Project: Factory of the Future Open Radio Access Network (FoFORAN)

Report Title	Final project closure report
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V1.2	13/05/2025	AMRC & Partners	Update the project closure report

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Acronyms

5G: 5th Generation
ACDA: Air Cyber Design Acceptance
AGV: Automated Guided Vehicle
AI: Artificial Intelligence
AR: Augmented Reality
BBU: Base Band Unit
CNC: Computer Numerical Control
CPE: Customer Premises Equipment
E2E: End-to-End
ENISA: European Union Agency for Cybersecurity
ERP: Enterprise Resource Planning
FoF: Factory of Future
FOFORAN: Factory of the Future Open Radio Access Network
HDD: High Demand Density
HI: Highly Interoperable
I2C: Inter-Integrated Circuit
IoT: Internet of Things
KPIs: Key Performance Indicators
MEC: Multi-access Edge Computing
MES: Manufacturing Execution Systems
MGW: Media Gateway
MOM: Manufacturing Operations Management
NDAC: Nokia Digital Automation
NSA: Non-Standalone
ORAN: Open Radio Access Network
PCIe: Peripheral Component Interconnect Express
PCB: Printed Circuit Board
PGW-U: Packet Gateway – User plane
PO: Purchase Order
RRH: Remote Radio Head
RTM: Real Time Milling
SA: Standalone
SALs: Security Assurance Levels
SGW-U: Serving Gateway – User plane
SIM: Subscriber Identity Module
SPI: Serial Peripheral Interface
STM: Surface-mount technology
UI: User Interface
UC: Use Case
USB3: Universal Serial Bus 3

Executive Summary

The Factory of the Future Open Radio Access Network (FOFORAN) project set out to explore how Open Radio Access Network (ORAN) and private 5G networks can support the digital transformation of the UK manufacturing sector. Led by AMRC Northwest and supported by a consortium of industry and technology partners. The project aimed to develop and test flexible, secure, and cost-effective 5G deployment models designed for industrial sector.

Over the course of the project, ORAN network was deployed across industrial sites, and a series of real-world use cases were implemented. These included remote robotic inspections using 5G, real-time optimisation of CNC machining, and blockchain enabled supply chain visibility. The project compared ORAN with single-vendor networks to assess performance, interoperability, and cost implications. Custom user equipment was also developed to meet specific manufacturing requirements.

Security was a key focus throughout the project. A comprehensive strategy was developed based on Zero Trust principles, ENISA guidelines, and continuous risk assessment. Workshops with each partner ensured that security risks were identified and addressed early, leading to a strong and resilient network architecture.

FOFORAN has demonstrated the practical value of ORAN based 5G in manufacturing, providing a blueprint for future deployment. The project has delivered reference designs, tested infrastructure models, and documented key lessons to guide the wider adoption of private 5G in industry. Through its collaborative approach and successful demonstrations, this project supports the UK's ambition to lead in advanced digital manufacturing.

1 Introduction

The FOFORAN project focuses on bringing reliable and flexible 5G ORAN connectivity into manufacturing environments. The project compared the performance of ORAN networks with traditional single vendor 5G systems. The main goal is to demonstrate how open and adaptable 5G networks can better support industrial operations.

FOFORAN explored how customised 5G ORAN solutions can meet the specific needs of modern factories, with a strong focus on adapting 5G for industrial applications. ORAN networks were installed at different locations to test real-world manufacturing use cases. These included remote control of mobile robots, secure supply chain tracking using blockchain, and real-time optimisation of CNC machine performance. The project outcomes include network architectures, performance evaluations, industrial use case demonstrations, high device density testing, and guidance to help other manufacturers adopt private 5G solutions effectively.

2 Project partners

FOFORAN combines the necessary capabilities and expertise to implement an end-to-end connectivity solution tailored for industrial-scale production. The consortium members are:

- AMRC led the project, using the team's strong expertise in 5G deployment, AI, manufacturing, and automation.
- BAE Systems brings its real-world industrial use cases and uses the findings to de-risk their future investment.
- Dassault Systemes provides the manufacturing process integration expertise and their software stack.
- AQL will supply its commercial private 5G network.
- Safenetics brings its cybersecurity expertise.
- Productive Machines is responsible for low latency use cases by remotely monitoring and controlling the process through a digital twin.

3 Objectives

This project will develop, test and showcase flexible 5G deployment approaches for the manufacturing sector. It will:

- Deploy an ORAN network from scratch.
- Extend and test a partially existing network comprising components from different vendors for interoperable characteristics.
- Use an existing functional single vendor network as a benchmark.
- Compare true ORAN approach with highly interoperable (HI) network approach.
- Build and test native 5G, high performance devices with manufacturing communication interfaces.

4 Outcomes

Comparing the developed network against current single vendor network deployment (existing state of the art), will assess technical characteristics, performance, deployment challenges. Initial deployment in a chosen industrial site, will be applied to an extended manufacturing network where more than one business is present. This will:

- Identify the possibilities of standardising network services for digital manufacturing use cases.
- Benchmark ORAN approach against the single vendor and HI approach to address high demand density (HDD) environment i.e, manufacturing facilities
- Produce a reference design, and lessons learnt in a format of use to manufacturing and telecoms industry sectors.

5 Infrastructure deployment

AMRC has the largest manufacturing testbed in the UK spanning across eight sites as illustrated in the figure 1. 5G ORAN infrastructure deployment has now been successfully deployed as part of the project at three sites as listed below:

- AMRC – Enterprise Network Park, Samlesbury, Blackburn
- BAE ASK - Enterprise Network Park, Samlesbury, Blackburn
- AMRC FoF – Catcliffe, Sheffield

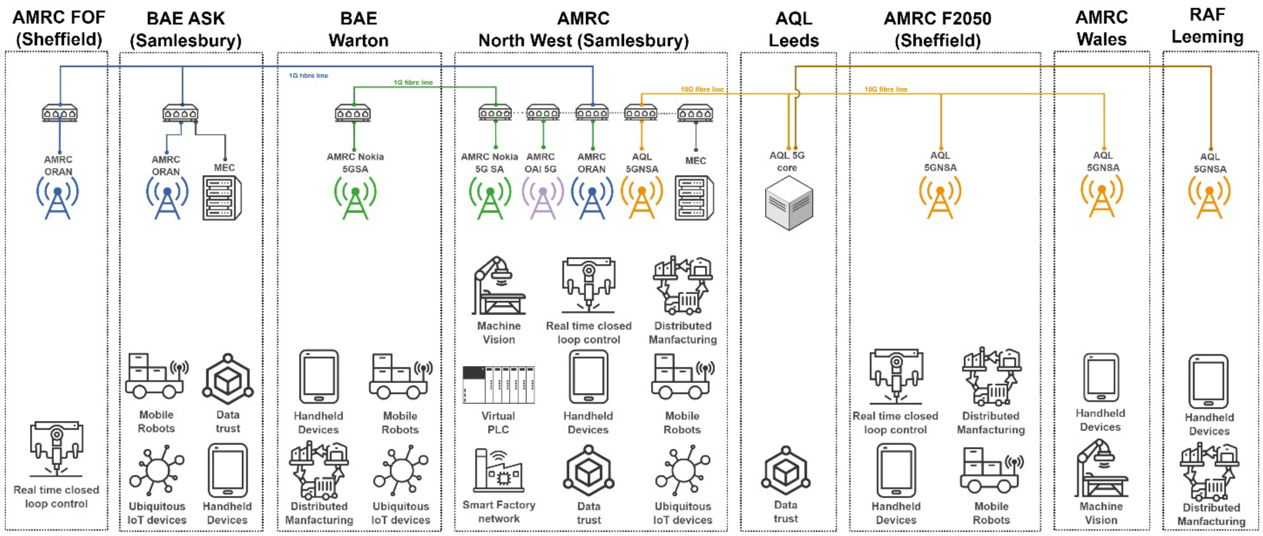

Figure 1 - Overall FOFORAN testbed architecture

5.1 User Equipment details (UE)

The UE used to connect and test the network capabilities of 5G networks: SA (Standalone), and NSA (Non-Standalone) and SA ORAN for different use cases.

- 5G mobile phones: The Nokia smart phone (Model: TA 1362) with 5G capabilities provide ultrafast data speeds, for great coverage. This device is enabled with robust security protocols and provides the platform to test the 5G network via SIM (Subscriber Identity Module) connectivity. It is also engineered for utilising the power to extend the lifespan of the battery.

- In-house built 5G industry ready devices: AMRC NW is developing the CPE (Customer Premise Equipment) boards for utilising the 5G capabilities devices as shown in figure 2 for the manufacturing environment. The first version (Ventus 1.0) of the 5G CPE is an in-house designed board optimised for reduced capabilities. This board lacks an embedded processor, necessitating a connection to a main controller via USB3 (Universal Serial Bus 3.0) or PCIe (Peripheral Component Interconnect Express). It offers compatibility with most readily available M.2 5G modules, ensuring flexibility in deployment, while the second version (Ventus 2.0) offers standalone processing capabilities for offline and cloud control for robots, sensors, actuators, and industrial equipment through industrial interfaces/LAN (Local Area Network) as well as I2C (Inter-Integrated Circuit) or SPI (Serial Peripheral Interface) through expansion ports.

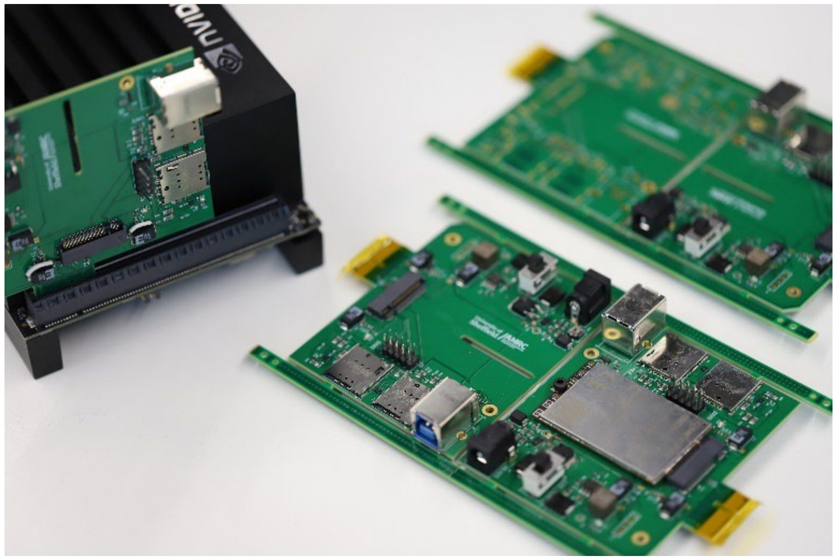

Figure 2 - In house built 5G boards

Both versions of the 5G CPEs hold significant value within the project. They contribute by facilitating an open and flexible link between high-speed 5G networks and real-time industrial control systems, enhancing resilience and reliability as well as simplifying development processes and offer a streamlined approach for integrating advanced functionalities into factory environments.

6 Manufacturing Use cases

Table 1 - Manufacturing use cases with description and partners involved

Use case (UC) ID	Use case Name	Use case Description	Partners
UC-1	Smart/Connected Factory	MES (Manufacturing Execution System) - Generates digital step by step guides and insights for planned work schedules and production, creating a smart factory environment	Dassault
UC-2	Data trust within supply chain	Blockchain Customer Supply Chain - Detailed insights into each stage process of parts with suppliers and vendors, ensuring authenticity, quality and price are consistent and trusted	BAE
UC-3	Mobile Robots	Spot the Robot - Scanning of aircraft sections for comparative status of any damage or	BAE

		inconsistencies and leveraging teleoperation remote presence	
UC-4	Real Time Machining	Reduction in machine chatter - Using sensors and IoT (Internet of Things) specific devices to monitor performance and consistency of manufactured machine part with option to intervene and disrupt production processes	Productive Machine
UC-5	IoT Platform & Highly interoperable networks	Network 5G dependencies, transitional uninterrupted interoperable ORAN connectivity	AQL
UC-6	Smart factory architecture	Develop architecture for future smart factory enabled with private 5G networks	AMRC

6.1 UC-1 Connected Factory

This use case focuses on how the future factories utilising MOM (Manufacturing Operations Management) and private 5G can be deployed to monitor and control manufacturing operations in real-time, allowing the agility to adapt to change when needed. Figure 3 illustrates the process flow of the drone manufacturing assembly line as demonstrated in the use case. The electronic circuit board are produced using STM (Surface-mount technology) pick and place method. Each drone manufacturing order is assigned a serial number which is used to track the production status and history. The serial number is assigned to a blank PCB (Printed Circuit Board) board at the start. As the board proceeds through the stages of solder application, pick and place, oven reflow and manual soldering, the serial number uniquely identifies the data generated and the digital trail of the process. The enclosure for the drone is 3D printed in batch and each batch of enclosures is assigned a lot number similar to serial numbers. During the assembly stage, the lot numbers of the enclosure consumed is assigned to the serial number linking the PCB manufacturing trail the enclosure manufacturing history. This ensures complete visibility over the entire history and capabilities of advanced analytics such as analysing manufacturing rather than individual processes.

Figure 4 describes the physical layout of the demonstrator. The demonstrator is divided into 2 areas: the PCB manufacturing area and the assembly area. A robot acting as an AGV (Automated Guided Vehicle) automatically triggered by the MES when there is a need to transport the PCBs from the manufacturing area to assembly area.

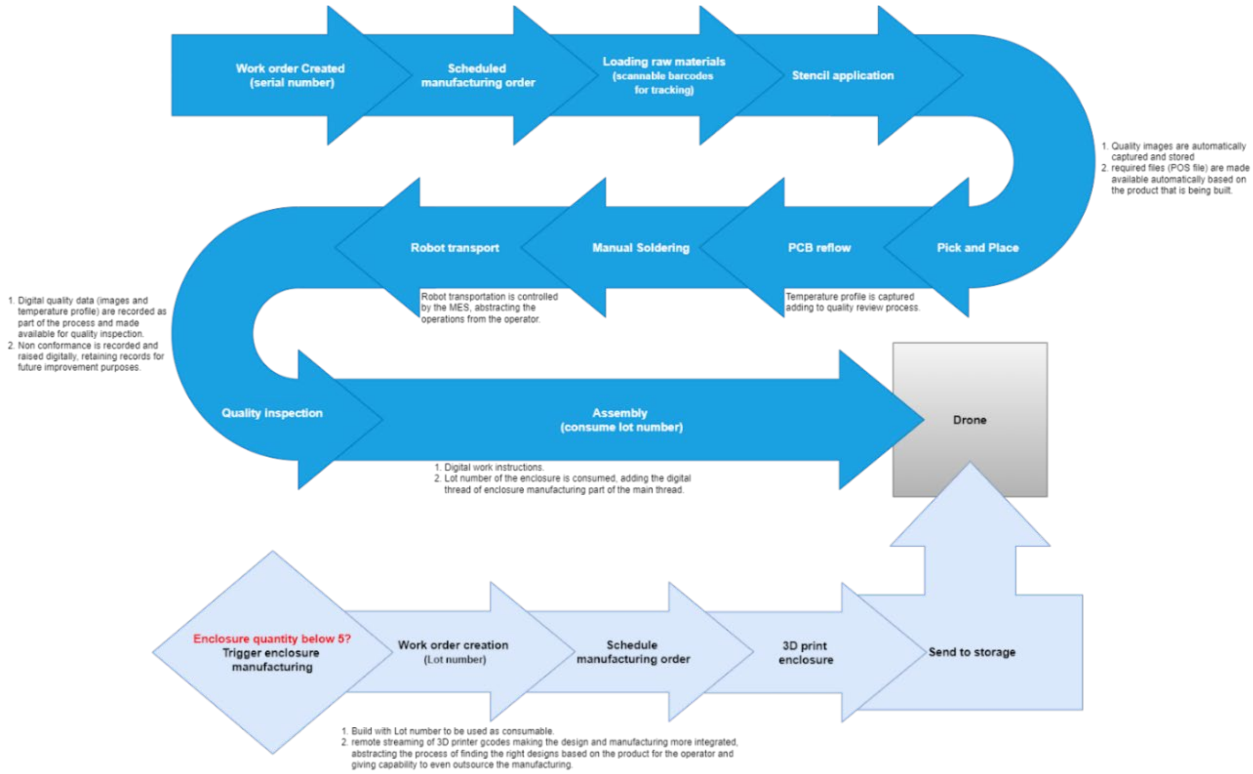

Figure 3 - Connected Factory use case process flow for drone manufacturing assembly line

6.1.1 Technical achievements

- Process definition ensures that the correct processes are performed in the correct sequence.
- Integrating and automating processes between the MES and the shop floor to streamline and error proof operator touchpoints, and opportunity for error.
- Provide digital operator instructions.
- Analyse the performance of the cell, expose data that could be useful in the supply chain, ensure that all trace data is collected and readily available.
- Connect the MES system and the use case equipment with 5G network.

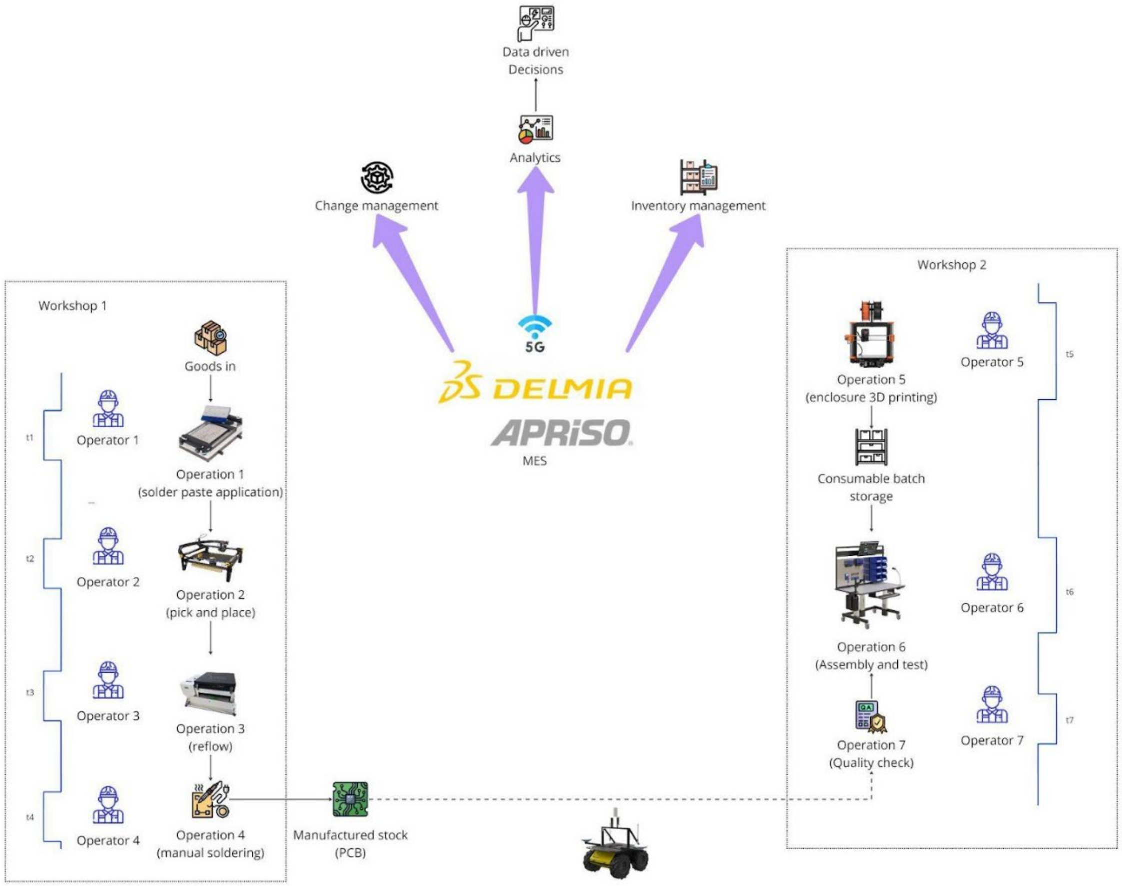

Figure 4 - Connected factory use case: Physical demonstrator layout

6.1.2 Outcomes

This use case demonstrates how the MOM functionality can be deployed to monitor and control manufacturing operations in real-time, allowing the agility to adapt to change when needed. It showcases the following:

- Digital work instructions: simplify how shopfloor operatives receive their instructions – leading to improved process, improved right-first-time delivery performance and quicker on-boarding and upskilling for new workers.
- Machine integration combined with process interlocking: reduces the amount of operator touchpoints and variation in the process. This significantly reduces many different opportunities for error, such as: loading wrong program, starting program at the wrong time, processing a part at the wrong operation, and processing a non-conforming part.
- Trace and genealogy data: the process ensures that accurate trace and genealogy information is captured, at the right time, ensuring that regulatory and customer requirements are adhered to, mitigating potentially costly recall activities. A single source of truth for data related to the manufactured product.
- High speed 5G connectivity: is beneficial to businesses who rely on a cabled infrastructure, as the infrastructure changes required when production lines are moved around, and machines are moved, can be difficult.

Ultimately, this demonstrator showcases the foundations and importance of building quality into manufacturing, maintaining lean, controlled and high-performing processes, and enabling a culture of continuous improvement.

6.2 UC-2 Data trust within supply chain

6.2.1 Use Case Description

This use-case was focused to develop an end-to-end digitally connected supply chain infrastructure, hosted in an Azure cloud environment, using blockchain as a means of enabling enhanced visibility into supply chain and digital trust in the data being transferred to the distributed ledger.

Additionally, the aim was to demonstrate capabilities on future supply chain management and collaboration through blockchain, demonstrating the manufacture of a part downstream within supply chain, using both a real-world Tier 1 and Tier 2 supplier for communication of data via the new platform the 5G network to also prove these systems as suitably secure vehicles for security marked and sensitive product data. The demonstrator will focus on three main areas:

- In-process monitoring
- Supplier performance insights
- Supplier management

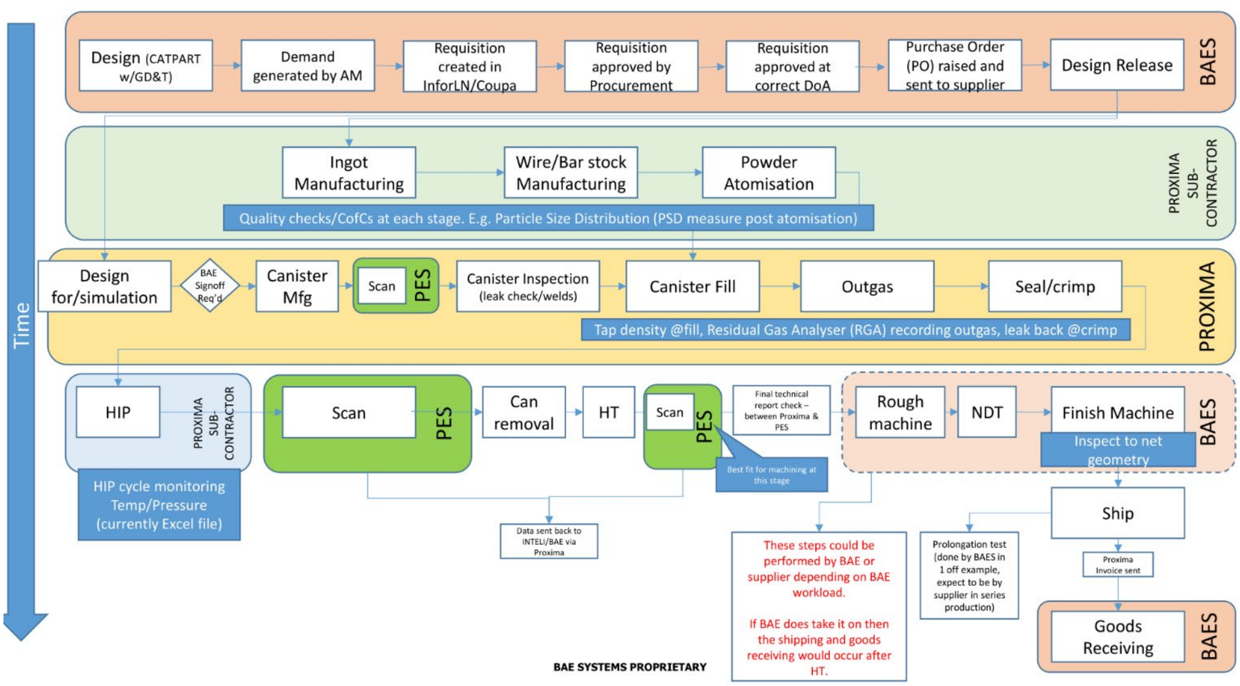

Figure 5 - Data trust within supply chain use case process flow diagram (with Tier 1 and 2 suppliers)

The figure 5 highlights the collaboration between BAE and T1/T2 suppliers on the blockchain infrastructure for enhanced visibility and improved collaboration within supply chain. The key procurement, manufacturing and logistics stages are highlighted, depicting the key stages within the end-to-end lifecycle for digital data sharing.

The headline challenges which are sought to be addressed through this innovation are as follows:

- Lack of end-to-end (E2E) visibility – procurement/manufacturing/logistics status and quality data
- Manual effort/human intervention required for updates in each critical area via a linear exchange in emails/phone calls
- Siloed data across suppliers, held in different databases
- Supplier acknowledgement of PO requires the need to upload to 2 different systems for audit purposes

6.2.2 Technical achievements

The achievements focus on four main areas of development as illustrated in the figure 6. A T2 supplier was introduce in the use case to demonstrate a multi-party blockchain ecosystem.

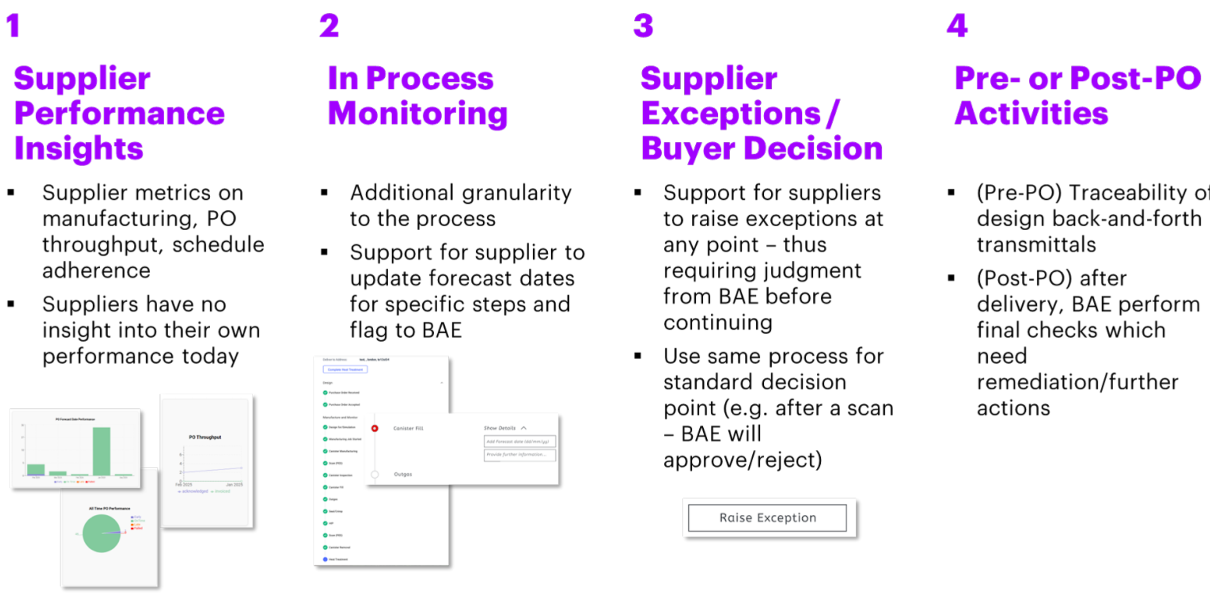

Figure 6 - Data trust within supply chain use case main objectives

1. <u>Supplier Performance Insights</u>

This dashboard has been designed to provide a holistic view for BAE to see supplier metrics, how they are performing against their contractual obligations. Suppliers also have a lack of visibility on their performance and the KPIs they are measured against, with a reliance on engaging directly with BAE to view this information. With blockchain and the monitoring occurring throughout the lifecycle of a downstream manufactured part, key metrics can be measured and logged throughout to enable these analysis and insights, with minimal manual effort required to capture the data. The chosen metrics to demonstrate how a performance dashboard could work in the future are:

- Purchase Order Forecast Data Performance: shown on a monthly basis, how many POs have been Early, On Time, Late or Failed?

- Purchase Order Throughput: shown on a monthly basis, how many POs were handled in total by the chosen supplier?
- All Time Purchase Order Performance: for the entire time range available, what is the aggregate number of Early, On Time, Late or Failed Pos
- Average Time Per Process: for the selected time range, what is the average time (in days) per process step (displayed per step)?
- Average Time Per Process Step: Average time (in days) across all process steps for the chosen supplier (displayed as a single number)

2. <u>In-process Monitoring</u>

This focusses on being able to have visibility of a supplier's manufacturing process, the current stage they are at and whether previous stages have been successful and the associated quality output from the key stages to ensure adherence to BAE's specifications.

The dashboard design for this involved bringing the process better in line with the actual process steps that take place in the real-world example with BAE, Proxima and PES.

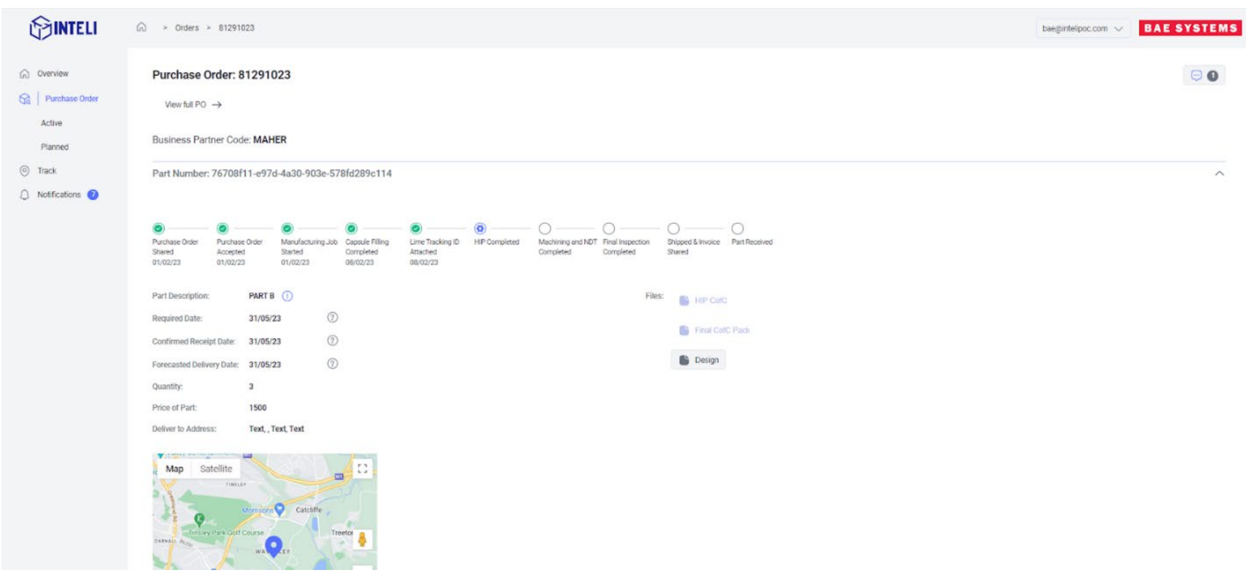

Figure 7 - Data trust within supply chain use case: initial PO monitoring User Interface (UI)

3. <u>Supplier Exceptions</u>

This functionality is to enable suppliers to raise exceptions at each of the manufacturing stages if any issues arise. This ultimately enables suppliers to inform BAE of any issues and the remediation action taken to resolve, however where critical, BAE can proactively be involved to address or authorise any manufacturing/process deviations to enable successful part manufacture and delivery.

This significantly improves current business processes as they are handled in a relatively unstructured format with reliance on linear methods of communication, therefore resulting in BAE being reactive and not as efficient to situations of non-conformances.

Future aspirations when scaling the solution up are to enable a digital log of all exchanges between BAE and the supplier, logging all exchanges and any changes to the agreed process in terms of manufacturing or process parameters.

Designs

Figure 8 - Data trust within supply chain use case: supplier UI for current step (with exception button alongside process step

Figure 9 - Data trust within supply chain use case: exception dialogue box

Figure 10 - Data trust within supply chain use case: Raised exception (sent to OEM to action)

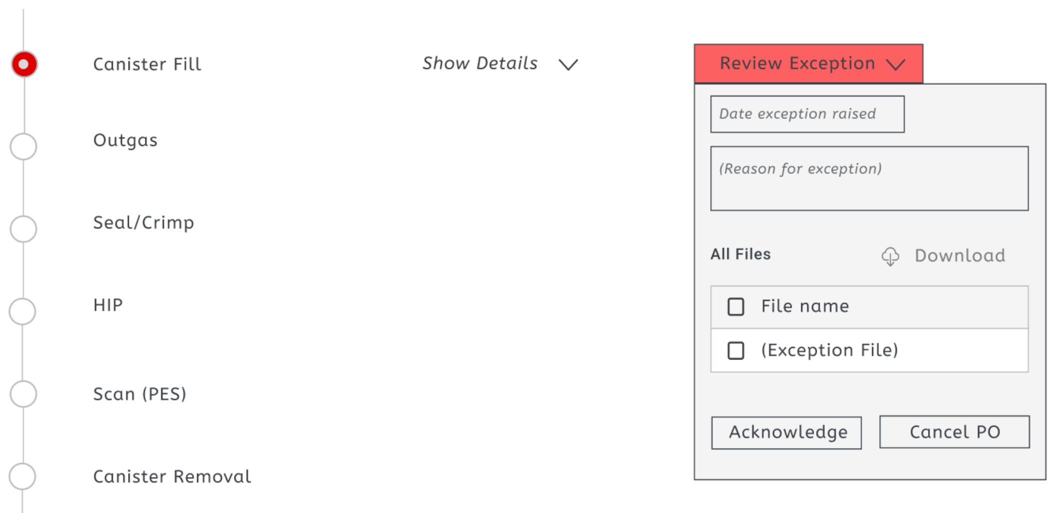

Figure 11 - Data trust within supply chain use case: OEM interface to review exception and any attached files

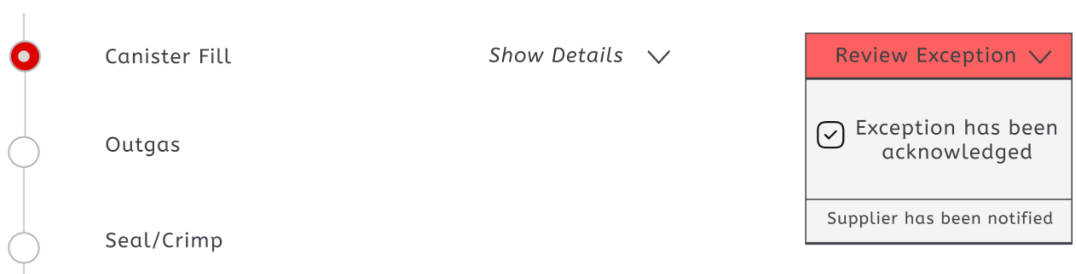

Figure 12 - Data trust within supply chain use case: acknowledged exception

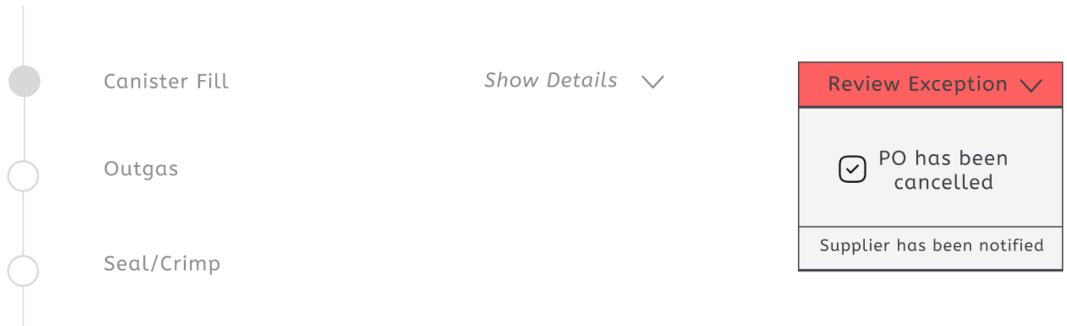

Figure 13 - Data trust within supply chain use case: PO cancelled (page greyed out)

4. <u>ERP (Enterprise Resource Planning) Test Harness</u>

An ERP Test Harness has been developed to prove how future ERP integration to the blockchain could work. The test harness uses the same messaging and communication methodology/protocols as BAE's current ERP system, demonstrating ultimately how the ERP would handle XML file conversion to JSON format for outbound data to the blockchain and vice-versa for inbound data to the ERP. As well as this, the test harness enables proving the blockchain REST APIs and the robustness for future integrations and two-way flow for inbound/outbound data.

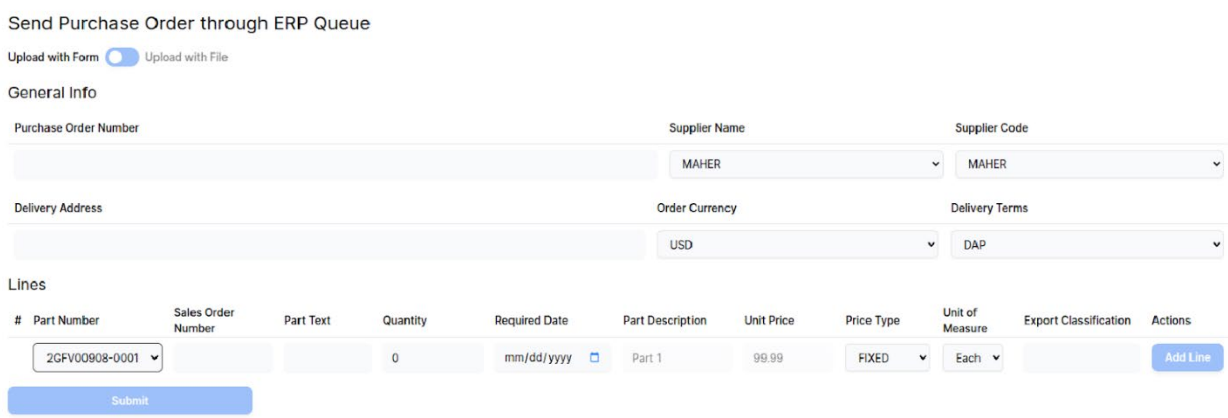

Figure 14 - Data trust within supply chain use case: ERP Test Harness UI

6.2.3 Results

Figure 15 and Figure 16 present targeted test scripts executed to validate the integration and performance of blockchain and 5G network technologies within the supply chain use case.

Test ID	Subject	Test Description	Results	Status	Tester	Date
Blockchain Tests						
T1.01	PO Creation	Procurement data fields, supplier, price, unit of measure, text, part number, description, design reference number, price type, T&Cs are available & can be populated, and supporting information can be attached	Successfully able to edit all fields and input data to requirements	Fully Passed	BAE	20/03/2025
T1.02	PO Creation	Ability to input purchase order data in ERP test harness UI and create PO	Successfully able to input purchase order data as a filled form into ERP test harness and send via API to blockchain	Fully Passed	BAE	20/03/2025
T1.03	PO Creation	PO can be issued to supplier through creation in test harness and upload to blockchain	PO successfully sent to blockchain via APIs	Fully Passed	BAE	20/03/2025
T1.04	PO Creation	PO at supplier is correctly populated, supplier can review all fields, Supplier can issue PO response (Accept, Acknowledge with Exceptions or Reject)	PO received by supplier through blockchain and all data matches issued version with supplier able to respond accordingly	Fully Passed	PROXIMA	20/03/2025
T1.05	PO Creation	PO response received from supplier	Able to receive and view supplier response to shared PO	Fully Passed	BAE / PROXIMA	20/03/2025
T1.06	PO Creation	PO status field is correctly updated in task bar	Ability to see status of PO i.e. sent to supplier, awaiting response, response received and status change logged and timestamped	Fully Passed	BAE	20/03/2025
T1.07	PO Creation	PO inbound data is updated in ERP test harness dashboard	Able to receive updated PO data from supplier inbound to test harness	Fully Passed	BAE	20/03/2025
T2.01	Multi-line PO	Work queue contains approved parts for purchase & PO containing multiple lines can be generated	Able to generate multi-line PO with different designs/parts	Fully Passed	BAE	20/03/2025
T2.02	Multi-line PO	Procurement data fields, supplier, price, unit of measure, text, part number, description, price type, T&Cs are available & can be populated against each	Successfully able to edit all fields and input data to requirements	Fully Passed	BAE	20/03/2025

Figure 15 - Data trust within supply chain use case: Test scripts (snippet) for blockchain

5G Network						
T9.01	Network Performance	Measuring 5G network speed, latency, bandwith, load and vulnerabilities through supply chain engagements	Not able to fully test capability due to blockchain issues in sending and synchronising data between nodes, only able send minimal data to which performance was good	Partially Passed	BAE/AMRC	27/03/2025
T9.02	Packet Loss	The loss of data packets during transmission over the networks	Network performance stable however unable to test extent of test script as unable to share significant data due to blockchain issues	Fully Passed	BAE/AMRC	27/03/2025
T9.03	Real time capability	Ability of the network to support real-time applications	Network able to support locally hosted ERP test harness and blockchain and performed well when able to test	Fully Passed	BAE/AMRC	27/03/2025
T9.04	Availability	Ensuring network and service availability when required	Network and service reliably available throughout duration of testing	Fully Passed	BAE/AMRC	27/03/2025
T9.05	SC Integration	Integrating supply chain processes with the network for improved efficiency	Successfully able to integrate supply chain technologies to 5G network and operate systems/process	Fully Passed	BAE/AMRC	27/03/2025
T9.06	Authentication	OEM/supplier user authentication (SSO) when logging into blockchain UIs	SSO embedded when logging into OEM/supplier specific UIs	Fully Passed	BAE/AMRC	27/03/2025

Figure 16 - Data trust within supply chain use case: Test scripts (snippet) for 5G network

6.2.4 Outcomes

The use case delivered a blockchain-enabled, digitally connected supply chain infrastructure; the key benefits achieved through this implementation are outlined below:

- Improved supply chain visibility: End-to-end digital tracking of procurement, manufacturing, and logistics was achieved using blockchain, enhancing transparency and reducing reliance on manual updates.
- Real-Time performance insights: A supplier performance dashboard was developed, enabling both BAE and suppliers to monitor key metrics (e.g., PO timeliness, throughput, and process durations) with minimal manual effort.
- ERP integration demonstrated: A test harness validated how existing ERP systems could connect with blockchain infrastructure using standard protocols, supporting future scalability.
- 5G ORAN and blockchain integration: Demonstrated the secure and efficient transmission of sensitive supply chain data over 5G network, proving their capability as a trusted medium for real-time industrial collaboration.

6.3 UC-3 Mobile Robots

6.3.1 Use Case description

The aim of this use case is to demonstrate and validate the ability for a remote expert to carry out a real time teleoperated robotic aircraft inspection using 5G ORAN network. Experts can be required to travel long distances to assess faults and damage on aircraft, which maybe in the UK or a different continent, incurring expert time, cost, and delays. Assessments may also be required in hazardous environments. It includes:

- A remote expert teleoperating a robot (Boston Dynamics Spot) to inspect a Hawk aircraft in the BAE Academy of Skills and Knowledge (ASK) capturing visual data, point cloud data and aircraft co-ordinates of anomalies.
- Live data integrated into a Hawk digital shadow.
- Assessment of performance and latency with data transmission increased beyond task requirement.
- An AR headset application integrated with the digital shadow to enable a maintainer to locate and review expert damage report damage at the aircraft.

6.3.2 Technical achievements

1. Cyber Security

Data Security is essential to BAE Systems, which is a target of bad actors from hackers to activists and state sponsored attackers. Therefore, Cyber Security is justifiably a key priority to the company with rigorous processes to assess systems and minimise risk before clearances can be given to our internal networks.

A new Air Cyber Design Acceptance (ACDA) procedure was launched at the beginning of 2024 designed to review the system parameters and security standards of newly proposed systems. It identifies twenty-four stages of documentation and review requirements to enable Cyber clearance. Cyber Security clearance was given as follows:

- The 5G network will operate in the Academy of Skills and Knowledge (ASK)
- It will operate on a private network connected to the AMRC but not connected to any BAE Systems network or the internet.
- The data being transmitted on the system is unclassified Hawk data.

2. 5G ASK Infrastructure

A primary objective of this use case was to teleoperate a Boston Dynamics Robot Spot over a private 5G network between the AMRC NW and the BAE ASK facility.

5G ORAN network with Airspan RUs were installed at BAE ASK facility as shown in the figure 17. The Athonet core was located at AMRC NW facility and backhaul system was configured for transmission of data b/w the sites (AMRC NW and BAE ASK).

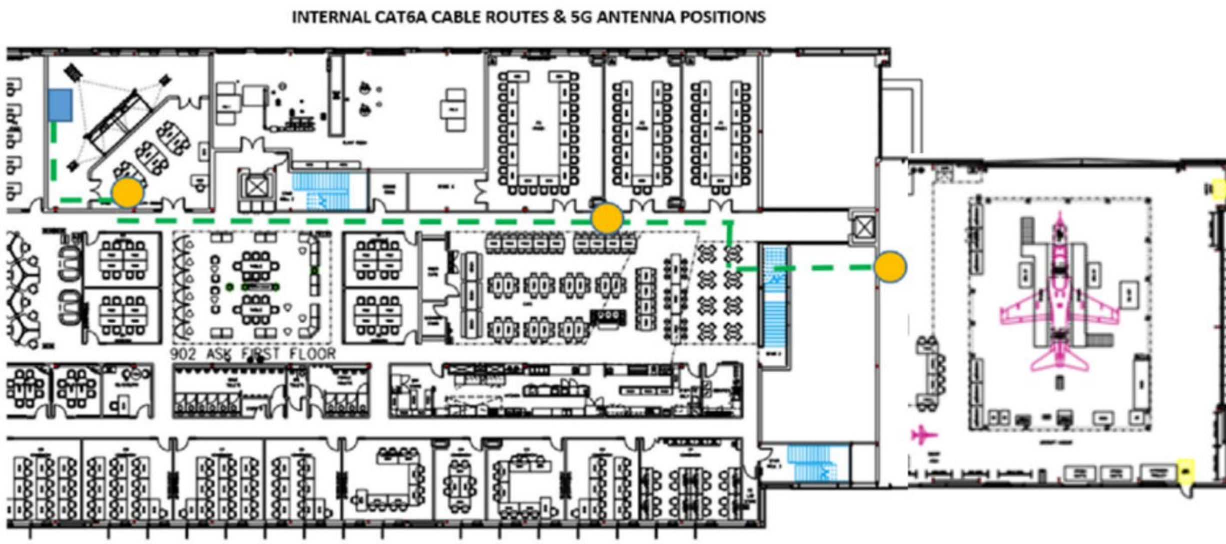

Figure 17 - BAE ASK floor plan with 5G antenna locations

3. <u>Robot teleoperation and data capture</u>

A Boston Dynamics robot Spot is used for the inspection. It is operated using a proprietary OS from Boston Dynamics with an inspection API developed by the AMRC. It has two payloads

- Core I/O provides the 5G connection to transmit data to and from Spot. It has additional computing capability with a GPU for intensive tasks.
- The BLK ARC is a laser scanner 360° x 270° field of view capturing up to 420,000 points per second LiDAR and has a 12 MP camera. It captures not just the aircraft but the whole environment.

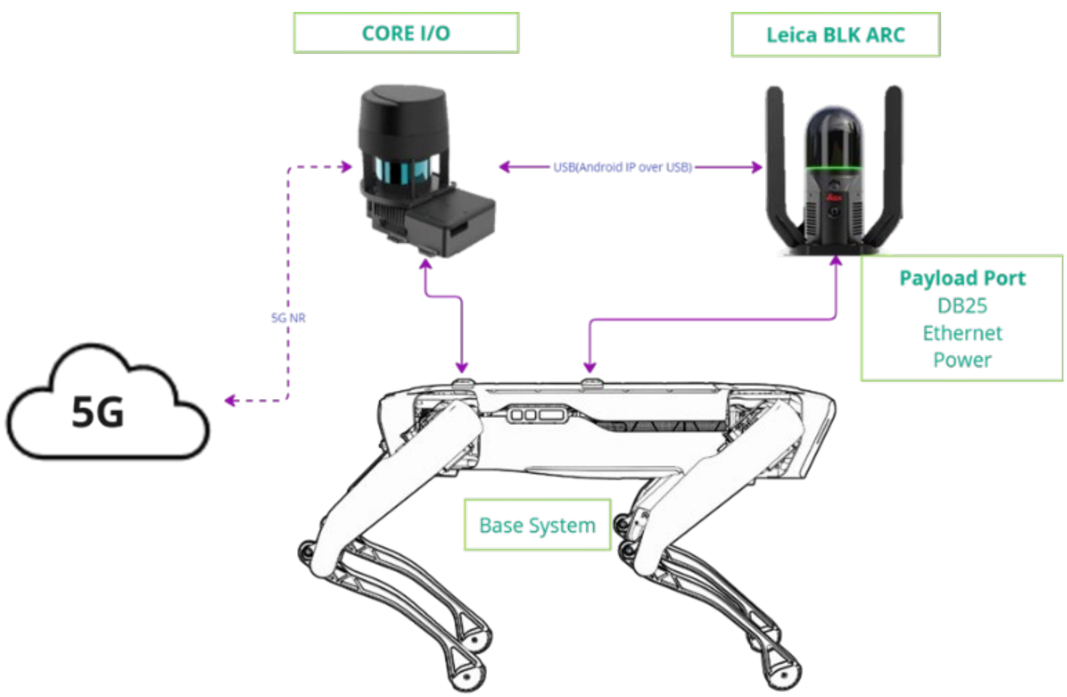

Figure 18 - Mobile Robot use case: with Spot robot connected to Leica scanner and Core I/O for 5G connection

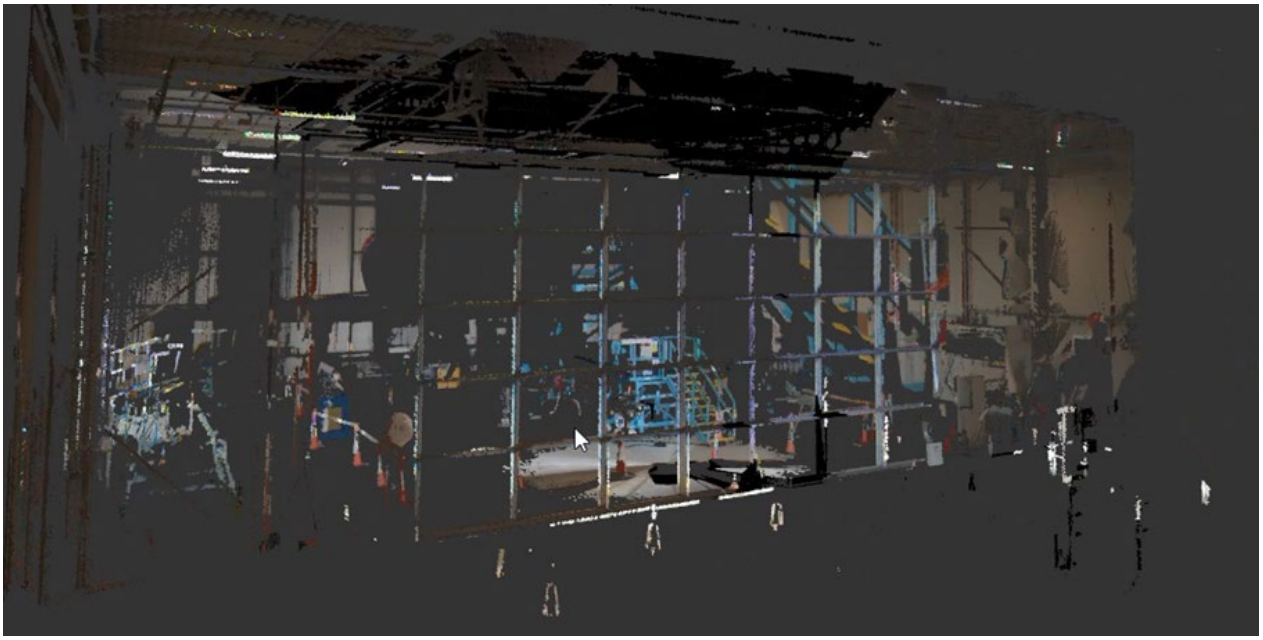

Figure 19 - Mobile Robot use case: Scanner on the Spot scanning the entire hangar along with aircraft

Figure 19 illustrates the inspection of the aircraft along with a view of the entire hangar. The image also captures the safety cones positioned outside the glass hangar door. Based on the conducted experiments, the BLK ARC scanner performs well on matte surfaces; however, it encounters difficulties when scanning shiny, highly reflective surfaces, resulting in noise and data gaps in the point cloud. To optimise this application for inspection it would be ideal to applied on aircrafts with matte surfaces such as Typhoon.

The use case seeks to push the envelope for 5G data transmission and explore remote expert teleoperation over 5G rather than optimise the application for inspection. Data transmission recorded between Spot and the remote expert was up to 120Mbps. Edge processing on the core I/O of the data captured to transmit aircraft data with minimal background data. The remote expert would be able to trigger live or recorded automated zonal inspections of the aircraft producing consistent data and data alignment.

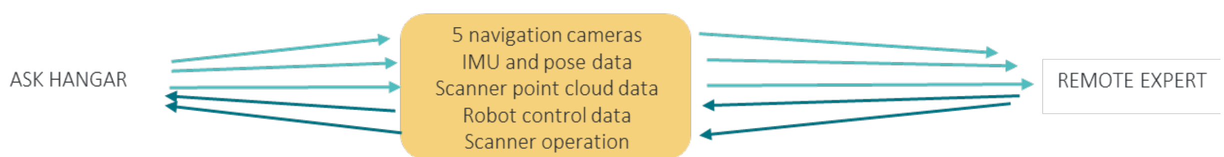

Figure 20 - Mobile Robot use case: Data points between robot (located in BAE ASK) and remote expert (in remote location)

4. Hawk Model

The Hawk aircraft was designed on paper as there was no digital model to use as a baseline model for a digital shadow. The Hawk was scanned using a Metra scan which is a scanner that uses structured light and cameras to scan objects with high accuracy. It performs well on shiny surfaces creating limited noise.

Figure 21 - Mobile Robot use case: Metrascan scanning the aircraft for digital twin

The point cloud data was processed to produce two 3D models as shown in figure 22.

- A detailed model which included more data particularly in the undercarriage bays which are a matte area and therefore the BLK ARC scanner was more likely to capture data.
- A simplified low polygon model.

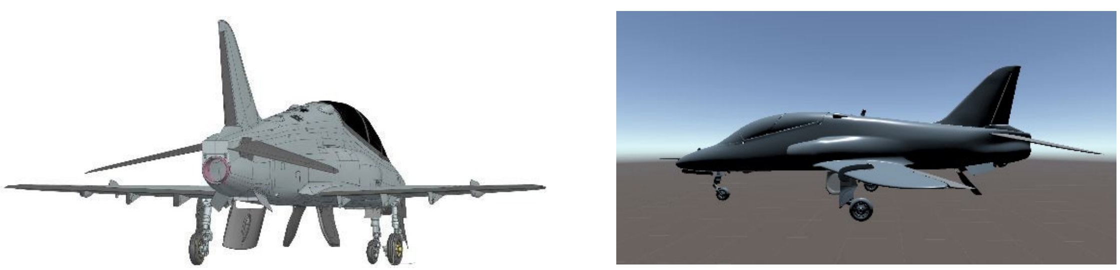

Figure 22 - Mobile Robot use case: polygon model of Hawk aircraft

5. <u>Teleoperator inspection application</u>

The remote expert operates the robot from a laptop using video feed from five navigation cameras on the robot as illustrated in figure 23. Spot is very flexible with a wide range of movements enabling the controller to inspect an area then select to carry out a scan on the area.

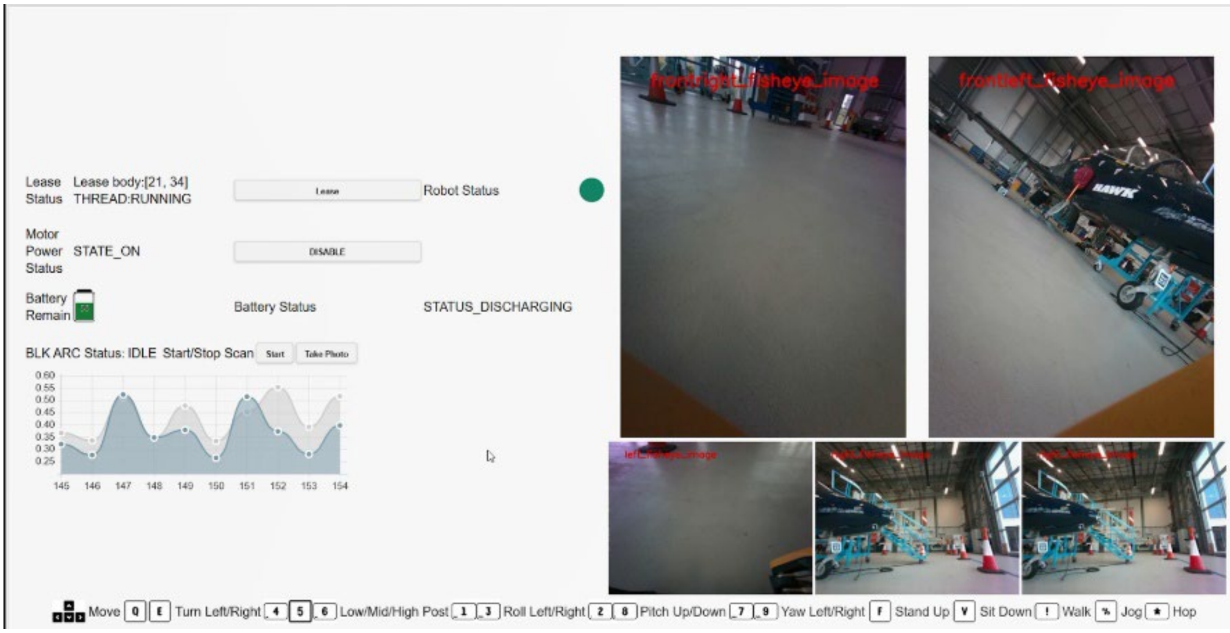

Figure 23 - Mobile Robot use case: Remote expert scanning the aircraft in real time via 5G network

6. Data streaming with multiple robots: To test the system with multiple devices operating an additional robot, an AR/VR application and the 3D Mapping and Digital Shadow application were operated simultaneously with the core application streaming live data. Although total data transmission was not captured there was no noticeable loss in performance or latency.

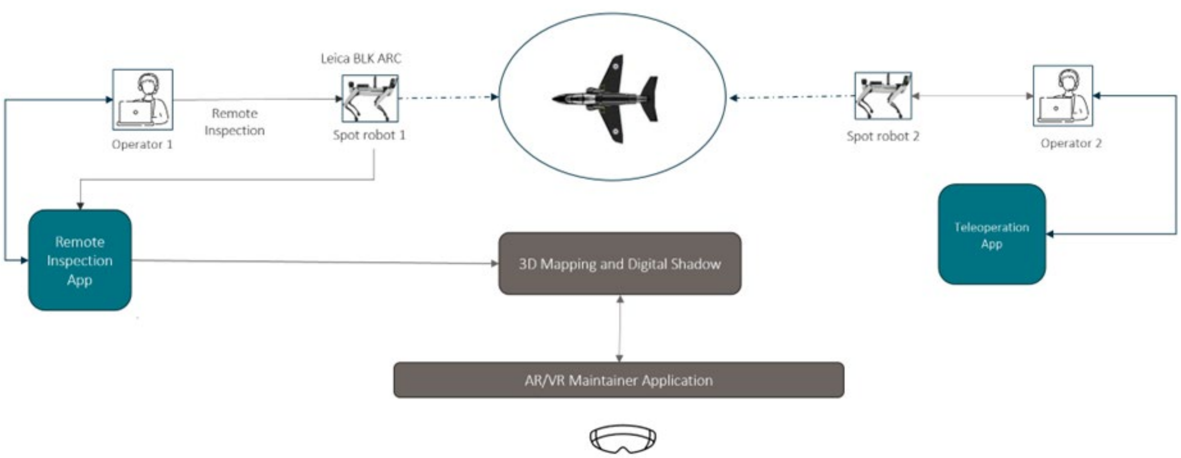

Figure 24 - Mobile Robot use case: Architecture of multiple remote operators scanning the aircraft in real time

7. 3D mapping and digital shadow

Aligning data to location on a digital shadow/digital twin of an aircraft, equipment or hangar is supports the optimisation of knowledge from data, the use of complex analytics and AI. Consistent data alignment and tracking has proved difficult on previous projects and is a theme for future work.

In this case the alignment of data to the Digital Shadow would allow the expert to compare data to previous condition and raise defect record with repair instructions. The alignment would enable a maintainer to be directed to the exact position to carry out expert instructions.

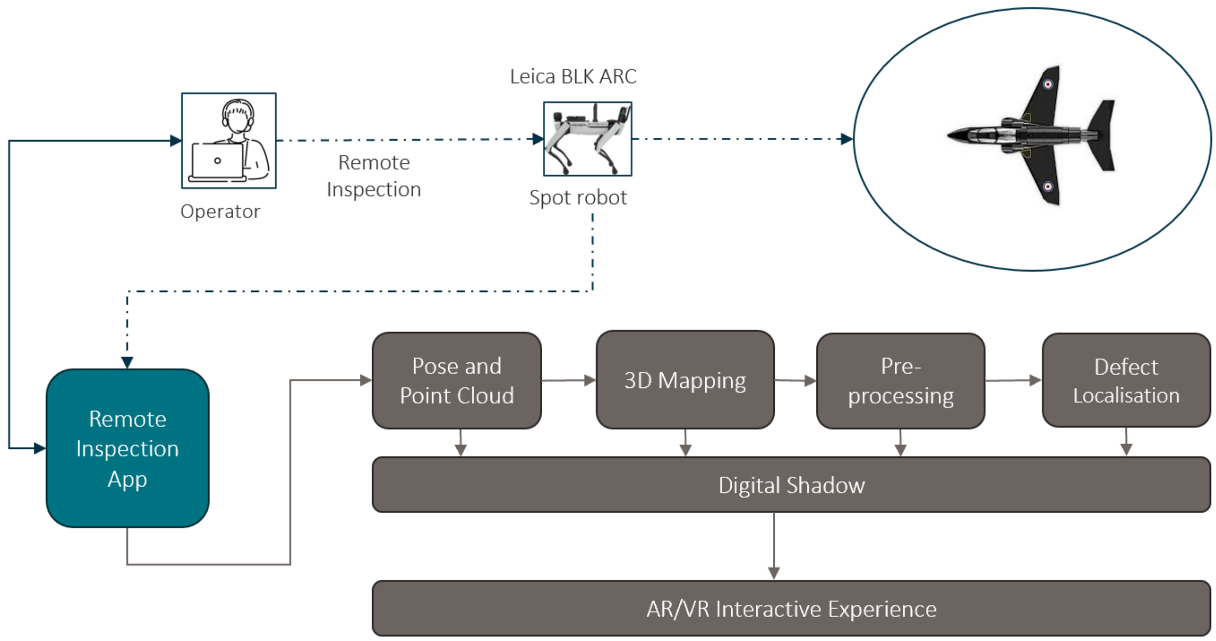

Figure 25 - Mobile Robot use case: Architecture of 3D mapping and digital shadow

The 3D mapping and digital shadow was hosted on a separate laptop to the inspection application increasing the volume of 5G data being streamed (see the figure 25).

A QR code marker on the nose undercarriage detected by Spot set the X, Y and Z coordinates to 0,0,0. As Spot moved around the aircraft, pose information was steamed to the inspection application and then streamed to the mapping and digital shadow application.

The table 2 below is an extract of Spot's pose data with the tag ODOM displaying Spot's odometry and FIDUCIAL_521 point, which calculates the distance Spot is from the QR code at the nose of the aircraft. Rot X,Y,Z and W is the current rotation of Spot at that moment in time.

Table 2 - Mobile Robot use case: Spot pose information

loc-X	loc-Y	loc-Z	rot-X	rot-Y	rot-Z	rot-W	Tag
0.000191	-0.086092	0.892339	0.001044	0.006333	0.000007	0.999979	OD0M
2.373464	0.998657	0.481139	-0.596499	-0.043026	0.798959	-0.063264	fiducial_521
0.000191	-0.086092	0.892339	0.001044	0.006333	0.000007	0.999979	OD0M

Alignment and tracking applications can often suffer from drift particularly as data tolerances accumulate. In this case the drift in the y axis could accumulate up to several meters when moving round the aircraft. It was addressed for this trial by using several QR codes round the aircraft reducing the drift.

During the inspection a live stream of a 3D visualisation of a simplified Hawk model tracked the robot view of the aircraft as shown in figure 26. Scanned data was filtered to capture the selected aircraft inspection area based on the pose position. The aim was to integrate the data in the digital shadow or geo tag it.

Figure 26 - Mobile Robot use case: Hawk 3D visualisation

8. <u>AR (Augmented Reality) Maintainer Application</u>

An XR application was developed for a Magic Leap 2 that was integrated with the digital shadow (see the figure 27). It could operate in 3 ways:

- View the digital shadow in virtual reality.
- A maintainer could view AR markers overlaid on the aircraft enabling inspection/repair of previously recorded damage.
- The maintainer could identify and record the position of damage.

Figure 27 - Mobile Robot use case: AR maintainer application view

6.3.3 Outcomes

The following outcomes highlight the key benefits and insights gained from this use case:

- <u>Cyber Security:</u> The project strengthened BAE Systems' cyber security posture by aligning with the newly established ACDA process, ensuring all systems meet stringent security standards before integration. Successful cyber security clearance was achieved for the private 5G network at the Academy of Skills and Knowledge (ASK), enabling safe operation on an isolated network with unclassified Hawk data, independent from BAE Systems' internal infrastructure.

- <u>5G ORAN integration:</u> Successful teleoperation of the Boston Dynamics Spot robot was achieved over a private 5G network.
- <u>Teleoperation and data transmission:</u> Demonstrated the capability of a 5G-enabled environment to support multiple high-data applications simultaneously, validating the network's reliability and low latency for advanced aerospace use cases.

6.4 UC-4 Real Time Milling (RTM)

6.4.1 Use Case description

The real-time milling use case focuses on implementing a closed-loop control system for milling operations using advanced 5G communication, machine optimisation algorithms, and digital twin technology. The primary objective is to optimise machining parameters dynamically in real-time to improve machining quality, reduce cycle time, reduce chatter, and enhance efficiency.

The setup features a PocketNC V2-10 CNC machine running on a custom LinuxCNC image, with a Beaglebone board acting as the machine controller. Control is achieved through Python-based scripts, integrated with Productive Machines' external library (dll/so file) to enable real-time optimisation. The machine is retrofitted with sensors (microphones and accelerometers) for vibration and frequency monitoring and uses AMRC's Ventus CPE 5G system for low-latency data transfer. Below is the overall architecture diagram of the RTM use case.

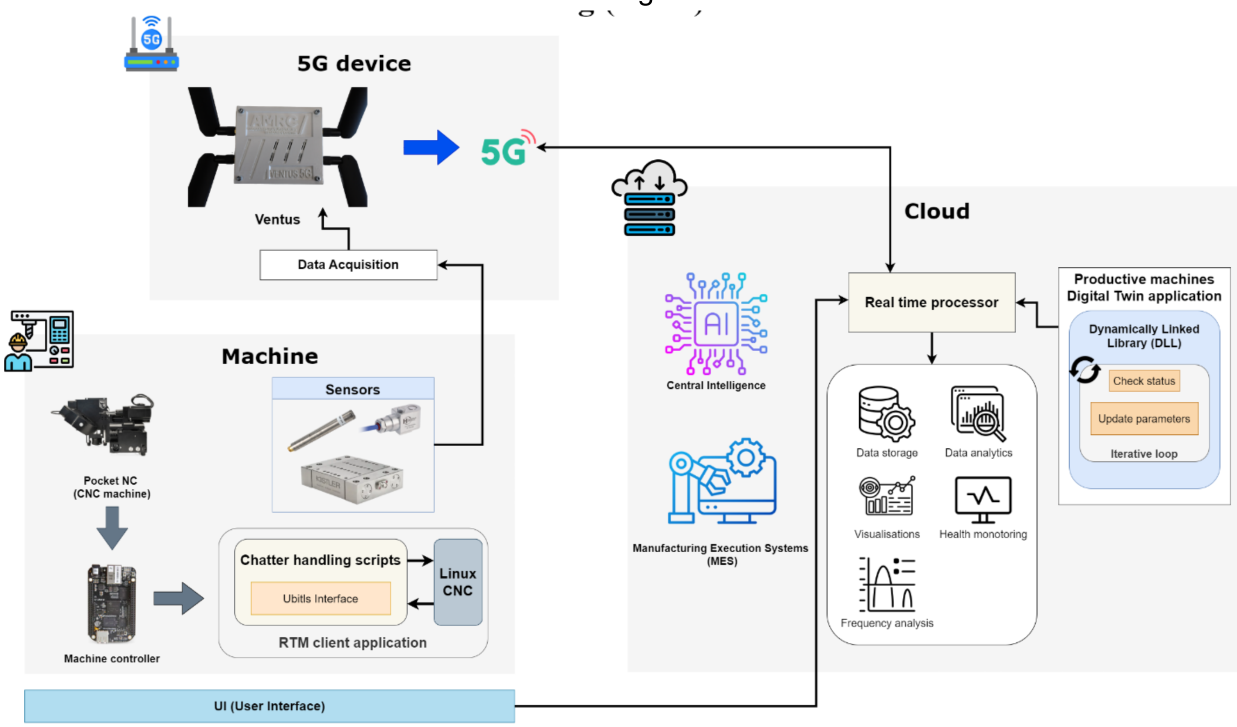

Figure 28 - Real Time Milling use case architecture diagram

The workflow comprises offline and online optimisation stages:

- Offline Optimisation: Digitally replicates the machining setup and generates pre-processed data (e.g., toolpath, material properties) to initialise the process.
- Online Optimisation: Uses real-time data from the sensors and machine to adjust machining parameters dynamically during the milling process.

This use case demonstrates how closed-loop systems can address common manufacturing challenges, such as chatter vibration, by utilising advanced optimisation strategies and advanced communication networks.

6.4.2 Technical achievements

1. System architecture and integration

- Closed-Loop Control implementation: Deployed closed-loop control algorithms on the MEC (Multi-access Edge Computing) platform, integrating Productive Machines' optimiser with AMRC’s in-house RTM application for real-time control. This enabled dynamic overrides of feed rate and spindle speed based on real-time data.
- 5G communication: Utilised AMRC’s 5G and Ventus CPE to ensure low-latency, high-speed data transfer between the PocketNC machine, sensors, and the RTM application.
- Digital Twin integration: Integrated Productive Machines’ digital twin system into the RTM application to predict and optimise machining parameters dynamically.
- Sensor data utilisation: Auxiliary sensors provided real-time data on vibrations and frequencies, enabling accurate detection of chatter during machining.

2. Optimisation Algorithms

- Offline Optimisation: Created a digital replica of the machining setup, including toolpath, stock geometry, cutting tool information, and material properties. This stage generated a JSON file with pre-processed data for runtime use.
- Online Optimisation: Implemented a window-based strategy to predict forces, chip thickness, torque, and vibrations, adjusting feed rates and spindle speeds dynamically during the milling process. The system calculated optimised machining parameters for each segment of the toolpath before execution.

3. Tests and trials

Conducted multiple trials to validate the system:

- RTM application standalone trials: Verified real-time control over feed rate and spindle speed.
- Air Cuts: Tested Gcode execution for safe machine operation.
- Machining trials with sensor integration: Demonstrated a reduced cycle time due to feed rate optimisation in real time. Additionally, large vibrations present at the start of the operation were smoothed out during the process, indicating potential chatter mitigation. Further analysis is required to identify the source and frequency of these vibrations to determine if they are chatter. A tap test to compare system and process frequencies was not possible on the small-scale PocketNC machine.

6.4.3 Outcomes

The outcomes below capture the main benefits and insights for this use case:

1. Improved Machining Operation
   - Achieved cycle time reduction, leading to increased productivity.
   - Observed reduced vibrations during optimised trials, resulting in smoother operations and improved surface finish.

2. Efficient Real-Time parameter control
   - Enabled real-time control of feed rate and spindle speed, supporting dynamic optimisation throughout the milling process.
   - Demonstrated effective synchronisation between machine actions and optimisation outputs, ensuring smooth closed-loop operation.
   - Enhanced overall machining quality and efficiency by mitigating chatter through adaptive adjustments.

3. 5G ORAN integration
   - Utilised 5G connectivity to achieve reliable, low-latency communication between machine, sensors, and the optimisation engine.
   - Supported stable multi-application operation, including data streaming, without performance degradation.

4. Reliance on high-quality pre-processed data
   - Highlighted the importance of accurate offline inputs (G-code, toolpath, material data, tap test results) for effective real-time optimisation.
   - Demonstrated that chatter mitigation required precise frequency input and appropriate machine mounting conditions (bench/floor installation).

5. Scalability Potential
   - Proven effectiveness on a small-scale CNC system (PocketNC).
   - Indicated the need for further validation on industrial-grade machines to confirm broader manufacturing applicability.

6.5 UC-5 IoT Platform and Highly Interoperable Network

6.5.1 Use Case description

This use case demonstrates seamless interoperability between multi-vendor network elements in a hybrid environment. Devices connected to a local RAN can roam onto a commercial mobile network while away from the 'home' BlueWave network, supporting both NSA (AMRC Northwest & Factory 2050) and SA (AMRC Cymru) architectures. Unlike typical private networks, access is restricted to users with a 'home' network SIM, ensuring controlled, secure, and localised connectivity while leveraging the flexibility of an interoperable 5G infrastructure.

6.5.2 Technical achievements

The performance tests conducted focused on both download and upload speeds, latency and coverage. The results are summarised as follows:

- Download Speeds: The network achieved download speeds up to 340 Mbps during testing
- Upload Speeds: Upload speeds up to 69 Mbps.

Following previous investigations into the bandwidth at AMRC NW and AMRC F2050, we discovered devices were only connecting to 4G and no data was passing over 5G. Changes were made to address this and as a result, the bandwidth seen during this test was much improved. The network latency was evaluated to assess the network's responsiveness for real-time applications. The measured latency values were:

- Latency Range: 39 ms to 48 ms (Unloaded).

Notably, this (as shown in figure 29 and 30) is a test using a well-known speed test website. This is measuring the latency to the public internet rather than a test of latency of the mobile connection to a local service (using the MEC/local breakout).

The network coverage was tested by running the above tests in various areas. Tests showed that the bandwidth was much improved over the previous tests at AMRC NW and AMRC F2050 however, latency remained higher than anticipated (taking into account the above statement regarding the latency measurement), The coverage was excellent with no 'not spots' found across the site.

6.5.3 Software Upgrades

For network upgrades - the majority has been at a mobile core level where we have moved the host operating system from CentOS 7 to Rocky Linux 9.4. The CentOS to Rocky Linux 9 upgrade covers many packages / functionality improvements - to highlight the Intel NIC driver changes (resulting in performance improvements) as well as Kernel changes (3.10 to 5.14) cover a wide variety of improvements, fixes, etc.
A brief description of changes includes optimisations to the MGW (Media Gateway) (SGW-U (Serving Gateway – User plane) and PGW-U (Packet Gateway – User plane) planes). The initial version deployed used a single thread to process FTPu data packets. The accelerated MGW uses multiple threads on separate cores to achieve an increase of up to 2-3x the previous bandwidth capacity. We also upgraded our Quortus core to the most recent release of 5006500620240801 (ie - late 2024). The release notes cover a large number of bug fixes - but the changes resulted in a more stable connection between MME / SGW / PGW - with additional functionality in the HSS for the command and control of the packet data sessions.

From an Ericsson RAN perspective, normal improvements to our eNodeB and gNodeB functions were implemented. These covered frame structure performance increases, assessment of radio broadcast levels within the licensing conditions to ensure adequate coverage, and also the upgrade and implementation of local breakout (MEC / SGW+PGW-U) for local handoff keeping GTP sessions local where possible.

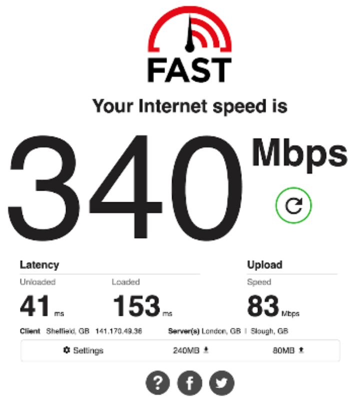

Figure 29 - Fast.com speed test on a laptop connected to the network via a Netgear MR5200 device

Figure 30 - Fast.com speed test on Oppo A54 mobile devices connected to the mobile network demonstrating up to gigabit capable speeds

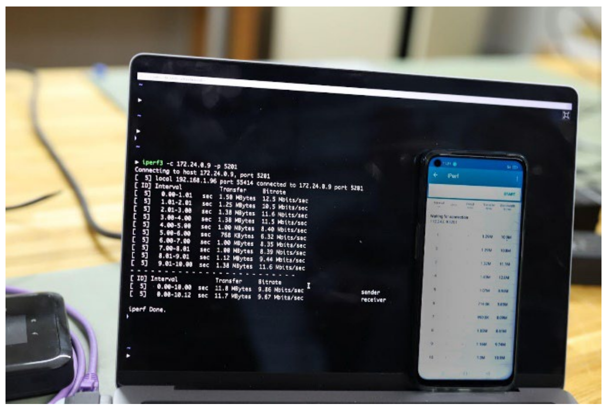

Figure 31 - Demonstrating iPerf (Device to device) test between laptop connected to the network via Netgear MR5200 and a mobile device connected to the network with a SIM

6.5.4 Outcomes

The outcomes below highlight the key outcomes for this use case:

- Improved 5G network performance, achieving download speeds up to 340 Mbps and upload speeds up to 69 Mbps, and latency around 39-48 ms
- Achieved full site coverage, with no connectivity black spots during testing.
- Enhanced data throughput, with multi-threaded MGW processing delivering up to 2–3× increase in bandwidth capacity.
- Upgraded Quortus core software, resulting in more stable and efficient packet data session control.
- Implemented MEC/local breakout, reducing latency and improving support for real-time applications.

7 HDD testing

High Demand and Density (HDD) is a method used to assess network performance under conditions of high user concentration and data traffic, often seen in environments such as stadiums, malls, or urban centres. In manufacturing environment, the tests would include devices like mobiles, PC (Personal Computer), mobile robots, industrial IoT devices and machines (CNC, milling machines, 3D printers etc).

As part of the project, a key activity involved simulating realistic network behaviour within the testbed. To achieve this, all available equipment on the shopfloor was activated simultaneously, creating a high-traffic, data-intensive scenario representative of a fully operational manufacturing facility. This setup allowed the team to test the 5G infrastructure under real-world load conditions, evaluating its ability to handle the demands of a smart factory in terms of connectivity, latency, and performance. Performance of three networks was assessed are as follows:

1. Nokia Digital Automation Cloud (NDAC) [3] (Nokia 5G SA) is deployed as a combined on-premises hardware and cloud management solution to manage private 5G networks. NDAC promises high-performance, end-to-end private wireless networking, low latency, and click-and-deploy applications. AWHQM AirScale Micro Remote Radio Head (RRH), the radio unit used to monitor and control the network. Setting up an NDAC and a private network is considered a reasonably easy process; it includes a DA edge device/core, firewall, a network switch, a radio unit, access points, Base Band Unit (BBU) and necessary cables.

2. A new private 5G network (with Airspan RU and Athonet core) was installed at three sites. A fully ORAN-compliant Airspan 2700 radios specifically for the AMRC site whereas remaining two sites, the network will utilise the all-gNB solution with Airspan 1901 radios. The solution also includes switches, GPS antennas, and firewalls to ensure strong and efficient network operations for all three sites.

3. aql (BlueWave) is a non-standalone Highly interoperable 5G network [4]. They offer public, private, and specialist network services across various sectors. This network offers lower latency and high capacity allow prioritisation of real-time traffic, enabling faster data delivery, increased reliability, and improved outcomes.

7.1 HDD tests and trials

The test environment depicted in figure 32 for stress testing consists of the following components:

- Connection Density: A total of 19 devices were used to stress test the network, including mobile phones, tablets, a robot, and UE/CPE devices. Out of the 19 devices, 6 CPE devices along with the SPOT robot were monitored for network performance metrics, while the remaining devices run the use case operations. The SPOT robot was connected via 5G, and a remote operator controlled it using the 5G network.
- KPI Measurement: Python-based Iperf3 scripts were used to measure the key performance indicators (KPIs) for bandwidth testing. These scripts interacted with network devices (such as routers and switches) to gather data and metrics, enabling detailed

monitoring and analysis of network performance. Iperf3 is used to generate and measure network traffic.

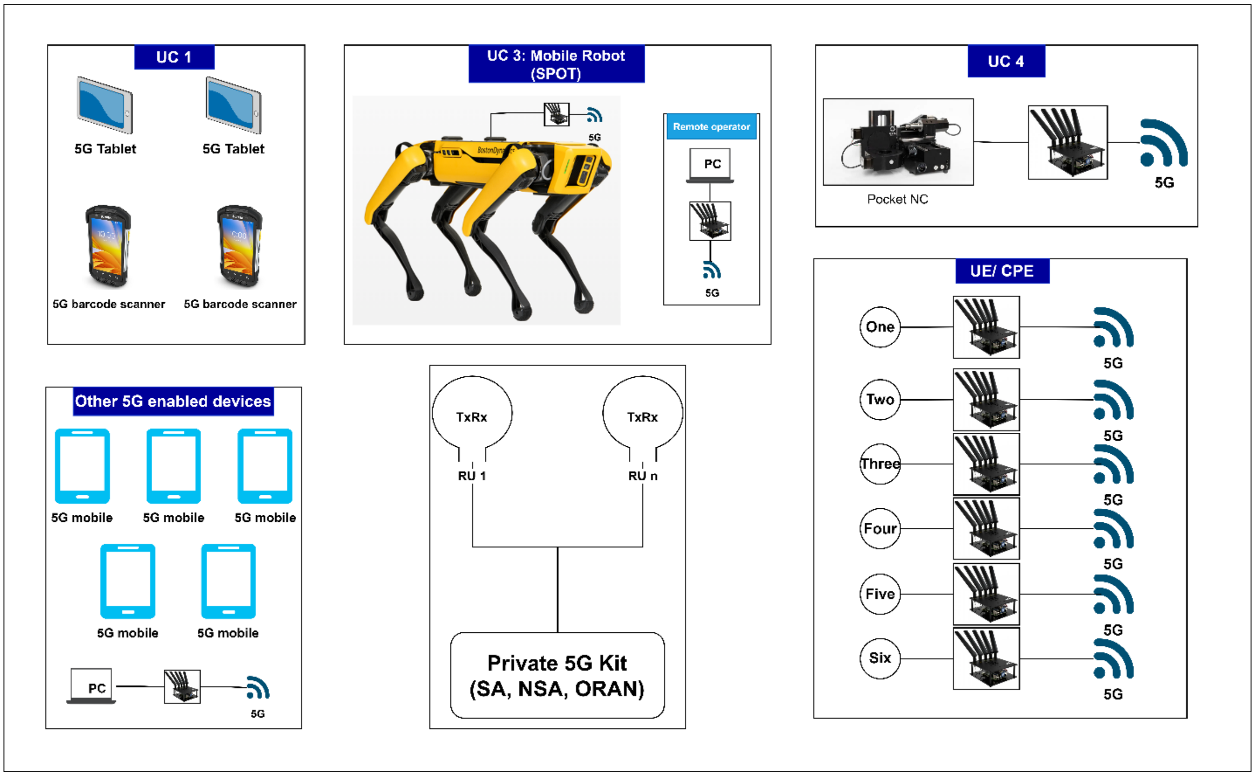

Figure 32 - HDD testing architecture

The detailed results are explained in D58.1. The overall networks performance showcases that Nokia 5G network is suitable for high demand mission-critical applications of transmitting large chunks of data or real time operations while ORAN offers vendor independence, and customisation features that are key for manufacturing industry.

8 Project assessment

8.1 Impact and benefits

The FOFORAN project is among the first globally to explore the application of OpenRAN in manufacturing. Initiated in 2019 by BAE Systems and the Advanced Manufacturing Research Centre, the project aimed to develop connectivity solutions for future factories. The initial "5G Factory of the Future" project, funded through testbeds and trials, demonstrated that 5G could serve as the primary connectivity infrastructure for advanced manufacturing, aligning with the UK's Tempest program - a 6th-generation combat aircraft initiative set to join the RAF fleet by 2035, supporting the Global Combat Air Programme.

Building on 5GFoF's insights, which used off-the-shelf technology, FOFORAN focused on overcoming key barriers to manufacturing adoption. This leads to key benefits and impact as listed below:

Consumer-Oriented RAN: Existing RAN hardware is designed for consumer use and lacks the required SLAs for manufacturing, such as guaranteed latency and high network capacity. This project demonstrated modular RAN configurations could meet diverse needs, including mobile robots, closed-loop process control, and machine vision.

Lack of Native 5G User Equipment (UE): Industrial devices typically daisy-chained to 5G via Ethernet or Wi-Fi, increasing latency and complicating endpoint management. FOFORAN developed native 5G devices, enabling direct, high reliability 5G access for machines and robots.

High Infrastructure Costs: Deploying 5G infrastructure is expensive, mainly due to vendor monopoly and integration costs. FOFORAN's open-source, configurable RAN and UE solutions significantly reduced private 5G costs - as low as £50,000 for indoor factory femtocells. This makes private 5G more accessible to SMEs in manufacturing.

High Density Deployments: Factories pack many devices in a small space, but feasibility data was lacking. Large-scale tests were conducted, proving its viability in a real manufacturing setting.

Through these innovations, this project has paved the way for the integration of ORAN technology in manufacturing, addressing critical challenges and promoting the adoption of advanced, cost-effective 5G solutions in the industry.

8.2 Learning from the project

All partners have provided some form of lessons learned also incorporated into the Benefit Realisation document. These key takeaways include:

- Focused on adoption of 5G and benefits of adoption ORAN network for manufacturing.
- Transfer of knowledge to support manufacturing partners to deploy 5G ORAN in manufacturing facilities.
- Governance frameworks within blockchain ecosystems help streamline collaboration, decision-making, and compliance across stakeholders.
- Integration of blockchain with 5G for data trust and traceability for supply chain use case (UC-2).
- Strong collaboration across partners and planning ensured smooth deployment and integration of complex systems.
- All partners gained valuable collective knowledge through collaborative development efforts.
- The project enabled accelerated joint development, leading to rapid scaling of both resources and outcomes.

- An iterative 'test and trial' approach was key to validating concepts, refining solutions, and driving continuous improvement.

8.3 Challenges and limitations

Here are the list of challenges and limitations based on the use cases:

- Tap Test and Frequency Analysis (UC-4): Tap tests to identify natural frequencies and spectrogram/FFT analysis to correlate them with chatter vibrations were not conducted. This was due to the small-scale PocketNC machine used in this use case.
- Scalability Challenges (UC-4): The system was tested on the PocketNC machine, which is a small-scale CNC machine. Scaling up to larger industrial machines was not explored.
- Legal agreements (UC-5): For deployment of aql Highly Interoperable Network several legal agreement challenges were faced as this building is owned by Welsh Ministry.
- Fiber Installation (UC-3): Installation of fibre between AMRC and BAE ASK site was not possible as there were no existing fibre circuits available in the BAE ASK site. This was mitigated using public backhaul link.

8.4 Similar outputs and benefits

To achieve similar results, a combination of technical infrastructure, industry collaboration, and use case driven development is essential. First, access to the testbed with various types of 5G solutions is required, including software-defined RAN components, radio units, and centralised control systems. It is also important to have manufacturing facilities such as testbeds in factory environments and the ability to build use cases to meet the unique industry requirements. Network configuration tools, performance monitoring systems, and spectrum management capabilities are also necessary for reliable operation and testing.

In addition, strong partnerships between industry, research organisations, and technology providers are key to tailoring the technology to real manufacturing needs. This includes expertise in industrial automation, robotics, network engineering, and data analytics. The ability to integrate advanced technologies like blockchain for secure data sharing and AI for performance optimisation also plays a critical role. Finally, careful planning and documentation are needed to guide implementation, capture lessons learned, and support knowledge sharing.

This project provides a practical model for how industry can adopt 5G and other advance technologies. By working closely with manufacturing partners and technology providers, the project demonstrated how open and flexible 5G networks can support use cases like robotic inspection, remote machine control, and supply chain data tracking. Industries can learn from FOFORAN's experiences to assess where 5G adds value, understand technical requirements, and avoid common deployment challenges.

8.5 Policy, Regulation, or Programmes suggestions

Based on the lessons learned from the project, the following suggestions are proposed to help shape policies, regulations, and programmes that support the wider adoption of 5G ORAN in manufacturing environments:

- Streamline the spectrum licensing process via portal for private networks.
- Support industry led testbeds and pilot programmes through government funding to lower the cost and risk of early adoption.
- Encourage collaboration between telecom providers, technology developers, and manufacturers to bridge knowledge gaps and share best practices.
- Promote standardisation efforts to improve interoperability across ORAN components and reduce vendor lock-in risks.
- Ensure that security and compliance requirements for private 5G networks are clear, practical, and aligned with industrial needs.
- Introduce or expand national programmes focused on digital transformation in manufacturing, with 5G as a key enabler.
- Support workforce training programs to upskill operators in advanced manufacturing technologies such as 5G and AI.
- Promote the adoption of 5G technology in manufacturing through subsidies and grants, enabling faster and more reliable data communication for advanced manufacturing systems.
- Promote open-source or low cost 5G solutions for manufacturing systems to reduce costs and improve accessibility.
- Use insights from projects like FoFoRAN to guide policy development and demonstrate the practical value of 5G in real factory environments.

9 Project security

Safenetics was lead on managing the consortium security aspects. Multiple workshops were conducted by Safenetics with each partner. This allows them to identify the risk and mitigate the risk on network infrastructure deployed and use cases developed during the project. The final security report D63.1 presents a comprehensive overview of the cybersecurity activities, assessments, and outcomes achieved throughout the project lifecycle.

The project adopted a multi-layered approach to security, focusing on identifying threats, evaluating vulnerabilities, and enforcing mitigations within the FoF (Factories of the Future) ecosystem. A significant outcome was the successful integration of Security Assurance Levels (SALs) into the system design, enabling risk-based tailoring of security controls. The application of methodologies such as threat modelling, security testing, and penetration assessments validated the resilience of the deployed 5G-enabled architecture. These actions collectively ensured the implementation of security by design principles across key components of the system.

Close collaboration across the consortium ensured that security requirements were aligned with the needs of advanced manufacturing use cases. The project successfully demonstrated secure integration of technologies such as edge computing, robotics, and augmented reality (AR), while maintaining key principles of data confidentiality, integrity, and availability. Continuous review and improvement of security measures helped strengthen the overall system. Overall, the project has created a strong foundation for deploying secure and scalable 5G solutions in industrial settings.

10 Conclusion

The FOFORAN project has successfully demonstrated the potential of ORAN 5G networks in transforming manufacturing environments. Through close collaboration between technology providers, manufacturers, and research institutions, the project delivered a flexible and secure connectivity platform designed to meet the needs of modern industrial applications. Key use cases including remote robotic inspection, real-time CNC optimisation, and blockchain-based supply chain data sharing. These use cases showcased how high performance 5G infrastructure can unlock efficiency, agility, and transparency on the factory floor.

In addition to technical achievements, a structured security framework was developed and applied across all activities, ensuring that risks were identified, managed, and mitigated throughout. The integration of Zero Trust principles, continuous monitoring, and use of industry best practices has resulted in a robust and future-ready platform. The outcomes of FOFORAN provide a practical reference for others looking to adopt 5G in manufacturing, offering insights into deployment challenges, performance benchmarks, and security considerations. As Industry 4.0 evolves, the work done in FOFORAN lays the groundwork for scalable, secure, and interoperable network solutions across the UK manufacturing sector.