitive so only a selection of the machine data available was translated and shown in the cloud in order to prove the concept.

### 2.2.2 Predictive maintenance

If equipment is monitored in sufficient detail then it is possible to detect when parts of a machine are not operating within normal parameters and then take action before any catastrophic failures occur. The Industrial Internet of Things (IIoT) and Industry4.0 have brought about greater availability of sensors which support predictive maintenance although this project did not use sensors which transmit directly via 5G. They are more difficult to source and expensive.

Ford has an approved list of suppliers for Industry4.0 equipment and Turck-Banner were selected due to local familiarity and availability. This system uses multi-feature sensors which transmit to a local hub using radio frequency communications and a selection of the sensors was added to the Hairpin welding machine. The 5G network was used to transmit the data from the hub to the Atlas cloud. Figure 11 shows how this works.

Again, the data transmission followed the MQTT protocol using JSON format and this data was then mapped and displayed in the Atlas cloud application. Once the data is available in the cloud it would be presented graphically for visual analysis and report structures be created to analyse the data. Limits and rules would then be applied to the data such that, if certain conditions occurred, warnings could be initiated that maintenance actions are required to prevent a reduction in performance or complete failure.

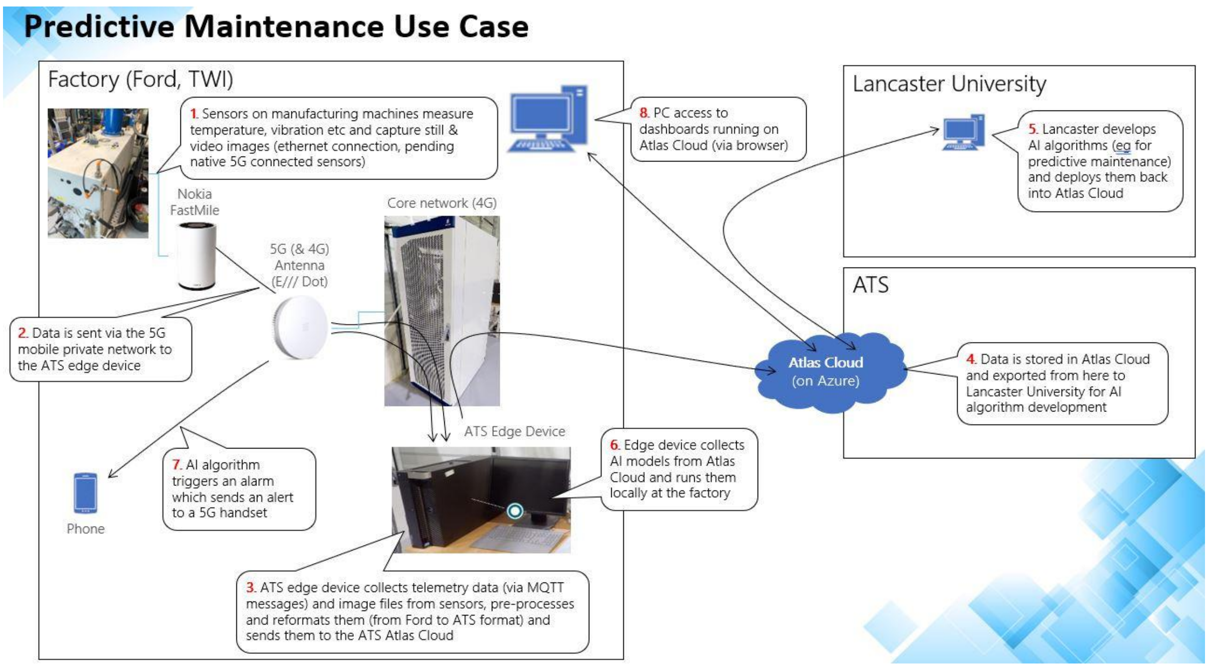



*Figure 11: Predictive Maintenance Use Case*

Note, the data from the *2.2.1 Factory monitoring* use-case could also be processed by AI to predict when maintenance is required.

### 2.2.3 Process monitoring and data visualisation (LU)

The aim of this part of the project, led by Lancaster University, was to take the manufacturing data produced by the use-cases at Ford and VFE and present it in a manner such that it may be easily interpreted or processed.

*Understanding the data*

At Ford, the IPG laser in the battery tab welder produces live process monitoring data using its LDD (Laser Depth Dynamics) system. The figure 12 shows the measurements which are taken by this system which uses a secondary laser within the welding laser. This data is being extracted from the machine and transmitted by the 5G network into the cloud.

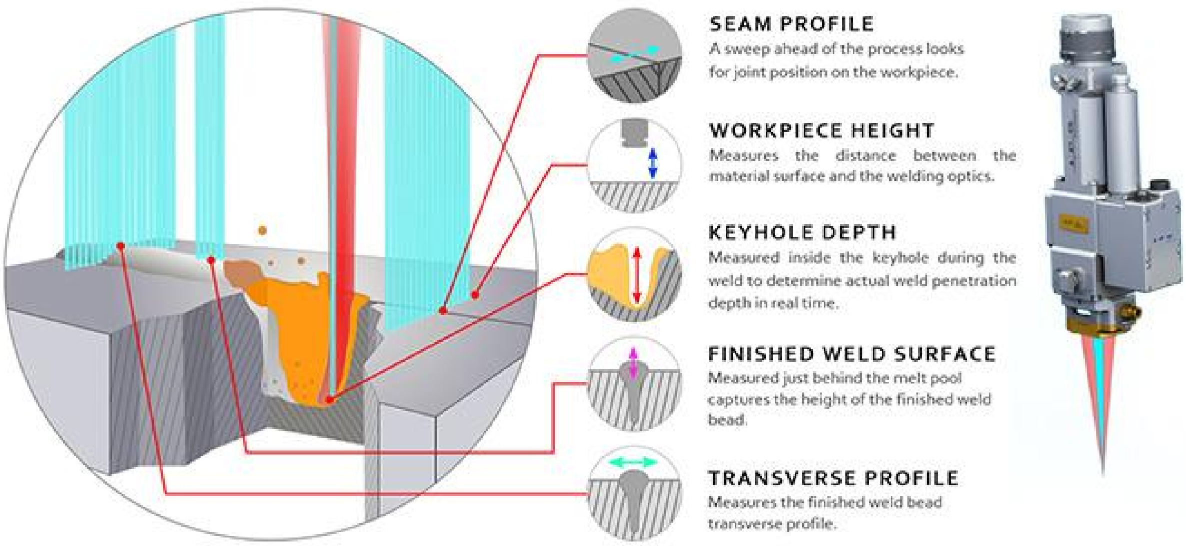



*Figure 12: laser weld measurements*

*Defining what was to be processed*

The weld (keyhole) depth data was selected for analysis and to prove the concept. This measurement is the most critical to confirm a good joint is made between the tabs (terminals) of the battery cells and the “bus bar” along each side of the battery module. It should be noted that the same data processing created in this project could be applied to all the measurement data produced by the LDD system.

The objective now was to process the data with a standalone, agnostic system rather than relying on the laser systems inherent capabilities and then look for immediate good versus bad weld indicators. With low latency data transmission from 5G and fast data (edge) processing, this provides us with an opportunity to re-weld whilst the battery array is still in process in the machine if a section of the weld is not found to be deep enough.

The benefit in this scenario is that production time is saved because the battery module is not rejected and removed from the process only to be re-inserted at a later date when time can be set aside to process battery modules needing rework.

The figure 13 shows the finished connection tab welds on a battery module.

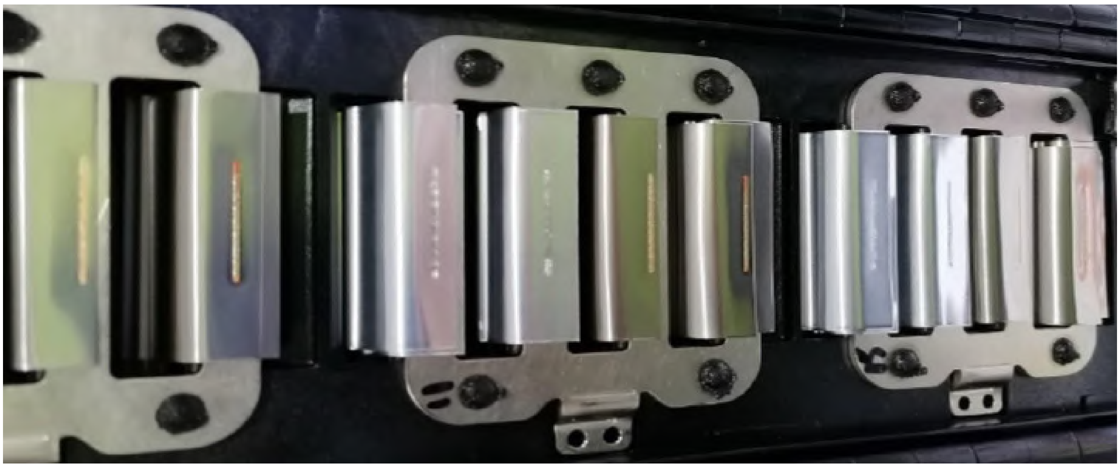


*Figure 13: battery connection tabs welded to busbars*

### 2.2.4 Weld analysis and remote support

This use-case had two elements. Firstly, was to test the ability of TWI to replicate the welding processes at Ford and then demonstrate that with a 5G network we can share results quickly or exchange new welding parameters for testing in a laboratory environment prior to implementing in production and again share the results quickly and securely. The second part of this use-case was to use images from the trials and then analyse them automatically using algorithms developed by Lancaster University.

The battery “seam” weld was produced first at TWI and the images taken provided sufficient data for Lancaster University to start working on automated analysis. Although later in the project TWI also set up a replication of the hairpin welding process and tried some different welding parameters this overlapped with the work described in the next section (2.2.5) so did not require further analysis by Lancaster University.

Ultimately, we were considering a scenario where the 5G MPN provides the low latency connection required to feedback to the welding machine that it must stop or adjust the process if the algorithm detects an issue. Alternatively, remote expert help can be provided if images are shared across the cloud and the AI can send a request for expert analysis.

The feedback network is envisaged in the 9 steps below:

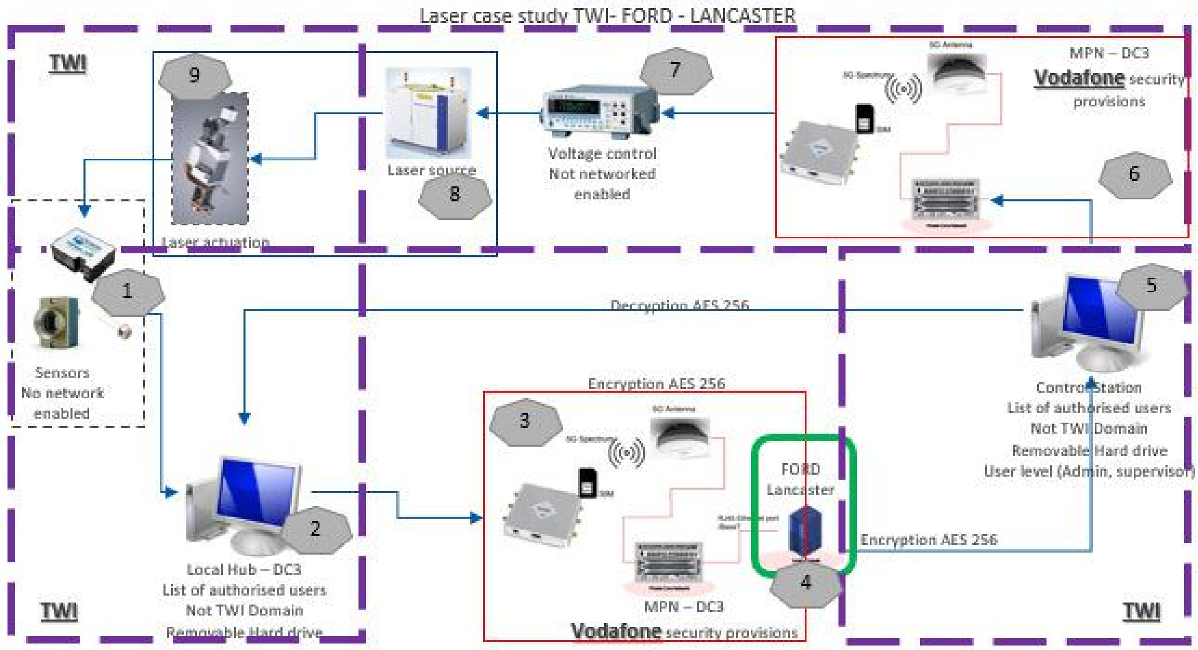



*Figure 14: laser case study information flow*

Figure 15 shows the initial results of battery welding trials at TWI.


*Figure 15: busbar welding trial*

And the picture below shows close up weld images taken to share with Lancaster University for analysis.

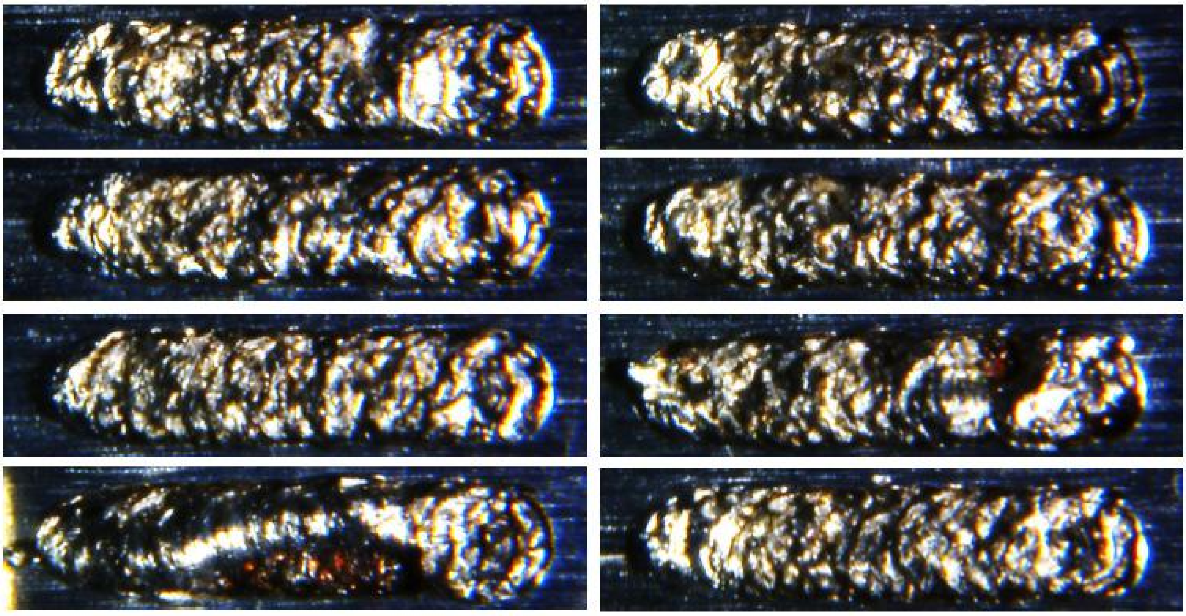
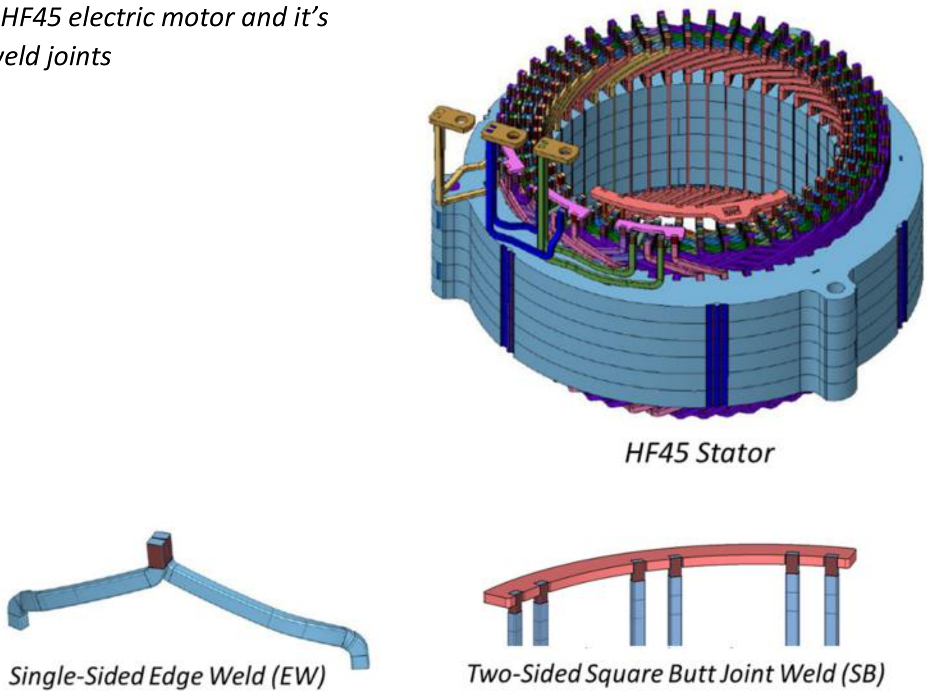


*Figure 16: close up images of busbar welds*

### 2.2.5 Weld analysis using agnostic vision system

The HF45 Motor electric hairpin winding (figure 17) is comprised of 192 discrete, formed, rectangular hairpin wires. These conductive elements are welded together and must be quality inspected.

*Figure 17: HF45 electric motor and it's differing weld joints*



Quality inspection is required to capture the following failure modes which are visualised in figure 18:

- Oversize welds
- Undersized welds
- Contaminated welds
- Pores in welds
- Cracks in welds
- Spatter
- Incomplete welds
- Other conditions


*Figure 18: images showing weld defects*

Currently there are two inspection methods:

1. Pre-weld - Camera images of the hairpins for hairpin welding.

   The weld machine contains a 2D camera within the laser welder which is used to target the laser weld pattern onto the pins for welding. The laser reads these outputs from the camera and adjusts the laser targeting to match the measured pin location (see image below).

Current system is limited by 2D view (figure 19) so cannot detect a deviation in the heights of the two hairpin ends.

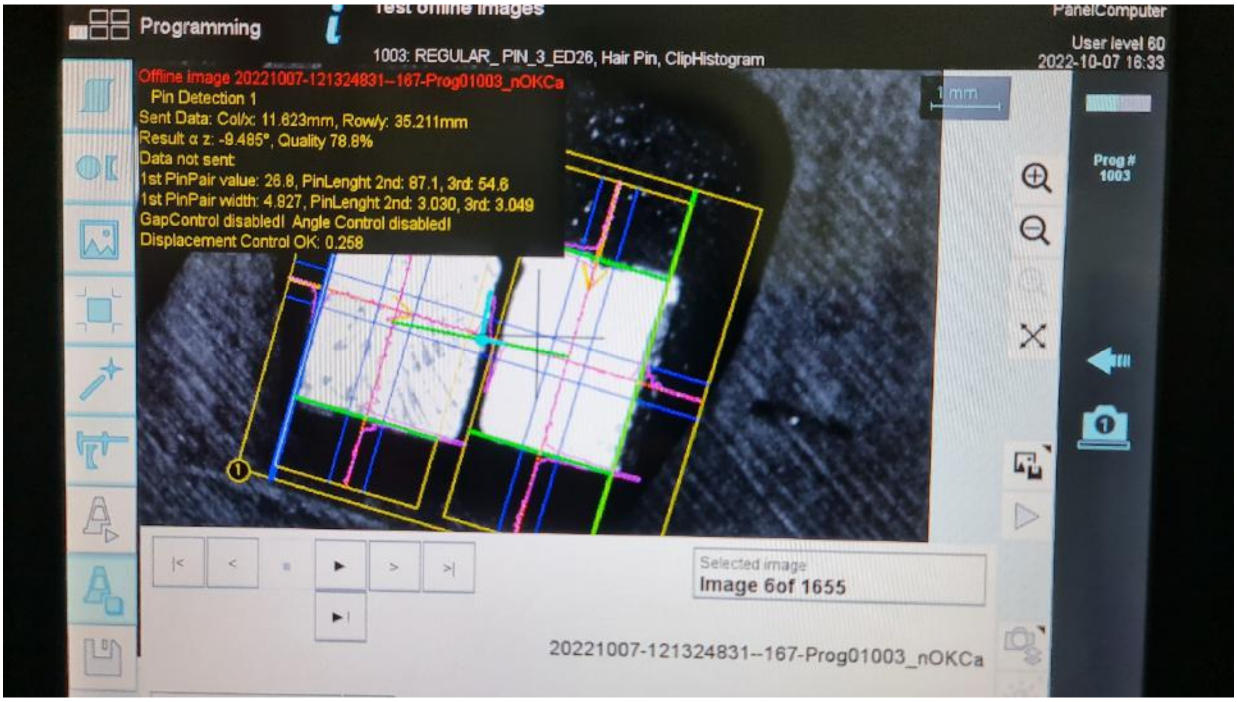



*Figure 19: 2D targeting camera*

2. Post weld - Electrical continuity check.

The post weld electrical continuity check is used to check the quality of the completed welds by identifying shorts which may be caused by the failure modes listed above.

The 5G use case with the agnostic weld analysis is to improve the pre and post weld inspection and analysis methods through:

- Implementing a 2D and 3D visual inspection camera for pre and post weld;
- Capture 200+ high resolution images (plus attribute data) of pre and post weld in near real time and share using 5G;
- Share images and data with welding and data analysis experts within the consortium to optimise the weld process;
- Process images and data using AI to detect sub-standard hairpin welds.

### 2.2.6 AR Maintenance support (HSSMI)

Augmented Reality (AR) allows you to visualise 3D models in real-time and in a real environment using a hardware technology from a portable AR headset or “AR Glasses”. As 3D computer graphics have continued to evolve in quality, 3D models were still solely used in Simulation and Engineering software platforms running on Desktop PC hardware. Now, AR developed applications can be used as another option as it’s the only way to see 3D models as an overlay to world in front of you.

Our AR application requires the user to be able to roam around a large manufacturing site or facility, and in our case, the 5G network infrastructure has enabled the high bandwidth real-time application with a stable and useable connection to data at any location on site.

Initial work started with research into the directly compatible hardware and software solutions for a mixed reality setup. On the hardware side we decided to choose the Microsoft HoloLens2 (HL2) Augmented Reality Headset because there was developer software support for the headset and there was news about OEMs developing new hardware solutions to retrofit 5G connectivity to the WiFi only enabled headset.

### *Hardware options: support for Mixed Reality AR/VR*

1. Microsoft HoloLens2 Augmented Reality AR/MR Headset (HL2)
2. Magic Leap 1 Augmented Reality AR/MR Headset (MR1)
3. Varjo XR-1 which a VR/MR headset (XR-1)

The first option above was chosen for the in-built support of enterprise-based applications which would make roll-out and deployment easier. E.g., Ability to natively log into the Ford and TWI corporate active directories with existing user login credentials without special setup steps required from the respective IT departments.

### *Software options: developing applications for the headset*

1. Epic Games - Unreal Engine – Gaming Engine with support workflows for Engineering CAD files
2. Unity – Gaming Engine – can enable a secondary plugin for PTC Vuforia
3. PTC Vuforia Native application
4. Microsoft Dynamics 365 – Remote Assist for HoloLens2 (Enterprise)
5. TeamViewer for HoloLens2

The third option above was chosen because of the direct support and contacts that Vodafone already had with PTC. Throughout the project, HSSMI worked closely with the contacts at PTC to undertake training for the Vuforia application and get technical developer support for the 5GEM use cases being developed.

### *Use cases*

Utilising the Microsoft HoloLens2 (HL2), an Augmented Reality/Mixed Reality Enterprise Headset, to develop and address the identified use cases below:

1. Assisted Maintenance Use Case;
2. Remote Expert Assistance Use Case (see section 2.2.7).

Some preliminary investigations were made to be able to establish a working connection for the headset onto the MPN (details below). Following successful connectivity, we worked with PTC an external software solutions provider who supplied us with an AR/MR platform so we could develop a fully operational demonstrator (Assisted Maintenance Use Case). In parallel Vodafone worked on some reconfigurations to the MPN to be able to support “Outbound Connections for the Private Network” whilst ensuring enterprise level security so that we were able to trial (Remote Assistance Use Case).

Figure 20 shows how the network architecture of the hardware required for the AR demonstrator is configured where a remote expert (at TWI) could help with machine set up.

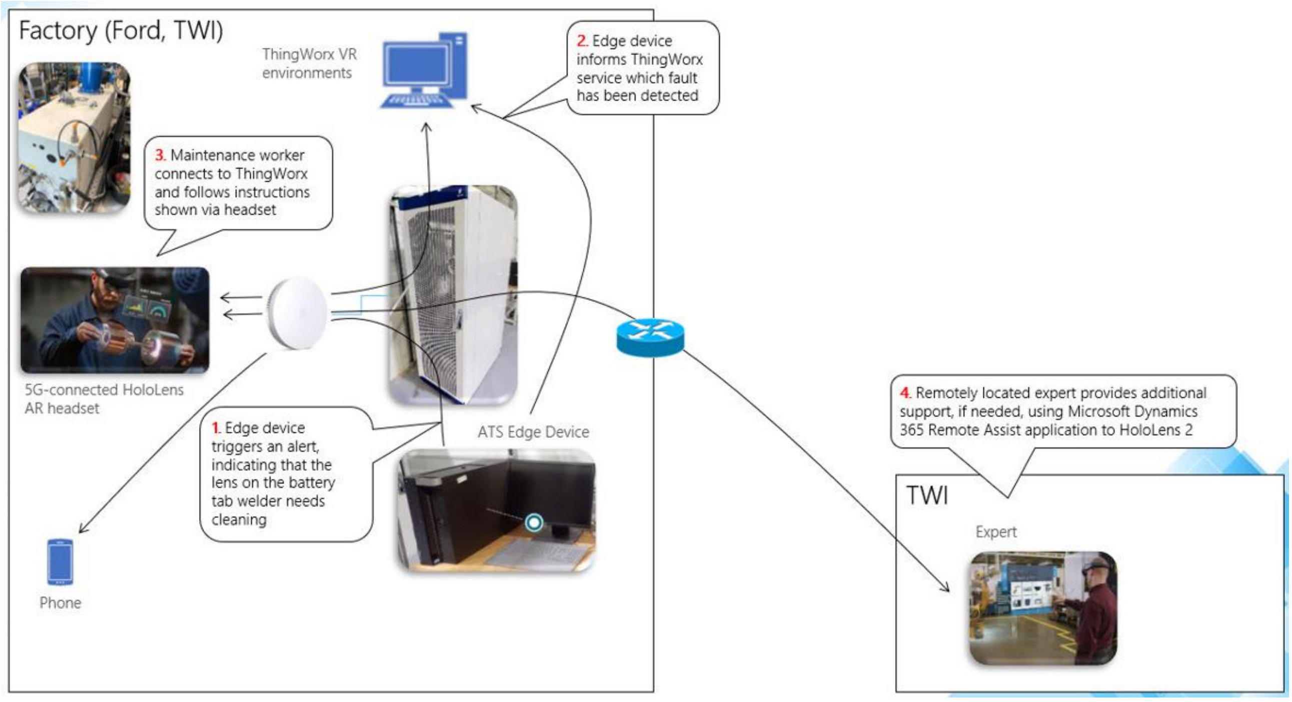



*Figure 20: AR demonstrator configuration*

### Hardware: Testing 5G connectivity

Intermediary auxiliary 5G native devices are required to bridge network connectivity from the HL2 to the MPN

- The HL2 is a WiFi 5 only native device
- Testing Xiaomi 5G Mobile Phone – USB-C tethered connection to HL2 allowed for 5G network connectivity to the MPN successfully
- Quanta 5G Dongle
- Contacts made with Nokia/Telit/Quectel/Quanta – for unreleased "industrial prototype 5G USB-C Dongles"

Several meetings and workshops were held around this topic to discuss possible strategies and share ideas with our contacts other external consortiums:

- Standards meetings/workshops to contribute our findings
- Digital Catapult workshops for 5G devices to learn what other consortiums are testing
- UK5G Basecamp online forum community for technical discussions about 5G hardware setup and compatibility.

### *Augmented Reality implementation approach for the use cases at Ford and TWI*

(Assisted Maintenance Use Case)

To create this demonstrator a dedicated local Ford desktop PC in the E:PriME facility was used to host the PTC Experience Server. It stored AR projects that were made in the Vuforia Studio package to serve locally networked HL2 headsets with the Vuforia augmented reality experience on demand. So, this enables 5G access to all locations on the 5G network at both Ford and TWI.

### 2.2.7 Remote Expert Assistance (REA)

With the Covid-19 pandemic restricting travel, the need for remote support became critical and the new business norm. Having a 5G network we planned to develop remote support beyond previous attempts, where using AR-MR facilities like the Microsoft HoloLens, have had mixed results due to poor connectivity (data capacity and speed). The extra capacity and reliability of a 5G connection should improve this. Our use-case scenario was again centred around laser welding so the Ford site would be seeking expert assistance from our partners at TWI and we would communicate with each other via HoloLens2 headsets. Rather than a phone or video call this would have the benefit, as well as being able to see each other’s facilities, that we could add mixed reality capabilities and share other information such as video, text instructions/documentation and CAD models.

Other potential benefits are listed below.

1. Solve problems in real-time - Engineers can share their real-time view with experts in remote location to get the help they need, reducing travel time and cost;
2. Walk the site without being onsite - Remote inspectors can assess technical machinery and components without traveling onsite by looking through the remote first person view of the headset wearer (video conference feed);
3. Communicate complex instructions visually - rather than communicating instructions via an audio call, onsite engineers can use drawings and arrows to refer to specific parts of a machine or component. These annotations are anchored at the onsite location and saved to the headset;
4. Scale expert knowledge - Experts can pull in maintenance schedule sequences and work with the assigned engineers to support them. Furthermore, Engineers no longer need to carry around paper-based manuals to perform their repair or inspection. Experts can assist with problem solving through voice communication and also by inserting digital content into the Engineers onsite view within the headset e.g. reference images, technical drawings and specifications sheets;
5. Handsfree operation - engineers are able to carry out the physical activities required for the sequenced operation because their hands/body are free. (Requires headset to be comfortably tightened to wearers head);
6. Data capture and logging - assets and processes can be captures through headset screengrabs/photos during the sequenced operation, issues and activities can be logged fully;
7. Compatibility - headset users can share their experience with other users from other platforms (PC/Mobile)

The use-case required an AR-MR software platform that would provide all the base line requirements to be able to have a “conference call” between sites or other remote locations either via:

1. Two HoloLens2 headsets or
2. PC and HoloLens2 headset.

Trials on site were conducted looking at the most popular platforms like Microsoft Dynamics 365 – Remote Assist for HoloLens2 & TeamViewer Pilot for HoloLens2, but some challenges were faced with initialising connections using in-built backend services from these providers. For example, we needed an outbound connection to the platform's server to provide the handshake when making calls. This was initially out of scope with the current setup of the network architecture due to network security reasons, so the alternative solution was to adapt the architecture to allow only "Outbound" connections. Which meant that it was only possible to start calls from the specified 5G sites.

## 2.3 VFE Use cases

The following sections describe in detail the VFE / TWI based use-cases.

- Process Monitoring – Using existing and additional sensors, flexibly installed using the 5G network, monitor real-time process data to improve process quality and reduce scrap.
- Predictive Maintenance – Monitoring of furnace equipment using data collected using the 5G network to detect changes in equipment operation. Use the data to optimise preventive maintenance and reduce unplanned downtime.
- Remote Expert – combine real-time and historical data with secure remote access to the machine and enhanced information exchange with local technicians through AR glasses/headset. Determine best practice for secure collaboration.

### 2.3.1 Process Monitoring

Currently most machines are installed only with the sensors required to control and prove the process to the programmed parameters and to operate safely. Fitting additional sensors to measure how the machine was operating in terms of energy use, gas flows, water flows / temperatures and valve operations could allow the tighter control of these ancillary systems. Measurement alone should allow us to correlate small changes in machine operation to the effects seen in product quality. Where these parameters can also be controlled, we would expect to improve consistency of quality and minimise waste (of energy and product). Traditionally, installing these additional sensors incurred cost not only in the sensors; in their wiring and installation; the additional PLC inputs to measure and record them; but also in analysing the data to find the variations requiring attention.

A second benefit of these additional sensors would be in the diagnosis of failure root cause in the event of breakdown. Real-time and off-site access to this information allows for the swift elimination of possible causes and better planning of requirements to fix.

NB. As this furnace is critical for TWI's research projects it was a requirement that no changes were made to its existing control systems. To achieve this, additional hardware was required to gather data from the existing systems for aggregation with the new data before onward transmission to the rest of the project.

For this use case VFE installed additional sensors to the TWI furnace, measuring additional data points such as water circuit flows and temperatures, gas flows and electrical power consumption of process critical components. Due to the shortage of 5G enabled sensors at the start of the project these were initially wired to a small PLC locally on the furnace, transmitting its data to a new panel containing a PLC to aggregate the data from the new and existing sensors plus the 5G networking components. The configuration was designed so that individual elements could be swapped out for 5G native units as they became available.

The measured data was displayed locally on a small HMI built into the panel which was also recording a backup log in case of wireless signal loss. The data transmission was configured to use the industry standard OPC-UA (Open Platform Communications - Unified Architecture), a platform independent standard for the secure exchange of information in industrial systems. This was chosen particularly as it is the common alternative industrial standard to MQTT being trialled on the Ford use case. Careful mapping of all variables was undertaken to ensure the range, units and relevance of each sensor to the process was captured.

### 2.3.2 Predictive Maintenance

The furnace was already equipped with sensors to detect fault conditions and trigger action - whether automatic or requiring manual intervention. These sensors have normally been switches with just binary states. For example

- Water flow - ok or bad from flow switch.
- Heater current - ok or tripped from circuit breaker.
- Pump vibration - ok or seized from bearing failure.

Replacing these switches with real measurement sensors allows the detection of trends leading towards failure, e.g. water flow reducing; heater current increasing; pump vibration becoming observable. If these trends are indeed leading towards failure then the machine can be stopped and maintenance performed at a lower cost and more convenient time. If these sensors can be fitted more cheaply and less intrusively then a larger dataset can be gathered. With a larger dataset the time to failure may be more predictable allowing much more effective, even automated, planning of preventive maintenance. For the use case at TWI we only have one machine's data to gather.

In addition to the process sensors above, VFE installed vibration sensors from IFM to the vacuum pump and cooling fan of the furnace. These sensors operate at high speed on IO-Link (a lightweight but wired industrial protocol for process sensors) and were selected in anticipation of IO-link to 5G bridging hardware becoming available to test. The data was included in the same mapping to OPC-UA and transmitted via the 5G MPN to the Atlas Cloud edge computer for onward communication to both the Atlas Cloud for visualisation and to Lancaster University for processing including trend analysis.

### 2.3.3 Remote Support

In most cases where there is a machine fault an engineer is able to speak to a local technician by telephone to collaborate in finding the cause of the breakdown. Often there is remote access to the machine via the internet so that process data and perhaps the control hardware can be monitored. This is typically through a dedicated 3G/4G mobile enabled VPN gateway attached to the system, or through the machine PC placed on the customer network with internet connectivity. The current methods are fast enough to fulfil the task but come with security concerns for some end users. Either the direct mobile connectivity method must be trusted that it only allows VPN access from the machine OEM or the OEM must be trusted to access the machine through the customer network without straying beyond their task. There is also the difficulty of managing which devices are connected to the network via LAN or Wi-Fi without specifically whitelisting every device.

For this use case a single internet access point was opened for remote support with tightly controlled access to the 5G MPN. Devices within the TWI premises can only be connected to the 5G network if they have been supplied a pre-provisioned SIM. It is hoped that the improved security of the 5G network increases the confidence of end users to permit controlled access to OEMs for the purpose of remote support.

An additional element was intended to plug the information gap in remote support by using a Microsoft HoloLens headset to allow the remote expert to see and hear exactly what is going on around the technician and to interact through AR tools, highlighting areas to investigate and sharing system diagrams etc.

### 2.3.4 Data management (ATS)

Activities for the VFE case study were expanded into using OPC-UA (Open Platform Communications United Architecture) protocols in addition to MQTT used in Ford's case study. This work included further activities:

- Real Time data capture from devices via standard interfaces (OPC UA)
- Creation of the Atlas Cloud Environments to support the TWI-VFE Use Case https://vfe.uat-5gem.weareatlas.com/
- Development of the specific Edge Solution OPC UA Interface Capability
- Configuration and Deployment of the Core Edge Devices at the TWI site
- Configuration and Deployment of the OPC Interface required for the TWI VFE Use Case
- Connectivity via OPC UA to support data collection from the VFE Machine and associated Sensors
- Data Interpretation/Translation of data from the OPC UA Standard data format to the Atlas Data Model to support visualisation

### 2.3.5 Data processing (LU)

Similarly to the Ford use-cases, data was shared in the Atlas Cloud, via the 5G network, for Lancaster University to analyse. Results are described in section 3.3.5.

## 2.4 Data standards (TMF)

The project ensured that the latest 5G standards were applied across the project. In addition, security standards and IoT standards were a key feature of the project, as well as ensuring that safety requirements to ensure Electromagnetic Field (EMF) levels were below all essential standards.

Figure 21 captures the end-to-end process for the Industrial Manufacturing AR/VR Maintenance support use case and shows in the grey boxes the standards and processes that were followed.

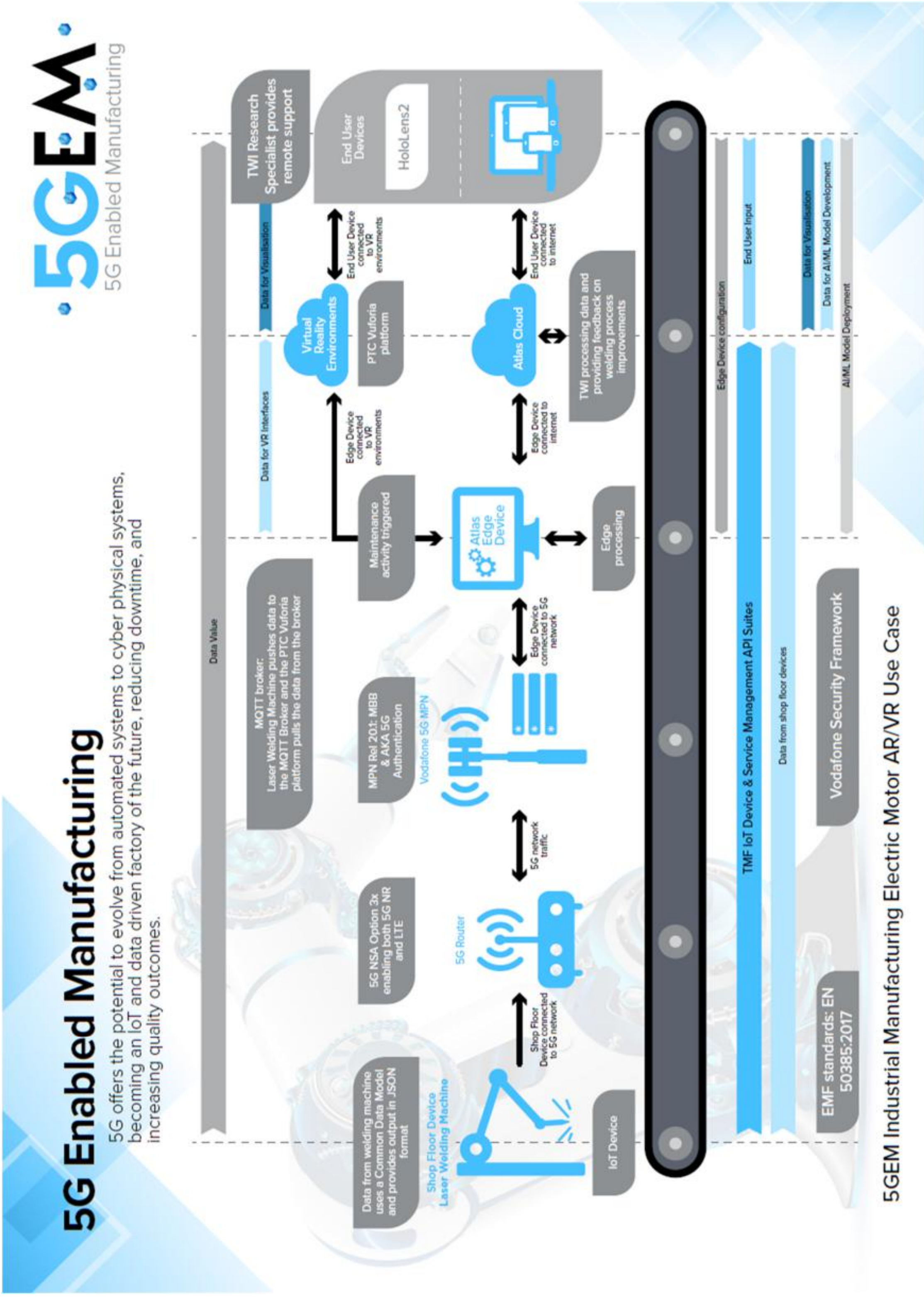



*Figure 21: 5GEM AR/VR use case and standards employed*

*5G Standards:*

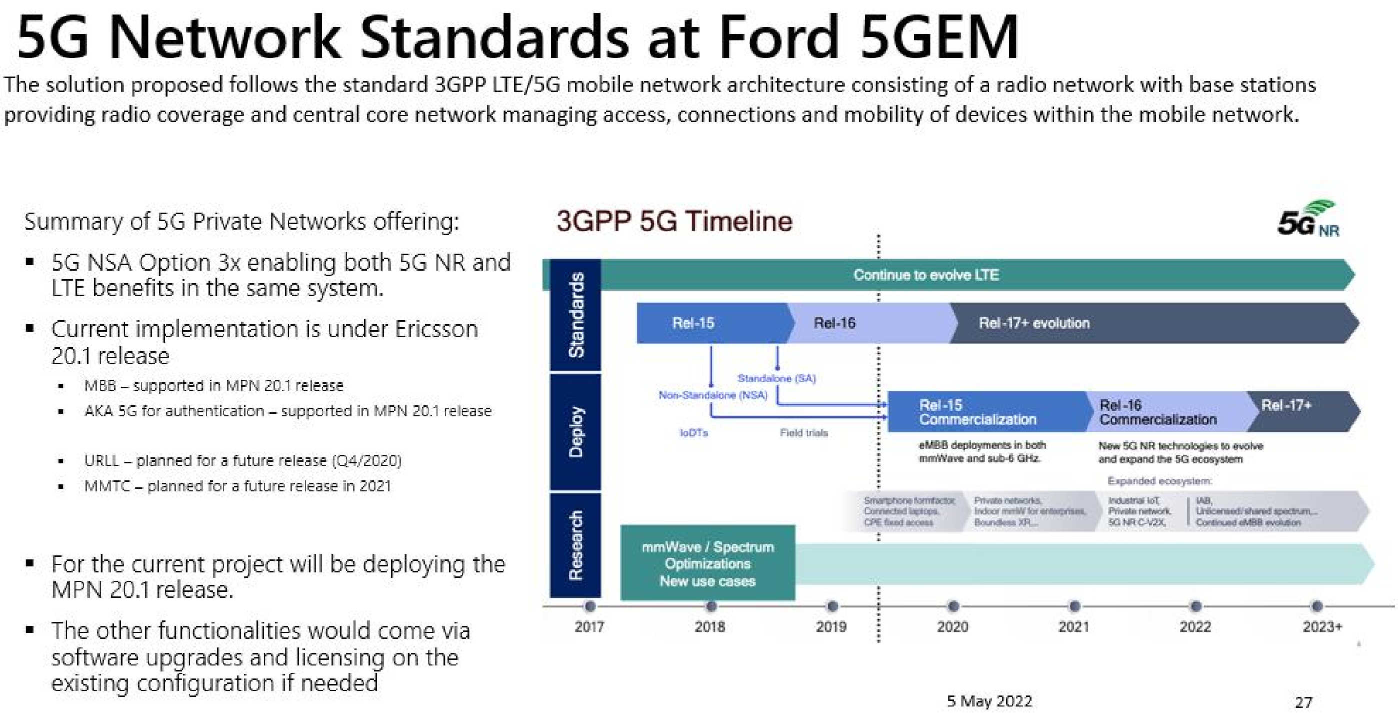



*Figure 22: 3GPP 5G development timeline*

*Security standards:*

Security by design principles were used to expose security risks in the design phase and built in from the beginning and not bolted on afterwards, with the exception of E2E overlay security which is a new area, the solution focused on existing policies and best practices, noting that private 5G systems are more secure than WiFi. Security was recognized as a continuous process for the lifetime of the product. See full document from Vodafone, Security Framework WP5 Security.

Secure by Default Principles used:

- Security should be built into products from the beginning, it can't be added in later;
- Security should be added to treat the root cause of a problem, not its symptoms;
- Security is never a goal in and of itself, it is a process – and it must continue throughout the lifetime of the product;
- Security should never compromise usability – products need to be secure enough, then maximise usability;
- Security should not require extensive configuration to work, and should just work reliably where implemented;
- Security should constantly evolve to meet and defeat the latest threats – new security features should take longer to defeat than they take to build;
- Security through obscurity should be avoided;
- Security should not require specific technical understanding or non-obvious behaviour from the user.

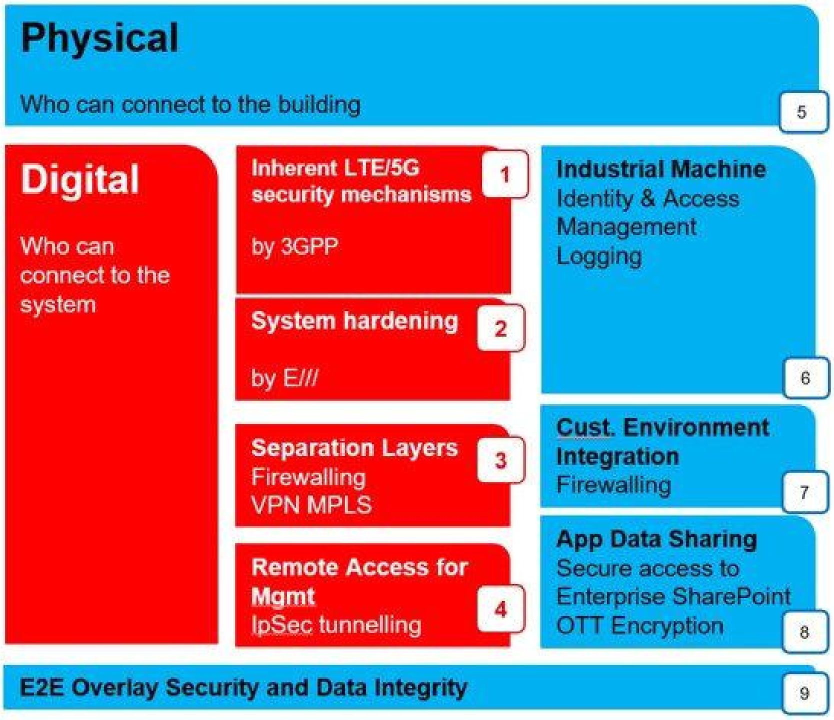



*Figure 23: Security framework*

A security strategy should always be risk based, holistic and proportionate. It is vital that the project tailors the strategy to suit the desired security outcomes and use cases. For some projects the key focus will be on compliance issues and the application of good practice. In this case the strategy will probably be short and 'high level'. For large, complex projects and those with research interests on security topics, it will be more comprehensive. Figure 23 shows the security framework considered on this project. More details can be found in the "Work Package 5 – Security Report".

The E:PriME facility at Ford Motor Company's Dunton Campus is physically secured using a Casi-Rusco card entry system. Access to the E:PriME building is limited to Ford personnel who have been inducted with the Health and Safety materials required. Visitors to E:PriME are also inducted and escorted around the site by an eligible Ford employee.

*IoT standards:*

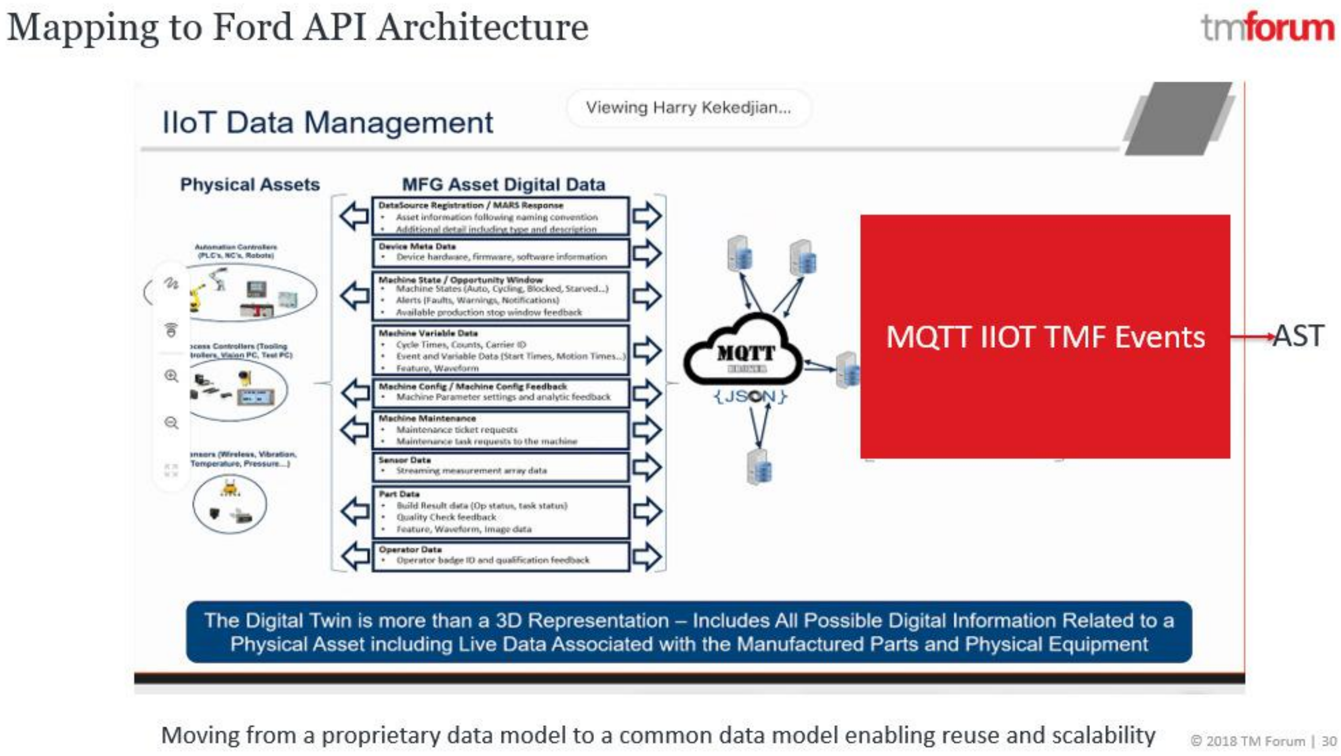



*Figure 24: Open API data model*

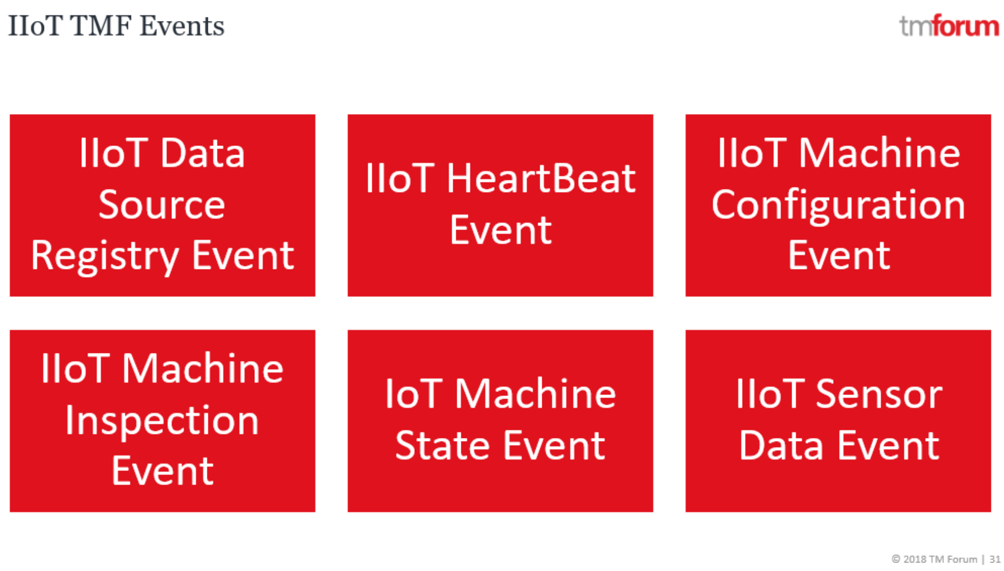



*Figure 25: IIoT TMF events*

- All IIoT TMF events (figure 25) are harmonized with the Open API TMF Data Model (figure 24)
- The Payload characteristic contents are aligned with the TMF Generic Characteristic Pattern
- All Events are derived from the TMF Base Event

- It is assumed that each type of Event is published to and can be consumed from dedicated <domain>/<EventType> Topics
- The MQTT specification is realized via the AsyncAPI specification
- The WebHook or REST callback-based specification is based on the TMF Event API (all the Events are Polymorphic to the TMF Base Event type).

*Recommendation for future Data Standards:*

With any project of multiple partners there is a need for harmonization of the data constructs across the different systems. Industrial Manufacturing does not have an agreed industry data model, as other industries have, telecoms, airline, health, smart cities etc. TM Forum offered for the data model of the telecommunications industry to be used as a baseline for the operational management aspects of the project and provided the mappings required to enable this. However, it was subsequently decided that the team would manage direct mappings between the parties. This was understandable given the time considerations. However, the industry best practice would recommend a common data model for industrial manufacturing, as follows:

> Create an industrial manufacturing data model, crowd sourced from major industrial partners and harmonized with key industry partners, such as telecoms, reusing from telecoms as much as possible to accelerate the effort and ease interoperability challenges in the future. The telecoms model is designed to be service agnostic and extendable for specific contexts and therefore could cater for industrial manufacturing. It has also been taken up by the smart city organisations. The effort would involve creation of extensions for specific industrial use cases. These could then be made available under open licenses.

# 3.0 Results

## 3.1 Network (Vodafone)

Network performance.

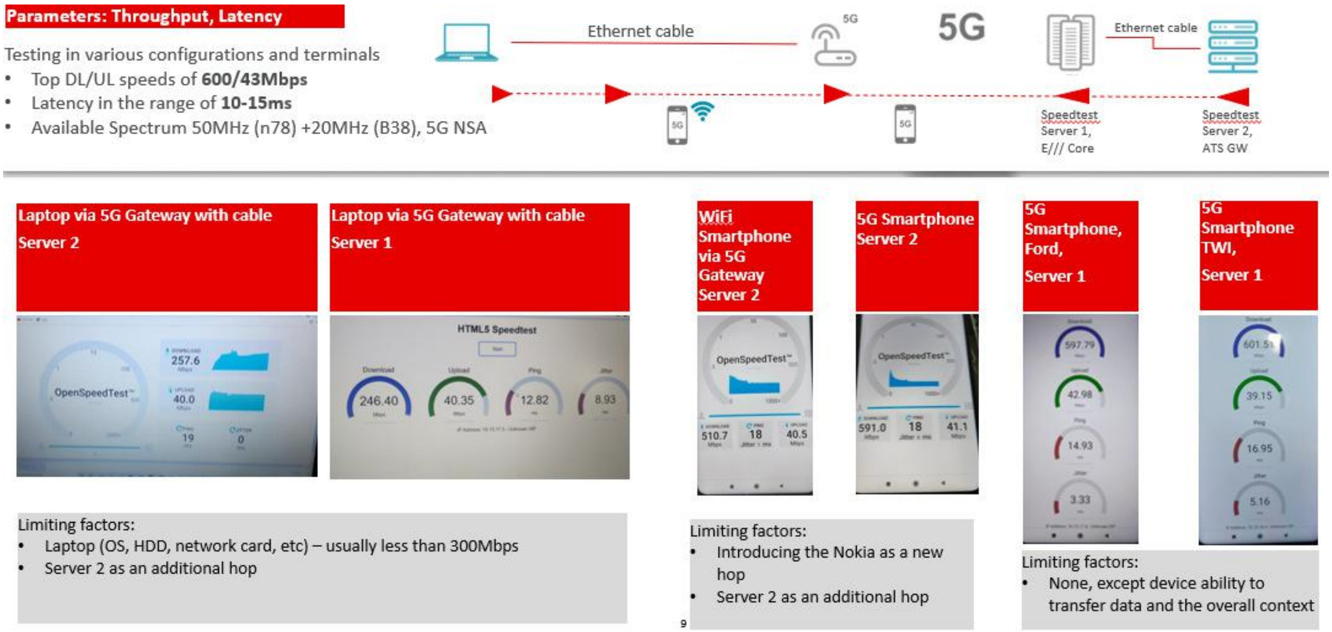



*Figure 26: network performance results summary*

Significant throughput was achieved by various devices (Laptop and Smartphone) connected via two different media (5G and WiFi) with two separate speed test servers in different nodes. Details are shown in figure 26 with the expected target of 600Mbps being reached. Where the laptops did not reach the same connection speed this is explain by the security packages which they run.

**Security Testing**

Security testing of the MPN system was mandated prior to go-live to verify the effectiveness of the hardening and the secure configuration of the system. Testing for MPN was two-fold:

• Security Test Reports, based on automated vulnerability scans on the single Enterprise Core components, were provided by Ericsson.

• A penetration test, based on realistic attack scenarios, was performed on the MPN lab environment by a Vodafone External Partner. on a hardened system that is **identical with Ford 5GEM MPN system** as laid out in figure 27**.**

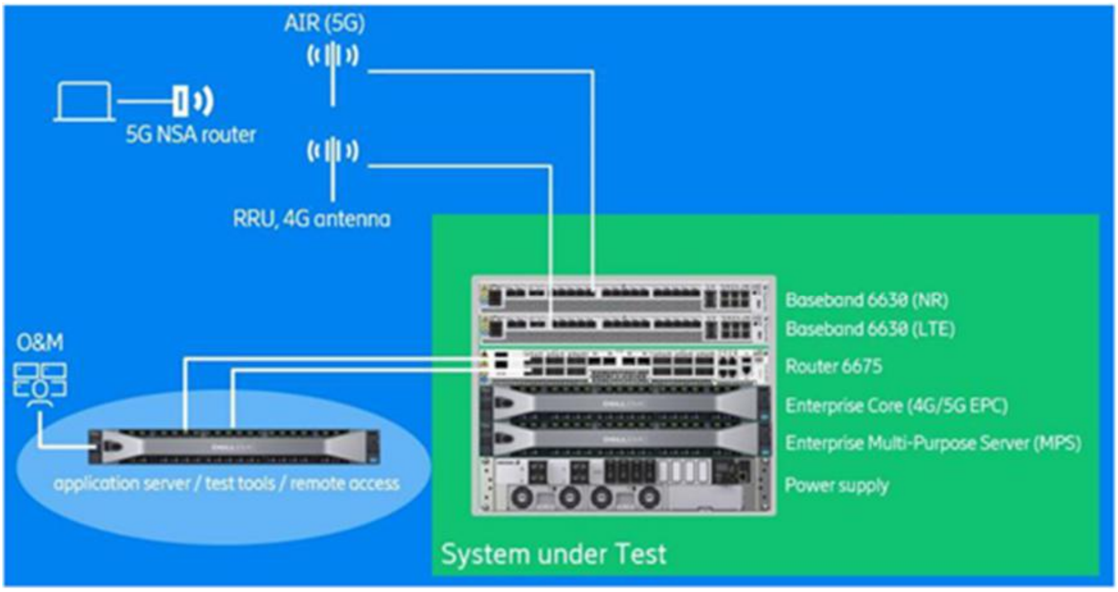



*Figure 27: Security testing*

### *Penetration test*

Manual activity based on realistic attack scenarios:

1. Gather information on a target system (Reconnaissance).
2. Use technical tools to further the knowledge of the system.
3. Gain access / skim information

Once an attacker has exploited a vulnerability, they may gain access to other machines to further penetrate the system.

Two attack scenarios tested:

1. Attack from the mobile network on EPC and MPS network services
2. Attack from the customer network on EPC and MPS network services

The findings and consequent actions are shown in the table below.

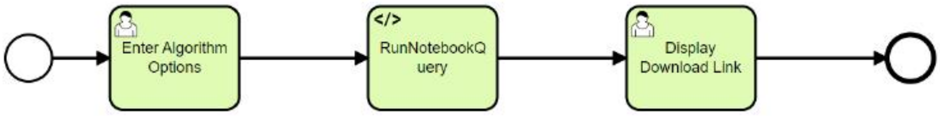
| System | Findings | Correction/Recommendation |
|---|---|---|
| MPN | A management interface (SSH to the router 6675) was exposed via the mobile network. | SSH service was incorrectly configured and it has been fixed via configuration update. |
| MPN | The NetRunner APIs seem to be insecure and expose to much information. NetRunner APIs might be vulnerable against NoSQL injections. | Ericsson provided proof that the NetRunner vulnerability is not exploitable. They also changed some configuration on the router in the Lab such that the sensitive interfaces are not exposed in the mobile network anymore. |
| MPN | Port 80/TCP and port 5060/TCP were identified as running web servers on R6K. Port 80 is reserved for the unencrypted http interface. | HTTPS only will be allowed.<br>Speedtest must not be deployed in a productive environment |
| MPN | General recommendation:<br>To reduce risks from outdated software components the MPN Core deployment must be protected by a Firewall in a productive environment.<br>Given the trusted, non-productive environment the customer side firewall is not present at 5GEM; Filtering functions implemented at R6K border router level. | |

## 3.2 Ford Use cases

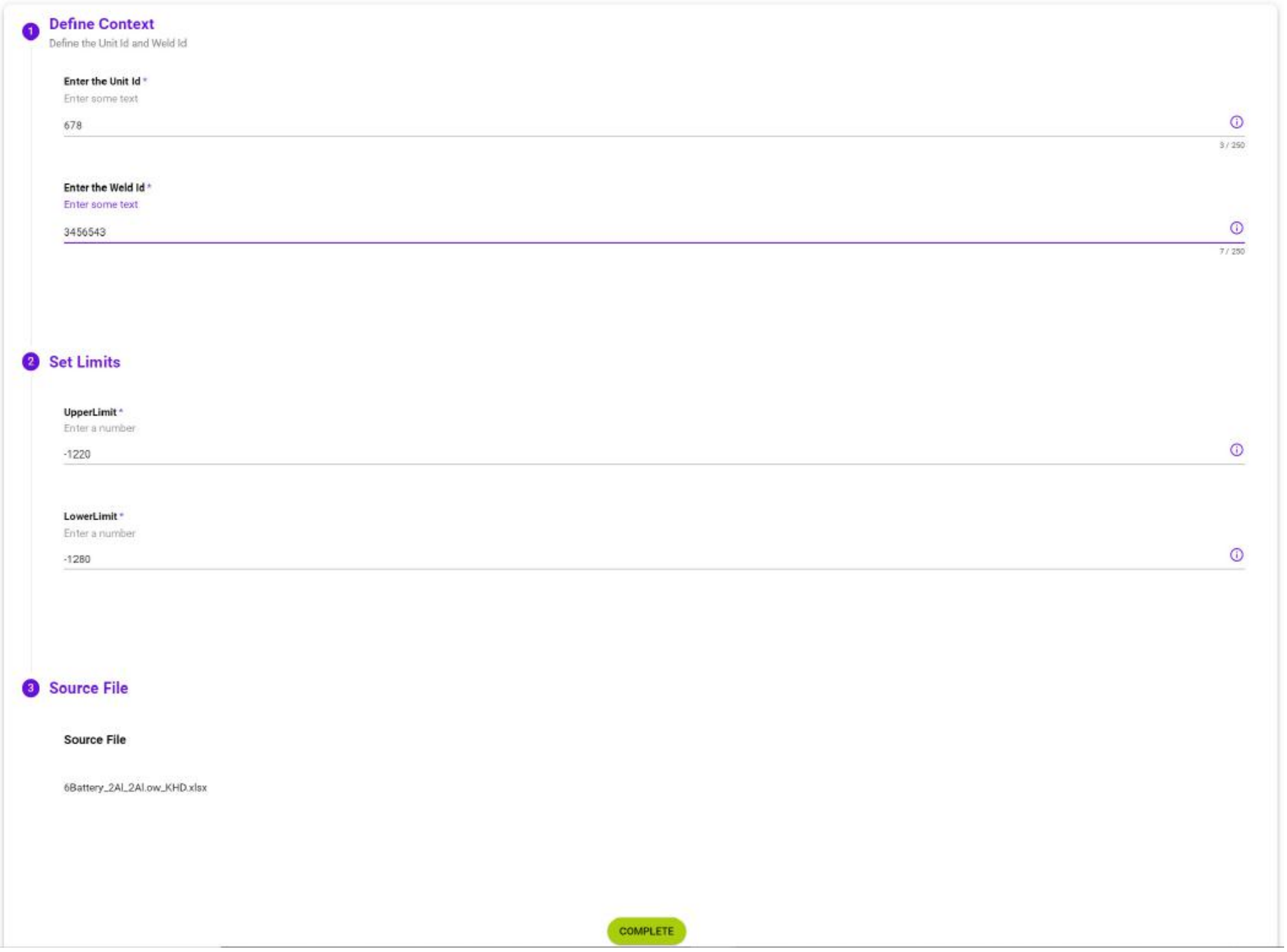
### 3.2.0 Data management (ATS)

This section describes Lancaster University's AI algorithm deployment in the Atlas cloud.

Executable process mapped as follows:




Input parameters (Task 1):

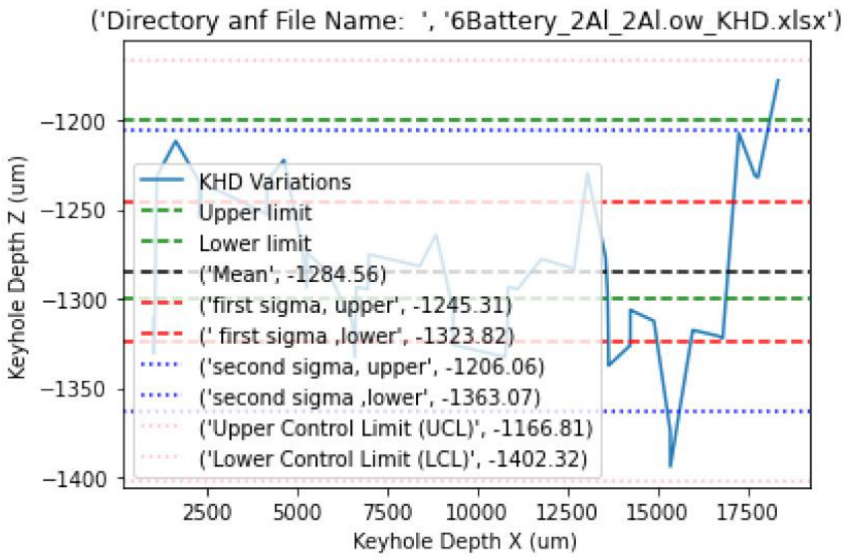


Output parameters (Task 3) in the format of raw data and graphical display:

source

March 21, 2022

```
You chose this directory for selecting xlsx file: 6Battery_2Al_2Al.ow_KHD.xlsx
length DF2 IS:  93
Consecutive breaches replaced by one:  [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1]
consecutive breaches :  [(0, 92), (1, 1)]
[0.0]
QS IS:  [(0, 0.0)]
pointa of breach of upper range are:  [92]
pointa of breach of lower range are:  [0, 1, 21, 22, 38, 39, 40, 41, 42, 43, 44,
45, 46, 47, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79,
80, 81, 82]
[0.3655913978494624, 0.6344086021505376]
[0.010752688172043012, 0.989247311827957]
1.6236559139784945
0.3763440860215054
```




Further to this ATS mapped other manufacturing processes with Ford including the laser lens replacement maintenance process the flow diagram for which is shown in figure 28 on the next page.

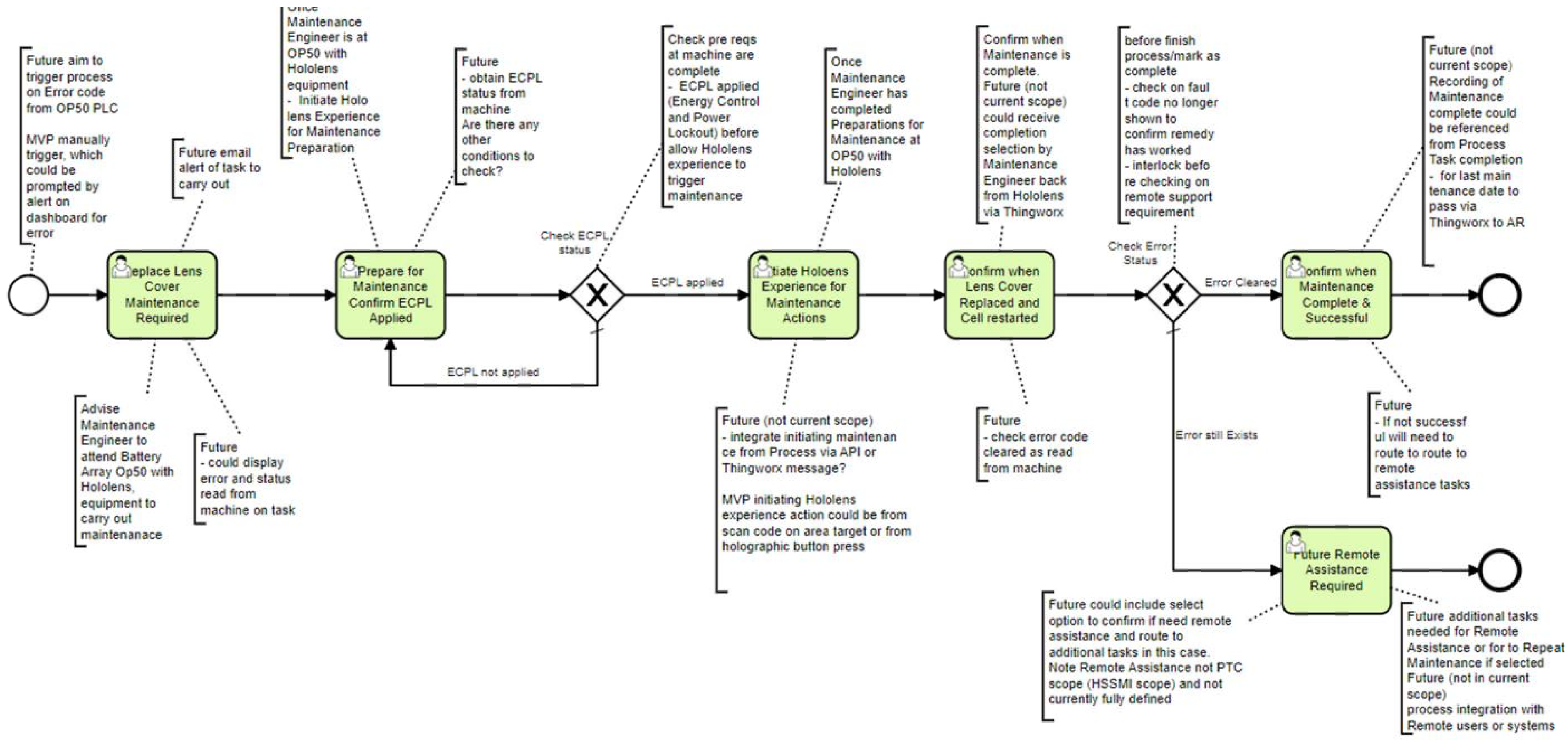



*Figure 28: Lens replacement process flow*

All machines and sensor data collected from the edge device is illustrated on customisable interactive dashboards as shown in figure 29.

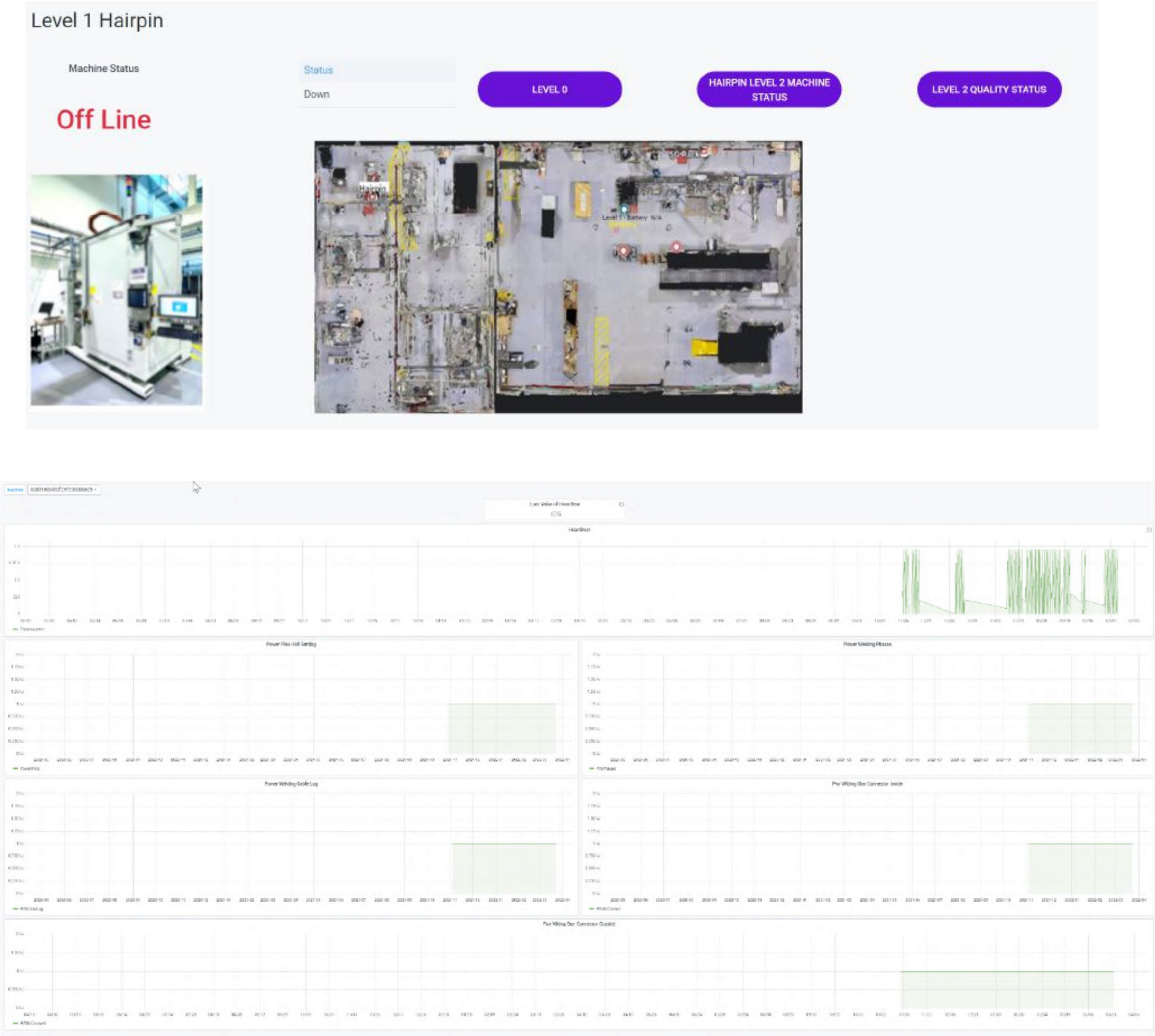
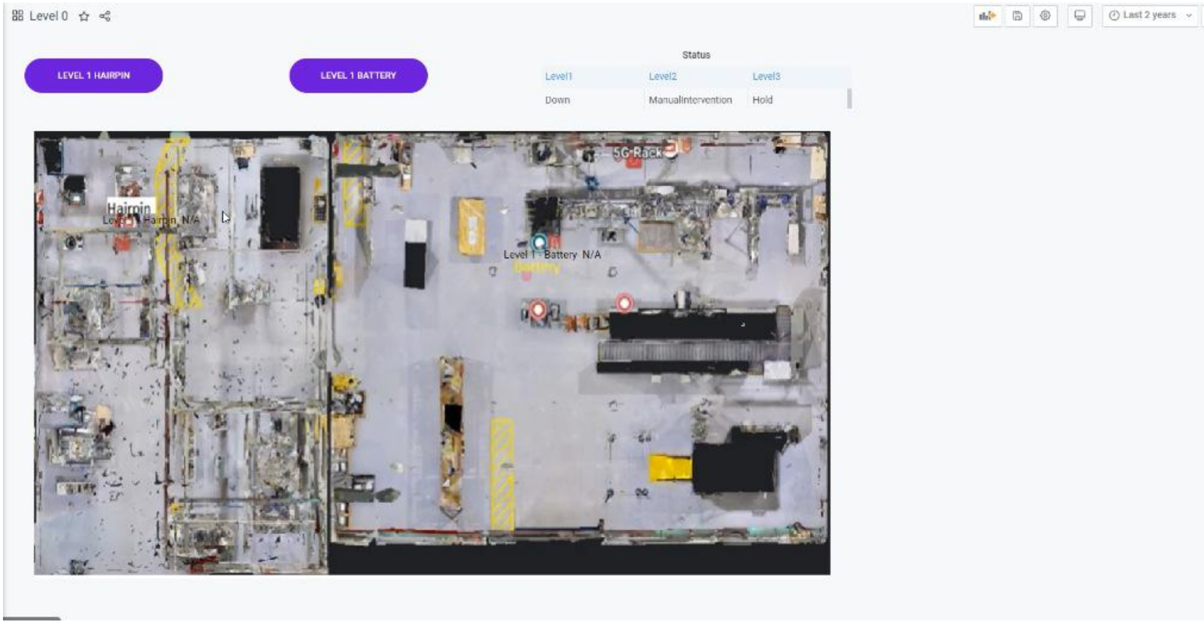



*Figure 29: Dashboard output in Atlas Cloud application*

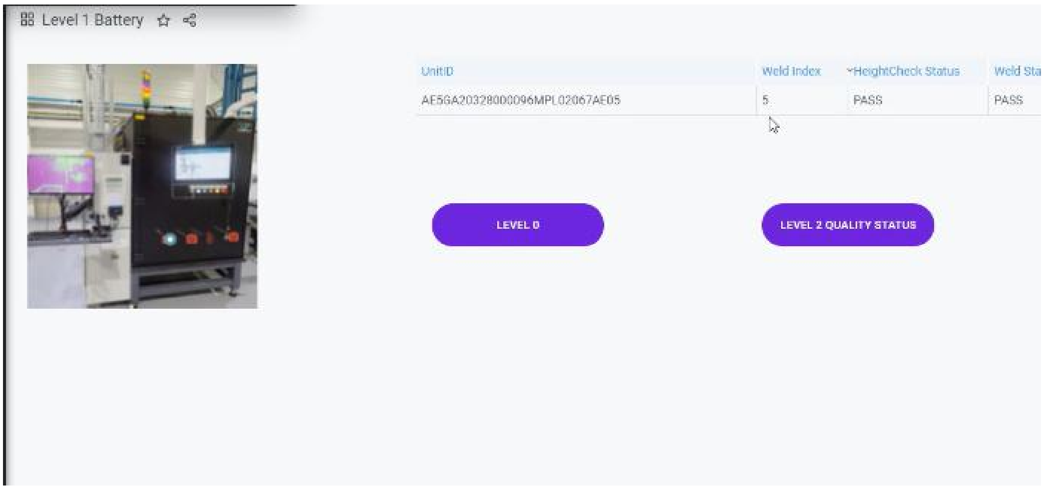
### 3.2.1 Factory monitoring

The factory monitoring results have been hinted at above in the ATS section. A multi-level structure was created which allowed the user to start with a map of the facility/factory (level 0), then select the equipment to view. At level 1 the user can then view some machine status and part quality status. This can be drilled down further into at level 2 where more detailed machine status can be viewed. Then finally there is level 3 where specific sensor data can be viewed.

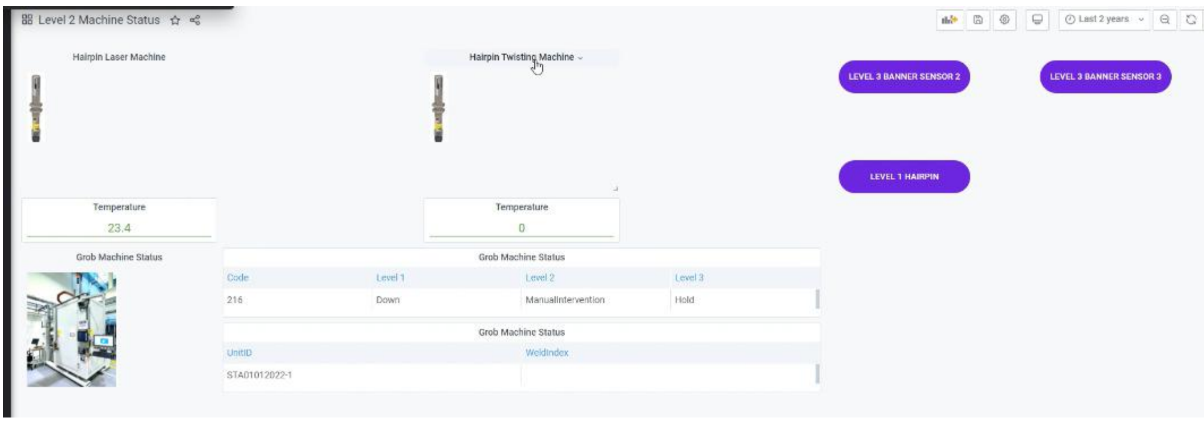
The images over the next few pages show examples of these “levels” of information. Note, the “heartbeat” value was added (in level 3) to demonstrate that there was communication between the machine and the cloud storage.



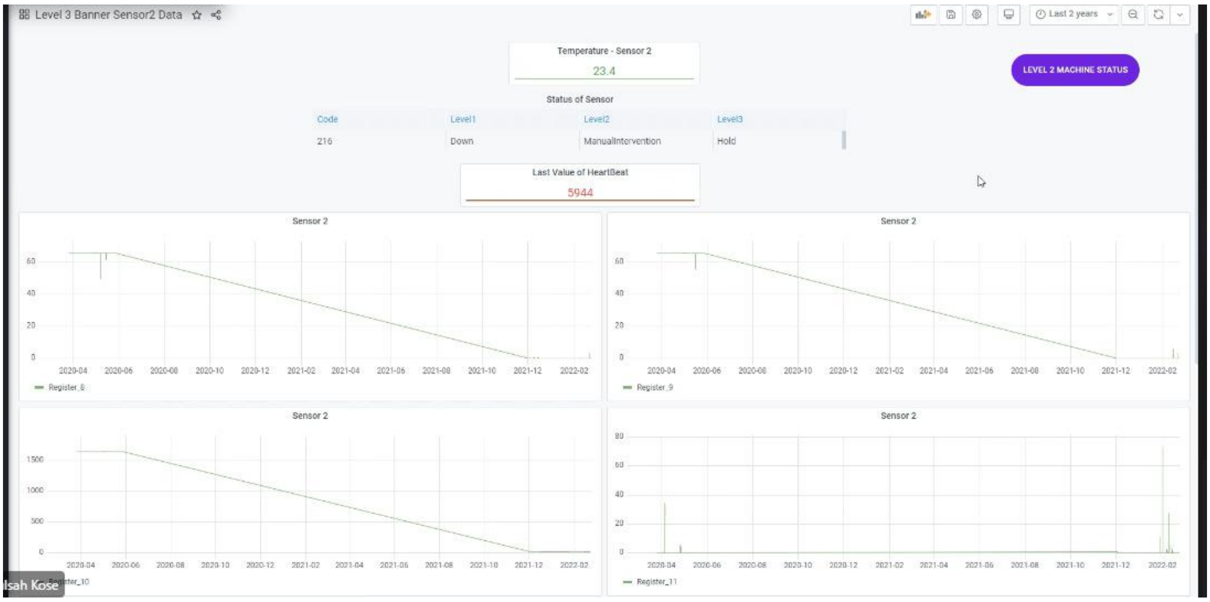

*Level 0 – view of factory*




*Level 1 – equipment/machine and part quality status*




*Level 2 – detailed machine status*




***Level 3 – detailed sensor information.***

Ultimately this was a demonstration of the system's capability. In reality, each laser welding machine is capable of producing hundreds of different pieces of data indicating machine and workpiece status and mapping all this data would have taken considerable resource

### 3.2.2 Predictive maintenance

Once in the Atlas cloud, the machine data could be analysed and shared with the project partners. Figure 30 shows an example of the output from the Turck-Banner sensors which had been set up to transmit temperature, electrical current, velocity of movement and acceleration (or vibration).

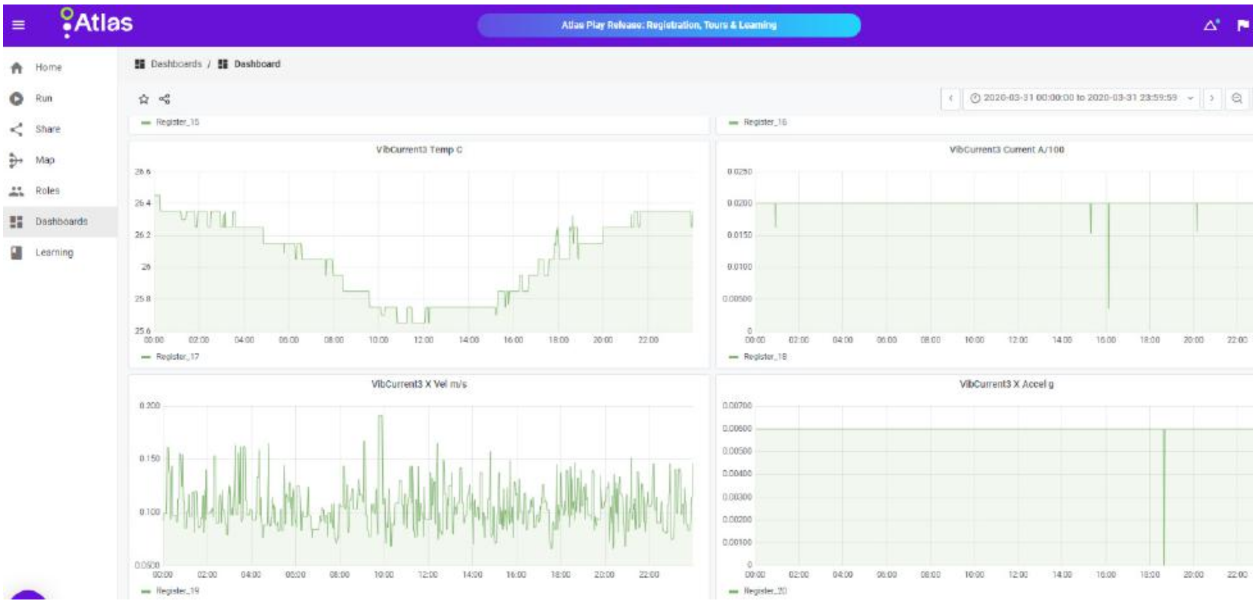



*Figure 30: Data in the Atlas cloud*

Figure 31 shows a further step of adding limits (or trigger points) to the data to indicate points beyond which action should be taken.

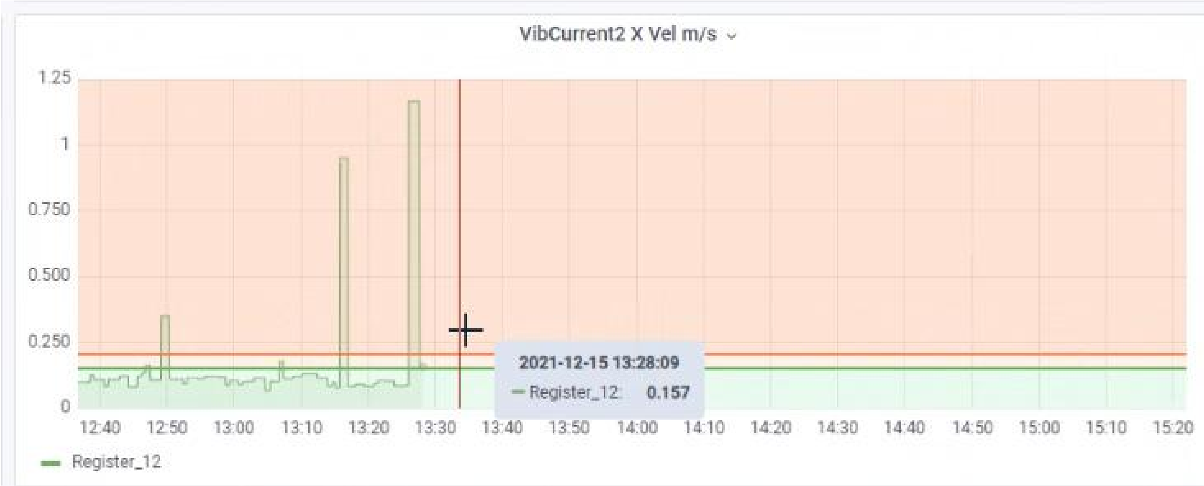



*Figure 31: coloured zones provide visual indication if measurements exceed limits*

Further work on this use-case would be to develop Artificial Intelligence (AI) to monitor the data and then predict if, for example, a motor is getting too hot, vibrating too much or drawing too much current, when an action needs to be taken. Should action be required, a message would then be sent to trigger a maintenance event. This could be via an email or directly into a maintenance planning system such as IBM's MAXIMO. Figure 32 describes how this would work.

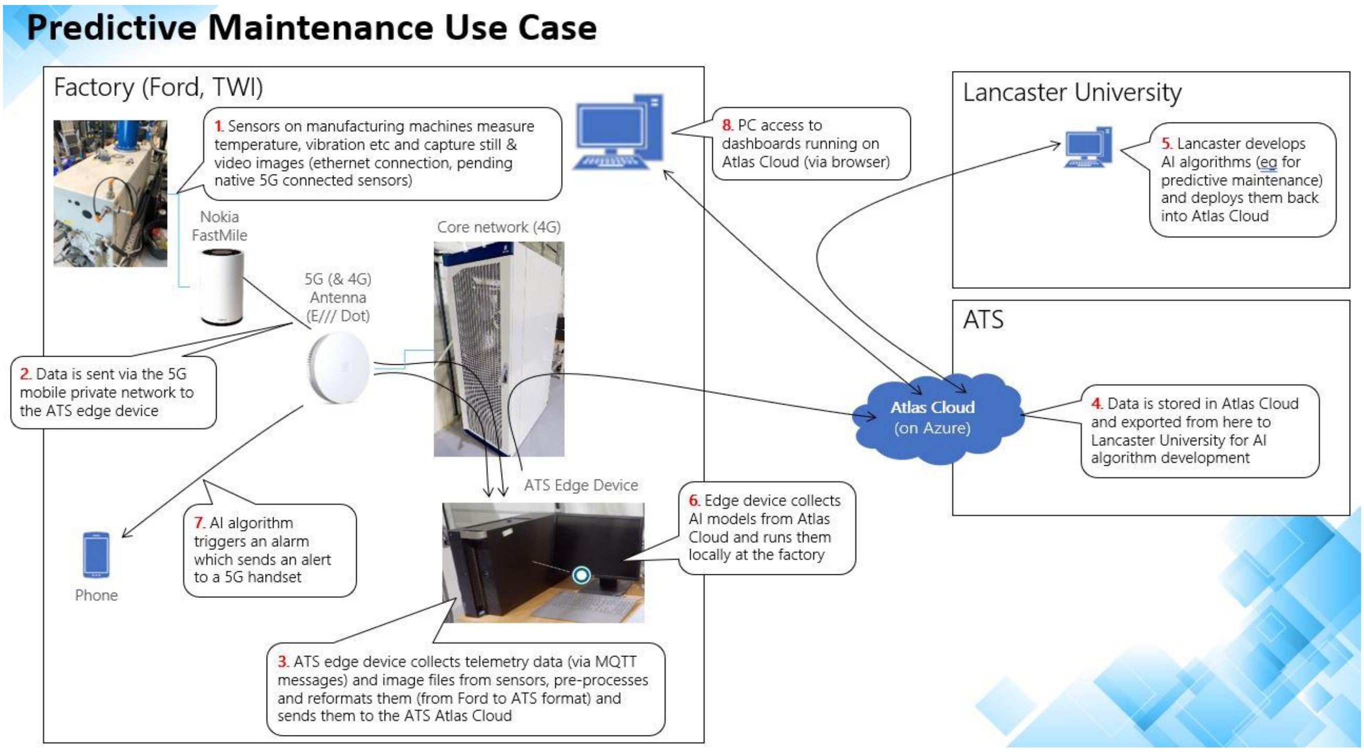



*Figure 32: Predictive maintenance use case*

### 3.2.3 Process monitoring

The first use-case selected for data acquisition and analysis at Ford was the battery tab welding process and specifically the measurement of the depth of the laser weld which is achieved using a secondary laser beam in the welding machine's Laser Depth Dynamics (LDD) system. This measures multiple parameters and weld depth was selected for this demonstration.

For the data visualisation, a Graphical User Interface (GUI) has been designed and developed in which user is able to upload an Excel (xlsx format) file of LDD data output from the laser welding machine. On execution of the GUI, prompts appear for the user to enter upper and lower limits for Key Hole Depth (KHD) based on the interest of seeing different range impacts for pass or fail weld assessment. Post data entry, a series of figures and pie charts are presented to include statistical value and visualization of welding outputs and limits. At the end, a summary box is presented which includes complete details and identification of chosen files.

The consecutive length of breaches from the upper and lower ranges, and length of total breaches from upper and lower control limits for different chosen files are presented as well as a confirmation of a pass or failure.

The below images show the process of executing the GUI.

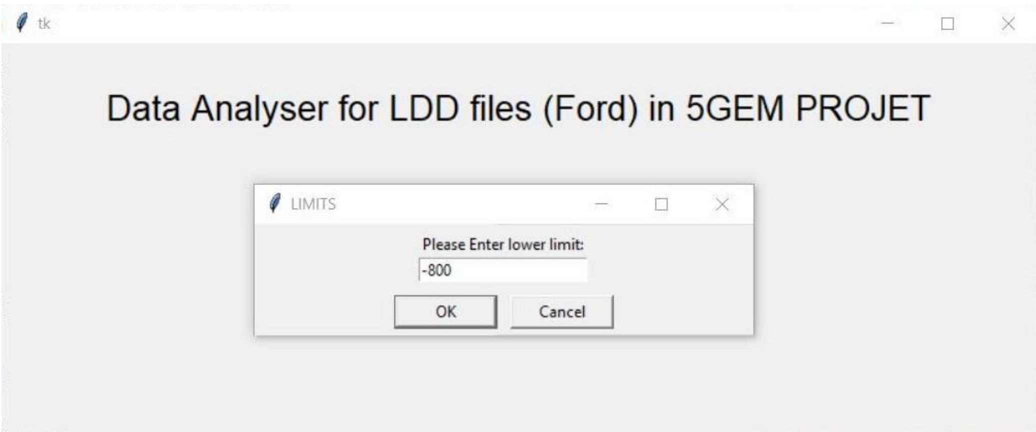



*Figure 33: GUI Upper and Lower limit interface*

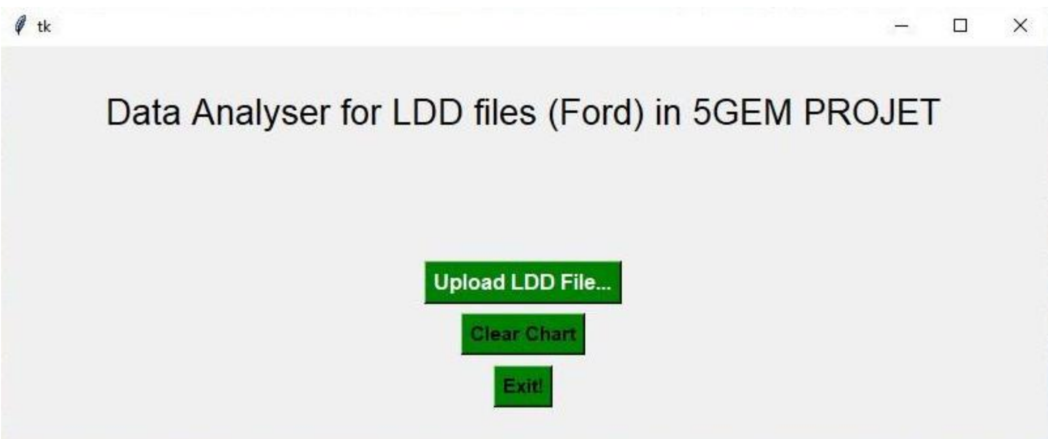



*Figure 34: File uploading interface*

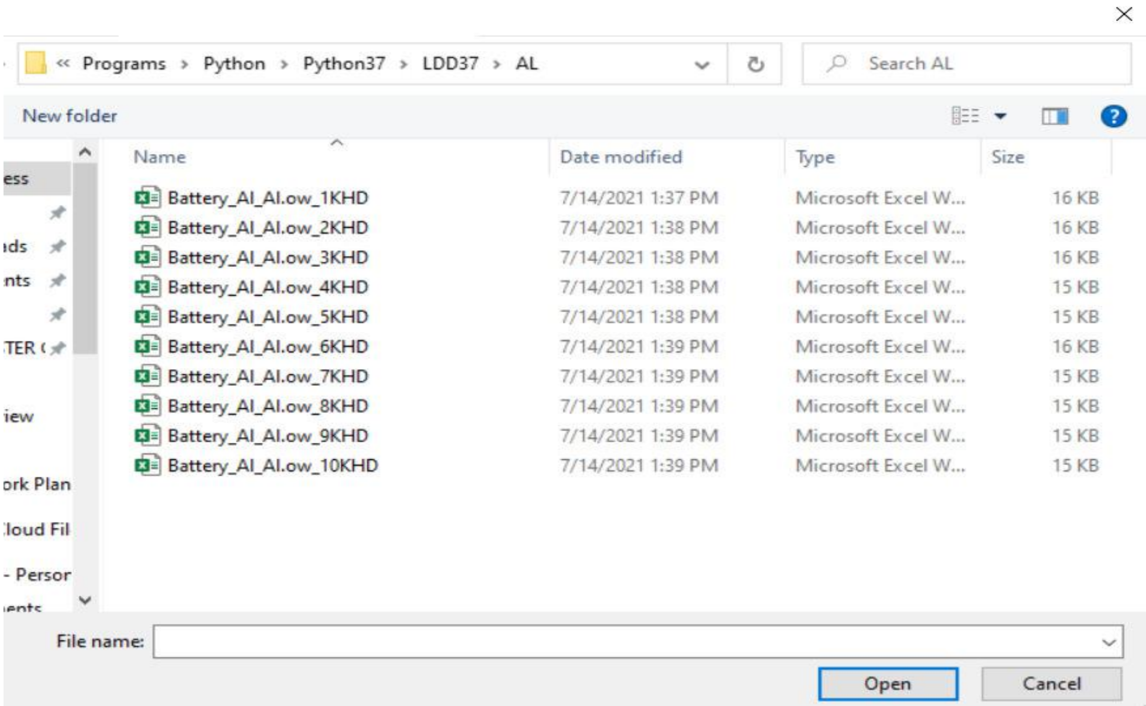



*Figure 35: File directory*

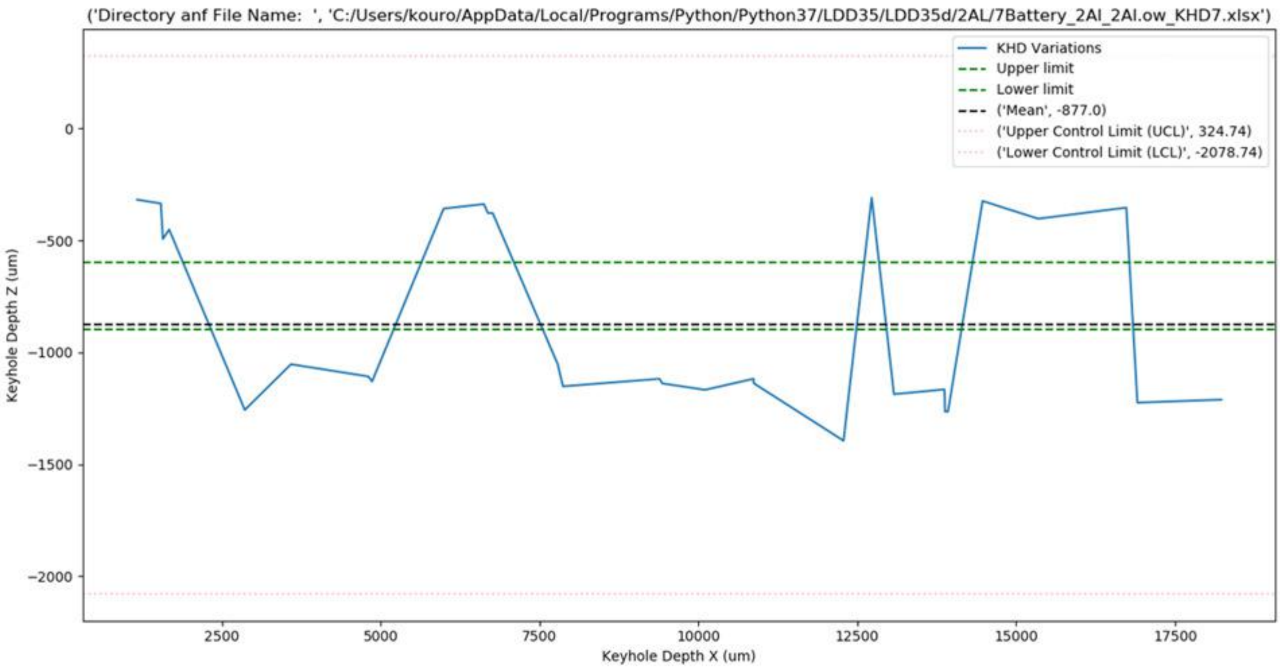



*Figure 36: File visualization, KHD vs welding length including statistical values*

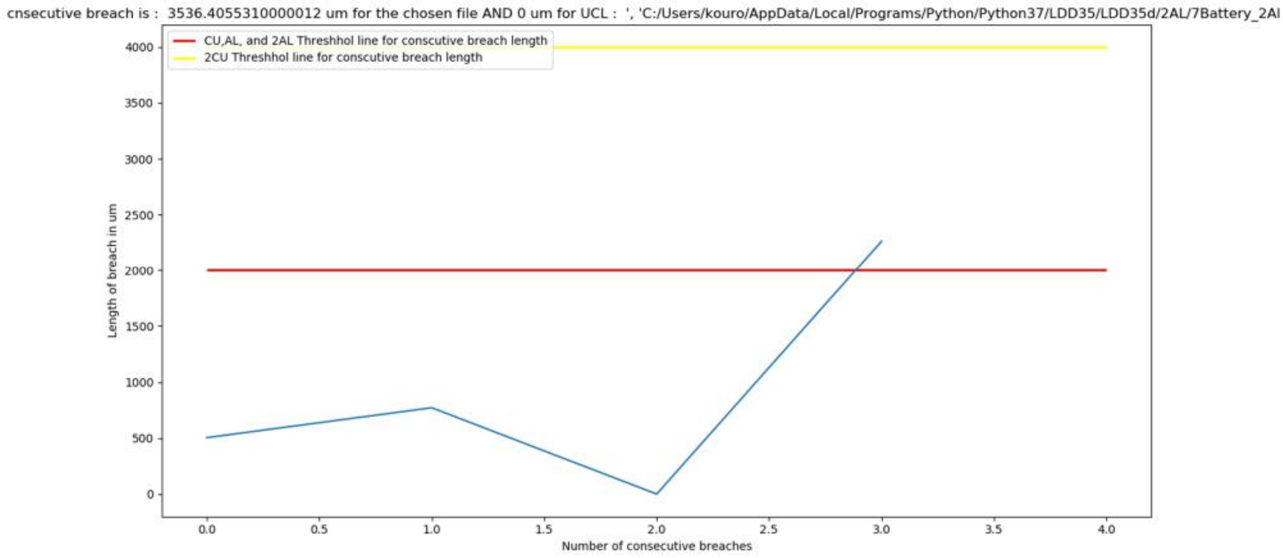



*Figure 37:  Breach length and consecutive length of breaches*

Summary of chosen data

```
{
Means are:
} {    Mean of each separate welding data
0                               -877.00
1                               -496.63}{
Standard deviations are:
} {    SD of each separate welding data
0                              400.58
1                              304.52}{
Number of non consecutive set of breach vs accosiated
consecutive breach for each number(Upper limit) for all
files :
} {{{0 503.91705100000013} {1 770.7373280000002} {2 0.0} {3
2261.7511520000007}} {{0 6594.470046} {1 4508.294931}}}{
The total length of breaches from upper limit for selected
file are respectively:
} {3536.4055310000012 11102.764977} {Fail {Super_Fail if
2CU}}{
The total length of breaches from lower limit for selected
file are respectively:
} {8784.331796999999 2.7649770000007265} {{Super_Fail if
2CU} Pass}{
The total length of breaches from UCL (3 sigma) for
selected file are respectively:
} {0 0} {Pass Pass}{
The total length of breaches from LCL (3 sigma) for
selected file are respectively:
} {0 0} {Pass Pass}{
  The files which are chosen respectively are :
}
{C:/Users/kouro/AppData/Local/Programs/Python/Python37/LDD3
5/LDD35d/2AL/7Battery_2Al_2Al.ow_KHD7.xlsx
C:/Users/kouro/AppData/Local/Programs/Python/Python37/LDD35
/LDD35d/2AL/16Battery_2Al_2Al.ow_KHD16.xlsx}
```

*Figure 38:  summary box (2 files chosen details)*

### 3.2.4 Visual analysis of battery welds

The tab-to-busbar coupon trials were carried out at TWI and delivered to Lancaster University on a CD for Image Processing analysis. The CD contained video frames of every single welding and its associated finalized image (176 different welds). The data was categorized into 4 different groups based on the RGB profile and red colour as a main feature.  Fig. 7 shows the content of DVD of images and videos.

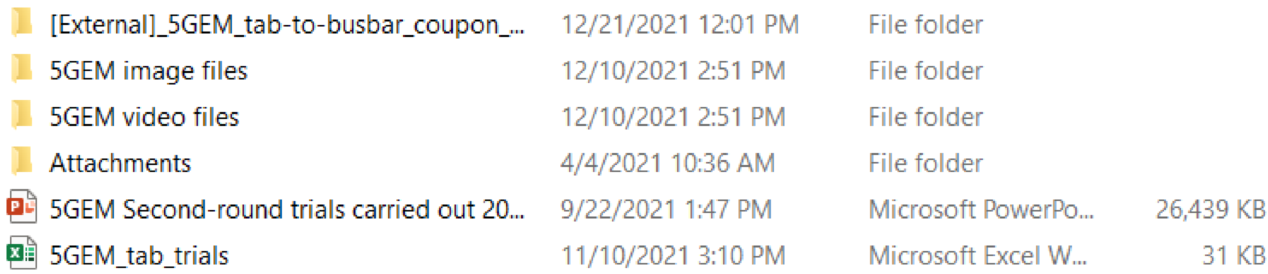



*Figure 39: Welding video frames and associated video frames*

The categorization is based on 3 approaches: (1) white, black, and red colour reference image using nearest neighbour distance function method, (2) brightness and redness percentage of the images, and (3) Bayesian ML Method, which are each discussed below.

#### Method and models

The image analysis approach is to categorise the non-labelled images into groups as defined by Ford. The grouping is based on the RGB profile to indicate an acceptable process.  With the pattern type known (i.e. a measured percentage of RGB profile present), a number of different algorithms and solutions are in the literature to achieve a successful analysis, an overview of the three most appropriate approaches is described below:

White colour reference

In this approach, a white colour image in the same size of real images will be compared with every image associated with the video frame folders. As there are not too many images, an algorithm of nearest neighbour (a Machine Learning approach) can be utilised. Based on this approach each corresponding part of image is divided into thousands of parts and each part has a certain RGB matrix. The RGB matrix is compared with white colour image and by using square distance of matrix arrays, a value is measured and associated with each image. It shows the similarity of white colour pattern in images. A top level of the approach is given in Fig.8.


*Figure 40: Welding image processing top level*

The Image processing box (identified in figure 9) allocates a value as a function of the RGB profile of image which, based on this measured value, it is allocated to one of the groups out of 4 defined groups - namely low level, medium level, high level, and very high-level brightness. The Image processing box is given in more detail in Fig.9.

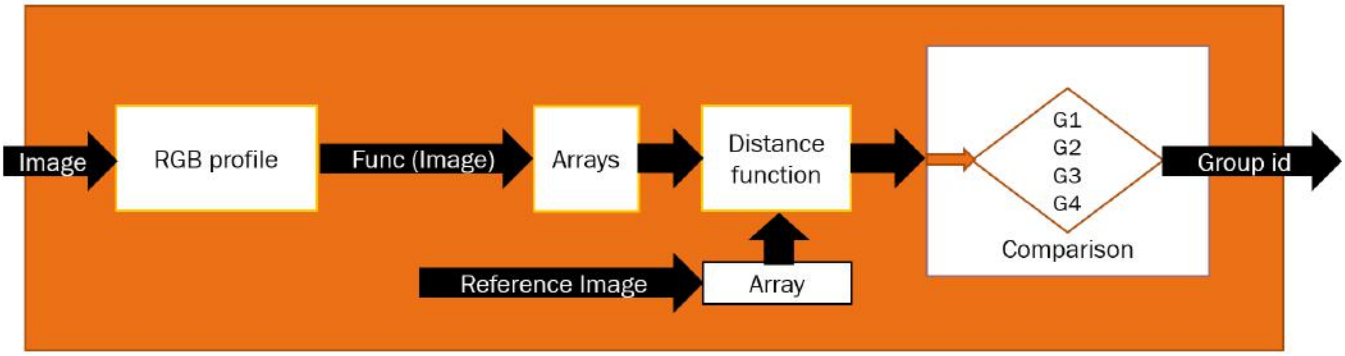



*Figure 41: Image processing box detail*

### Red colour reference-based grouping

The red colour reference-based approach is where images can be categorized into different groups based on a red reference image. In this case proportional parts of a reference image are compared with original images to find red colour profile similarity, and based on this similarity they will be grouped into failure or pass groups.

### Red colour percentage-based grouping

As the data (images) are not labelled and the number of them are not high, classification and supervised machine learning based method cannot be used. Unsupervised ML method may be used and based on the defined categorization which can be done, we may see some specific pattern on it. But still, the number of images, 176, is not too much. Data augmentation method can increase the number of data but finding and comparing the images pattern with a defined approach, for instance percentage of Red colour profile in each image is a good grouping method which Ford is interested in it.

### Red colour percentage-based grouping

The finalized method which is based on the percentage of red colours in an image, has a very high accuracy. In this method Bayesian Machine Learning method is implemented.

We create a GUI to upload an image, then image is appeared with its associated group. The steps are shown in below images.


*Figure 42: GUI for image uploading*

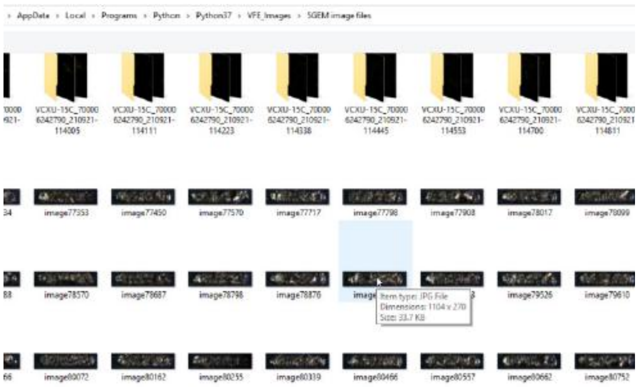


*Figure 43: File directory to select image*

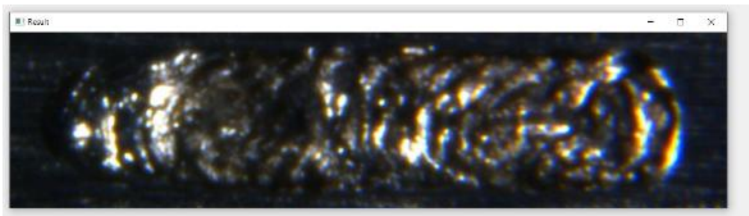


*Figure 44: Chosen image is shown*

```
>>>  This welding in Normal. Method which is used is Baysian ML and belongs to group: 1
Control and Normal Weld, Accuracy (average) around 95%
```

*Figure 45: Status (fail or pass) of Chosen image is shown*

Based on the Bayesian ML method, the percentage of images belonging to each group is measured. Then a Gaussian distribution is made for the redness value of all the images belonging to each group. Then by using Bayesian rules, ML method is implemented and user can choose an image and its redness value is measured. The highest percentage of Bayesian probability amongst the three groups is chosen as the winner label and the image is associated to that group. ML based method was selected and it has around 95% of accuracy. As the redness percentage range is considered, then maximum and minimum value of the range are assumed and any images can be considered as a test and it can be seen that the accuracy is around 95%.

## 3.2.5 Weld analysis using agnostic vision system

On completion of the project the agnostic vision system (2D and 3D camera) laid out in figure 46 was deployed and commissioned.

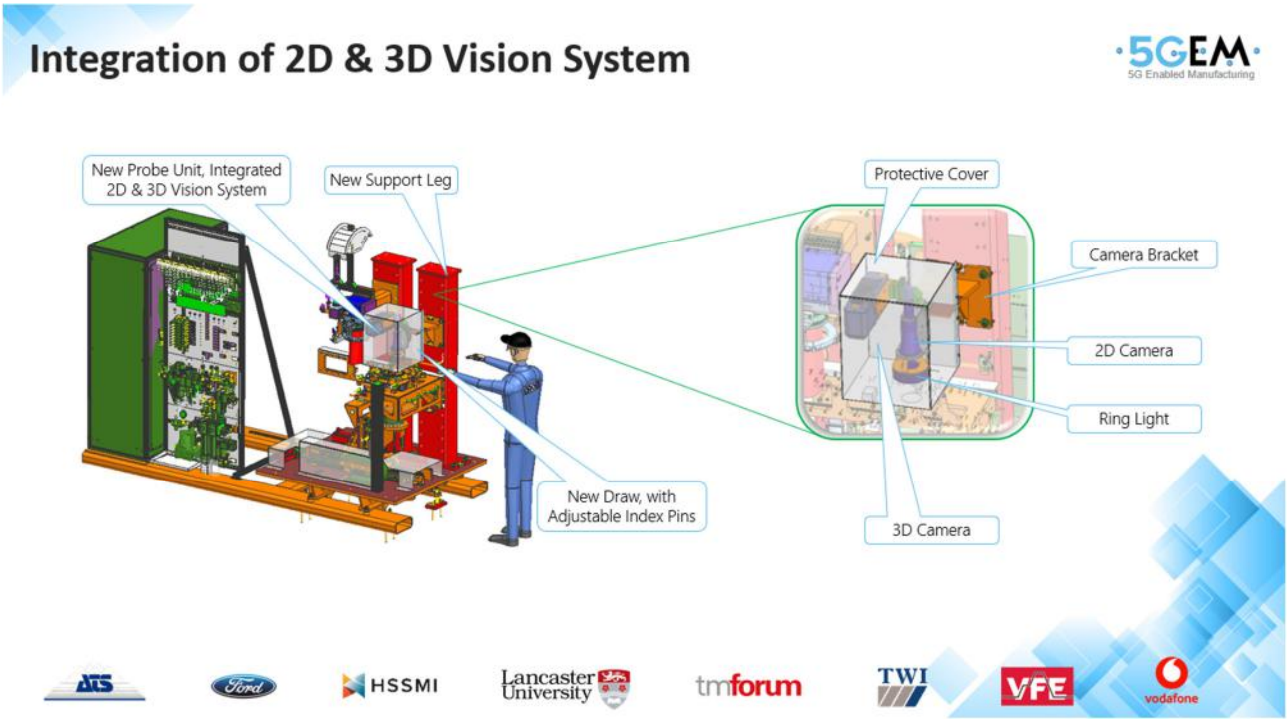
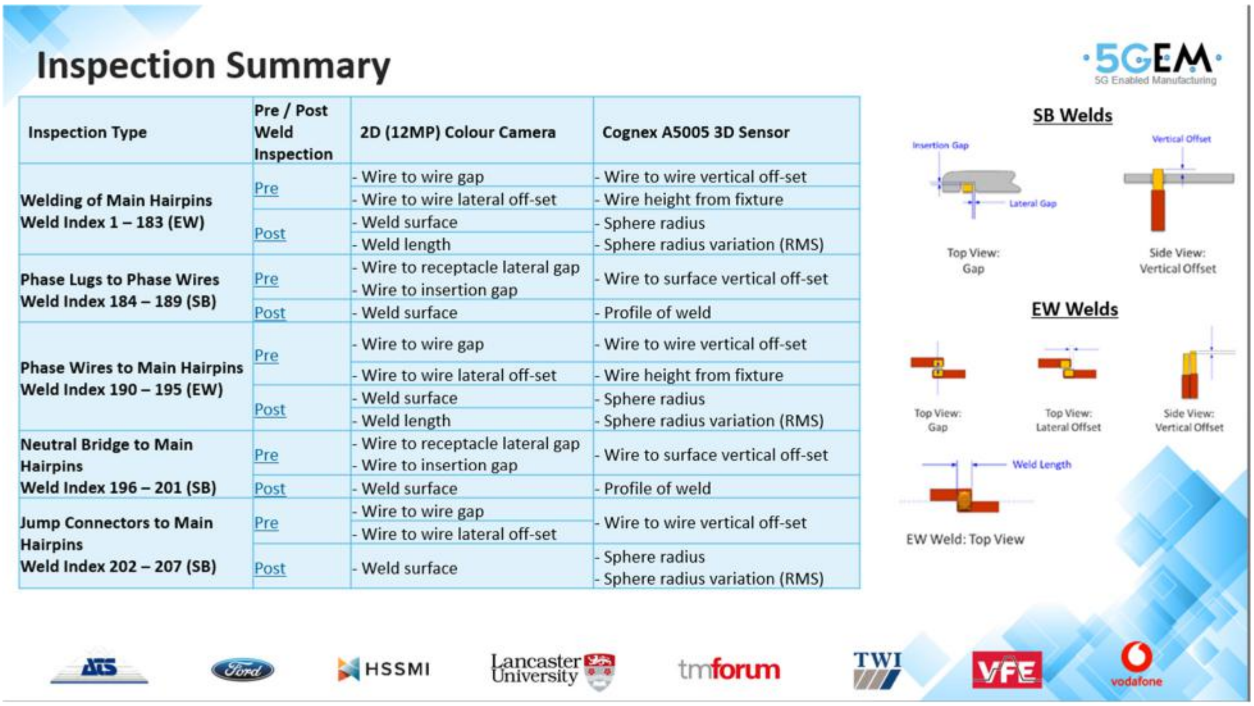



*Figure 46: Vision system*

The system successfully measured the gap between pins, the height difference between pins for pre-weld checks, and the weld diameter post weld described in figure 47.




| Inspection Type | Pre / Post Weld Inspection | 2D (12MP) Colour Camera | Cognex A5005 3D Sensor |
|---|---|---|---|
| Welding of Main Hairpins Weld Index 1 – 183 (EW) | Pre | - Wire to wire gap<br>- Wire to wire lateral off-set | - Wire to wire vertical off-set<br>- Wire height from fixture |
| | Post | - Weld surface<br>- Weld length | - Sphere radius<br>- Sphere radius variation (RMS) |
| Phase Lugs to Phase Wires Weld Index 184 – 189 (SB) | Pre | - Wire to receptacle lateral gap<br>- Wire to insertion gap | - Wire to surface vertical off-set |
| | Post | - Weld surface | - Profile of weld |
| Phase Wires to Main Hairpins Weld Index 190 – 195 (EW) | Pre | - Wire to wire gap<br>- Wire to wire lateral off-set | - Wire to wire vertical off-set<br>- Wire height from fixture |
| | Post | - Weld surface<br>- Weld length | - Sphere radius<br>- Sphere radius variation (RMS) |
| Neutral Bridge to Main Hairpins Weld Index 196 – 201 (SB) | Pre | - Wire to receptacle lateral gap<br>- Wire to insertion gap | - Wire to surface vertical off-set |
| | Post | - Weld surface | - Profile of weld |
| Jump Connectors to Main Hairpins Weld Index 202 – 207 (SB) | Pre | - Wire to wire gap<br>- Wire to wire lateral off-set | - Wire to wire vertical off-set |
| | Post | - Weld surface | - Sphere radius<br>- Sphere radius variation (RMS) |

*Figure 47: Inspection summary*

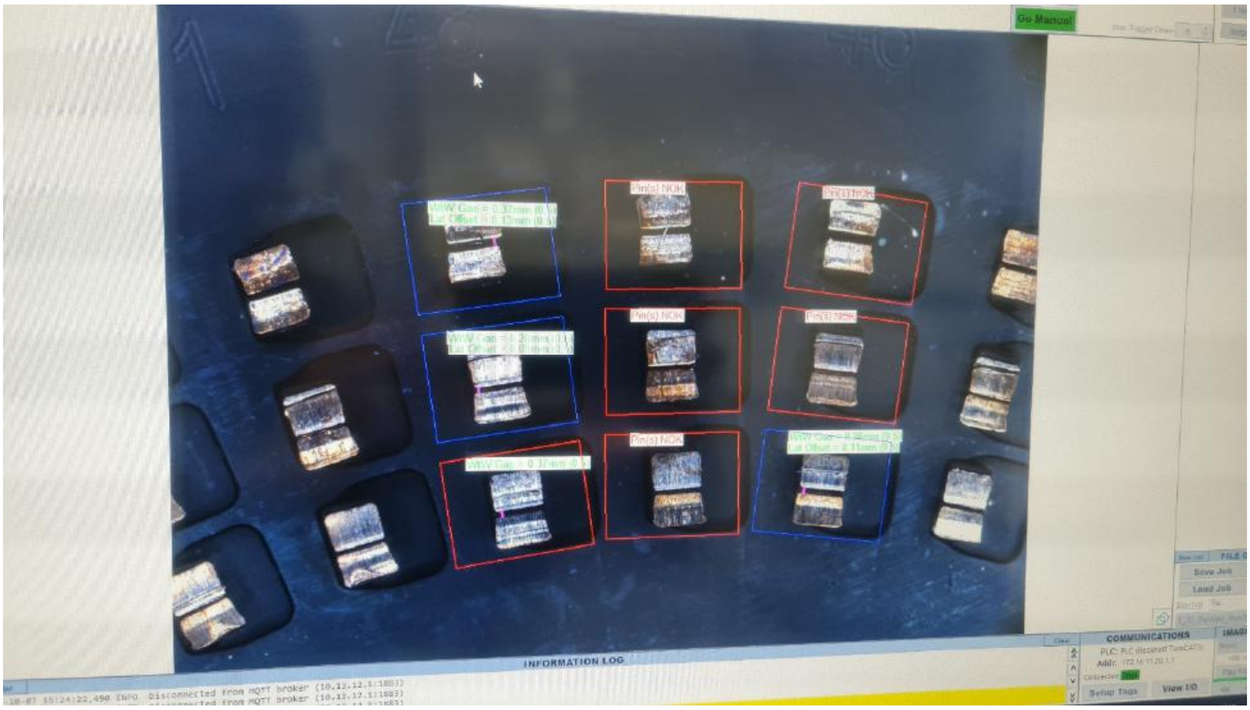



*Figure 48: 2D Camera results*

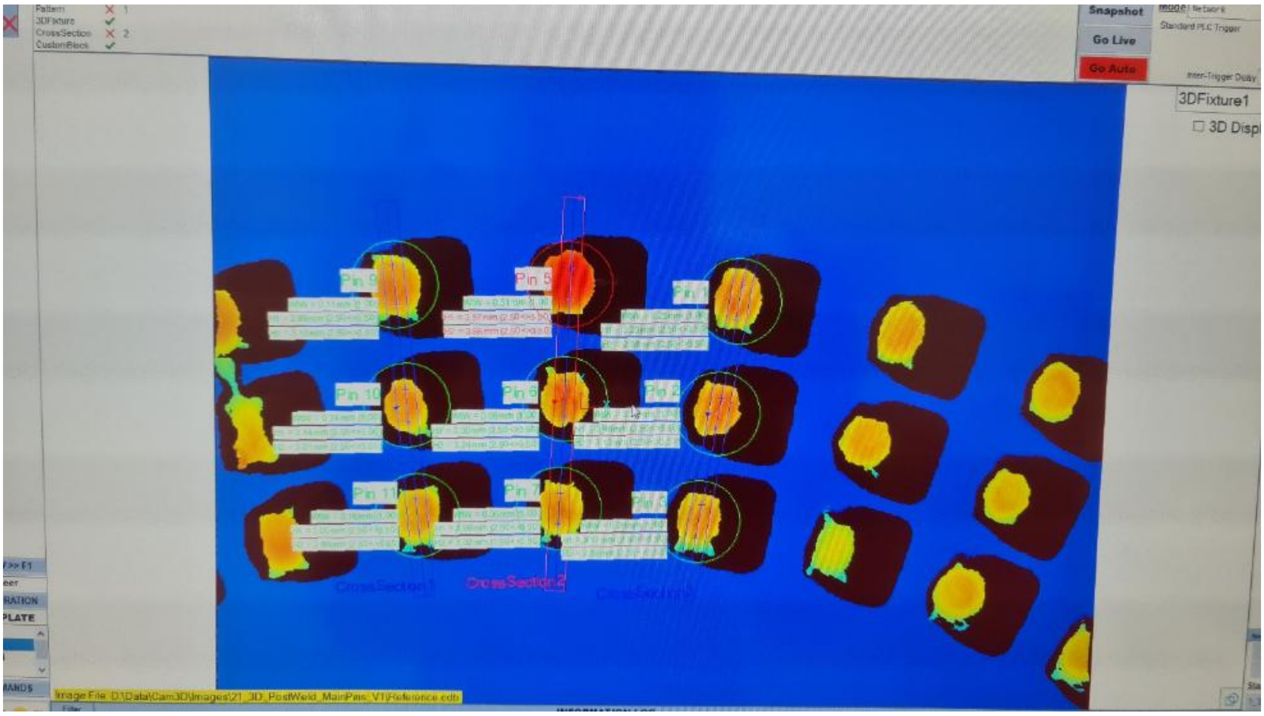



*Figure 49: 3D camera results*

The 5G network enabled the transfer of large files (pre and post weld images as shown in figures 48 and 49), additional data on pin gaps, height differences, and weld sizes from the machine to the cloud.

With the data now located on the cloud, this enabled:

- Collection of a larger data set of images;
- Access to more powerful PCs to carry out ML on the collected weld data;
- Data sharing to consortium partners for expert assistance;
- Improvement of weld parameters based on data analysis.

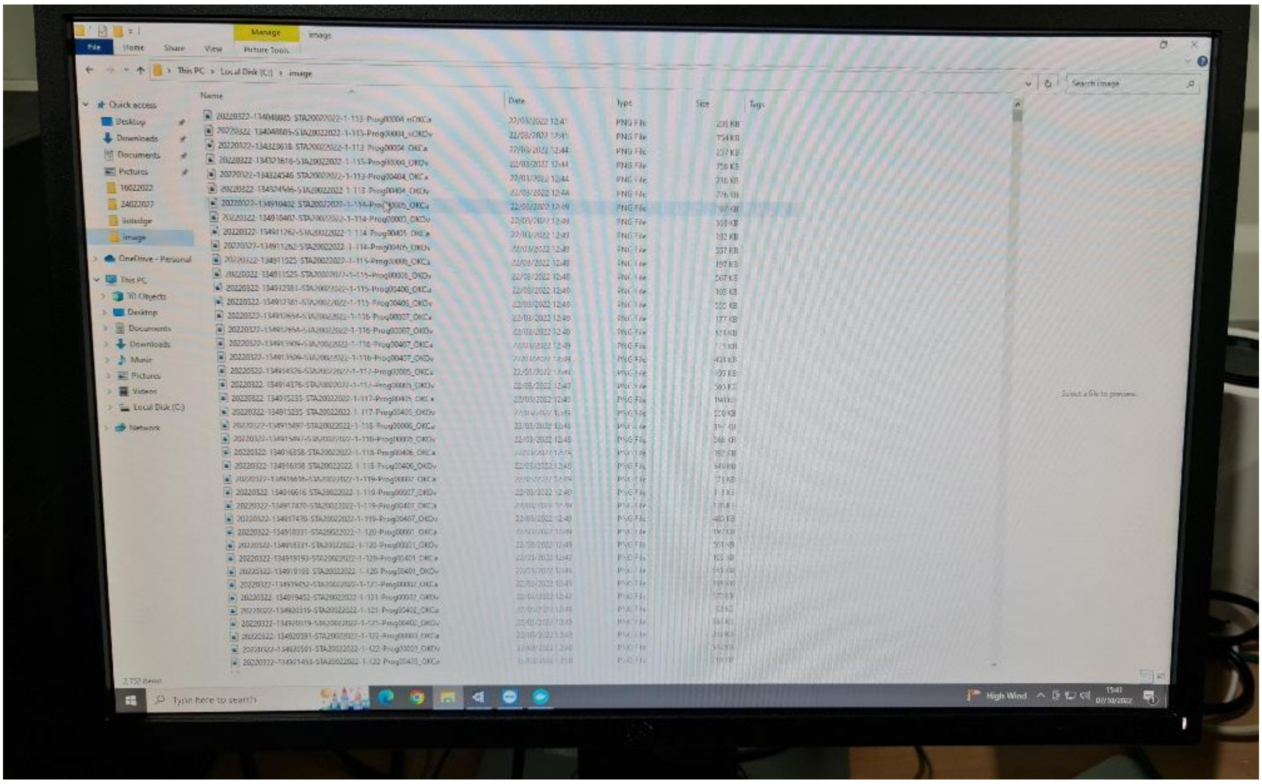


*Figure 50: ability to store large number of images in new system*

Unique solutions provided by the 5G network were:

- Large file sharing wirelessly of pre and post weld images (figure 50);
- High speed connection from cloud to machine for real time image analysis and automated feedback to machine controller (future opportunity).

### 3.2.6 AR-MR Maintenance support (HSSMI)

Using the HL2 hardware and PTC Vuforia software platform a maintenance support scenario has been fully developed. Figure 51 shows the network architecture. The use-case is based on the need to change or clean the laser lens rather than looking up maintenance files and then cross checking the schedules with the deployed equipment, the headset could visually alert the personnel to possible arising issues as they walk around the site/facility.

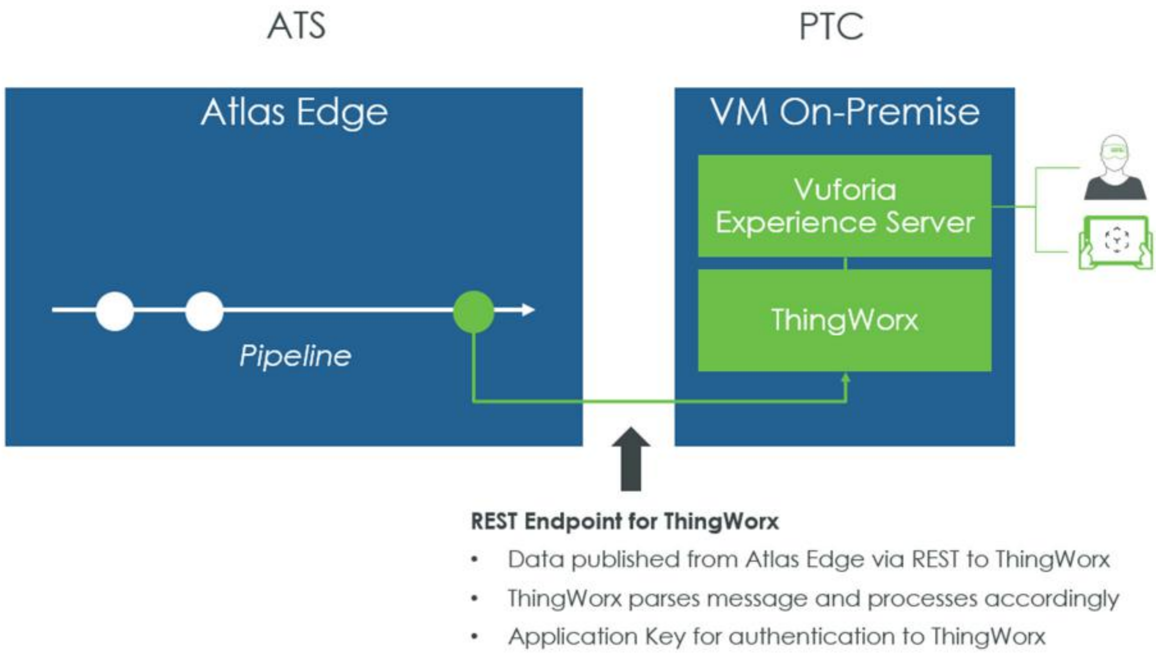
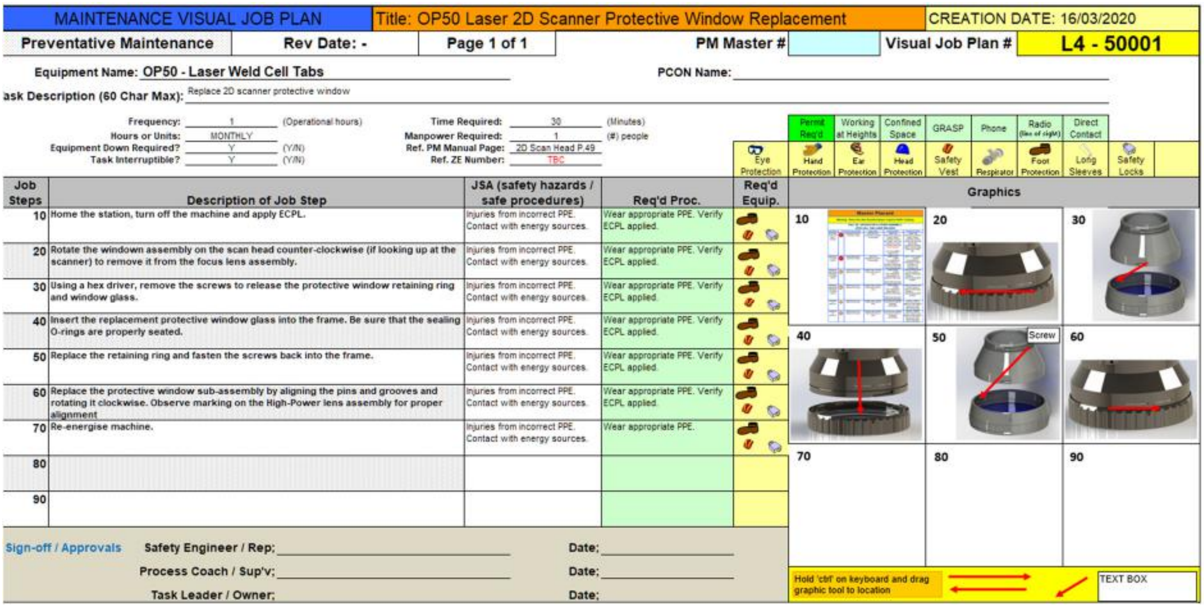



*Figure 51: Initial network architecture diagram*

With expert support from PTC and using their AR/MR developer platform, PTC Vuforia Studio, we developed and refined an application for the battery tab welding machine, "maintenance work instructions – OP50 – replace lens of laser welder". The work instructions (figure 52) were augmented and shows step-by-step instructions overlaid atop the physical machine. Also, data from other use-cases with ATS will provide rich insight in the AR-MR experience by updating relevant machine information within the headset (machine data on Atlas Edge communicated via REST API to PTC ThingWorx)

Results:

1. Used "Area Targets" to locate real world objects and align preconfigured AR/MR holograms e.g. 3D CAD reference model – laser welder external enclosure and access doors
2. Developed context aware work instructions as holograms (translate machine providers maintenance instructions into the application
3. Developed context aware animations from 3D CAD model to demonstrate actions for the user in the application. E.g., animate the attachment and securing of the new lens cover to the laser welder.
4. Configure ThingWorx application to provide machine data feed into the HL2 headset



MAINTENANCE VISUAL JOB PLAN | Title: OP50 Laser 2D Scanner Protective Window Replacement | CREATION DATE: 16/03/2020

Preventative Maintenance | Rev Date: - | Page 1 of 1 | PM Master # | Visual Job Plan # L4 - 50001

Equipment Name: OP50 - Laser Weld Cell Tabs PCON Name:

ask Description (60 Char Max): Replace 2D scanner protective window

Frequency: 1 (Operational hours) Time Required: 30 (Minutes)
Hours or Units: MONTHLY Manpower Required: 1 (#) people
Equipment Down Required? Y (Y/N) Ref. PM Manual Page: 2D Scan Head P.49
Task Interruptible? Y (Y/N) Ref. ZE Number: TBC

Permit Req'd | Working at Heights | Confined Space | GRASP | Phone | Radio (line of sight) | Direct Contact

Eye Protection | Hand Protection | Ear Protection | Head Protection | Safety Vest | Respirator | Foot Protection | Long Sleeves | Safety Locks

| Job Steps | Description of Job Step | JSA (safety hazards / safe procedures) | Req'd Proc. | Req'd Equip. |
|---|---|---|---|---|
| 10 | Home the station, turn off the machine and apply ECPL. | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. Verify ECPL applied. | |
| 20 | Rotate the windown assembly on the scan head counter-clockwise (if looking up at the scanner) to remove it from the focus lens assembly. | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. Verify ECPL applied. | |
| 30 | Using a hex driver, remove the screws to release the protective window retaining ring and window glass. | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. Verify ECPL applied. | |
| 40 | Insert the replacement protective window glass into the frame. Be sure that the sealing O-rings are properly seated. | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. Verify ECPL applied. | |
| 50 | Replace the retaining ring and fasten the screws back into the frame. | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. Verify ECPL applied. | |
| 60 | Replace the protective window sub-assembly by aligning the pins and grooves and rotating it clockwise. Observe marking on the High-Power lens assembly for proper alignment | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. Verify ECPL applied. | |
| 70 | Re-energise machine. | Injuries from incorrect PPE. Contact with energy sources. | Wear appropriate PPE. | |
| 80 | | | | |
| 90 | | | | |

Graphics: 10 | 20 | 30 | 40 | 50 Screw | 60 | 70 | 80 | 90

Sign-off / Approvals Safety Engineer / Rep; Date;
Process Coach / Sup'v; Date;
Task Leader / Owner; Date;

Hold 'ctrl' on keyboard and drag graphic tool to location | TEXT BOX

*Figure 52: Maintenance Visual Job Plan – Documentation example*

Developing the AR application using PTC software:

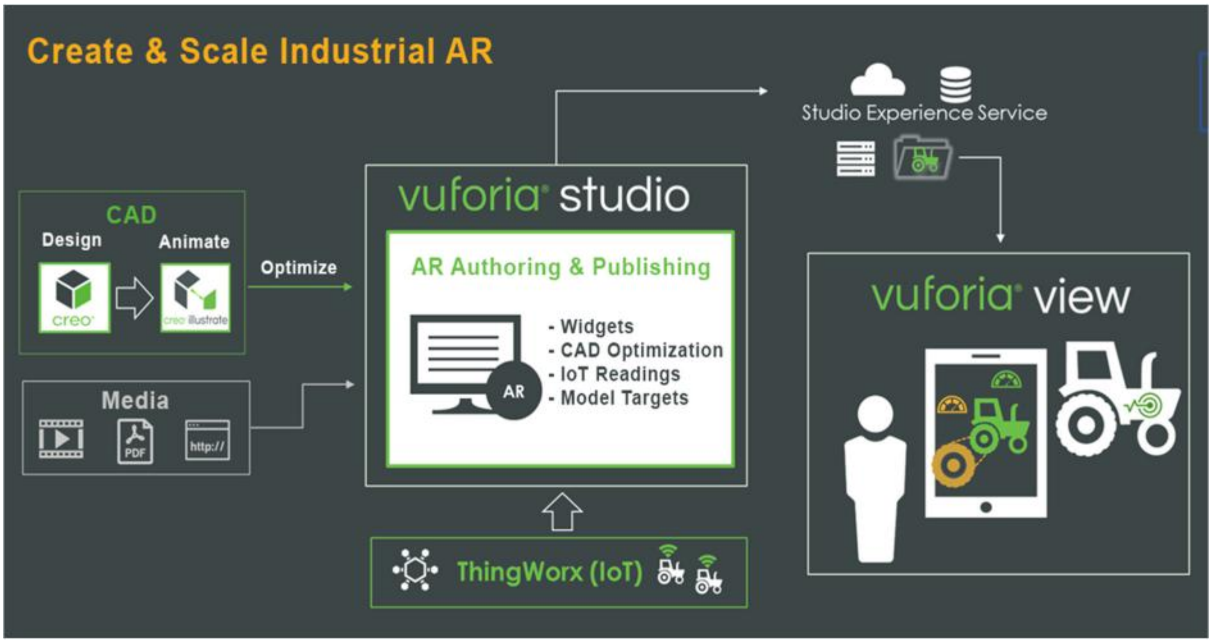



*Figure 53: PTC – AR software architecture*


*Figure 54: PTC Vuforia Studio – view of software platform for AR development*

A basic project template (figure 53) was used to start the project, after which all the main 3D CAD files were imported and positioned to match the real-life physical asset to give a 3D environment (figure 54).

Animations sequences are then generated for the 3D assets to be able to overlay onto the physical machine inside the AR application

With PTC Vuforia, the camera on the HoloLens2 recognises the pattern of a designated 3D positioned marker that we can place on the battery tab welding machine to use as a reference point. Vuforia's engine is able to estimate the HL2 position and orientation of the 3D marker to render the real-time holographic image to the user. This two-step process is how Vuforia powers augmented reality experiences with image recognition. As you walk around the real 3D marker, the holographics in the headset will move in sync as well. This is because the Vuforia platform is not only able to recognise the pattern of the real marker but is also able to estimate the HL2's position and orientation using the image recognition as its reference point.

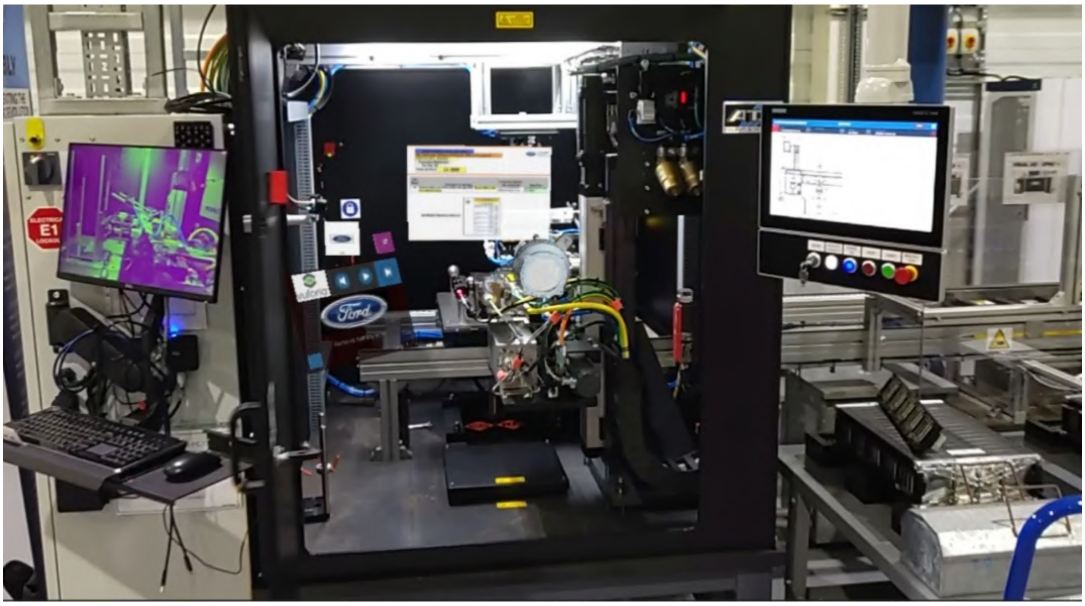


*Figure 55: Battery Tab Welding Machine – OP50 Laser welder – with AR view 1*

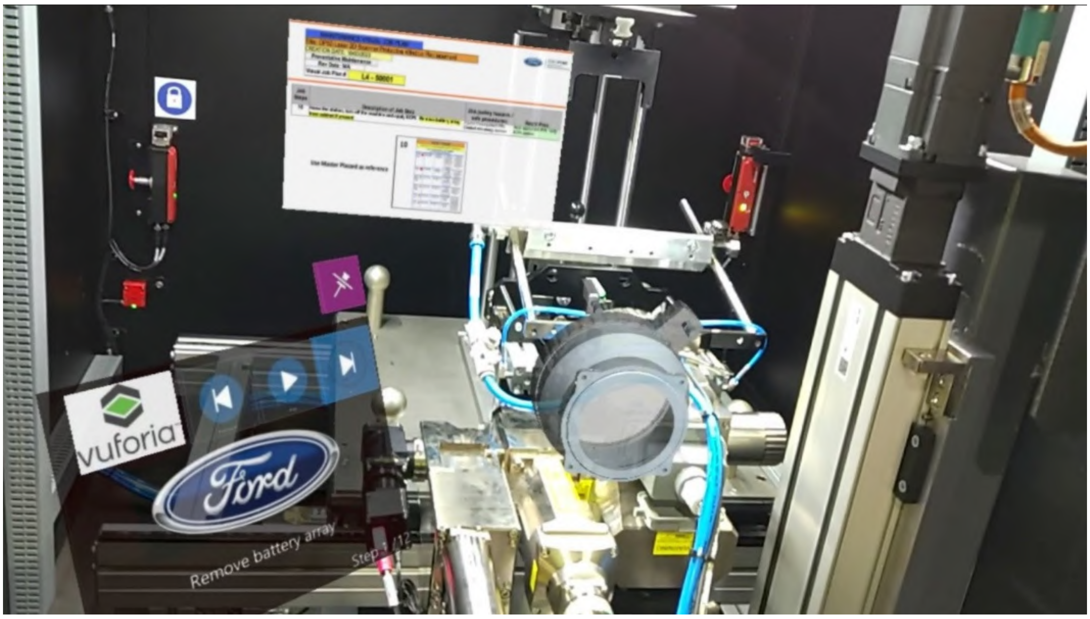



*Figure 56: Battery Tab Welding Machine – OP50 Laser welder – with AR view 2*

The generated user interface panels and menus shown in figures 55 and 56 are holographs that are locked in real 3D space. They will stay at the location of the machine as you walk around the facility, this as a demonstration shows how a stable connection using 5G really enhances the end user experience for the engineer.

In this project demonstration the engineer is able to quickly learn about how to change the lens cover on the welder with best practice standards and all the required health and safety requirements. During the sequence of the demonstration, they have full visuals of a 2D poster showing step by step text instructions whilst an animated 3D model of the lens cover being removed and then replaced.

### 3.2.7 Remote Expert Assistance results

Microsoft platform – Dynamics 365 Remote Assist a native HoloLens2 (HL2) application was used to connect and communicate with "remote experts". HL2 users can initiate and interact on calls using voice and video allowing remote call participants to communicate and visually understand the environment of the HL2 user in a first-person view.

Results:

1. HL2 users and remote call participants have full video conferencing features
2. HL2 user can create and edit Pen annotations to environment
3. HL2 user can attach Arrow holograms to environment
4. Remote call participants can create and edit Pen annotations – positioned into HL2 environment
5. Remote call participants can attach Arrow holograms – positioned into HL2 environment
6. Remote call participants can insert holographic 2D images/documents into the Engineers environment

Using a 5G enabled HL2, the user is able to roam unrestricted around the whole facility/site maintaining a stable and highly reliable connection as shown in figures 57 and 58.

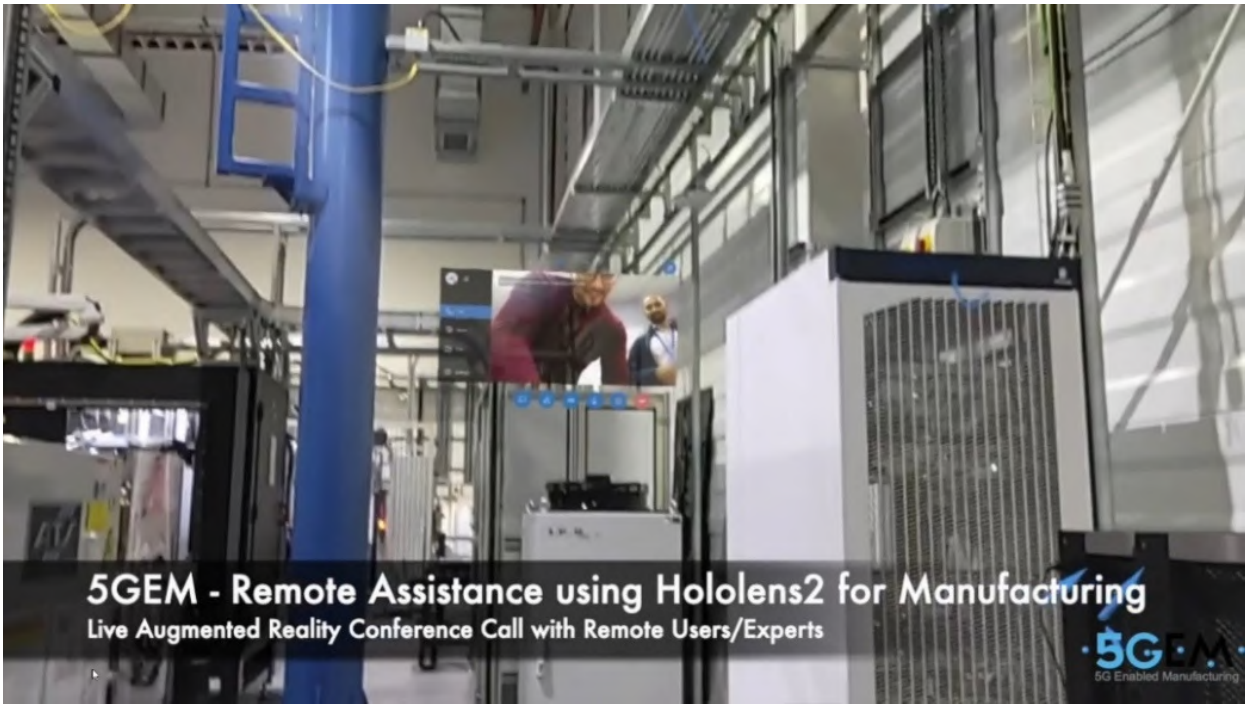



*Figure 57: Actual image captured from HL2 whilst walking around E:PriME pilot plant with inner image showing experts at TWI.*

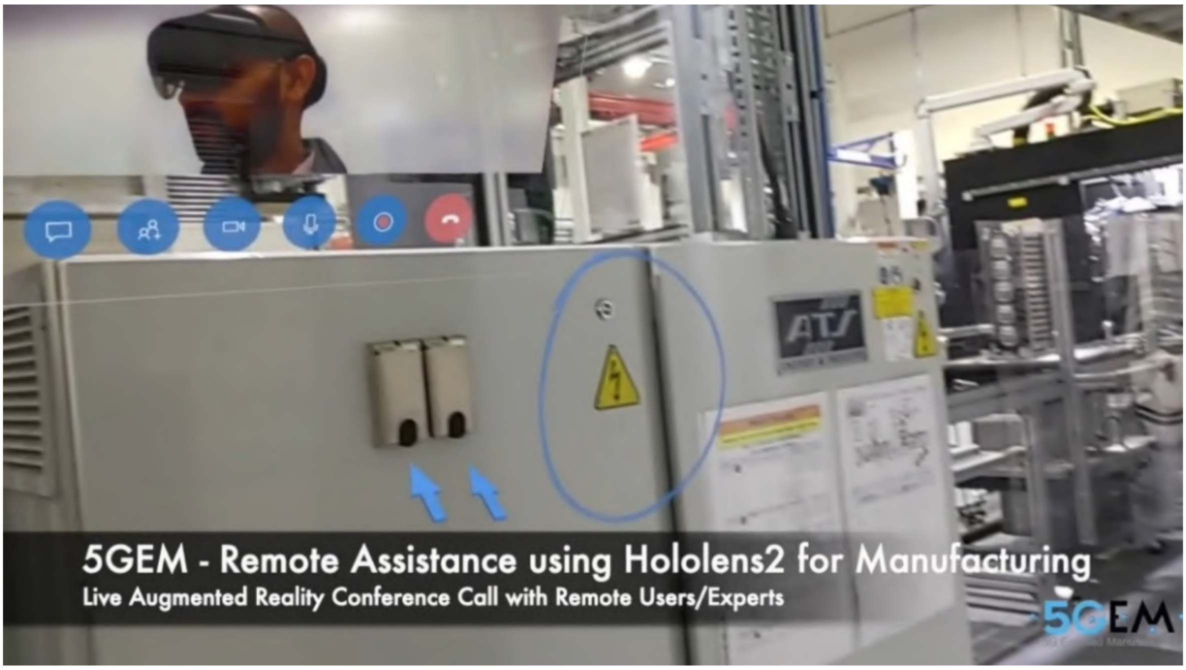



*Figure 58: Second image captured from HL2 whilst walking around E:PriME pilot plant with inner image showing experts at TWI.*

We also tried to communicate HL2 to HL2 but this did not work. After a number of attempts of failing to make a connection Microsoft were contacted and we discovered that the software packages supporting the HL2 hardware are not designed for this type of communication. They are only designed for communication between a roaming, user wearing the headset, and a fixed user on a PC who is providing the expert assistance.

In Ford, where we have multiple facilities making the same product with the same equipment around the world, the ability to connect HL2 to HL2 has clear benefits for sharing knowledge and problem solving whilst walking around the shop floor. Maybe this capability will come in the future but for the moment we will just have to manage with video calls.

## 3.3 VFE Use cases

### 3.3.1 Process Monitoring

The 5G process monitoring element quickly came across a problem that existed throughout the project - the lack of 5G native sensors. The decision was made to install available sensors initially so that data collection, visualisation and processing was not unduly delayed, but also to design the system (figure 59) so that sensors could be swapped out for 5G ones as they became available.

VFE designed and manufactured a small control panel (figure 60) to install in parallel to the vacuum furnace control system. The distributed sensors were connected using IO-Link back to profinet hubs and into the PLC. Initially this was connected through a standard network switch to the Nokia Fastmile router and the 5G MPN.

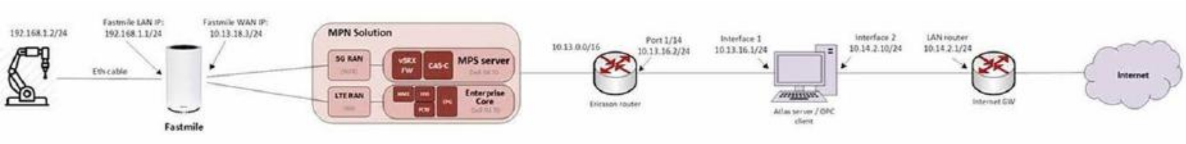



*Figure 59: Initial Network Configuration*

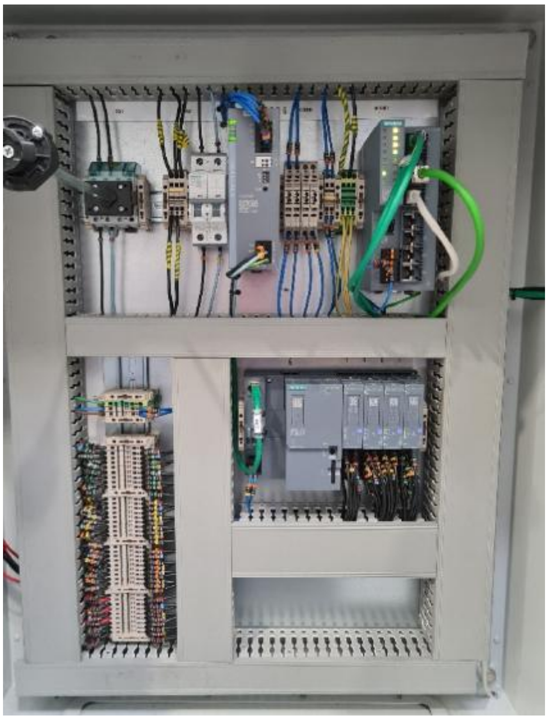


*Figure 60: VFE Furnace Monitoring Cabinet*

Additional sensors for flow and energy monitoring were installed, configured and tested using the local display. Local data logging to the HMI (figure 61) was also started so that data could be manually recovered and uploaded to cloud storage for Lancaster University to begin data processing design.

*Figure 61: Local Process Data Monitoring HMI*

The OPC-UA service was configured and tags mapped in conjunction with ATS before being published. Once published and with the Nokia Fastmile connected to the MPN it was possible to consume the OPC data using the Xiaomi M10 smartphone (figure 62) over the 5G connection. System response to induced errors was immediate and allowed VFE and TWI to simulate some system faults and correlate the symptom and causes.

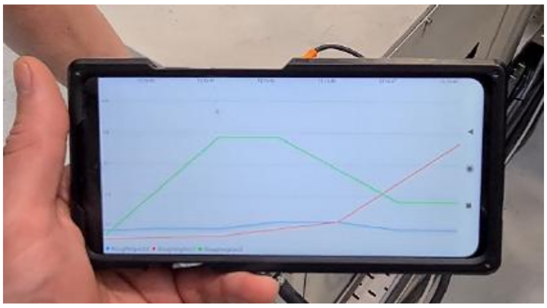


*Figure 62: Smartphone Trend Chart – OPC-UA over 5G*

In this state we had delivered a much richer dataset to engineers on site to diagnose faults. However, the data visualisation and processing required the data to be manually uploaded to the cloud.

ATS installed their Atlas Server/OPC client PC in TWI's data centre and the 5G connectivity to the remotely located furnace was tested successfully. The OPC client software required to read the data published by the furnace and link it to the Atlas Cloud was installed but we were unable to connect to the data source.

The data appeared to be getting lost at the Nokia Fastmile router. Numerous attempts were made to alter the configuration of the unit without success. Because the unit was designed as a consumer device it lacked diagnostic tools to monitor its actions, even sharing the configuration with Ericsson engineers was only possible through screenshots.

VFE were able to secure a pre-release unit of an HMS Networks NV1000 5G industrial router on a short trial and installed it in place of the existing switch and Fastmile (figure 63).

*Figure 63: Furnace Monitoring Cabinet with NV1000 5G Router*

The device connected immediately to the MPN. Port forwarding rules were implemented and connectivity through from one end to the other was proven but it still remained impossible to read OPC data over the 5G network. An early production unit was ordered.

Once installed a series of troubleshooting sessions were held with Vodafone, Ericsson, HMS Networks, Matrikon (OPC software supplier) and VFE. The root of the issue was found to be that the 5G routers expected the cellular network to be public (WAN) rather than part of the local network. This is the same as a consumer home internet router - both wired and Wi-Fi network are part of the local area network and can communicate freely. Anything on the broadband side is insecure and requires routing through the firewall with address translation. Here, the 5G MPN is treated as insecure/public rather than secure/local.

To read OPC-UA data in our configuration, the client device is on the cellular (unsafe) side of the firewall and initiates a connection to read the data source (the PLC). The 5G router performs network address translation (NAT) to forward that request to the device according to the port-forward rule. The device responds and data follows the reverse route back to the client device. By using the port-mirroring and packet sniffing diagnostic tools it was seen that the data read request is made to the router (in our case 10.13.18.3) but is tagged as returning from the machine (192.168.1.2) - see original network diagram above. The OPC client sees the difference as an insecurity and drops the connection. This issue does not affect MQTT protocol data because the connection is initiated from the secure side, pushing data out to the insecure side.

Ericsson and HMS suggested the use of "pass-through mode" where the address allocated to the router is passed through to a specific device, making the router completely transparent on that route. Where the device was the PLC it still failed. Because the PLC was only capable of static addressing rather than by DHCP*, the transparency failed even where the address was correct. An alternative network gateway device was used called eWon (also from HMS), able to be dynamically addressed by passthrough mode. The OPC connection across the 5G MPN was now successful.

*an updated version of the Siemens PLC software adds DHCP functionality.

Unfortunately, the eWon was now on a different network from all the rest of the furnace devices so could not gather the live data to publish over OPC. The ideal solution for this would be to enable RBMS (Routing Behind the Mobile Station) in the core network but this would require extensive changes and incur costs that the project could not fund. Further modifications to the machine network (figure 64) were made to resolve the problem.

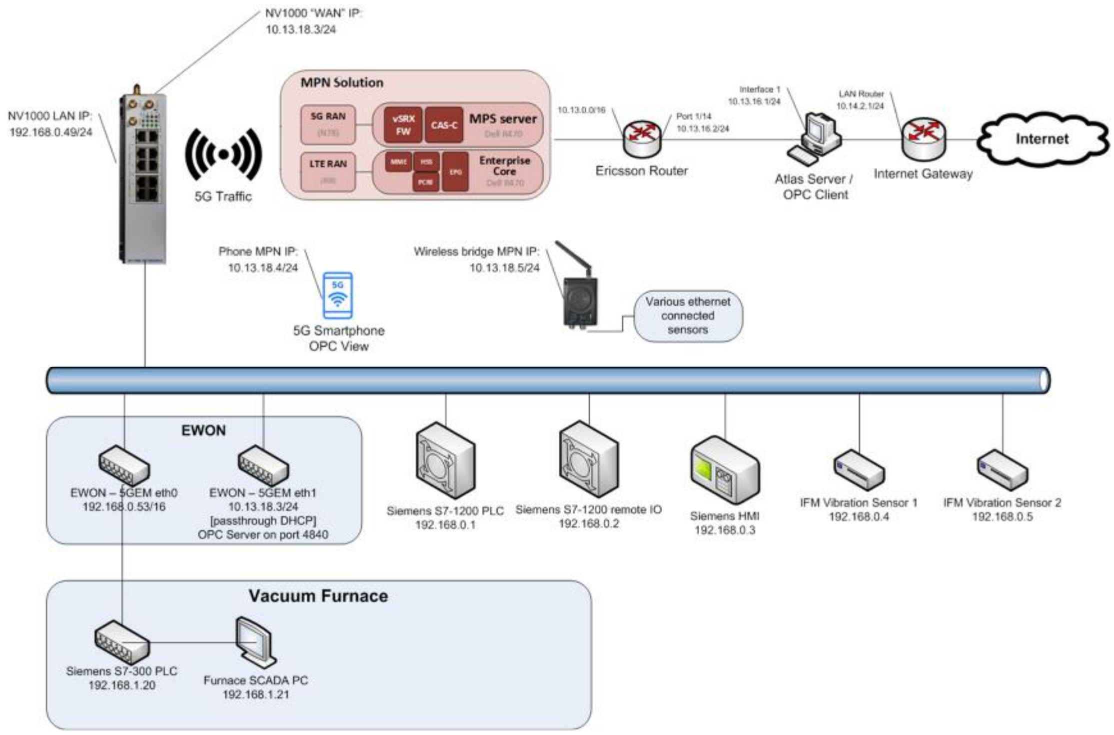
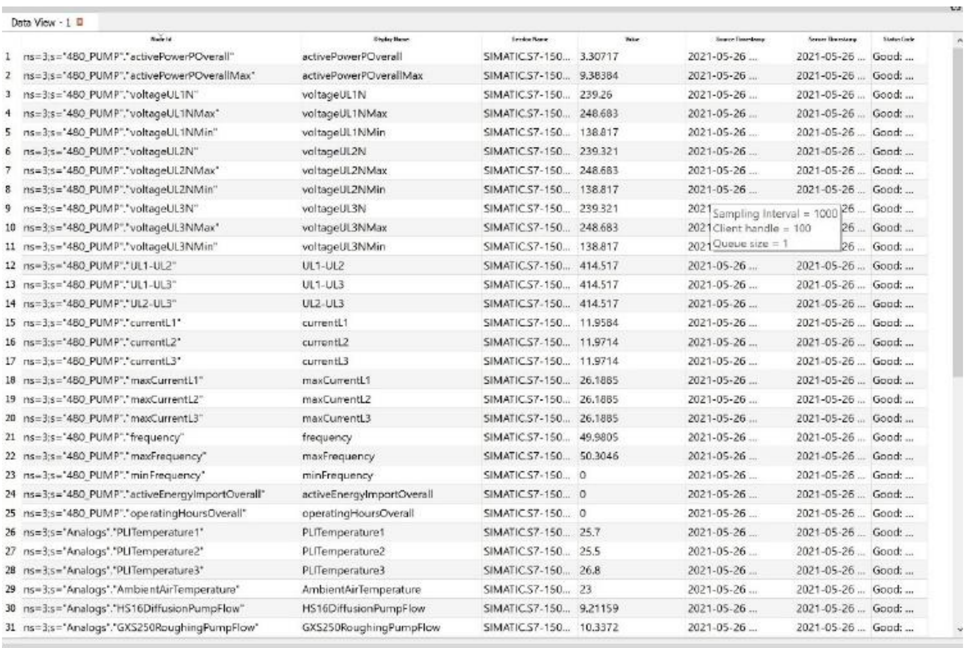



*Figure 64: Final Network Configuration*

In the new configuration real-time data was able to flow from the furnace to the Atlas Cloud over OPC-UA (figure 65).



Data View - 1

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | ns=3;s="480_PUMP"."activePowerPOverall" | activePowerPOverall | SIMATIC.S7-150... | 3.30717 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 2 | ns=3;s="480_PUMP"."activePowerPOverallMax" | activePowerPOverallMax | SIMATIC.S7-150... | 9.38384 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 3 | ns=3;s="480_PUMP"."voltageUL1N" | voltageUL1N | SIMATIC.S7-150... | 239.26 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 4 | ns=3;s="480_PUMP"."voltageUL1NMax" | voltageUL1NMax | SIMATIC.S7-150... | 248.683 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 5 | ns=3;s="480_PUMP"."voltageUL1NMin" | voltageUL1NMin | SIMATIC.S7-150... | 138.817 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 6 | ns=3;s="480_PUMP"."voltageUL2N" | voltageUL2N | SIMATIC.S7-150... | 239.321 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 7 | ns=3;s="480_PUMP"."voltageUL2NMax" | voltageUL2NMax | SIMATIC.S7-150... | 248.683 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 8 | ns=3;s="480_PUMP"."voltageUL2NMin" | voltageUL2NMin | SIMATIC.S7-150... | 138.817 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 9 | ns=3;s="480_PUMP"."voltageUL3N" | voltageUL3N | SIMATIC.S7-150... | 239.321 | 2021 Sampling Interval = 1000 | 26 ... | Good: ... |
| 10 | ns=3;s="480_PUMP"."voltageUL3NMax" | voltageUL3NMax | SIMATIC.S7-150... | 248.683 | 2021 Client handle = 100 | 26 ... | Good: ... |
| 11 | ns=3;s="480_PUMP"."voltageUL3NMin" | voltageUL3NMin | SIMATIC.S7-150... | 138.817 | 2021 Queue size = 1 | 26 ... | Good: ... |
| 12 | ns=3;s="480_PUMP"."UL1-UL2" | UL1-UL2 | SIMATIC.S7-150... | 414.517 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 13 | ns=3;s="480_PUMP"."UL1-UL3" | UL1-UL3 | SIMATIC.S7-150... | 414.517 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 14 | ns=3;s="480_PUMP"."UL2-UL3" | UL2-UL3 | SIMATIC.S7-150... | 414.517 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 15 | ns=3;s="480_PUMP"."currentL1" | currentL1 | SIMATIC.S7-150... | 11.9584 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 16 | ns=3;s="480_PUMP"."currentL2" | currentL2 | SIMATIC.S7-150... | 11.9714 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 17 | ns=3;s="480_PUMP"."currentL3" | currentL3 | SIMATIC.S7-150... | 11.9714 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 18 | ns=3;s="480_PUMP"."maxCurrentL1" | maxCurrentL1 | SIMATIC.S7-150... | 26.1885 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 19 | ns=3;s="480_PUMP"."maxCurrentL2" | maxCurrentL2 | SIMATIC.S7-150... | 26.1885 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 20 | ns=3;s="480_PUMP"."maxCurrentL3" | maxCurrentL3 | SIMATIC.S7-150... | 26.1885 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 21 | ns=3;s="480_PUMP"."frequency" | frequency | SIMATIC.S7-150... | 49.9805 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 22 | ns=3;s="480_PUMP"."maxFrequency" | maxFrequency | SIMATIC.S7-150... | 50.3046 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 23 | ns=3;s="480_PUMP"."minFrequency" | minFrequency | SIMATIC.S7-150... | 0 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 24 | ns=3;s="480_PUMP"."activeEnergyImportOverall" | activeEnergyImportOverall | SIMATIC.S7-150... | 0 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 25 | ns=3;s="480_PUMP"."operatingHoursOverall" | operatingHoursOverall | SIMATIC.S7-150... | 0 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 26 | ns=3;s="Analogs"."PLITemperature1" | PLITemperature1 | SIMATIC.S7-150... | 25.7 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 27 | ns=3;s="Analogs"."PLITemperature2" | PLITemperature2 | SIMATIC.S7-150... | 25.5 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 28 | ns=3;s="Analogs"."PLITemperature3" | PLITemperature3 | SIMATIC.S7-150... | 26.8 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 29 | ns=3;s="Analogs"."AmbientAirTemperature" | AmbientAirTemperature | SIMATIC.S7-150... | 23 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 30 | ns=3;s="Analogs"."HS16DiffusionPumpFlow" | HS16DiffusionPumpFlow | SIMATIC.S7-150... | 9.21159 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |
| 31 | ns=3;s="Analogs"."GXS250RoughingPumpFlow" | GXS250RoughingPumpFlow | SIMATIC.S7-150... | 10.3372 | 2021-05-26 ... | 2021-05-26 ... | Good: ... |

*Figure 65: OPC Data Tags at Atlas Server over 5G*

Once data was flowing securely, we continued to trial other methods to get sensor data on to the 5G network. A prototype 5G wireless bridge device was secured from HMS Networks, designed to wrap data from sensors with ethernet based protocols such as Modbus-TCP or Profinet into a secure network tunnel over the cellular network (figure 66).

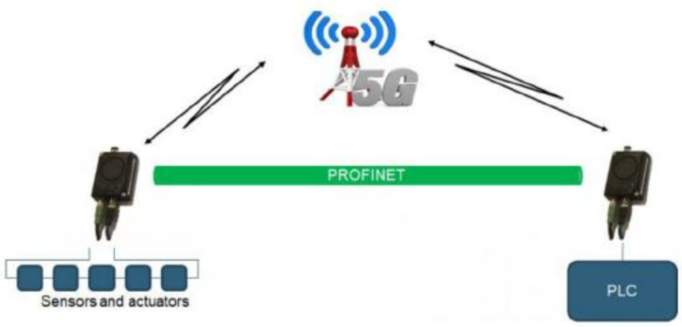



*Figure 66: Wireless Bridge – Profinet over 5G example*

In the VFE/TWI furnace application 2 alternative applications of this were tested.

1. The vibration sensors are profinet devices. A sensor was removed from the cabled system and instead routed over the 5G network using the wireless bridge and the edge gateway device in the cabinet.
2. The cabled connection between the hub at the furnace and the PLC in the main cabinet was removed and the devices connected using the wireless bridge and edge gateway over the 5G connection.

Up to 7 devices can be wirelessly routed per bridge, removing the time, costs and constraints associated with cabled sensors. While connectivity was achieved the system was reverted back to the previous configuration to avoid re-mapping the data tags.

Using the Atlas Cloud data visualisation it was possible to overlay the new sensor data with the furnace production data without having made any alterations to the original furnace control systems.

During the project period there was a breakdown of a vacuum pump. Data from the additional sensors showed that the cooling water flow rate and temperature, as well as the vibration and energy consumption were stable in the build up to the failure. This allowed the elimination of several possible causes of the failure and faster determination of the true cause and subsequent repair.

### 3.3.2 Predictive Maintenance

With the additional sensors in place the furnace was operated normally by TWI for a period to gather baseline data. This was monitored locally, via the Atlas cloud, and through data uploads to Lancaster University.

Generally, apart from the pump failure mentioned above, the furnace operated with no scrap or degraded performance that could give useful predictive insights for the Lancaster University learning models.

Some interesting trend data was seen – for example in figure 67 below: Normally PLI (Power Lead In) temperatures increase as electrical energy for heating is applied and high currents are flowing through the conductors. The PLIs are water cooled to prevent them overheating and melting the insulators. Comparing the overall heating power we can see that there are near limit peaks of temperature that correlate to heating (6000 & 15000 EU) but additional peaks that do not (~25000 EU). These later peaks are simply due to increased water flow temperature as the machine cools and present no risk of insulator damage. These data allow us to refine PLI replacement triggers to temperature peaks during heating, not cooling.

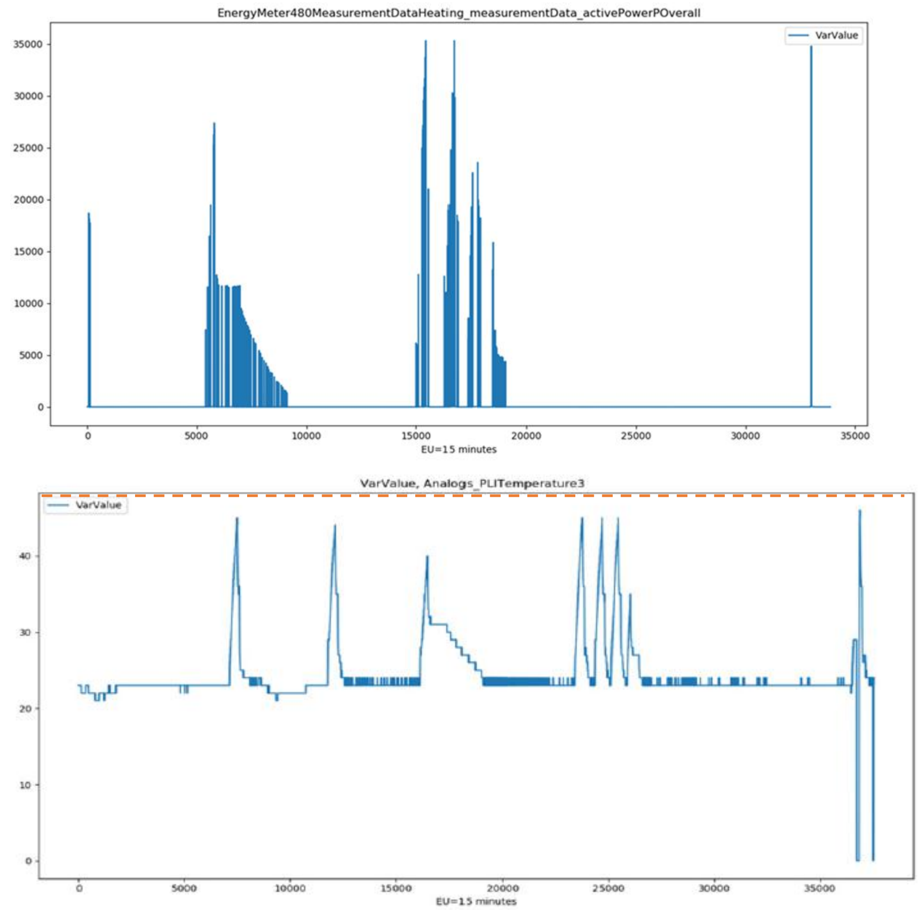



*Figure 67: Trend data for heat power (top) and PLI temperature (bottom)*

To give the learning models some more meaningful data, TWI gave permission for VFE to operate the furnace with controlled faults introduced. This included manufacturing and fitting heavily aged heating elements to see the change in electrical load which may indicate at least a loss of performance and, at worst, imminent failure.

In trial 1 the heater for the diffusion pump (a special type of high vacuum pump) was partially disconnected to simulate an electrical heating fault. The power sensors picked up the partial failure through the unusual phase imbalance. The fault was maintained for a period until the pump temperature eventually dropped below the critical level and the conventional alarm triggered. At this point the cycle would be aborted and the product within usually scrapped. The time duration between the initial anomaly and the failure was long enough to permit corrective action to be taken and avoid the failure.

The analysis showed how bigger datasets can highlight notable features but still require human interpretation of their importance. Future work would include the refinement of these alarm thresholds using the data from multiple machines and communication of the updated thresholds back to the machines.

### 3.3.3 Remote Support

A Microsoft HoloLens2 was acquired to test at the TWI site. The unit was able to be connected to the 5G MPN using a tethered Samsung S20+ 5G smartphone. Site network security restrictions prevented further trials of remote expert support as connection to the wider internet was required.

Experimentation with solutions like Teamviewer Pilot and Microsoft Remote Assist showed again the known advantages of the shared vision and hands-free operation.

### 3.3.4 Data management (ATS)

Similar to the Ford case study, ATS used Atlas Play to collect user requirements by mapping VFE's machine running process shown in figure 68.

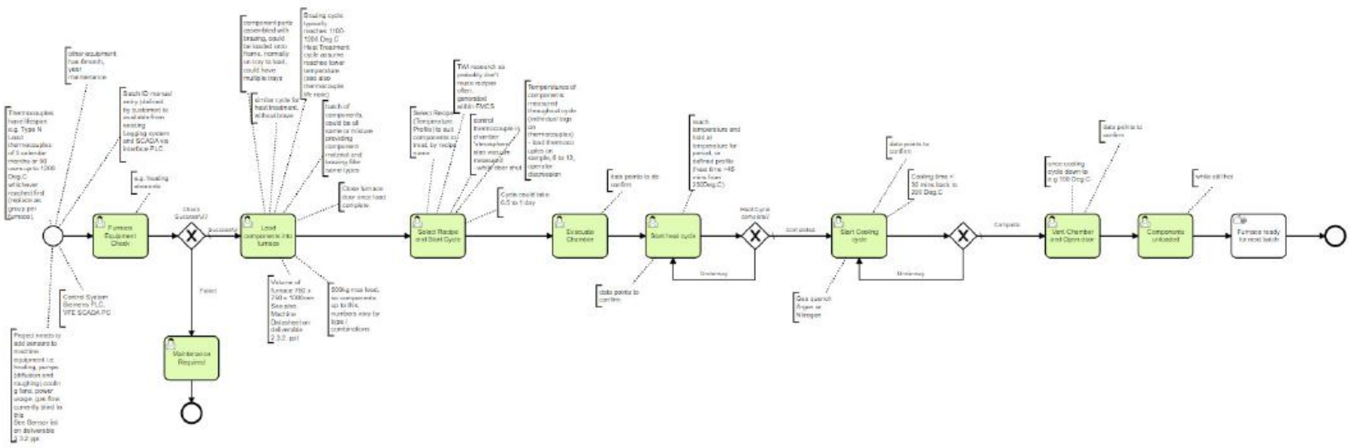


*Figure 68: VFE machine running process*

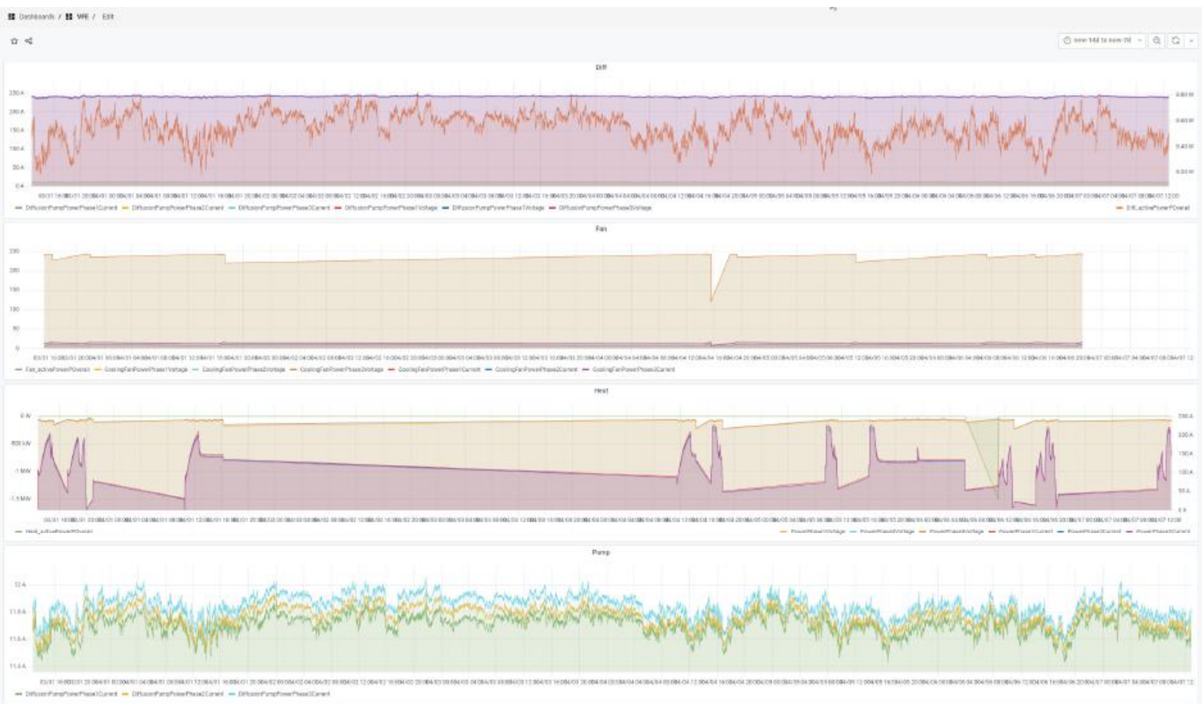


*Figure 69: Data collected from the edge device is illustrated on real-time dashboards.*

This data (figure 69) can be filtered and processed to gain new process insights through analytics.

### 3.3.5 Data processing (LU)

The data was generated, analysed, stored, and processed in the cloud using the flowchart in figure 70. The algorithm comes as following:

- Start
- Read data from sensor
- Is data used for actuator usage in real time? If No go to 8
- Compute the time required to data being processed and is implemented with actuator
- Data delay sensitivity < Edge delay, if No go to 15
- Possibility to upgrade Edge and processing capability, if No go to 18
- Upgrade it to support, possible?, if yes, go to 15, if No, go to 18
- Compute data delay sensitivity
- Data delay sensitivity < Cloud based data , if Yes, go to 5
- Traffic in cloud is heavy, preferred in edge, if Yes go to 13
- Needed for AI, if No, go to 15
- Transfer it to cloud to be processed, save it for AI use
- Retransmit the analysis to the edge
- Repeat the process, go to 2
- Process it in Edge
- Needed for AI, if No, go to 14
- Send a copy to Cloud when is possible for AI, go to 14
- No possibility to support
- Finish

It mostly shows the algorithm where the data should be analysed and the results should be stored at cloud, Edge, or both. This algorithm and flowchart is used in the next section main and comprehensive flowchart to show the use case flowchart for predictive maintenance, failure detection, etc.

Once the data has been pre-processed a further algorithm defined anomalies and faults – both in machine learning and real-time approaches.

1. Start
2. Define all anomalies types
3. Define frequency of sampling, By aid of sensors details and sensory data features
4. Check to detect anomalies
5. Update anomalies list if any
6. Prioritize anomalies list respect to the level of risk, By aid of using main flowchart
7. Should be analysed in cloud or edge?
8. All anomalies are detected? If No go to 10
9. Instantaneous action, Non- instantaneous actions (By aid of using main flowchart), go to 15
10. Increasing frequency of sampling? If Yes go to 3
11. Anomaly detection using hidden data (ML and AI)
12. All anomalies are detected, if Yes go to 9
13. Check dependency of data
14. Increase collected data, go to 4
15. Finish

The overall view of the data flows from the vacuum furnace sources, through edge and cloud processing is also shown in figure 70. Outputs are both data feedback to the machine and analysis reports as shown in figure 71.

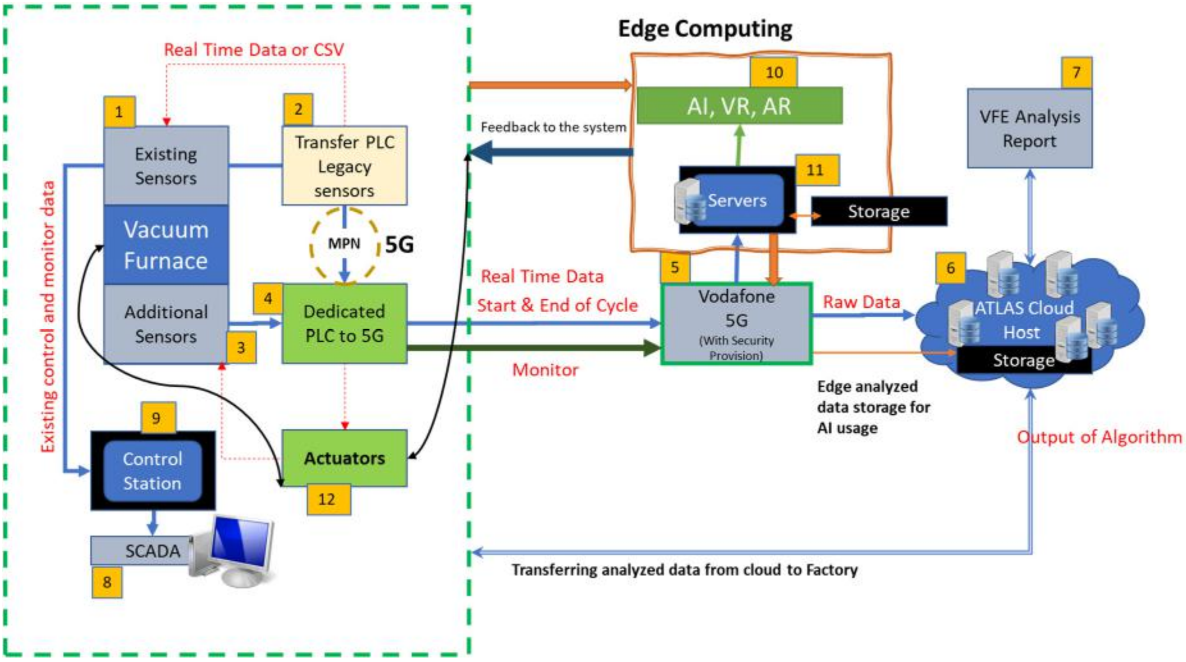



*Figure 70: Vacuum Furnace Data Processing Flows*

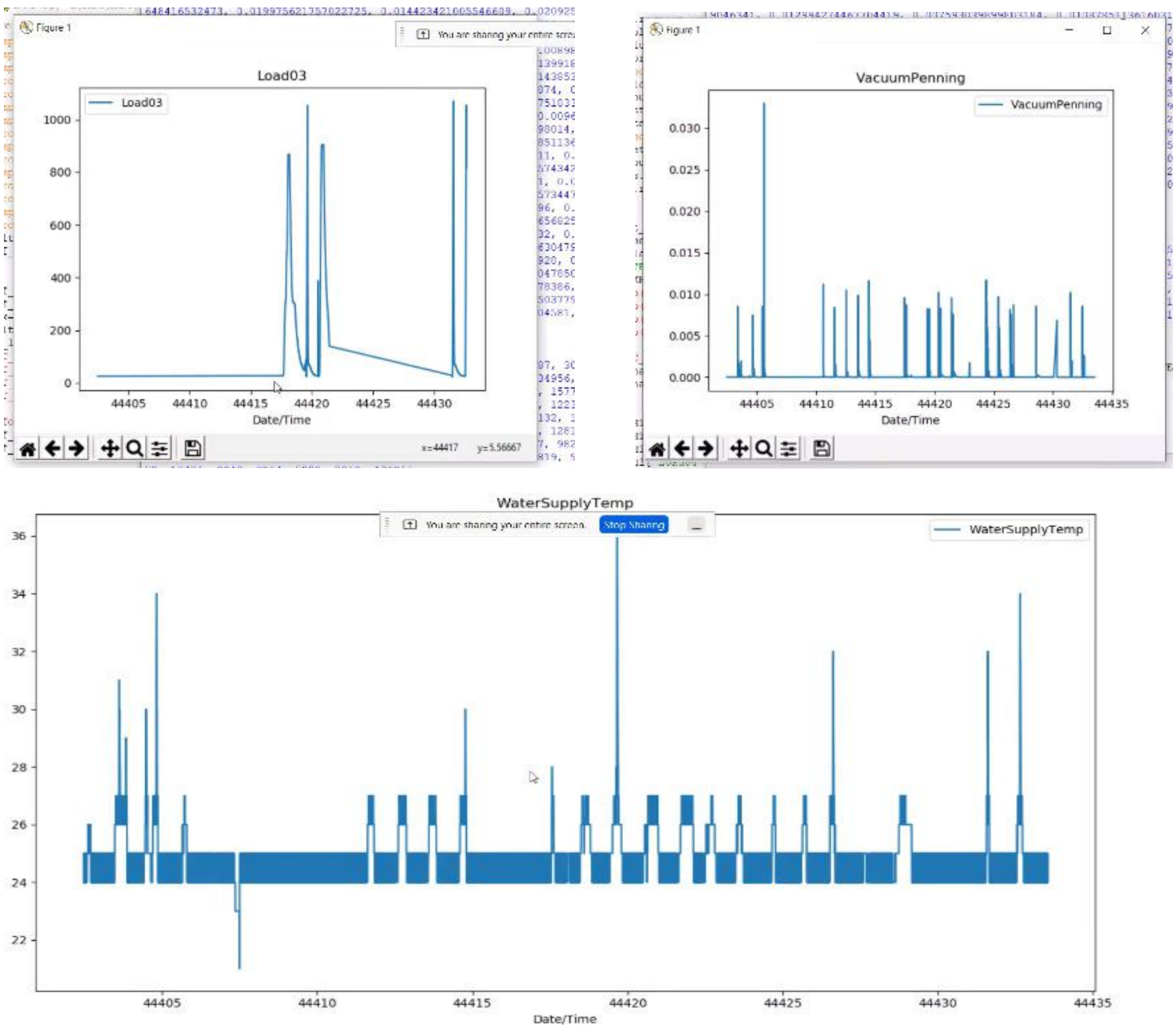



*Figure 71: Examples of the analysis*

## 3.4 Device trials

### *Nokia Fastmile Router*


This device was part of the original Vodafone installation and was tested by Vodafone and Ericsson prior to being used. Consequently, it has been working OK in the Ford applications. However, we have noticed the limited diagnostic capabilities and accessibility of configuration information. In our opinion the Fastmile is more suited to an office/home environment when compared to the other more industrial devices we have tried. It has no IP rating and a maximum operation temperature of 40degC.

### *Siemens Scalance MUM856-1 Router*

Siemens visited the E:PriME building four times before they were able to successfully connect to the network and transmit data. They made some software changes and upgrades to the device but the connection issue was finally resolved on the fourth visit with a config/set up change. We suspect this might be related to the unique PLMN IDs for a private network which the device might not have been designed to work with.

The Siemens unit is IP65 rated and would withstand high temperatures in a control cabinet to 60degC.

### *HMS NV1000 5G Router*


After problems diagnosing network issues using the Nokia unit VFE contacted a longstanding supplier of industrial networking devices and were able to trial a pre-release unit of HMS Networks industrial 5G router. This unit is designed to install in an industrial control enclosure with a standard 24V supply and is able to operate between -40°C and +70°C.
The unit worked on the MPN immediately and its more advanced diagnostics allowed identification of the problems with the OPC data protocol. Further updates and remote support were received from HMS during the trial to further aid troubleshooting and pointed us to the need for “passthrough mode” to permit the OPC data to route.

*HMS Anybus Edge Gateway with Switch*

This device (as a pair) was tested as an option to solve the routing difficulties experienced with OPC-UA over 5G. The gateway device can be configured to create a secure VPN tunnel over the 5G network through which OPC data (or many other industrial protocols) can transit without being blocked or dropped by firewalls and routers on the path.
Can be used with the cellular bridge (below) to receive sensor data over 5G

*HMS NV1005 5G Cellular Bridge (prototype)*


One long standing issue was in acquiring 5G capable sensors. This wireless bridge device was developed by HMS from existing Bluetooth/Wi-Fi models to securely connect sensors to other devices such as PLCs over the 5G network. The prototype model received was used to connect ethernet capable devices (in this case the vibration sensors) to the 5G network. The palm sized device is IP65 rated. As tested the device was very much a prototype with some configuration issues.

*Cradlepoint R1900 Mobile Router*


Cradlepoint offered to trial their router (they are owned by Ericsson who supplied the hardware for our MPN). Initially they thought we were looking for an in-vehicle application but after correcting their understanding of our requirements they were still keen to continue with a trial. The unit was brought to site on 5$^{th}$ November and was up and running within 45 mins. It is IP64 rated and can operate at up to 70degC.

*Xiaomi Mi10 lite phone*

This phone was tested by Vodafone in their lab before being sent out for use on the project and so it connected without issue to our MPN on site. It was used during the network sign-off and a speed test was completed using this phone. After some initial set up issues we also managed to tether the HoloLens2 headset to the phone via a USB C cable and get a connection to the 5G network to enable both the Maintenance support use-case and the REA use-case to be trialled.

*HoloLens2 Headset*

This was our Augmented Reality / Mixed Reality device of choice throughout the 5GEM project. It was chosen due to familiarity and availability within both Ford and HSSMI. At Ford we had had some previous success using it to connect with remote experts but it was noted that connecting to the headset using 4G or WiFi signals was not reliable and there was scope for improvement with the higher data rates a 5G network can provide.


*Quanta 5G dongle*

This device was only discovered through a conversation at the 5G Showcase event in Birmingham in March 2022. It was the device which we had been looking for throughout the project i.e. a small and low cost dongle that could connect a device into a 5G network.

With a USB C plug, it connected directly to the HoloLens2, and from there we could modify the settings and access our 5G network.

The only problem we found using this dongle was each time it was disconnected it lost the settings for our 5G MPN so they had to be set up again via the menus accessible in the HoloLens2 headset. This was reported back to our contacts at Quanta.

## 3.5 Electromagnetic Field (EMF) compliance study

Before starting the project, the members of the consortium were aware of some of the negative publicity around mobile network transmissions, and in particular 5G which was assumed to use even more power than previous generations to create its transmissions. This publicity increased during the COVID-19 pandemic as some conspiracy theorists even suggested it was the cause of the spread of the virus.

See BBC report at this link https://www.bbc.com/news/av/stories-53285610

To allay any fears of the health impact of working in proximity to a 5G MPN the 5GEM team wanted to survey the EMF in a building where the installation had been made. To this end, we hired an experienced EMF measurement company called Siroda (http://siroda.co.uk/) who are based in Hungerford, Berkshire.

They measured the EMF in the Ford E:PriME building using a Narda Selective Radiation Meter (SRM) against the Control of Electromagnetic Fields at Work Regulations 2016 (CEMFAW) which require employers to assess exposure to electromagnetic fields (EMFs) in the workplace. The CEMFAW Regulations introduce limits, explain the effects of electromagnetic fields and provide details of safety conditions which must be met.

The requirements in the CEMFAW Regulations are based on measurable values related to EMFs. These physical quantities are derived from the recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP); more information can be accessed via the ICNIRP web pages. http://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf

ICNIRP exposure guidelines for radio frequency fields and microwaves are set to prevent health effects caused by localised or whole-body heating. ICNIRP applies a further safety factor of ten to derive occupational exposure limits, and a factor of 50 to obtain the guideline value for the general public.

The measurements made included all sources of EMFs in the range 420MHz to 6GHz. This includes all cellular and Wi-Fi bands, including the dedicated internal Vodafone LTE 2600MHz (4G) and NR 3500MHz (5G) private network at the facility.

At the time of survey, all test locations were found to be within guideline levels for general public exposure to electromagnetic fields.

The highest average level, measured at test location 12 (see summary table) was 0.2% of the ICNIRP General Public guidelines, with a peak reading of 10.6% of the guideline level at this point.

For internal systems such as that at used in 5GEM, both the transmitting power of the equipment and the gain of the antennas are very low, so such systems generally produce a maximum EMF field that is well below the ICNIRP general public guideline levels, even in very close proximity to the antennas.

A summary of the results appears in the table on the next page and the full report can be accessed by clicking on this icon.

Ford Dunton EMF
Exposure Complianc

**SUMMARY EMF MEASUREMENTS FOR ALL TEST LOCATIONS.**

| Test Point | Description | Time Stamp | % of ICNIRP General Public. Peak Levels | % of ICNIRP General Public Average Levels | PASS/FAIL |
|---|---|---|---|---|---|
| 1 | Adjacent to Vodafone BTS Rack | 2022-06-04 09:32:40 | 0.326 | 0.138 | PASS |
| 2 | Southeast Corner of Building | 2022-06-04 09:39:06 | 0.022 | 0.008 | PASS |
| 3 | Under 4G/5G Antenna | 2022-06-04 09:57:52 | 0.056 | 0.008 | PASS |
| 4 | Training Room | 2022-06-04 10:15:36 | 0.081 | 0.010 | PASS |
| 5 | Centre of Building | 2022-06-04 10:29:20 | 0.027 | 0.006 | PASS |
| 6 | Stator Laser Welder (Idle) | 2022-06-04 10:36:10 | 1.713 | 0.046 | PASS |
| 7 | Vibration Sensors (Active) | 2022-06-04 11:01:18 | 2.029 | 0.056 | PASS |
| 8 | Adjacent to Loading Bay Door (Open) | 2022-06-04 11:26:26 | 0.067 | 0.008 | PASS |
| 9 | South End of Building | 2022-06-04 11:40:12 | 0.024 | 0.005 | PASS |
| 10 | Battery Welder (Active) | 2022-06-04 11:46:50 | 2.350 | 0.066 | PASS |
| 11 | HoloLens Mobile Device (Streaming Video) | 2022-06-04 12:25:36 | 0.294 | 0.017 | PASS |
| 12 | Stator Laser Welder (Active) | 2022-06-04 12:37:56 | 10.570 | 0.234 | PASS |

# 4.0 Achievements & Impact

## 4.1 Network achievements (Vodafone)

The envisioned architecture consisted of a single core with 5G NR radio coverage in both sites (figure 72) to achieve the two locations via IPVPN and NBIA for remote management.

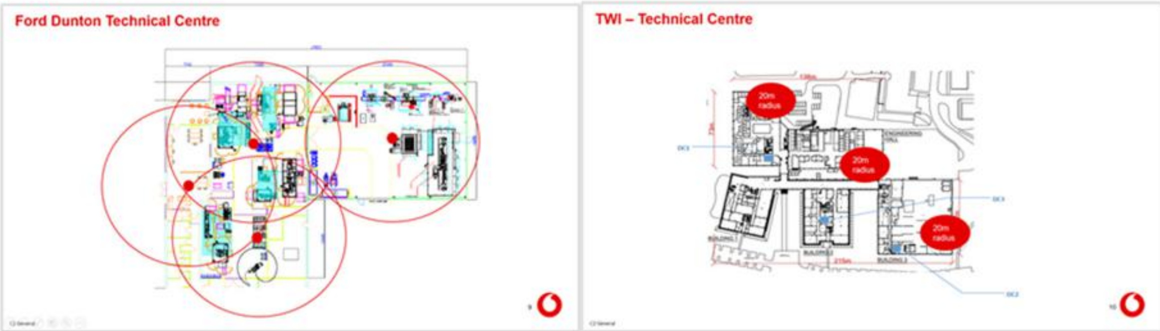



*Figure 72: Site layouts*

With this architecture in mind, Vodafone achieved the first 5G multi-site mobile private network in the UK. The advantages of having this set up as one network meant that it was then supported (by Ericsson and Vodafone) as a single entity.

## 4.2 Ford achievements

### 4.2.0 Data Management (ATS)

ATS has successfully developed a brand new product offering: Atlas Edge capable of connecting through OPC-UA and MQTT protocols by deploying and testing it in Ford’s E:PriME (Electrified Powertrain Pilot Line) and TWI’s (VFE use case) facilities.

ATS also enabled MQTT message transfer and upload of files up to 256Mb on the edge and cloud as well as mapping of Ford data model into Atlas data model. This is a significant achievement as the MQTT protocol (selected by Ford for its Industry4.0 messaging) is designed for small data packets as would be expected from IIoT sensors

As part of the work with Lancaster University, ATS developed capability for deploying third party AI algorithms in Atlas Cloud and Edge which was the GUI described in section 3.2.3.

### 4.2.1 Factory monitoring

The factory monitoring system within the Atlas Cloud has demonstrated that alternative systems can be developed beyond Ford’s own internal FIS reporting tool. The wireless connection proved reliable thus demonstrating that the first benefit listed in the Benefits Realisation document, to remove the need for cables to be installed, can be achieved. Sharing of data in a cloud-based system has the added benefit, with the right security in place, of allowing external monitoring of the equipment performance. This means that the original equipment manufacturers (OEMs) can monitor the performance of their equipment and seek continuous improvement resulting in better performing machines benefiting the OEM and customer (Ford) alike.

This was the demonstration of the first project benefit for Ford where a wireless connection system could replace the previous need to hardwire all equipment to a network. This proof of concept is over a small scale which makes the 5G MPN installation and running costs appear high but if the system was scaled up to a full production Plant and the running costs reduce through economies of scale then the MPN and its benefits of flexibility become more viable.

### 4.2.2 Predictive maintenance

Being able to show when machine performance is deteriorating and then create a maintenance action is not new. But this project has shown you can do this across multiple system with data sharing and not be tied to a single system as ATS have linked to IBM's Maximo asset management system in other projects. This means that data analysed from the production process can then trigger an action which could generate a maintenance notification in a system like Maximo. And in general, reacting sooner to data which shows degradation in equipment performance will always be beneficial through prevention of total failure and extended downtime.

Currently at Ford the factory status monitoring and predictive maintenance data is held separately and what this project has shown is that you can put the data in the same system and create new value. For example, if the factory information system indicates a machine is running slowly then this could be matched with data which shows a particular motor is overheating and hence running slowly. Or if the feedback from the welding image analysis is showing a reduction in weld quality and a vibration sensor is detecting excessive vibration then the two events could be linked to find a solution. This data analysis could be programmed in AI for automated responses and maintenance decisions.

We were unable to prove the benefit of reduce maintenance and material costs in the coolant system of the laser welding machines because in the E:PriME pilot plant the demand on the coolant system, and coolant usage, is very low and no activity was required during the monitoring period of this project. However, comparing to other laser equipment in Ford and looking at their coolant costs, and the consequential cost of damage caused when coolant systems degrade, there are potential savings in this example. When laser generating equipment overheats the cost of replacement is high. And the opportunity for savings will increase in production facilities where there are many laser welding machines as opposed to our pilot plant where there are just two.

### 4.2.3 Process monitoring

This is a good example of where, previously, a lot of data had been generated in the production process but usage of the data was very limited and tied to the capabilities of the existing systems Ford had purchased. This use case, based on the laser "key-hole depth" measurement demonstrated that the data could be displayed, analysed and then decisions made as to future actions like accept, reject or rework a part based on in-process laser weld measurements.

Creating standalone agnostic systems means bespoke AI/ML can be developed for internal purposes but it can also drive the OEM to produce better analysis systems of their own which they can sell as a package with their equipment.

A further benefit is to drive consistency in decision making because in a manufacturing plant there may be multiple shifts running a production line and different operators stationed on different machines each day. An AI based system, in this case based on the rules that were written in the Python program, will make the same decisions whereas human choices will vary when the data is complex or ambiguous.

### 4.2.4 Visual analysis of battery welds

The results from the welding trials at TWI, along with their expert analysis led us to focus this use case on analysing the battery tab connector welds for red colouring. If there are patches of red in the image it can indicate that the weld has gone too deep into the copper layer. The resultant algorithm which achieves this analysis is therefore very useful in developing the quality of the welds and the fact that it can be "tuned" to a particular level of red colour to trigger a pass or fail decision means that further development can take place in our pilot plant to optimise the welding process.

### 4.2.5 Weld analysis vision system

This work combined the skills of a machine tools supplier, a vision system supplier and a company who are expert at processing vision data and it demonstrated that there does not need to be a reliance on the in-built systems that are available with the machine tools Ford purchases. Using vision and data processing experts means that the machine tool performance can be enhanced.

At a basic level the results demonstrated that images from the welding process could be transmitted, stored and analysed for the benefit of analysis at some point in the future or as a record of product quality. Taking the system capability to the next level and moving towards real-time analysis, because of the rapid data transfer and AI (or machine learning) algorithms, could result in the limitation or even complete prevention of sub-standard stator hairpin welds. The 2D (colour) and 3D high resolution cameras can respectively detect visual and dimensional defects post welding automatically. This is a massive process improvement over human visual analysis post process – remembering there are 192 welds to inspect in each stator (refer to section 2.2.5).

The 3D camera can also analyse the hairpin position prior to welding and if the welding surfaces are not in the correct position stop the welding process and prevent a scrap part being made. Enhancing this with real time analysis means that the welding path and power could be adjusted to suit the hairpin positions. It should be noted that the laser does not strike the hairpins at a single point but, typically, traces a circular path over the hairpin ends.

Overall, the continued development of this technology could lead to the benefit of significant savings in the reduction of stators needing to be scrapped from the production process.

The previous four sections (4.2.1 to 4.25) all have a common theme of data analysis and expanding the use of available production data to improve the production process through greater efficiency and reduced product quality losses. What the 5G MPN creates is the opportunity to do this at greater speed, with connection reliability and security of data transfer when compared to our existing 4G and WiFi connectivity. Ultimately this moves us towards real-time processing and the ability to react to events before a process drifts out of control or a piece of equipment fails.

The network allows further choices to be made as to where the data is best stored and processed. For true real time analysis edge computing can be used, keeping the processing local to the production system, cutting down any data delays and using AI algorithms for near instant response.

This speed of reaction is required when it is considered that a hairpin laser weld is formed in just 0.8 seconds. For less time sensitive data, e.g. that where a remote expert might be required to review data and provide human centred feedback, this can be achieved through the ability to share large quantities of data (images and video) via cloud based systems remote to the production facility.

### 4.2.6 AR-MR Maintenance support

This use-case is arguably the most impressive due to its very visual nature and the ability to demonstrate the capabilities of AR-MR technology. The use of the HoloLens2 headset and the PTC Vuforia platform created a scenario where a maintenance action can be performed with written instructions and guiding images and drawings all within the field of view whilst the task is being performed. Our demonstrator was a relatively simple exercise of changing a lens cover but the real opportunities for this technology would be seen on more lengthy and complicated maintenance actions which require frequent reference to a maintenance manual, thus delaying the fix. Longer maintenance tasks also carry a greater risk of being carried out incorrectly which will result in further damage or production losses. The set up can be used as a training tool, off-line, or in a live production situation.

The 5G network in this instance provided a much more reliable connection capable of handling the high data transfer rates demanded by such a use case. As previously mentioned, this was a huge improvement on our usage of a HoloLens2 connected to a local WiFi network during a ventilator manufacturing project in Ford. In this case we were trying to connect to a remote expert but the quality of connection was poor and the link frequently paused.

### 4.2.7 Remote Expert Assistance

In section 3.2.7 the REA connection made using a HoloLens2 headset connected through the 5G network is described. Once a connection was made to the headset, via the Xiaomi phone or latterly with the Quanta 5G dongle, it was easy to demonstrate how useful these devices are and how good the connection can be using 5G. When this is combined with methods of connecting to the equipment and being able to update machine programs then the true power of remote or virtual commissioning can be realised.

As described in the benefits realisation document, using different forms of remote support has an immediate impact allowing for quicker response from support services (like machine tool vendors), removing travel costs and reducing the support costs. This is a win-win situation for both the customer, due to the aforementioned benefits, and the supplier as their expert resource is able to resolve issues quicker and hence able to help more customers. Furthermore, as the COVID-19 pandemic has taught us, remote support can be invaluable to enable support services to continue when physical travel is restricted and stop the spread of a virus which can, as cases have identified, shutdown whole businesses when a large proportion of the workforce is affected.

A further reference to virtual commissioning using a remote expert is made in section 6 on sustainability.

## 4.3 VFE use-cases

### 4.3.1 Process Monitoring

The project demonstrated that additional sensors can be added to an existing machine with minimal interference, using a 5G MPN.  Combining the data sources improved visibility of the furnace operations and was used to assist in the diagnosis of faults experienced on the machine.  Making the sensors available widely to the network allowed their data to be accessed and used in multiple ways.  It would be possible to achieve this using other technologies but with some disadvantages; either in intrusively hard-wiring sensors into the existing machine or using Wi-Fi, Bluetooth or proprietary radio technologies in shared bandwidth.

The publishing of data using OPC tags meant that multiple users could access and use the data using standard tools.  The cloud-based visualisation tools allowed the end user and OEM to share a common understanding of the machine performance and possible improvements.

### 4.3.2 Predictive Maintenance

The reliable and high-speed collection and sharing of data from a wider range of sensors, and incorporation of batch processing data allowed a more nuanced analysis of potential failures by Lancaster University.  Feedback from experienced technicians looking at the report outputs would help to refine the warning triggers.  If these could be pushed back out to the machines and service planning teams securely then the timeliness and efficiency of preventive maintenance can be improved and serious failure minimised.

### 4.3.3 Remote Support

The shared data visualisations and the ability to see real-time sensor data as a local technician made adjustments to the machine improved the speed of fault diagnosis without compromising the customer's internet security.

# 5.0 Key Learnings

## 5.1 Vodafone

To achieve the first 5G multi-site mobile private network in the UK, Vodafone had to implement a long list of features that exposed various operational challenges, was given the opportunity to learn and brought the benefit of having at work a very diverse set of other connectivity services from Vodafone's portfolio as well as partners for solutions to run on top of connectivity

1. **Environment** – The Ford location is temperature controlled only to the same extent as the normal UK shop floors i.e. Heating to keep temperature above 18$^{o}$C but only ambient ventilation and so no upper temperature limit. The maximum facility temperature will only be reached on a few days in the summer. The principle Ford work on is that air conditioning for the building is not cost effective in the UK versus a small amount of downtime. There are no major sources of heat in the building
2. **Pre-requisites** – Whilst pre-requisites for MPN are detailed in the HLD, a separate Pre-requisites document needs to be created to cover the whole scope and whole list of stakeholders, to provide a full list of requirements, demarcation points, ownership and responsibilities
3. **Logistics** – Some deliveries arrived without prior notification to Ford, this made it difficult to manage in terms of resource & space at both sites (Ford/TWI). Also, deliveries were received with no contact name on the package and in some cases incorrect/unknown contacts
4. **SIM** – During the SIM provisioning process there were issues in getting the process to work which resulted in one of the Vodafone team going to the Ford site but still not being able to rectify the issue. Whilst Vodafone had a process in place the scripts had to be modified to allow the SIM provisioning to be done.
5. **Devices** – During the project we experienced issues with devices whereby they could not connect to the 5G network. Initial discussions with ERICSSON led us to believe PLMN ID's were causing the issues with device, however once the SIMs were provisioned correctly the PLMN ID issue went away and was in fact a red herring!
   When trying to obtain 5G devices it became clear that we needed a clear process of how to find 5G compatible devices as no catalogue currently exists
6. **Lifecycle** – Need to understand how in life upgrades are managed once in life for example new versions of network runner, security etc. excluding hardware and installed in the lab/tested/deployed to the customer etc.

## 5.2 Ford use-cases

### 5.2.1 ATS and data management learnings

Whilst MQTT has become one of the de-facto communication interface standards within IIOT (Industrial Internet of Things), the handling of the payload within the MQTT Message presents a significant problem, as no common protocol standards exist for the format of data within the MQTT Message Body.

For example, a simple sensor could be supplied with an MQTT Message Body containing a simple comma separated list of numeric values, whilst another supplier could create a JSON structure to represent the data. Furthermore, individual large organisation may define their own specific data model that is unique to that organisation, e.g. the Ford Common Data Model.

Consequently, this lack of a single standard for MQTT Payload data models has driven the development of competing standards, e.g. Eclipse Sparkplug, or many organisation specific data models.

Given that for each different implementation of an MQTT Interface, a different data model could apply, this complicates any translation activities to convert data from the input source data model into the Atlas Internal Data Model that is optimised for Cloud Data ingestion, Reporting and AI Algorithm execution.

Initially a view was taken that a specific input JSON format (or Schema) could be simply converted from the input format to the Atlas Internal Data Model format, via a standard utility JSONPath. However, this proved unworkable due to the complexity of the Ford CDM format. As a result, a new capability had to be developed to translate the JSON data from the Ford Common Data Model to the Atlas Internal JSON Data Model. For a different organisation, this translation capability will have to be adapted to meet the new requirements of that organisation.

This problem will continue to exist until a single standard is agreed for the format of data within an MQTT Message. However, many obstacles exist preventing this from happening:

1. MQTT is a generic messaging interface and a standard protocol for data transmission was specifically not defined by the creators of MQTT to provide for a fully generic messaging solution. A more complex Standard may impose a significant processing overhead to a solution where simplicity is a must, e.g. very simple sensor devices and low latency networks.

2. Differing standards exist, which one is the better solution and how does the provider prove that their solution is the correct one to use for all Use Cases?

3. Each provider of a Standard has no authority to impose it on any external organisation.

4. Organisations adopting a new Standard may need to re-visit legacy equipment so that any existing interface can be upgraded. This could be prohibitively expensive, thus preventing the uptake of any newly agreed Standard.

5. Complex organisation specific Standards may meet only the requirements of that specific organisation, but the complexity prevents simple conversion of the data to other formats.

### 5.2.2 Data mapping

Mapping data from the welding machines (in MQTT – JSON format) into something which can be presented in the Altas cloud took a long time. It consumed far more resource than either ATS or Ford had anticipated. Ford equipment suppliers will face the same issue as we migrate away from the existing Factory Information System to using the new Common Data Model. Methods will need to be found to simplify this, perhaps through some automation/algorithms, and train our equipment suppliers how to map data quickly and correctly so it can be presented and utilised in Ford systems.

The consequences of not learning from this experience will slow down production launches and cost both Ford and its equipment suppliers a considerable amount of money.

### 5.2.3 Upload versus download rates

This was probably the most considerable oversight on the 5GEM project. Once the network was set up and tested it did achieve its target download rate of 600Mbps. The designed upload rate was also achieved but this was only 40Mbps. We soon recognised that this upload rate could easily be overrun with the output of images from the stator hairpin welder if running at production rate, let alone if we had multiple similar scenarios running on the same MPN. Ultimately, in an industrial setting, the objective is to get the data off the shopfloor and do something useful with it so the bias must be towards upload speed. This is as opposed to the typical mobile device user whose primary objective is to download as much data as possible to their device e.g. movies, videos, on-line gaming etc.

When this was recognised, we explored the options to change the set up with Vodafone and Ericsson. The outcome of this discussion was that it would be difficult and costly. As the use-cases were based in trial environments and not true production environments, and the objectives were to prove the concepts, we decided the project would still work with the limited upload rate. The lesson learnt here must go right back to the early days of the project when discussing the network requirements and performing the initial survey, and at this point the customer and supplier must fully understand what are the needs of the network.

### 5.2.4 Costs of a 5G MPN

There is no doubt that a 5G network is a fast, reliable and secure means of wirelessly connecting equipment but it comes at a cost. The initial costs of hardware and installation were well understood and known to be high, at the start of the project, especially when compared to the cost of installing a WiFi network. In addition to this, the cost of the network support must be added. The support service will monitor the performance of the network, enable remote shutdowns and re-starts of the network and send software updates (including those related to security) to the network. This was particularly useful if only due to the number of power shutdowns for maintenance work at Ford that occurred during the project.

In order to maintain the support service from Ericsson beyond the end of the project there was a six-figure bill to pay and this is challenging our ability to keep the network running. In fairness to Ericsson, part of the problem in this scenario is that the technology has moved on. Our Non StandAlone (NSA) network is now out of date as 5G installations are now of the standalone variety and this meant Ericsson had to provide a service which was spread over just the 5GEM project and one other customer.

In conclusion we can see that the cost of 5G networks and their support will come down as the technology becomes more commonplace and economies of scale kick in but there is a price to pay when you are a first mover which can result in higher than anticipated running costs or hardware becoming redundant much sooner than planned.

### 5.2.5 Data processing

There is significant opportunity for production system improvements with a good strategy for data processing and having this combined with the right communication process. Today we produce a lot of data on the shopfloor which is not used and there is the potential to use this data to much greater effect if it can be handled and processed automatically without the need to human intervention or analysis. The factory monitoring, process monitoring and maintenance related use-cases have all demonstrated this.

The 5GEM project has approached the possibilities in an agnostic manner such that we have added value through the skills and capabilities of the partners involved in the project. The alternative approach is to drive the machine tool suppliers to work with other experts to build the technology into their equipment as standard. This way Ford does not need to approach third parties to design and install these enhancements after the equipment has been purchased.

### 5.2.6 Learning outcomes for AR/MR using the Microsoft HoloLens2 – MPN connectivity

To be able to utilise the HoloLens2 (HL2) on the MPN we first had to identify its initial hardware specs; the headset is a native WiFi 5 device with a USB-C interface running a Mobile hardware internals and software operating system (OS) – the minimum requirements for compatibility with 5G were tested during this project as this also represents the strategy for implementing legacy devices with no native support for 5G. Current hardware on the market was not readily available to purchase and we used our contacts within the wider community to consult and acquire auxiliary hardware (e.g. USB 5G Dongles) to be able to test solutions. Our initial approach:

1. Engage hardware suppliers/support for expert assistance during investigations
2. Check minimum requirements for hardware meets standards
3. Check OS is compatible between components (Mobile/WindowsPC/LinuxPC etc.)
4. Check auxiliary interfaces are compatible or if additional adapters are needed e.g. USB-A to USB-C adapter (for conversion)
5. Check necessary drivers are compatible between components
6. Test all scenarios in full to identify any issues

It is possible to connect multiple auxiliary components from multiple suppliers to get a working solution, however, testing under different scenarios is the final and most important requirement to ensure reliability.

## 5.3 VFE use-cases

### 5.3.1 Network Specification

Different environments require the network performance to be balanced to suit them and this is best understood by all parties prior to starting. In this industrial environment, uplink speed was much more important than downlink speed, but the network was not configured that way.

### 5.3.2 Data Management

The Ford use-case utilised MQTT with the issues discussed above. The VFE use-case operated with OPC-UA, a common alternative in industrial platforms. This format reduced some of the data mapping and formatting requirements because these are built into the tag definitions and can be read at the client.

The disadvantage of the OPC protocol was that the client initiates the connection to the data source. On the MPN we had assumed that all devices would appear as if on a local network together (as if on Wi-Fi). This was not the case as almost all routers and devices assumed that the cellular network was public and therefore insecure.

This caused significant issues for routing OPC-UA with additional hardware required to "tunnel" data through the network.

As with the uplink/downlink speed, understanding that the RBMS network feature was needed came too late in the project and would have been costly to implement.

### 5.3.3 Security

As demonstrated above, the MPN brings significant fundamental security benefits in its design. In making use of the network in practice there are many ways in which this security can become compromised. The physical security of the machines and their software can, of course, produce vulnerabilities but many of the third party tools and devices required some sort of cloud-based connection to implement – particularly for remote support. These routes must be carefully considered and managed rather than falling into a trap that the MPN is a security panacea.

### 5.3.4 Devices and sensors

It was possible to demonstrate the benefits of connecting distributed sensors to a 5G MPN during the course of the project, but this was generally only possible by using more hardware to bridge the device and the network. Connecting at a system level was less complex but significantly reduces the number of connections needed, weakening the business case.

### 5.3.5 Takeaways

Our key takeaways on the 5G MPN were:

- The network providers need to present the configuration options to end users when planning. Industrial and manufacturing needs are quite different to consumer needs.
- End users need to have a good idea about what they are connecting to the network, how they connect and what are their data flows.

- A 5G MPN is not yet plug-and-play like Wi-Fi.
  Expert knowledge was repeatedly necessary to utilise the technology.
- Gateway devices, such as 5G routers, add much more complexity than expected. MPN based configuration options need adding to firmware.
- A MPN is not automatically secure.
- An increase in availability of 5G enabled devices at the sensor level is needed to add weight to an MPN business case for the industrial use cases in this project.

# 6.0 Future Plans for Network (sustainability)

### *Hardware plans*

Discussions are ongoing with Vodafone and Ericsson regards what happens next with the 5GEM project MPN.  There is a desire in the 5GEM team at Ford to keep the network in our E:PriME building for the purposes of further experimentation and trials.

Ford's Digital innovation team have some ideas regarding further connectivity work and Ford has equipment suppliers who can use the network to prove out the latest 5G enabled equipment. One example of this is a torque gun supplier who Ford approached to join the project at the midway stage however their product was not ready for testing beyond their R&D department at the time.

The likelihood of this being realised will depend on the ongoing running costs of the network and how Vodafone want to employ the 5G spectrum which they own. There may also be opportunities for Vodafone and Ericsson to use the network for demonstrations or gain publicity from its existence at Ford Dunton in exchange for ongoing network support.

If these options cannot be realised, then Vodafone are considering how the hardware can be re-used and it is possible that it could be re-installed at other locations as a demonstrator for what 5G networks can achieve. This would be for development and proof of concept purposes until a new and bespoke network is installed for long term use.

At TWI the 5GEM team have agreed that there is no requirement to keep the MPN in place so it will be decommissioned. There is a suggestion from VFE that the network is moved to their training centre for development and education purposes but this requires further investigation.

### *Virtual Commissioning opportunity*

A late addition to the project was the virtual commissioning work performed by HSSMI on the battery welding machine at Ford. A brief animation on the battery welding machine was developed using the Siemens NX MCD (Mechatronics Concept Designer) as shown in figure 73.

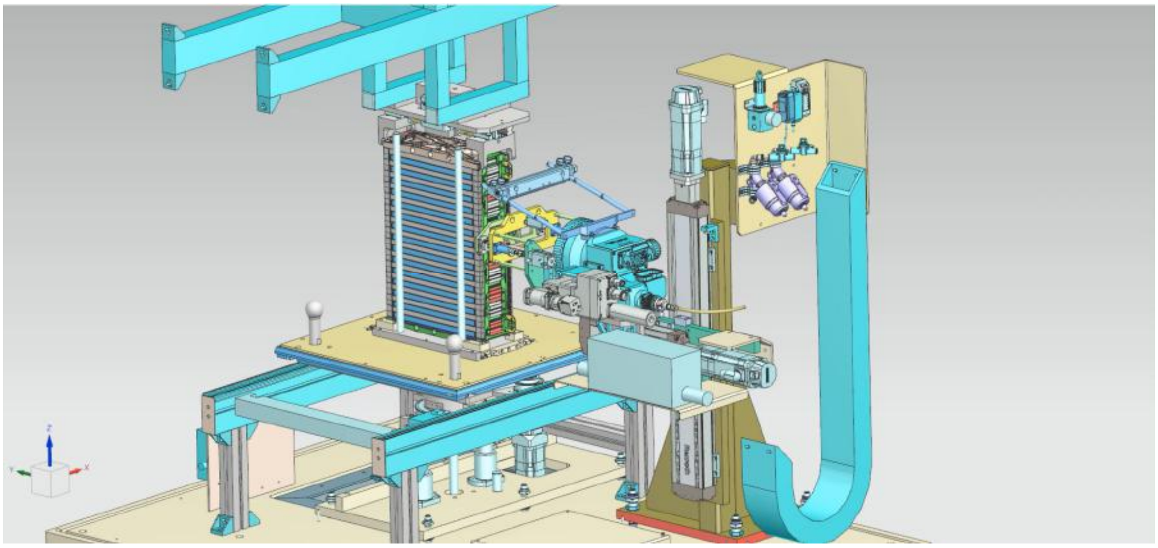


*Figure 73: image from animation of the battery tab laser welding station*

The 3D CAD model received contained the entire space with facilities in all the workstations. The required facility CAD was imported into the NX and was isolated for the animation. Further, the necessary physics/kinematics were assigned to the objects in the CAD and the animation was performed.

For the processes where machines from vendors are required to be setup, test and commissioned, there could be an opportunity for remote engineers to work collaboratively on kinematics and PLC code with a low latency connection to directly interact (Live) with the physical machine at a facility. The machines would be connected with 5G enabled sensors and controls to be able to communicate across the challenging environments of a manufacturing facility at a reliable throughput.

The development of this opportunity came to a close due to the limited time available and additional support required from the original equipment manufacturer (OEM) to interpret some of the machine code. However the potential benefits from such a development are significant when the code for a new machine can be proven before the actual machine is built. The time for final commissioning will be much reduced and the need for lots of machine cycles using tryout parts, which could be expensive prototypes on a new product programme, can be reduced.

This is a great demonstration of 5G capabilities for data capacity and speed but also for the data security because the ability to restrict access to machine control programs is important for both product quality and personnel safety.

### *Knowledge acquired*

Beyond this, the legacy of the 5GEM network lives on in the knowledge and education it has provided and specifically at Ford we have been able to share the knowledge gained with our colleagues (globally) as follows:

- Our local Digital Innovation team, who have supported this project, have the knowledge gained from the use-cases at Ford and the challenges overcome across the whole project. Looking forward, the role for this team is introducing new technologies into our manufacturing facilities which has now been influenced by the 5GEM project;
- In Ford Valencia there is an EU sponsored trial taking place with 5G controlled Automated Guided Vehicles (AGVs);
- In Ford Cologne there is a project to upgrade the IT infrastructure which includes the installation of a 5G network. We have already connected with this team and shared learnings from 5GEM and we are jointly planning to visit https://www.arena2036.de/en/ at Stuttgart University to review 5G opportunities for the automotive factory of the future;
- In Ford US the global strategy for IT, shopfloor connectivity and the overall design for future factories is determined by the advanced manufacturing team. Throughout the project we have been in communication with this team sharing our activities and knowledge;

Furthermore, in parallel with the 5GEM project, a 5G network has been installed in Ford's new truck factory in Dearborn (US) for improved communications on the shopfloor and software delivery to vehicles. A report is available at this link https://about.att.com/story/2021/ford-manufacturing-facility.html .

# Appendices

## Security report from Vodafone

This document is large (54 pages) has been submitted to DCMS separately.

It has been cleared by Vodafone for sharing publicly.

## Summary of Dissemination and Exploitation Activities

### Online presence

- Website: 5g-em.org
- LinkedIn: 5GEM Enabled Manufacturing
- Twitter: @5gem_org
- TM Forum Catalyst: 5G Enhanced Manufacturing

### Events

| | |
|---|---|
| 22-23 Mar 2022 | UK5G International Showcase Conference & Exhibition, Birmingham<br>Fully physical event with a booth/stand<br>Ian Jenner spoke on Track 4 - Industrial & Manufacturing Sectors |
| 10 Mar 2022 | Webinar with themanufacturer.com<br>Björn Odenhammar (Ericsson), Jennifer Didoni (Vodafone) + Chris White from 5GEM - video recording here. |
| 10 Mar 2022 | National Manufacturing & Supply Chain Expo<br>20 min panel (with other 5GTT projects), F2F, Milton Keynes<br>Adrian Goodbrand from VFE represented 5GEM |
| 28 Feb - 3 Mar 2022 | Mobile World Congress, Barcelona<br>Joint exhibition with 5G-ENCODE on the UK pavilion |
| 18 Jan 2022 | Digital Catapult webinar: Learning from the first wave of deployments<br>Presentation on security, network design & integration (Vodafone) + panel on standards (Joann) - video here |
| 1 Dec 2021 | TWI Digital Manufacturing Conference (virtual event)<br>30-minute panel: TM Forum, Ford, Vodafone, VFE |
| 17 Nov 2021 | UK5G 5G & Manufacturing \| Productivity & Efficiency<br>Use case presentation for Manufacturing vertical campaign - video here |
| 16 Nov 2021 | Digital Catapult Industrial 5G Uncovered online event<br>Panel: "How can 5G accelerate digital transformation in manufacturing and logistics?" - video here |
| 21 Oct 2021 | Cambridge Wireless 5GTT Collaboration Workshop Event<br>Collaboration round table for 5GTT projects |
| Sep/Oct 21 | TM Forum Digital Transformation World (virtual event)<br>Catalyst showcase / Catalyst Arena (Ford & Vodafone) - video here |
| 7 Oct 2021 | Digital Transformation Expo, London (Excel)<br>Panel on "Deploying private mobile networks: What's the ROI?" (Ford) |
| 20 & 22 Sep 2021 | 5G World, London / virtual<br>Panel: "How to avoid private networks' past mistakes" (Ford) |

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| 21 Sep 2021 | Connected Britain 2021 - “Digital infrastructure is delivering real world benefits for manufacturing”<br>TM Forum, Ford, Vodafone, VFE case study panel |
| 15 Sep 2021 | Privacy Symposium “Data protection and cyber security for IoT, Edge and Cloud computing” (TM Forum) |
| 31 Aug 2021 | IoT Week “Next Generation IoT for a Sustainable Future” (TM Forum) |
| 20 Jul 2021 | Bloomberg event on the Future of Connectivity<br>Panel with Vodafone Business CEO, Vinod Kumar, and Chris White (Ford) |
| 1 Jul 2021 | Mobile World Congress, Barcelona<br>Virtual presentation on THE BENEFITS OF 5G IN MANUFACTURING: A FOCUS ON FACTORY EFFICIENCY |
| w/o 21 Jun 2021 | Catalyst takeover week (TM Forum)<br>Catalyst profile page here \| LinkedIn post here \| Twitter post here |
| 1-2 Jun 2021 | Presentation on Practicalities of Industrial Deployment as part of 5G Week’s 5G Realised event - video here \| Virtual exhibition using Remo platform |
| 25 May 2021 | Private Networks Forum<br>Building the business case for private networks (Ford) |
| 23-24 Mar 2021 | DCMS & UK5G Be Better Connected Conference<br>Virtual exhibition space, Lightning Talk… |
| 18 Mar 2021 | TM Forum Hard Talk webinar<br>What enterprises expect and need from 5G (Ford) |
| 2 Mar 2021 | Bits & Chips Industrial 5G Conference<br>Ford and Vodafone presented |
| 8 Feb 2021 | DCMS UK and Nordic-Baltic Countries Virtual 5G Forum<br>Round table on the future of industrial manufacturing |
| 3-Dec 2020 | TWI Digital Manufacturing conference<br>Panel session TM Forum, Ford, VFE, Vodafone |
| 1-Dec 2020 | Financial Times & Ericsson Private Roundtable<br>Schneider, Siemens, Ericsson, ABB, KPMG… Chris White represented 5GEM |
| 11-Nov 2020 | 5G Techritory 2020 panel discussing 5G service delivery standards across industries (TM Forum) |
| 11-Nov 2020 | Private Networks in a 5G World (Informa)<br>Chris White (Ford) with Tony Sceales - on-demand playback here |
| 14-Oct 2020 | Digital Transformation World Series 2020<br>Erik Brenneis (IoT Director, Vodafone Business) \| Chris White (Ford)<br>On-demand playback here |
| 13-Oct 2020 | GSMA IoT WebTalk: 5G Private & Dedicated Networks for Industry 4.0<br>Marc Sauter (Head of MPN, Vodafone) \| Chris White (Ford) |

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|---|---|
| 8-Sep 2020 | Industrial 5G in the UK Chris White & 5G-ENCODE, 5G Week webinar |

## Publications, PR, Media, Awards

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|---|---|
| Apr-22 | Contribution to a network security study by NCC Group |
| Apr-22 | Contributions to UK5G round table for report on the Mobile Private Network Industry Landscape |
| Mar-22 | Shortlisted for UK5G Awards (*Most Innovative use of 5G Technology*) |
| Mar-22 | Contribution to special edition of UK5G magazine |
| Mar-22 | Vodafone / Ford video |
| Feb-22 | Contribution to Digital Catapult *Factory of the Future* article |
| Feb-22 | Standards infographic and blog/article |
| Feb-22 | FT article "Industry turns to private 5G to speed digital change"<br>From an interview with Chris White |
| Jan-22 | Contributions to ITU-R WP5D paper Applications of IMT for specific societal, industrial & enterprise usages |
| Dec-21 | 5G for Manufacturing: Realising the True Potential of the Fourth Industrial Revolution (UK5G article) from journalist interview with Ford & TWI |
| Nov-21 | UK5G Productivity & Efficiency webinar<br>Write-up & video in The Manufacturer (here) |
| Oct-21 | Contributions to UK5G Manufacturing Vertical campaign hub (e.g. here) |
| Aug-21 | Full back page advert in issue 6 of UK5G's Innovation Briefing magazine |
| Jul-21 | Vodafone's 5G Manufacturing report (*Powering Up Manufacturing, Levelling Up Britain*) - Report here \| Press Release here \| Publicity here |
| Jul-21 | Feature in Innovation Briefing magazine on Ford's keynote at **5G Realised** |
| Jul-21 | Virtual tour of E-PRIME published here:<br>https://my.treedis.com/tour/sandbox-E:PriME |
| Jul-21 | Expert comment on "5G in a heatwave" for UK5G newsletter |
| Jul-21 | Chris White recognized as a Connected Britain Top 100 Influencer |
| Jun-21 | TM Forum Catalyst videos published |
| Jun-21 | *Hybrid cloud data architectures* use case published here on TM Forum Inform |
| May-21 | GSMA Private & Dedicated Networks case study published |

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| Apr-21 | *Intelligent Maintenance* use case published here on TM Forum's Inform channel |
| Mar-21 | techUK blog published as part of Diversifying Telecoms campaign week |
| Mar-21 | Joint paper on MEC published together with Dorset Rural 5G project |
| Feb-21 | *Real-time process analysis & control* use case published here on TM Forum's Inform channel |
| Feb-21 | Use cases provided to DCMS for Private Networks Blog |
| Jan-21 | Ford interview with Automotive World resulted in two published articles<br>5G just one component needed to achieve Industry 4.0<br>Hurdles remain in maximising 5G's manufacturing potential |
| Jan-21 | Vinod Kumar (Vodafone Business CEO) used Ford video clips in new year video (not for public distribution) |
| Jan21 | Chris White selected by Ericsson as a UK 5G Trailblazer |
| Sep-20 | Mobile World Live video: interview with Chris White published as part of Mobile World Live's Smart Manufacturing focus week |
| Sep-20 | 5G Week Award win (see award ceremony video clip starting at 4m:40s) Vodafone's 5GEM private network deployment at Ford won ***Operator with the Best Industry Deployment.*** Vodafone UK News announcement here (covered here) |
| Sep 20 | Chris White / Ford invited to participate in GSMA's 5G IoT for Manufacturing Forum |