

University of Wales Trinity Saint David School of Engineering



Undertaking a Green Belt Project Six Sigma Green Belt ACMA 5005

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02/2026

(Word Count 4118)

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1 Introduction

This report details a green belt project using the DMAIC methodology on an observed customer complaint of a high-frequency noise coming from the hydraulic cooling fans. General Dynamics Land Systems UK (GDLS-UK) is the prime contractor for the AJAX family of Armoured Fighting Vehicle (AFV) and with a contract of delivering 589 vehicles across six variants to the British Army (General Dynamics UK, 2026). GDLS-UK is responsible for the manufacture, validation and the delivery of the platforms as shown in *Figure 1*. This project was initiated because, since 28 June 2024, a high number of recurring issues involving high-pitch noise from the cooling fans have been raised by the customer at the acceptance inspection point. Although the noise did not appear to compromise the functional cooling performance it did trigger a repeated defect report and concern to the customer that the noise could potentially be an indicator of a potential mechanical failure that may affect the reliability of the vehicle in the future. The benefit of this project is to reduce the number of fan noise related snags, decrease parts replacement, labour cost and vehicle acceptance delays. By increasing the consistency of fans performance, the project will also increase the British Army's confidence in the product.



Figure 1 - GDLS-UK AJAX Vehicles (The Telegraph, 2015)

2 Define

2.1 Problem Statement

Between 28 June 2024 and 2 March 2026, 72 defect reports related to high-frequency noise from cooling fans were recorded in the Data Reporting and Corrective Action System (DRACAS) across five vehicle variants, as shown in Appendix 1. The issue consistently occurred within the operating range of 110-1450 rpm (18-24 rev/s). Although cooling performance remained within specification, the noise was interpreted as a potential mechanical fault, triggering unnecessary component replacement *Figure 2* and rework. This resulted in increased labour costs, inconsistent fault diagnosis, and delays at the vehicle acceptance stage.

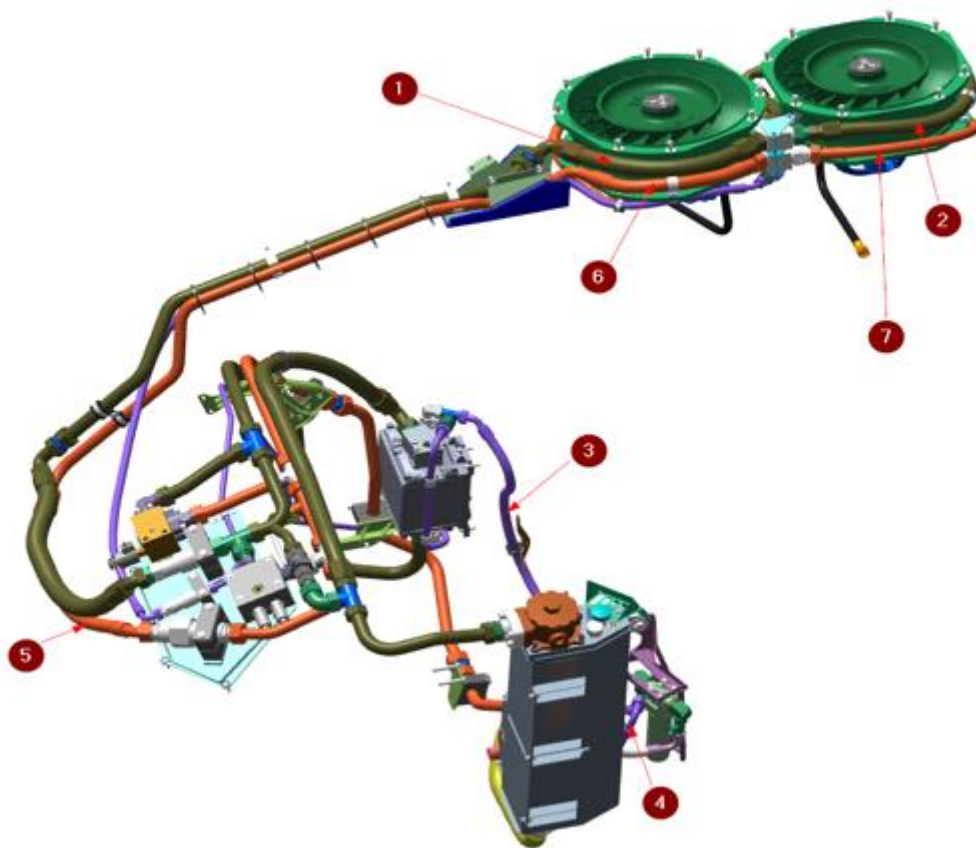


Figure 2 - Cooling Fans and Hydraulic System (GDLS-UK)

2.2 Process Mapping

A SIPOC mapping process of the cooling fans *Figure 3* was developed to define the boundaries of the cooling fan process, from supplier inputs through to final customer acceptance.

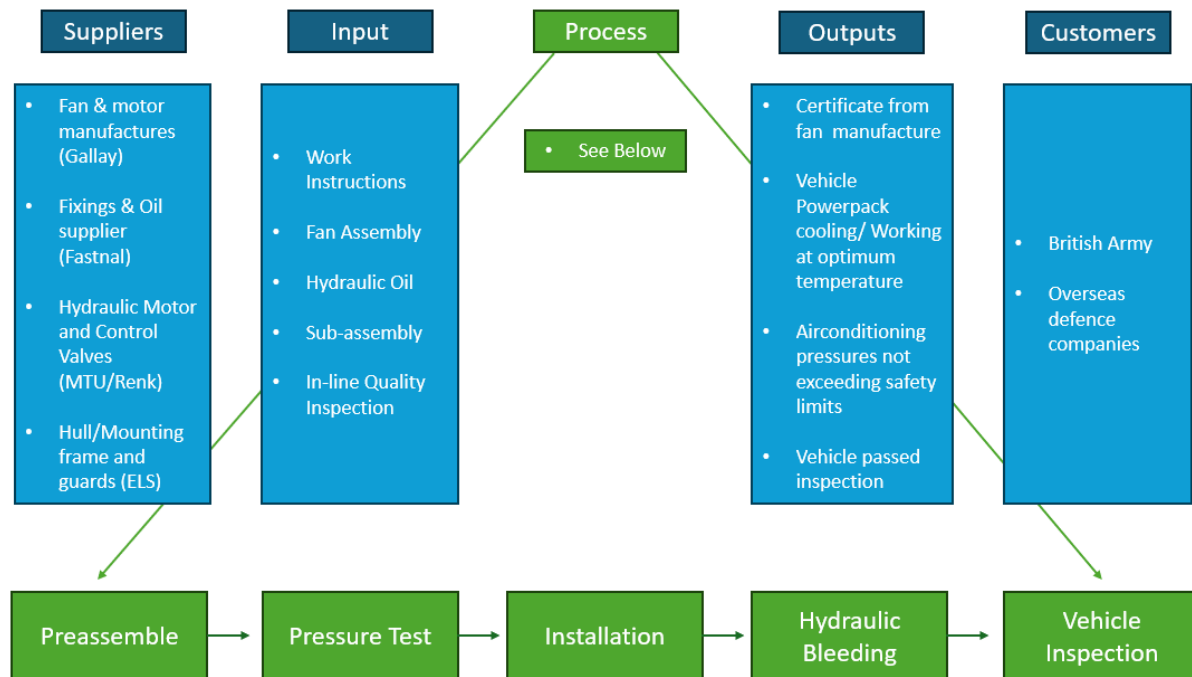
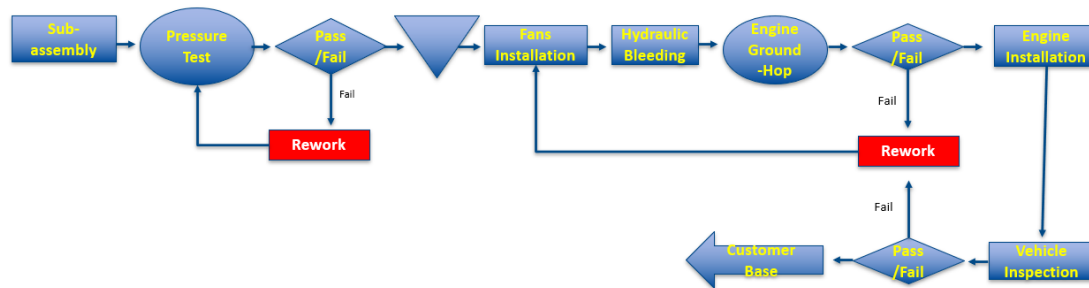


Figure 3 - SIPOC Diagram of Cooling Fans Process (Niemann et al, 2024).

A detailed process flowchart *Figure 4* below was then constructed to represent the actual production sequence including the rework loop “hidden factory”. This highlights inefficiencies within the system, where defects identified at the vehicle inspection stage results in additional labour, material usage and extended lead times, Apte et al, (2025).

Process Map

A graphical view of a process



GENERAL DYNAMICS
Land Systems–United Kingdom

PRIVATE INFORMATION

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Figure 4 - Process Flowchart (GDLS UK, 2026)

2.3 Voice of the Customer (VOC) & Critical to Quality (CTQ)

By carrying out questionnaires to the British Army's product inspectors, users and maintenance team, and while reviewing the internal and external fault reporting database, Data Reporting and Corrective Action System (DRACAS). This has given us a table of customer requirements (VOC) regarding the cooling fans and with the aid of Engineering and Health & Safety stakeholders of all parties (British Army, General Dynamics and Defence Equipment & Support (DE&S)) a Critical to Quality targets are aligned against the customer needs. This data is shown in *Table 1* below helping understand the customers' needs and improve the product to the required standard requested as explained by Freeman and Radziwill, (2018).

Table 1 - VOC & CTQ table

Voice of the Customer	Critical to Quality
Fan noise as quiet as possible	No up-contract requirements
- No high pitch noise - Consistency in fan tone across all platforms	Noise Frequency must be below 2,000Hz
No hydraulic oil leak	Zero tolerance for oil leaks
Reliability	2yrs maintenance free

2.4 Project Scope

Aim of the project scope *Table 2*, is to provide a clear boundary of what aspects of the cooling system and the vehicle can and can't be modified if required to achieve the end goal. As reported by Pyzdek and Keller (2024), these boundaries are driven by timescale, labour power, expertise, product safety, functionality and cost. Table 2 below shows the “In Scope” the items that can be altered and the “Out Scope” the components that can't be modified.

Table 2 - Project Scope

In Scope	Out of Scope
Oil	Powerpack
Fan Speed	Cooling Performance
Fan Guards	Hull
Bleeding Process	Fan Quantity
Assembly Process	

2.5 Project Charter

The Project Charter, as illustrated by Pyzdek and Keller, 2024, is a summary of the official plan and authorisation for the project. *Figure 5* as shown below is a contract between the project team and its sponsor, if any changes in goals, scope or other factors arise an approval from the team and sponsor would be required.

COOLING FAN NOISE ISSUES - PROJECT CHARTER

1 THE BUSINESS CASE – Why are we doing this?				4 THE TEAM																			
The high-pitch noise generated by the hydraulic-drive cooling fans between 1100rpm and 1450rpm has led to 72 recorded customer rejections since June 2024. Although the noise does not correlate with the measurable loss of cooling performance, it is frequently misinterpreted as a mechanical defect during acceptance inspections. This has resulted in repeated re-bleeding, rework, cooling fan replacement and unnecessary troubleshooting steps, creating avoidable cost, schedule disruption and reduced confidence in vehicle quality. 2 PROBLEM STATEMENT – This is what is happening and it is bad because? Between 28 June 2024 and 2 March 2026, 72 defect reports related to high-frequency noise from cooling fans were recorded in the Data Reporting and Corrective Action System (DRACAS) across five vehicle variants. The issue consistently occurred within the operating range of 110-1450 rpm (18-24 rev/s). Although cooling performance remained within specification, the noise was interpreted as a potential mechanical fault, triggering unnecessary component replacement and rework. This resulted in increased labour costs, inconsistent fault diagnosis, and delays at the vehicle acceptance stage. 3 GOALS – What does success look like? 1. Achieve reduction from the baseline average of 10 reported per month to two or fewer per quarter. 2. Elimination of unnecessary rework activities. 3. Improved customer confidence. 4. Validated root cause and an implemented action that fully resolves the issue.				<table><tr><td>SPONSOR</td><td colspan="3">Nathan Jones (Head of Quality), Jon Richards (Head of Production)</td></tr><tr><td>IMPROVEMENT TEAM</td><td colspan="3">Mauri (ELS), Kevin King (Operation), Scott Summerhall (ME), Shane Lewis (Quality), DE&S, British Army</td></tr><tr><td>CHAMPION</td><td colspan="3">James Humphries (Head of Engineering)</td></tr><tr><td>FACILITATOR</td><td colspan="3">Gedlin Davies (Product Support Engineer)</td></tr></table>				SPONSOR	Nathan Jones (Head of Quality), Jon Richards (Head of Production)			IMPROVEMENT TEAM	Mauri (ELS), Kevin King (Operation), Scott Summerhall (ME), Shane Lewis (Quality), DE&S, British Army			CHAMPION	James Humphries (Head of Engineering)			FACILITATOR	Gedlin Davies (Product Support Engineer)		
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5 TIMELINE																							
<table><tr><td>PROJECT KICK OFF</td><td>10/11/25</td></tr><tr><td>SIPoC WORKSHOP</td><td>25/11/25</td></tr><tr><td>AS-IS WORKSHOP</td><td>11/12/25</td></tr><tr><td>LEAN INNOVATION EVENT</td><td>17/12/25</td></tr><tr><td>INNOVATE COMPLETE</td><td>27/03/26</td></tr></table>				PROJECT KICK OFF	10/11/25	SIPoC WORKSHOP	25/11/25	AS-IS WORKSHOP	11/12/25	LEAN INNOVATION EVENT	17/12/25	INNOVATE COMPLETE	27/03/26										
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LEAN INNOVATION EVENT	17/12/25																						
INNOVATE COMPLETE	27/03/26																						
6 SCOPE																							
WHAT'S IN?		WHAT'S OUT?																					
• Oil • Fan Speed • Fan Guards • Bleeding Process • Assembly Process		• Powerpack • Cooling Performance • Hull • Fan Quantity																					
METRIC	OPERATIONAL DEFINITION	BASELINE DATE	COMPLETION DATE	BASELINE (IF KNOWN)	TARGET	IDEAL																	
Total 'High Pitch Fan Noise' reported on DRACAS	Vehicle reported by the customer, with high pitched fan noise equal or above 2000Hz	28/06/24	02/03/26	72 (avg. 10 per month)	2 Per Quarter	0																	

Figure 5 - Cooling Fans Project Charter (GDLS-UK, 2026)

3 Measure

3.1 Identify Measurement Variation and Data Type

A thorough measurement of the existing process is essential to find the true failure of the process or component as stated by Taghizadegan (2006), using the SIPOC as aid we can ensure that not only the process is considered but the measurements of all areas where variation may be identified is included. Below is a list of measurable variants and categorised against its relevant data type, variable or attribute. Variable is quantitative data that can be measured in decimals and units providing a more precise, whereas attribute as International Six Sigma Institute (2026), then explains is the attribute le data is accountable, whether it is a pass or fail or even just number of failed components.

Component Variation

- Fan Dimension [[Variable](#)]
- Oil Quality [[Attribute](#)]
- Hydraulic Motor & Control Valve Pressure [[Variable](#)]
- Hull/Mounting Frame Dimension [[Variable](#)]

Process Variation

- Work Instruction accuracy with respect to engineering documents (Sub Assembly) [[Attribute](#)]
- Work Instruction accuracy with respect to engineering documents (Fan unit installation to Vehicle) [[Attribute](#)]
- Sub Assembly Pressure Test Results [[Attribute](#)]
- Ground-Hop Test Results [[Attribute](#)]

Operator Variation

- Assembly accuracy to the work instruction (Sub Assembly and Vehicle Installation) [[Attribute](#)]

Vehicle Performance Variation

- Noise Frequency [Variable]
- Hydraulic Oil Temperature [Variable]
- Fan Speeds [Variable]
- Vehicle Dynamics/Loads [Variable]
- Pulse Width Modulation (PWM) Cycle Demand on Fans [Variable]
- Coolant Temperature [Variable]
- ECS function ON or OFF [Attribute]

Environmental Variation

- Deck Open or Closed [Attribute]
- Vehicle Indoor or Outdoor [Attribute]

3.2 Develop Data Collection Plan

A structured data collection plan was developed to ensure consistency and minimise operator bias. The plan defined measurements variables, data type, collection methods and responsible personnel, as summarised in *Table 4*. Relative audit sheets are stored in Appendix 2 in Appendices. Due to the high numbers of potential variables identified, a prioritisation exercise *Table 3* was conducted to eliminate low-impact measures, reducing unnecessary data collection effort while maintain focus on the critical factors influencing the defect.

Table 3 - Justification of Removal of Variation

Measurement Variation	Justification Of Removal
Oil Quality	Oil used from same tank used across all vehicles
Hull/Mountain Frame Dimensions	Shims for frame tolerance defects are in the Work Instruction and have been used on most platforms
Ground Hop and Sub Assembly Pressure Test Results	No physical DATA documented when item fails at this process point. (No DATA present)

Table 4 - Variation & DATA Collection Method

Task	Owner	How	Location
Fan Dimension	Quality	Manufacture Drawings and Audit Sheet MAN-T1075 Fan 1	Material Review Board (MRB) and Acceptance Inspection Area
Hydraulic Motor and Control Valves Pressure	Engineering	Using digital pressure gauges on pressure test points and Audit Sheet ASPR1	Acceptance Inspection Area
Work Instructions Accurate against Engineering Documents	Engineering & Manufacturing Engineers	Validate documents against each other. Record findings on Audit Sheet ASWIVED	Online/Teams
Assembly Accuracy against the Work Instruction	Manufacturing Engineering, Operator & Quality	Validate against Work Instruction after the task above has been carried out and is correct. Record result on Audit Sheet MAN-T1075 CF-FITMENT	Sub Assembly and Production Line
Noise Frequency level and audio recording against Fan Speed	Engineering	Record the fan RPM and fans frequency. Noted with CANalyzer Document	Acceptance Inspection Area
Confirm if high frequency is present when vehicle is in these states. ECS ON/OFF Deck Open/Close Indoor/Outdoor	Operator/Inspector	Record findings in Audit Sheet MAN-T1075 AUDIO2	Acceptance Inspection Area
Collect data regarding temperatures, fan speeds, PWM, Vehicle Load	Engineering	Carry out CAN Bus recording and analyse via CANalyzer	Acceptance Inspection Area

3.3 Measurement System Analysis

To ensure that the collected data is a true representation, three types of measurement system analysis, operational definitions, walking the process and gage R&R. These methods are to ensure as confirmed by Keller (2011) is to ensure that measurement error is minimised by ensuring suitable equipment, clear measure points and operator competence. Operational Definition were established using standardised audit forms to ensure consistent data interpretation. Process walkthroughs were carried out with data collectors to verify correct measurement procedures. Gage R&R was applied to assess repeatability and reproduce ability, with measurements taken multiple times by different operators under varying environment conditions.

3.4 Data Collection and Assess Process performance

3.4.1 Process Performance

Process performance was evaluated using Defects Per Million Opportunities (DPMO). Based on 72 recorded defects across 108 vehicles, with the opportunities per unit is taken as one, as the cooling fans are received in pairs. The DPMO was calculated as:

$$DPMO = \left(\frac{\text{Total Defects}}{(\text{Total Units} \times \text{Opportunities per Unit})} \right) \times 1,000,000$$

$$DPMO = \left(\frac{72}{(108 \times 1)} \right) \times 1,000,000$$

$$DPMO = 666,667 \text{ DPMO.}$$

This corresponds to an approximate sigma level of 1 ($\sigma 1$), indicating a highly unstable process with significant variation and poor capability as stated by Setijono (2010). The result highlights the scale of the issue and justifies the need for a structured root cause analysis to improve consistency and reduce defect occurrence.

3.4.2 Data Collection

The data collected is in Appendix A and documented on the audit sheets that correspond to the data collection method in *Table 4*. The audit sheet for fan dimensions MAN -T1075 Fan 1 show that out of eighteen sets of fans inspected, fourteen were out of the fan dimension tolerance and with one also incorrectly shimmed. The four that were within tolerance, two were found to be incorrectly shimmed as well.

The hydraulic pressure checks found no irregular behaviours across the variants and operated as per the engineering design. The pressures started at 10 bar then reached a peak of 273 bar after three seconds and settled on 20 bar without overloading the return line that ran at a constant 4 bar pressure. There were no irregularity or errors found in the work instruction regarding its accuracy to the engineering drawings.

Audit sheet MAN-T1075 CF-FITMENT shows out of the nineteen vehicles inspected, four vehicles were found to have had the cooling fans fitted incorrectly by not correctly shimming the fan to ensure that there was no clash with the shroud, this in return would leave score marks on the shroud and fans. The high frequency noise was still present even when all the variable elements, Environmental Control System (ECS) status, deck position or vehicle location were altered.

The frequency recording in conjunction with the CAN data recorded and analysed with the CAN Simulation and analysis software found no abnormal disturbances or behaviour and confirmed that the range of fan speeds would create the high pitch frequency which was between 1100 rpm and 1450 rpm. This data has been sent to the cooling fans manufacturer.

4 Analyse

The purpose of the analyse section as stated by Pyzdek and Keller (2018), is to carry out a detailed examinations of the value stream to identify methods to eliminate the gap of the current performance and the desired performance

4.1 Process Analysis Methods

The process map can be analysed indicted by Rahani and Al-Ashraf (2012), with highlighting the value-added steps, the work and idle time across all steps of the assembly process. The Value Stream Mapping in *Figure 6* below helps locate the largest sources of down time and rework, providing us with a visual guidance that finding defect at the Vehicle inspection stage is the least efficient place adding an additional three days and seven hours to the build time. This also indicates that the test after subassembly and the ground-hop is inadequate to detect the failure. *Figure 6* also shows that there are only four added-value steps in the process as these are shown with the drop-shadow boxes. *Table 5* also confirms this, providing areas to review on improving efficiency by analysing the non-value-added steps as the Process Analysis Work Sheet in *Table 5* shows that out of the process cycle time of 226.75hrs, with no reworks required only 4.10% of it is value added.

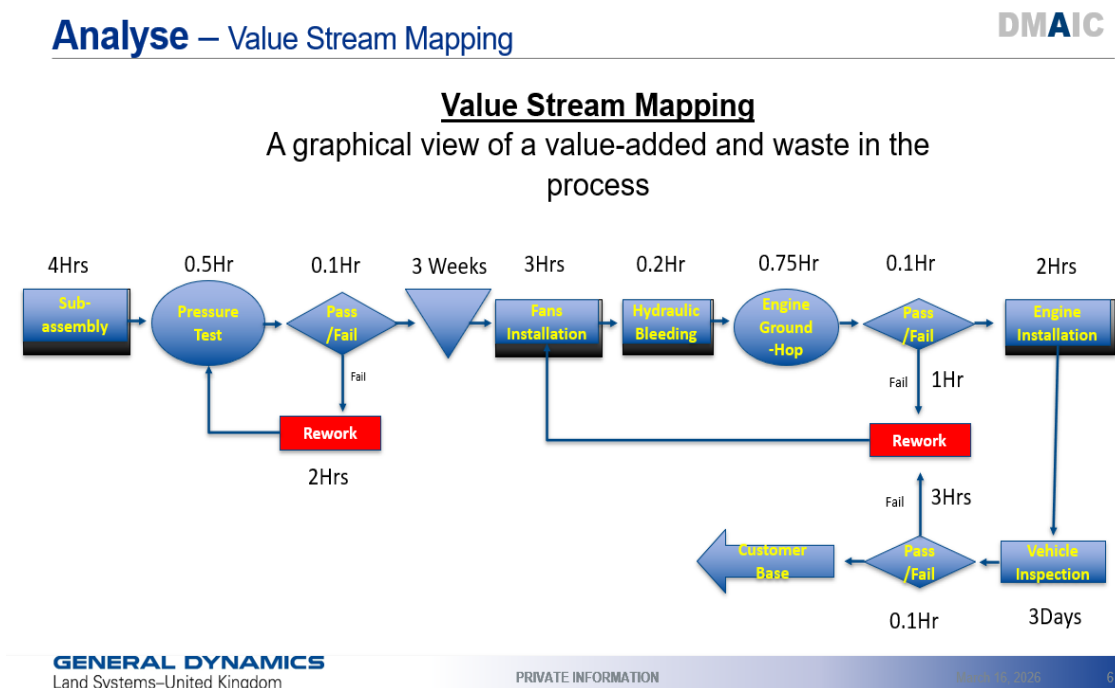


Figure 6 - Value Stream Mapping (GDLS-UK, 2026)

Table 5 - Process Analysis Work Sheet (GDLS-UK, 2026)

Process Task	Sub-Assembly	Pressure Test	Pass/Fail	Storage	Fans Installation	Hydraulic Bleeding	Engine Ground-Hop	Pass/Fail	Engine Installation	Vehicle Inspection	Pass/Fail	Total	% Total
Value Added												4	36%
Non-Value Added												7	64%
Value Added Time (Hrs)	4				3	0.2			2			9.2	4.10%
Process Time (Hrs)	4	0.5	0.1	180	3	0.2	0.75	0.1	2	36	0.1	226.75	100%

4.2 Review Analysis Methods

A range of graphical analysis tools were selected to investigate process performance and identify sources of variation. A Pareto chart was used to prioritise the primary causes of defects, specifically comparing dimensional non-conformance and incorrect installation. A run chart was applied to assess trends in noise-related complaints over time. A scatter plot was used to evaluate the relationship between fan speed and noise frequency, identifying the critical operating range associated with the defect. A histogram was used to compare failure disturbances across vehicle variants.

4.3 Graphical Analysis Tools

Pareto Chart of Defect Cause

Figure 5 (below) contains the data from the fan dimension audit sheet (MAN-T10075 Fan 1) and (MAN-T1075 CF-Fitment) the assembly accuracy against the work instruction where fitment tolerances was incorrect due to incorrect shimming applied. Figure 7 shows that 67% of the total vehicles inspected with high frequency noise had fans that were outside of the design dimensions and that 33% were found to have been installed incorrectly.

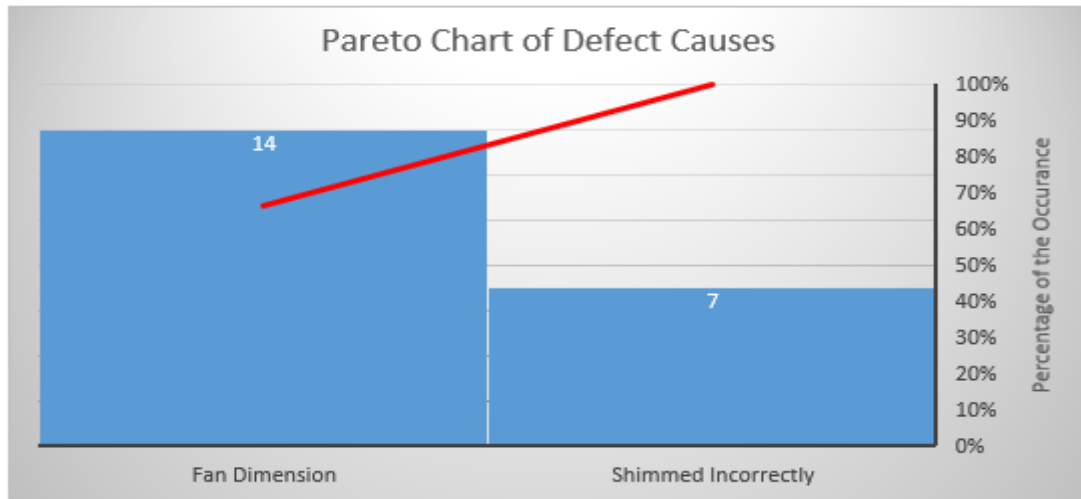


Figure 7 - Pareto Chart of Defects Cause

Run Chart Data of Complaints Against Time

Figure 8 as shown below, shows the number of complaints against each month from June 2024 up till December 2025 with the data retrieved from the Data Reporting and Corrective Action System as shown in Appendix 1. Figure 6 shows that there has been a big increase in the number of complaints from July 2025 onwards.

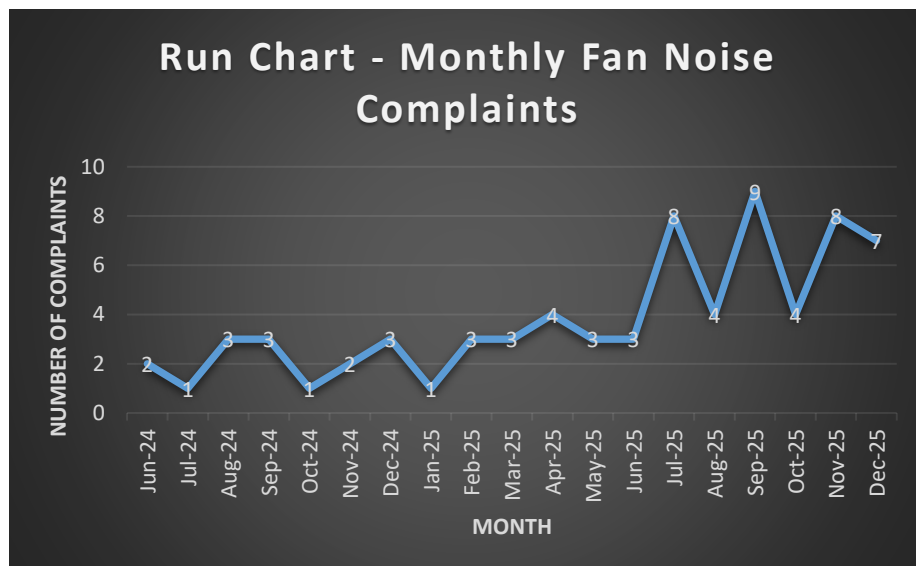


Figure 8 - Run Chart of Monthly Fan Noise Complaints (Jun-2024 – Dec2025)

Scatter Plot of Cooling Fan Frequency v Engine Revolutions

Figure 9 shows the relation of the fan frequency and the vehicle engine speed; the graph contains the data of all nine vehicles that was still within the companies control prior to delivery at time of CAN log investigation. Figure 9 shows that majority of the frequencies above the critical to quality set tolerance is between the 1100 rpm and 1450 rpm except for Ajax 3, noting that Ajax 3 was raised in purge for incorrect shimming and fans dimension.

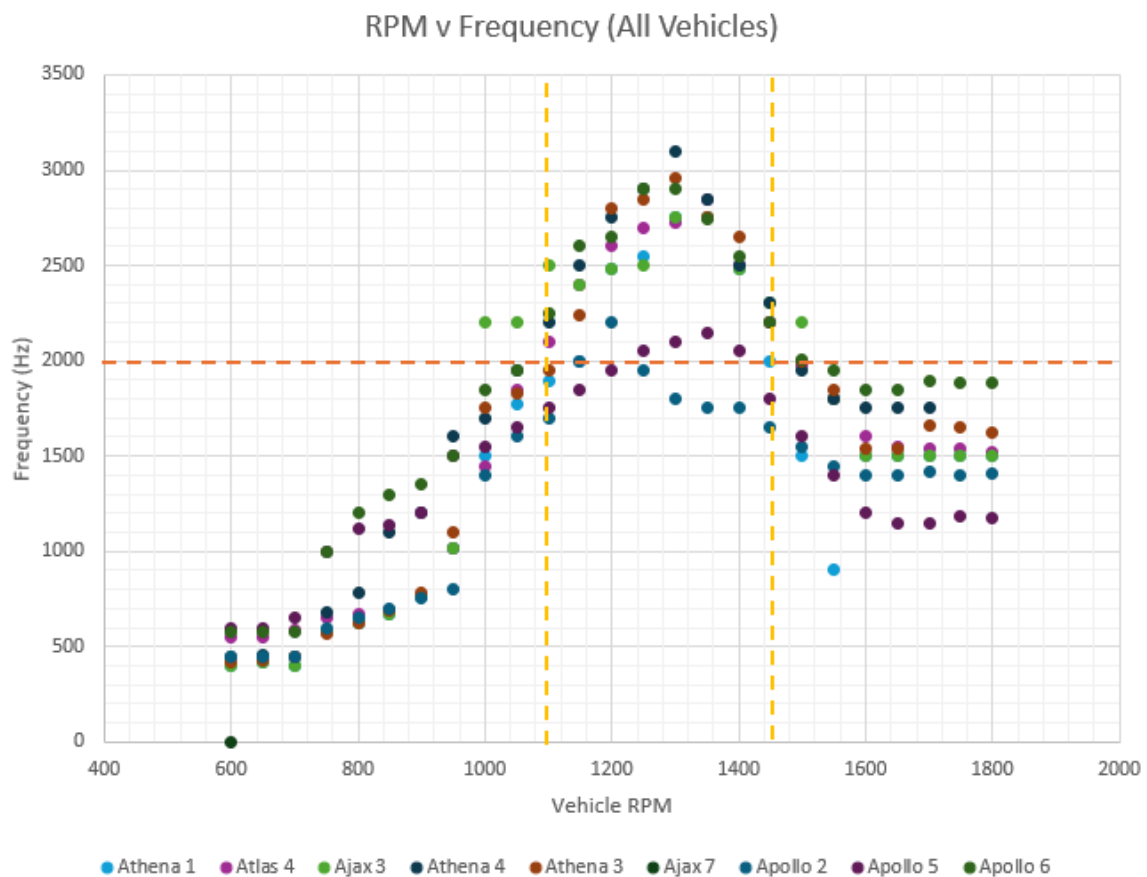


Figure 9 - RPM v Frequency Scatter Plot (Nine Vehicles)

Histogram

Figure 10 (below) shows the percentage of each variant failures due to high frequency from cooling fan noise. This has been carried out by getting the percentage against the order request to show a truer reflection across the batch build policy of the company. Figure 10 shows there is consistency in the

percentage of failures across four of the variants, Athena, Ajax, Atlas and Apollo but with the Ares failure rate at 12% better than Atlas. Batch build data shows that a higher output of Ares was produced before July 2025 and using *Figure 8* this can help explain the difference.

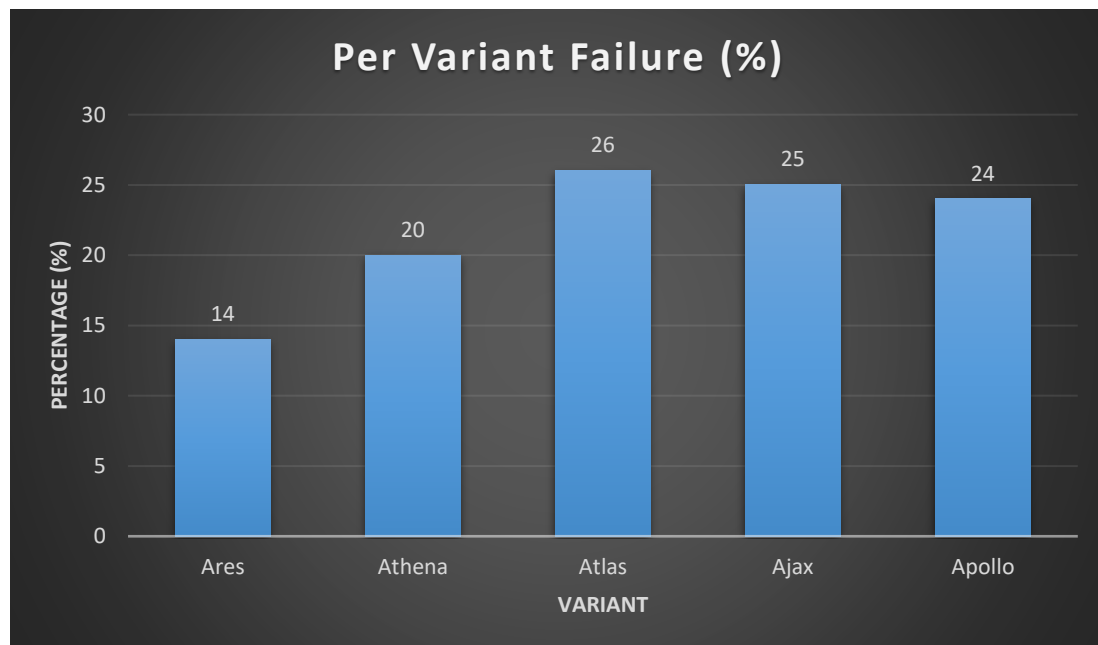


Figure 10 - Variant Failure Percentage

4.4 Identify Sources of Variation

On the system the noise could be classified as hydraulic cavitation, as Luo and Tsujimoto (2016) explain it as a hydrodynamic phenomenon occurring through movement of liquid and can cause noise, vibration and material damage. To ensure that the hydraulic cooling fan noise is related to the pareto chart results of fan dimension inaccuracy and installation errors in correct shimming, firstly the fan stators are removed from the motors, and the system is run working all the hydraulic elements. No high pitch frequencies occurred in any range during the test, indicating that the noise isn't hydraulic related. Blade passing frequency noise generally is the most challenging to remove in fan design as stated by Cai and Qi (2012). Ensuring that the design isn't the cause of the high frequency noise cause a blade passing frequency (BPF) formula can be used.

$$\text{BPF(Hz)} = \frac{(\text{Number of blades } (n) \times \text{Rotational Speed (RPM)})}{60}$$

$$n = 18$$

$$\text{RPM} = 1450 \text{ (Highest RPM of the range of noise)}$$

$$\text{BPF(Hz)} = \frac{(18 \times 1450)}{60}$$

$$\text{BPF} = 435\text{Hz}$$

This indicates that the design in blade count is not the cause of the observed high-frequency tone, and can also confirm with the guidance of the charts and experiments that the change in dimensions away from design via either the fan or shimming causes an aerodynamic flow change that causes vortex shedding, where non-uniform flow induces vibrations that causes frequency changes as explained by Kaneko et al (2008). Results and root cause analysis was sent to the fan supplier, and the supplier confirmed the findings were correct with their reply quoting “The 93350 fans are designed with a focus on delivering high airflow rates against high static pressure as often found in military engine cooling applications, so the stator vane and impeller blade geometry is optimised to give the best performance under these operating conditions. Over the years, we have had a few isolated reports of this fan making this type of noise in some applications. The occurrence of the noise it is heavily dependent on the installation and has only been reported at low fan speeds – typically below the normal operating speed of the fan. The noise is thought to be caused by ‘vortex shedding’ as the air flow detaches from the trailing edge of the stator vanes. The vortex shedding does not affect the performance or durability of the fan. We’ve investigated into the dimensional issues that you have also raised and have seen wear in the stamping mould used at are facilities” (Gallay, 2026).

4.4.1 Fishbone Diagram (Ishikawa)

During the stage of identifying the sources of variation the fishbone diagram tool was used to follow and plot possible causes, as stated by Li and Lee (2011) Ishikawa is used in engineering to investigate causes while analysing direct and indirect factors. *Figure 11* contains the factors considered by the team’s expertise and factors of the results collected in the measure and analysis sections.

Fishbone (Ishikawa)

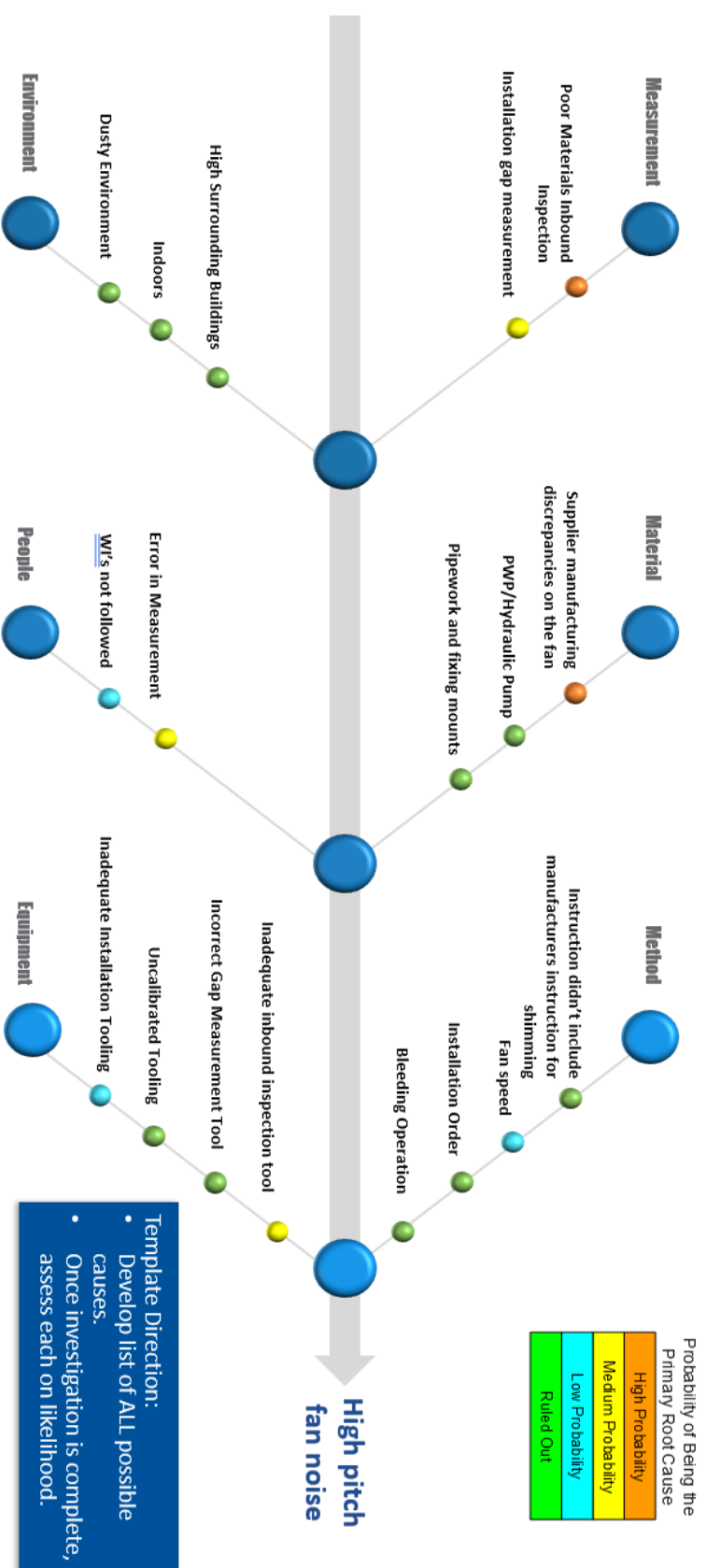


Figure 11 - Fishbone Diagram of Root Cause (GDLS-UK)

5 Improve

The improve section aim is to develop, implement and validate improvement options.

5.1 Generate Improvement Ideas

Brainstorming technique has been carried out for improvement ideas shown in *Figure 12*, as a time as the first stage of generating ideas. Wojtaszak and Bialy (2015) states these benefits facilitating the generation of a wide range of ideas out there, allowing quantity of options without the need of judging its effectiveness. Following the brainstorming session a group task to consolidate the ideas into affinity diagrams *Figure 13*, using the KJ method that helps as indicated by Interaction Design Foundation (2026) to go from a state of information chaos to an organised state of grouped information. *Figure 13* has the brainstorming ideas grouped into three sections design & manufacture change, contract & behaviour change and quality improvements.

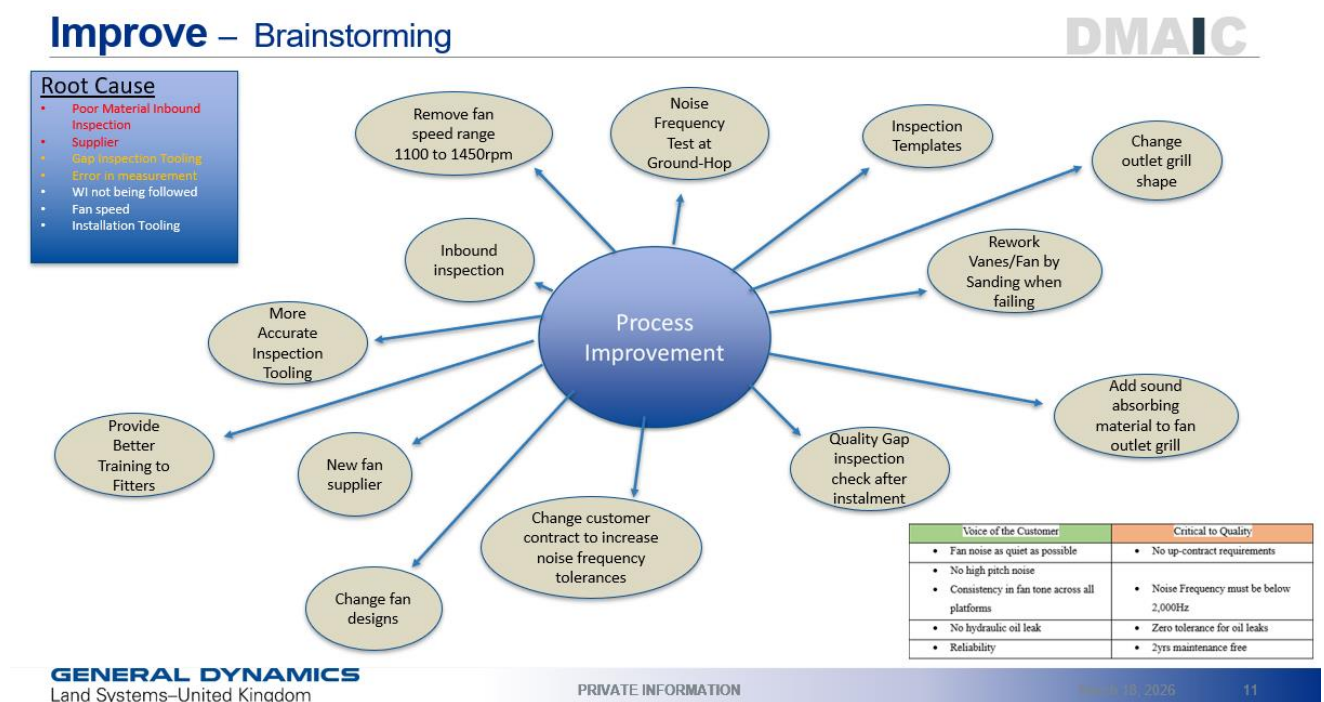


Figure 12 - Brainstorming Improvement Ideas (GDLS-UK)

Improve – Affinity Diagram

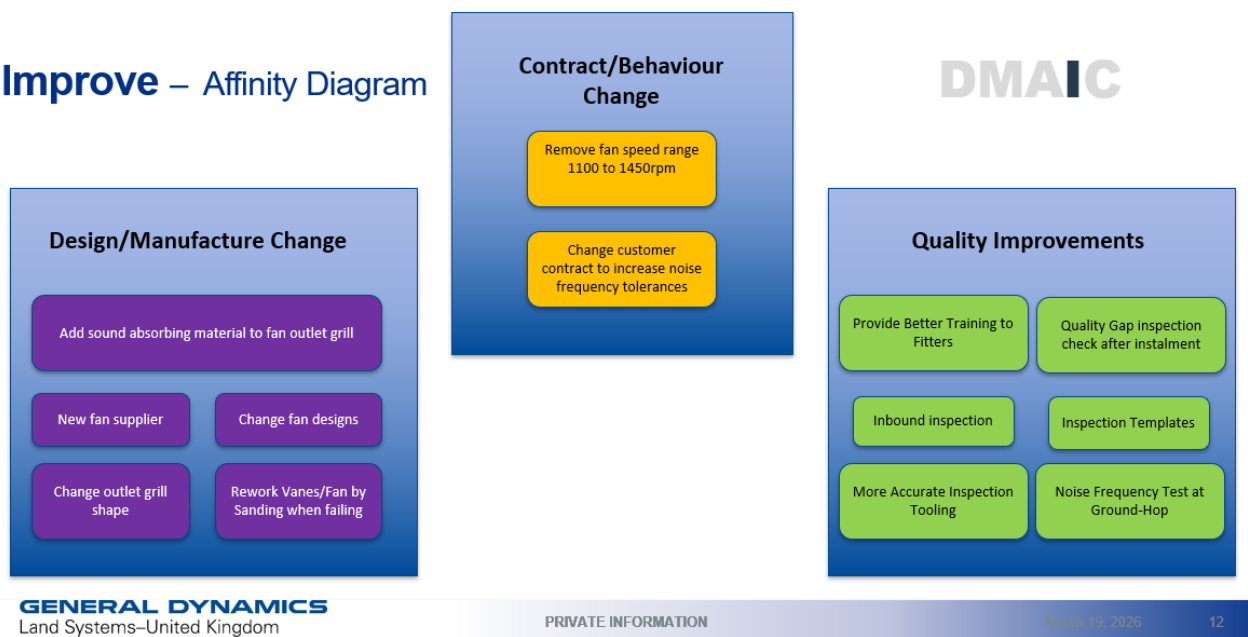


Figure 13 - Affinity Diagram (GDLS-UK)

Figure 14 shows the payoff matrix used to evaluate improvement options by implementation effort and expected benefits as explained by SixSigma.us (2024), this was also carried out as a team activity.

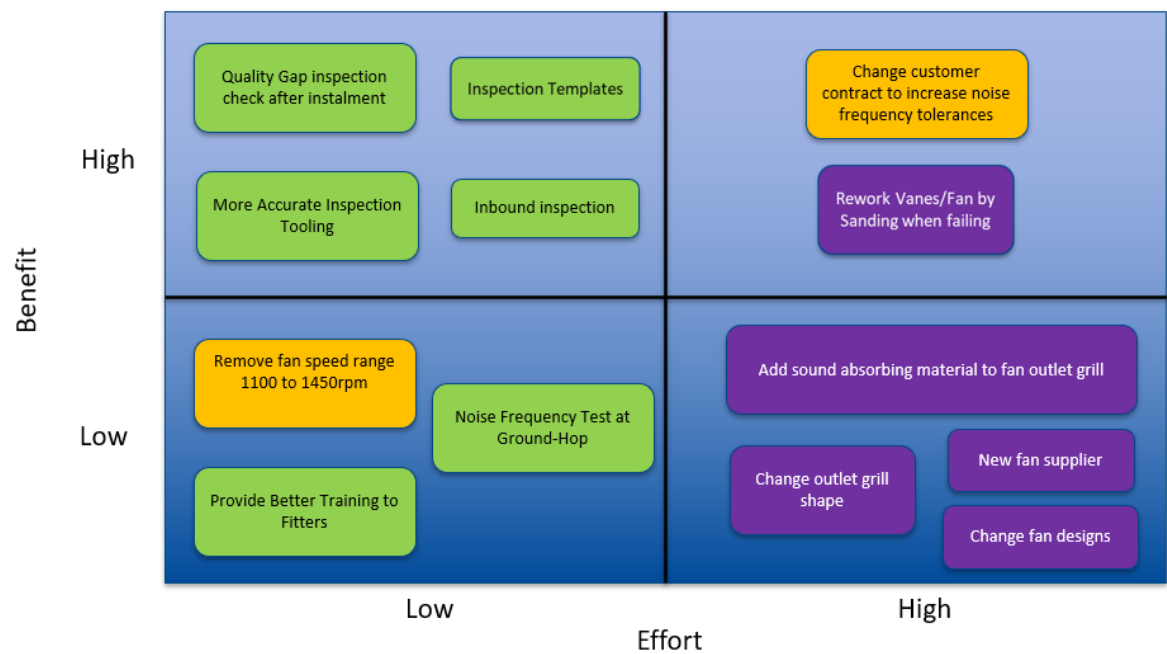


Figure 14 - Payoff Matrix (GDLS-UK)

Reviewing *Figure 14* while discarding all options that offered low benefits, a review of high effort high benefit was carried out to review if they achieved the must criteria that is pre-set in the critical to quality in *Table 1*. Changing the customer contract did not fall under the must as the frequency would fall out of the 2000Hz maximum tolerance set, reworking the vanes would also not fall in the must category at current time as reworking the items in house would void the warranty of the component from the supplier, this option may be considered in the long-term to achieve quicker turnaround of parts supplied but must be agreed by both parties. Then all options in the high benefits and low effort are considered and due to the nature of the of the options and their link to each other a criteria matrix was decided to be unnecessary, and an amalgamation of all four options would be desirable to reduce the two root causes discovered in the Pareto chart *Figure 7*. Below in *Table 6* is the result of the Design of Experiment, Eriksson et al (2000) says this is a structured approach for monitoring what effects the outcome, in this case the noise frequency when inputs which tolerances of shimming and fans dimensions are adjusted. *Table 6* clearly shows the importance of ensuring both factors are within the engineering design tolerances to ensure the noise frequency is below the contracted frequency limit.

Table 6 - Design of Experiment

Test	Correct Dimension Fan	Correct Shimming	Frequency Below 2000Hz
1	No	No	No
2	Yes	No	No
3	No	Yes	No
4	Yes	Yes	Yes
5	No	No	No
6	Yes	No	No
7	No	Yes	No
8	Yes	Yes	Yes
9	No	No	No
10	Yes	No	No
11	No	Yes	No
12	Yes	Yes	Yes

5.2 Improve FMEA Phase

The Failure Mode and Effect Analysis was conducted, identifying the severity, occurrence and detection of the cooling fan installation process allowing a baseline to be set for comparison against the recommended improvements ensuring that there's a clear reduction in the RPN score. *Figure 15* shows by adding two inspection points - one at inbound and the other on the installation clearance - the RPNs have significantly reduced indicating a strong improvement.

FAILURE MODE AND EFFECTS ANALYSIS															
Item: <u>Cooling Fans</u>		Responsibility: <u>Shayne Lewis</u>		FMEA number: <u>Coolin Fans 1</u>											
Model: <u>Gallay GLY130664</u>		Prepared by: <u>Gethin Davies</u>		Page : <u>1</u>											
Core Team: <u>Gethin Davies, Shayne Lewis, Daniel Horwood, Manu</u>		FMEA Date (Orig) <u>28/11/2025</u>													
Process Function	Potential Failure Mode	Potential Effect(s) of Failure	S e v	Potential Cause(s)/ Mechanism(s) of Failure	O c c u	Current Process Controls	D e t e	R P N	Recommended Actions(S)	Responsibility and Target Completion Date	Action Results				
											Actions Taken	S e v	O c c	D e t	R P N
Inbound Inspection	Cosmetic Damage	Aesthetic Degradation	2	Transport damage	2		8	32	Quality Inspector and inbound inspection sheet/criteria	Supplier Quality - 02/02/2026	Inbound inspection sheet and team	2	2	1	4
	Mechanical Damage	Damage to Hydraulic Systems and components within the area	8	Incorrectly assembled	1			64				8	1	3	24
	Incorrect dimensions	Damage to components within the area	6	Incorrect fan dimensions	3	Fitters' observation (No inspection section present)	9	162	Quality inbound inspection and dimensional metal templates and a two-part silicone impression for blades. (Go/No-Go gauge)	Supplier Quality- 19/03/2026	Quality inbound inspection and dimensional metal templates. (Go/No-Go gauge) Vernia for blade thickness	6	3	3	54
		Reduced cooling performance	5	Incorrect fan shape and dimensions	1			45				5	1	3	15
		High Pitch Noise	4	Incorrect fan shape and dimensions	8			288				4	8	3	96
	Fan clearance shimming during installation	Damage to components within the area	Other components require replacing due to damage	6	Shimmed below requested tolerance	4	Fitters measure with feeler gauge during installation	4	96	Quality Inspection Point after instalment & Fitters supplied with tolerance gauge block (Go/No-Go gauge)	Production Quality - 02/02/2026	Quality inspection point placed	6	4	7
High Pitched Noise		Discomfort for users	4	Shimmed above requested Tolerance/ Incorrectly measured	4	7		28	4				4	16	
				Shimmed below requested tolerance/ Incorrectly measured		4		64							

Figure 15 – PFMEA

5.3 Cost and Benefits Analysis

The purpose of the cost and benefit analysis is to confirm that the proposed improvement delivers a tangible business value and that the benefit of the implementation outweighs the associated costs.

5.3.1 Cost Of Implementation

The costs associated with the implementation are summarised below and have been estimated using the suppliers tooling costs, GDLS-UK task time data and labour rates.

One-off Costs

- Design and manufacture of cooling fans dimension go/no-go gauges = £2300
- Post installation fan clearance go/no go gauges = £779.87 (RS Components, 2026)
- Work instruction and controlled documents creation and amendments. 14hrs of engineering time at £22hr = £308
- Toolbox talks are already scheduled as a weekly activity for the shopfloor operator and others that are in direct working relationships. This activity adds no additional expected cost.

Total one-off cost = 3387.87

Ongoing Operational Cost

- Inbound inspection time per set of fans = 30 minutes
- Post installation clearance check per vehicle = 6 minutes

Total ongoing annual cost at a production rate of 68 vehicles a year and quality technician cost £19 per hour. Total time 0.6 hours x 68 x £19 = £775

Total Cost = 4162.87

5.3.2 Benefits of Implementation

45 vehicles a year were recorded with fan noises related defects, resulting in:

- Fan removals and replacements
- Rectification labour
- Vehicle acceptance delays (approximately 4 days per vehicle)
- Increase customer concerns and loss product confidence

Based on the internal rectification records each set of fan related rework incurs.

- 9.15 hours of labour £19 per hour = £173.85
- Parts logistic and handling = £174.80
- Programme delay £193.55

Cost per defect is £542.20 and with an average of 45 defect a year the annual cost is £24,399, but with as stated in the project charter *Figure 5* an improvement of 90% reduction in fan noise reported. This therefore provides an annual cost reduction of £20,061.40.

Table 7 - Financial Summary Table

Item	Value (£)
One-Off Implementation Cost	3,387.87
Ongoing Operational Cost (annual)	775
Total year 1 cost	4162.87
Baseline annual defect cost	24,399
Expected annual saving (90% reduction)	20,061.40
Net annual benefit after year 1	19,286.40
Net benefit in year 1	15,898.53
ROI (Year 1)	382%

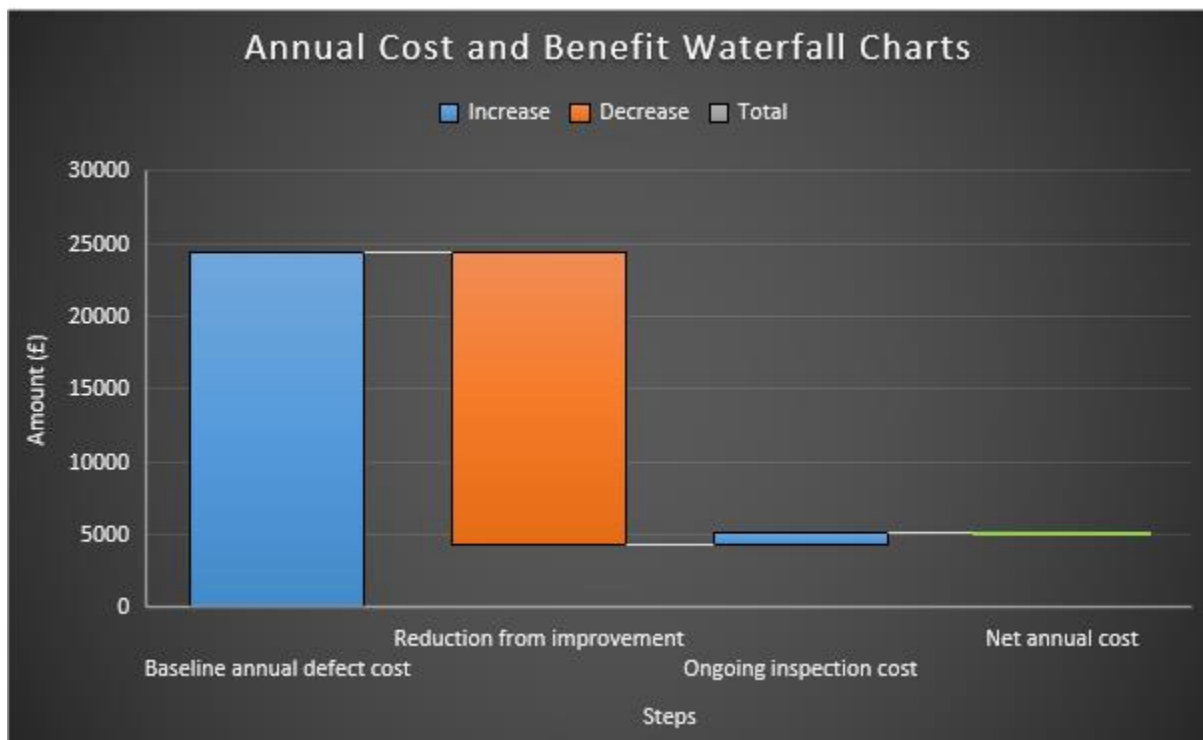


Figure 16 - Cost and Benefit Waterfall Chart

Table 7 shows the investment will provide a highly positive financial saving within the first year, with a Return of Investment percentage of 382% and then with Figure 16 showing a annual saving of £19,286.40 from year two onwards.

5.4 Future State Process Map

With the improvements selected, Figure 17 show the future state map which include the additional inspection points and decision points that can be seen with red circles around them. This indicates the difference between Figure 2 current state process map and the future state process map. The process map was verified with a walk-through with the starting point now at the materials inbound with the inspection of the cooling fans using the go/no-go gauges allowing for a swift and precise decision to be made then the process follows the original path until the installation step where after the installation a gap clearance is validated also with a go/no-go gauge again allowing for a effective, fast and correct decision. The process then carried on to the bleeding, ground-hop and follows the original

path, the rework sections are still required if a mechanical or hydraulic failures occur but with the additional steps, we can ensure no fan rework would be required due to in high pitch noise.

Improve – Future State Process Map

DMAIC

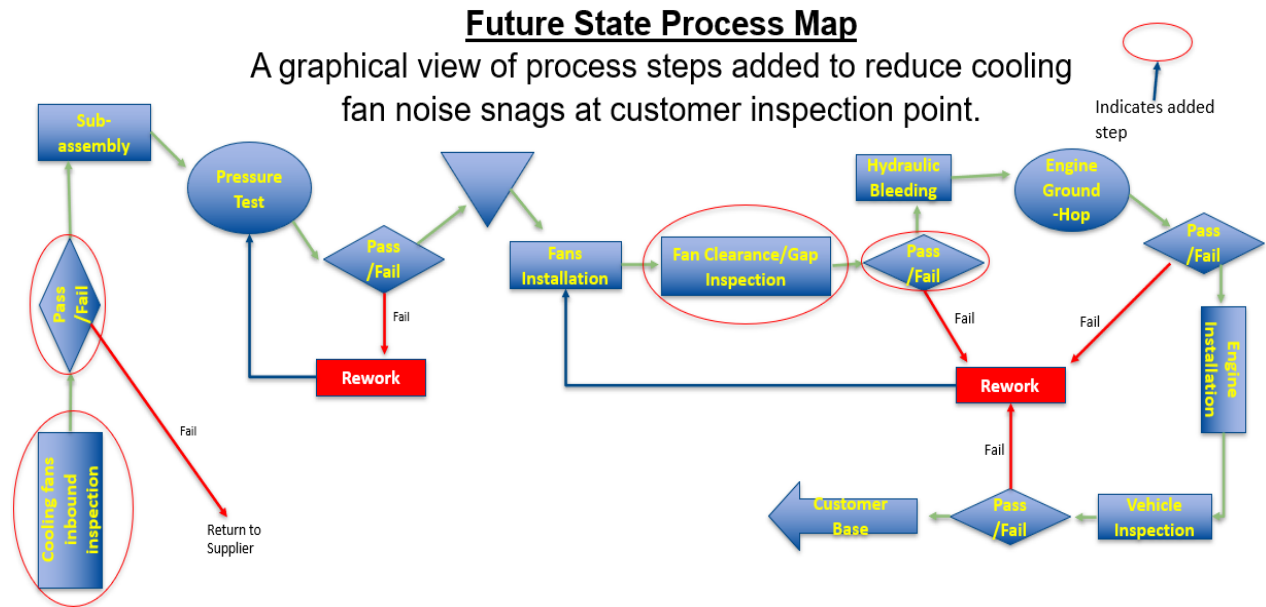


Figure 17 - Future State Process Map

5.5 Pilot Proposal

Due to the high numbers of cooling fan high pitch noises being raised at the vehicle inspection point the pilot proposal is to apply the part inspection and installation gap inspection in the rectification rework point to ensure a first-time fix. This ensures that the current process does not get impacted but the pilot items still receive the same customer inspection at the final point ensuring a customer-based feedback. *Figure 18* below shows the pilot proposal.

COOLING FAN NOISE ISSUES – Pilot Proposal

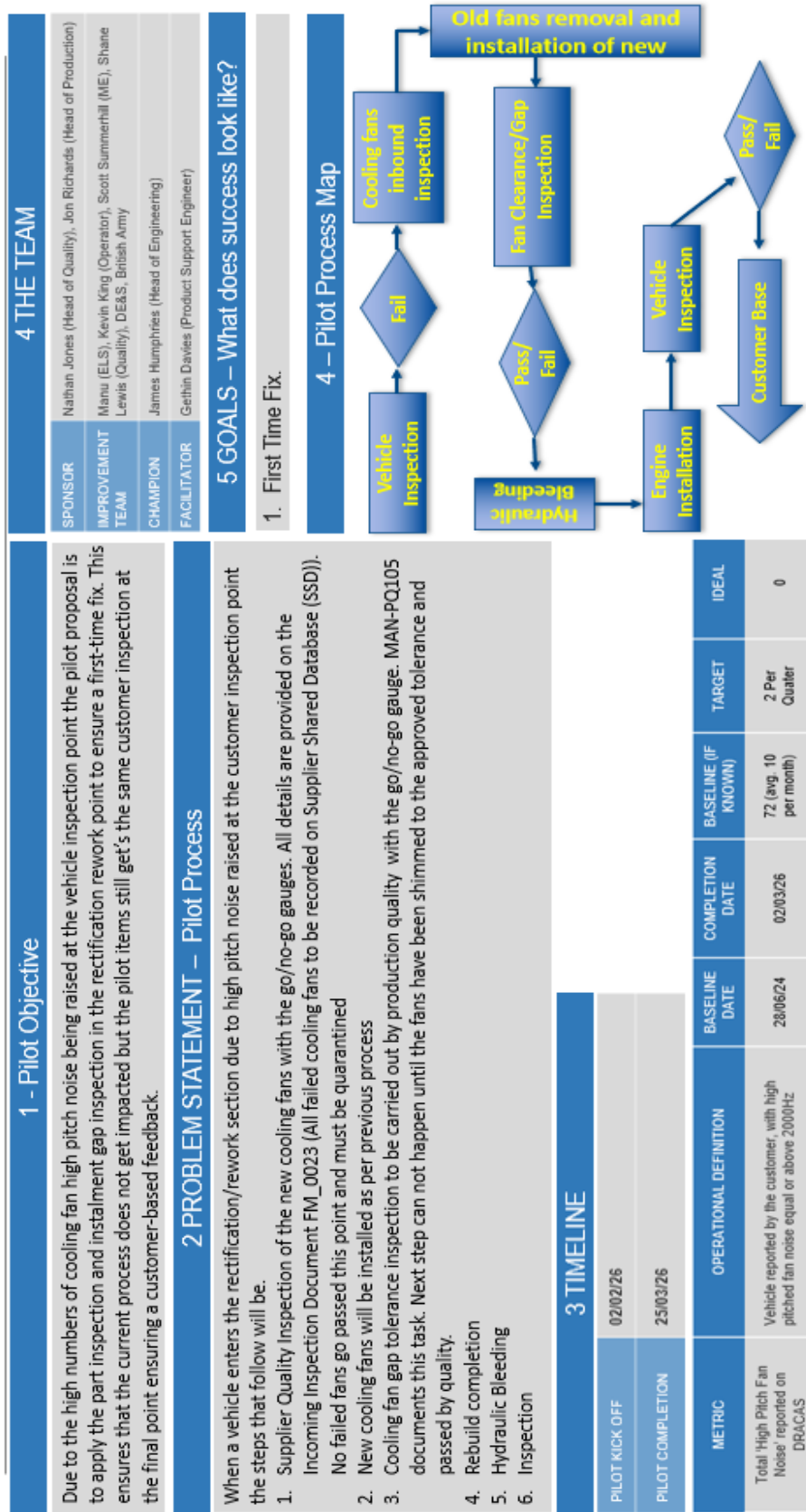


Figure 18 - Pilot Proposal Plan

5.6 Improvements Validation

The improvement validation phase is to confirm that the implemented solutions have effectively addressed the identified root causes and achieved the targeted improvement failure reduction. With the pilot being applied on the vehicle that have failed the vehicle inspection due to fan noise issue this reduces other possible factures as confirmed failures are then rectified by the two solutions only and must still be confirmed by the customer that the repair was successful. The nine vehicles that were recorded and rectified during the pilot period using the proposed pilot plan as explained in *Figure 18* had a result of all vehicle's fan noise levels were then below the acceptance level set in the CTQ shown in *Table 1*. This data was recorded and tracked on GDLS-UK JAG DRACAS system as shown in *Table 8* below.

Table 8 - JAG DRACAS First Fix

JAG21879	COMPLETE	Fan noise at 750RPM.
JAG22266	COMPLETE	Fan noise @750rpm
JAG22271	COMPLETE	Fan noise on start up
JAG22362	COMPLETE	High pitch fan noise at 850RPM.
JAG22411	COMPLETE	Fan noise @ 1300 RPM
JAG22424	COMPLETE	Fan noise present throughout the rev range.
JAG23564	COMPLETE	Fan noise can be heard above idle.
JAG23565	COMPLETE	Fan noise can be heard above idle.
JAG23663	COMPLETE	FAN NOISE - Fan noise can be heard on idle.

The table collects strong evidence that the process improvement steps will have a positive impact as proven in the pilot trial, while the full post-improvement sigma performance can not yet be statistically confirmed due to the limited number and time of the trial, but does provide a strong indication that the sigma level will improve dramatically from sigma 1 ($\sigma 1$) as raised in the process performance earlier in the report.

6 Control

The control phase is to ensure that the improvements implemented during the improve phase are sustained and the process does not revert to its original state. This will be achieved by clearly defining responsibilities, implement monitoring systems with a clear and defined standardisation of procedures and documentations. *Table 9* shows the structure control plan to be implemented when the improvements are introduced to the production lines.

Table 9 - Control Plan Table

Control Plan					
Process Step	CTQ Characteristics	Control Method	Frequency	Responsibility	Reaction Plan
Inbound fan inspection	Fan dimensional tolerance	Go/No-Go two-part gauge inspection	Every fan	Quality inspector	Reject and notify supplier
Post installation gap clearance inspection	Clearance between fan and shroud	Go/No-Go gap inspection	Every Vehicle	Assembly operator & quality inspector	Re-shim to correct tolerance
Vehicle acceptance inspection	Noise frequency	Acoustic Measurement	Every Vehicle	Joint Acceptance Inspector	Investigate root cause and provide finding
Process performance	Defect rate (DPMO)	Monthly KPI review	Monthly	Production Manager	Initiate DMAIC

Standardisation, Documentation and Training

To ensure consistency across all operations, the work instruction updated and verified during the pilot process will be implement and toolbox talk and competency validation will be carried out by the team that carried out the successful pilot trials. The Go/No-Go gauges will require monthly validation of tolerance to ensure no test tool tolerance failures occur. All this provides clarity and allow the understanding of the importance of the process and its impact toward the final performance.

Performance Monitoring Control and Reaction Plan

X-bar and R charts will be used to monitor fan dimensional measurement, post installation gap and with the data also transferred to a histogram to visualise potential differences between variants and different production lines. Run charts will track monthly fan noise complaints and a scatter graph to provide the frequency of each vehicle during the inspection process. This all allows an early indication on of change in trends or cycles to be highlighted and will trigger an investigation. These data will allow also a monthly review and provide a DPMO performance score with the aim to retain it above 90% reduction in failures. Any data points outside the control limits will trigger an investigation, a structured reaction plan ensures a rapid response to any deviation. If a cooling fan fails, its inbound inspection it will immediately be quarantined via the Material Return Board (MRB) system retaining the GDLS standardisation policy and any defects found in the post installation will be reworked in situ and further operator training will be provided if failure is repeated. If the noise complaint arises in the acceptance inspection area a root cause investigation will be triggered and a DMAIC review cycle.

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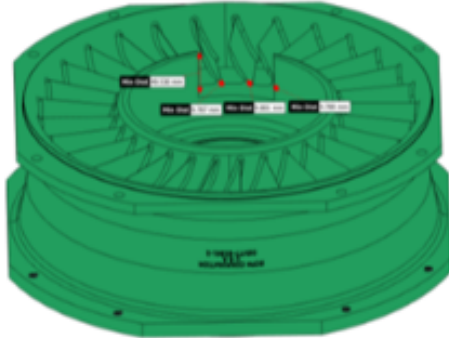
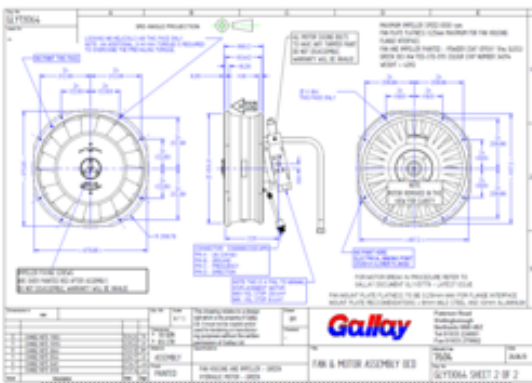
8 Appendices

8.1 Appendix 1

SNAG ID	CONFIGURATION	ENTRY DATE	ROLE	SNAG ID	CONFIGURATION	ENTRY DATE	ROLE	SNAG ID	CONFIGURATION	ENTRY DATE	ROLE	SNAG ID	CONFIGURATION	ENTRY DATE	ROLE
JAG20522	TU89AB	05/11/2025	ARES	JAG17513	TU61AB	28/07/2025	APOLLO	JAG13839	TU69AB	24/03/2025	APOLLO	JAG03588	TV21AB	28/06/2024	ARES
JAG17513	TU61AB	28/07/2025	APOLLO	JAG17916	TV72AB	11/08/2025	AJAX	JAG14038	TT60AB	28/03/2025	ATHENA	JAG03594	TW04AB	29/06/2024	AJAX
JAG17916	TV72AB	11/08/2025	AJAX	JAG18101	TV46AB	21/08/2025	AJAX	JAG14227	TU68AB	03/04/2025	APOLLO	JAG03894	TV17AB	18/07/2024	ARES
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								JAG13555	TV83AB	17/03/2025	AJAX	JAG12342	TT62AB	14/02/2025	ATHENA

8.2 Appendix 2

Audit Sheet Man-T1075 Fan 1

Unit Containment Worksheet					GENERAL DYNAMICS Land Systems-United Kingdom																																																			
					Fan 1																																																			
					PURGE NUMBER																																																			
Requestor's Name		Gethin Davies		Date Completed		20/12/2025																																																		
Part Number		2930900263		Part Description		Cooling Fan																																																		
Variants Affected		Ajax	Apollo	Atlas	Athena	Ares	Argus																																																	
Highlight variants																																																								
Problem Description - <i>take completed by requestor</i> Inspect cooling fan vanes thickness and shape to Galloy document GLY130664 (CAD Images shows inconsistency in blade measurements and measuring points)																																																								
<table border="1"> <thead> <tr> <th>MRB ID</th> <th>OK</th> <th>NOK</th> <th>able to che</th> <th>Comments</th> </tr> </thead> <tbody> <tr><td>13100</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> <tr><td>14280</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> <tr><td>16107</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> <tr><td>16503</td><td></td><td></td><td></td><td></td></tr> <tr><td>17336</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> <tr><td>17398</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> <tr><td>17740</td><td></td><td></td><td></td><td></td></tr> <tr><td>18104</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> <tr><td>18452</td><td></td><td></td><td></td><td>Out of Tolerance</td></tr> </tbody> </table>							MRB ID	OK	NOK	able to che	Comments	13100				Out of Tolerance	14280				Out of Tolerance	16107				Out of Tolerance	16503					17336				Out of Tolerance	17398				Out of Tolerance	17740					18104				Out of Tolerance	18452				Out of Tolerance
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MAN-T1072 REV 003 24/08/2022																																																								
						<i>Shayne Lewis</i> Stamp or signature if applicable																																																		

INVESTIGATION – Pressure Readings ASPR1

Determine failure conditions:

Pressure readings Config A

Leads connected to Pressure and Return side

Pressure: 10 bar at startup -> peak of 273 bar after 3 secs, stabilises at 20 bar

Return: 4 bar (TBC)

Pressure readings Config B

Leads connected to Pressure line of Fan1 and Pressure line of Fan2

Pressure: 10 bar at startup for both -> peak of 273 bar after 3 secs for both, stabilises at 20 bar

Return: 4 bar (TBC)

Pressure readings Config C

Leads connected to Pressure, Return and Leak line (common)

Same readings, peak changes to 80 bar and leak line is 2 bar max.

GENERAL DYNAMICS

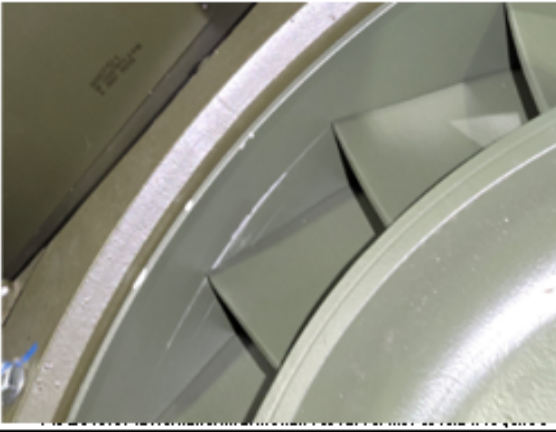
Land Systems–United Kingdom

PRIVATE INFORMATION

INVESTIGATION (ASWIVED)

Work Instructions Validation V Engineering Drawings

Variant	Work Instructions		True to Engineering Drawings
	Fitment	Final Assembly	
AJAX	WI200339839		Yes
ARES	WI200265812	WI200340289	Yes
ATLAS	WI200300491		Yes
APOLLO	WI200279572		Yes
ATHENA	WI200338939	WI200269046	Yes
ARGUS	WI200339799	WI200300103	Yes

Unit Containment Worksheet				GENERAL DYNAMICS Land Systems-United Kingdom																													
				CF-FITMENT																													
Requestor's Name		Gethin Davies		Date Completed																													
				23/12/2025																													
WI Number		200338933 ++		WI Description																													
				Cooling Fan																													
Variants Affected		Ajax	Apollo	Atlas	Athena																												
					Ares																												
					Argus																												
Highlight variants																																	
Problem Description - <i>take completed by requestor</i> Validate vehicle installation of cooling fans against Work Instruction (Clash possible if fitted incorrectly)																																	
NOK Condition																																	
																																	
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Results of Purge		NOK Qty		OK Qty																													
		4		15																													
Comments <i>Kevin King</i> Stamp or signature if applicable 																																	

Unit Containment Worksheet					GENERAL DYNAMICS Land Systems-United Kingdom		
					AUDIO2		
Requestor's Name		Gethin Davies		Date Completed		03/12/2025	
Variants Affected		Ajax	Apollo	Atlas	Athena	Ares	Argus
Highlight variants							
Problem Description – <i>to be completed by requestor</i> Confirm if high frequency I present when vehicle is on these states ECS ON/OFF, Deck OPEN/CLOSED, Vehicle Indoors/Outdoors							
Vehicle	ECS ON	ECS OFF	OPEN	CLOSED	NOK Condition		
Athena 1	Yes	Yes	Yes	Yes			
Atlas 4	Yes	Yes	Yes	Yes			
AJAX 3	Yes	Yes	Yes	Yes			
Athena 4	Yes	Yes	Yes	Yes			
Athena 3	Yes	Yes	Yes	Yes			
AJAX 7	Yes	Yes	Yes	Yes			
APOLLO 2	Yes	Yes	Yes	Yes			
APOLLO 5	Yes	Yes	Yes	Yes			
APOLLO 6	Yes	Yes	Yes	Yes			
Vehicle	Indoors	Outdoors					
Athena 1	Yes	Yes					
Atlas 4	Yes	Yes					
AJAX 3	Yes	Yes					
Athena 4	Yes	Yes					
Athena 3	Yes	Yes					
AJAX 7	Yes	Yes					
APOLLO 2	Yes	Yes					
APOLLO 5	Yes	Yes					
APOLLO 6	Yes	Yes					
Please refer to Additional Information Tab for further details if required							
OK Condition							
Please refer to Additional Information Tab for further details if required							
Results of Purge		NOK Qty		OK Qty			
Comments MAN-T1072 REV 003 24/08/2022							
Chris Costigan Stamp or signature if applicable							

INVESTIGATION (ASCAN)

Determine failure conditions:

To find failure patterns, CAN have been captured and analysed.

Observation 1: Delay of front fan turning by 3 secs (believed to be inherent to design)

Observation 2: High-pitched noise is always heard between 1100 rpm – 1450 rpm approximately (NOTE: this is fans speed, not engine speed).

Observation 3: Slowing down the engine from idle speed (750 rpm) to stealth speed (600 rpm) also slows down the fans to around 350-400 rpm, which completely negates the noise.

Observation 4: Similarly, revving up the engine also clears the high-pitched noise (1500 rpm and above).

