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Original Article

Weibull Analysis of Sabroe Chiller Reliability at Heathrow Airport: Implications for Infrastructure Management

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Abstract *- This study examines the reliability performance of Sabroe chillers at Heathrow Airport using Weibull statistical analysis to compare failure characteristics with industry benchmarks. The aim is to determine whether the airport's chillers exhibit different reliability patterns that could inform maintenance strategies for critical infrastructure. The methodology involves fitting Weibull distributions to time-to-failure data for Heathrow's chillers and corresponding industry reference data, enabling estimation of key reliability metrics, including the shape parameter (β) and B10 life. Results indicate that both datasets are in a wear-out failure phase (β > 1), but Heathrow's chillers have a more gradual increase in failure rate (β ≈ 1.63) compared to the industry standard (β ≈ 2.35). The estimated B10 life is approximately 46,855 hours for both sets, overlapping 90% confidence intervals, suggesting comparable early-life reliability. However, the Heathrow units exhibit a more distributed failure timeline and maintain significantly lower failure incidence (around one-third of the industry baseline by 160,000 operating hours), implying more effective maintenance or operating conditions. These findings have direct implications for reliability-centred maintenance and infrastructure planning, illustrating the critical role of statistical modelling in shifting maintenance paradigms from reactive repairs to proactive interventions. In essential infrastructure settings, such as international airports, data-driven approaches are pivotal for strategic asset management and ensuring operational continuity.*

Keywords - *Weibull analysis, Chiller reliability, Infrastructure maintenance, Failure rate modelling, Critical cooling systems*.

1. Introduction

The complex network of chillers throughout Heathrow Airport's sprawling terminals operates largely unnoticed. These Sabroe units quietly maintain optimal temperatures for millions of passengers and temperature-sensitive cargo year-round. However, when these systems fail, the consequences manifest as operational chaos with far-reaching implications [1, 2].

In August 2019, Terminal 5 experienced this reality firsthand when a single chiller failure triggered a cascading system breakdown, resulting in unacceptable temperature fluctuations throughout the building. Passengers endured uncomfortable conditions whilst staff struggled to manage the situation. Beyond the immediately apparent human discomfort, the economic impact proved severe. Airlines faced mounting compensation claims for delayed and cancelled flights, and Heathrow witnessed declining retail revenue as passengers avoided shopping areas intended as recreational spaces [3].

Passenger comfort represents merely one aspect of the critical nature of these systems. Heathrow handles tonnes of temperature-controlled pharmaceuticals, produce, and perishable goods daily. Even minor temperature deviations can prove catastrophic, potentially resulting in substantial product losses.

For pharmaceutical shipments, temperature variations may render expensive medications ineffective or harmful. Such incidents impact the companies involved and undermine the UK's reputation as a reliable trade partner.

1.1. Research Gap and Problem Statement

Airports' essential cooling systems face a major information deficiency regarding their reliability performance relative to standard industry benchmarks when operating under equivalent conditions. Industrial refrigeration system reliability studies exist, but the specific operational requirements of airport facilities, which involve changing loads, continuous operation, and strict temperature management, need a more thorough statistical investigation.

The research fills this knowledge gap through Weibull statistical analysis, which evaluates Heathrow chiller failure patterns against industrial benchmarks. The approach enables the creation of evidence-based maintenance strategies that minimise service interruptions while safeguarding airport financial interests, according to Hall and Strutt 2003 [4].

The Weibull distribution provides exceptional value because it adjusts to different failure patterns to reveal information that standard time-to-failure statistics cannot detect. Luko's 2019 [5] research demonstrates that the Weibull distribution has become the standard tool for evaluating equipment reliability within maintenance engineering. Comparing Heathrow chiller data with industry benchmarks enables a transition from reactive maintenance to proactive data-driven strategies, which ageing infrastructure needs to sustain operational excellence [6].

The central research inquiry of this study investigates whether Sabroe chillers operating at Heathrow Airport demonstrate different reliability characteristics than industry standards and how these differences affect maintenance strategy development and infrastructure management.

1.2. Research Novelty and Comparative Context

The research presents multiple original findings which differentiate it from previous reliability studies in the field. The research papers [7, 8] studied general chiller performance deterioration but focused on efficiency losses instead of statistical failure patterns. Yan et al. [9] investigated lifecycle optimisation without including the essential industry benchmarking approach underpinning our research. The main contribution of this research involves using Weibull analysis to evaluate critical airport infrastructure while developing statistical methods for maintenance decisions that unite theoretical reliability engineering with practical asset management. This research differs from Yadav's [10] fuzzy logic approach optimisation models because it focuses on identifying unique failure patterns of individual chillers in major international airport operations. The comparative methodology shows the timing of failures and how Heathrow's maintenance procedures affect the component longevity parameters, providing valuable insights that standard time-based maintenance planning cannot deliver.

2. Literature Review

2.1. Evolution of Reliability Analysis in Critical Infrastructure

Critical cooling systems have undergone substantial development in reliability analysis throughout the last several decades. Alabdulkarim et al. [6] observed that predictive data-driven approaches have fundamentally changed critical infrastructure management beyond traditional reactive maintenance systems. The Heathrow Airport complex operates with critical infrastructure requiring exceptional operational reliability from its cooling systems [2]. Chiller system failures at these facilities produce extensive repercussions, which exceed comfort-related problems, as Porter [3] shows through the examination of the Terminal 5 August 2019 incident that caused flight delays, passenger compensation claims, and decreased revenue from reduced spending.

2.2 Weibull Distribution in Reliability Engineering

Reliability engineering uses the Weibull distribution as its fundamental analysis method, especially for analysing complex mechanical systems such as chillers. According to Luko [5], the distribution's versatility in modelling various failure patterns makes it an indispensable tool for reliability engineers. Weibull analysis proves effective in characterising failure modes through its shape parameter (k) because it contains three distinct failure mode characteristics.

The distribution demonstrates "infant mortality" failures with decreasing failure rates when $k < 1$.

When $k = 1$, it indicates a constant failure rate (exponential distribution)

The failure rate increases steadily as k surpasses 1, representing "wear-out" failures.

The Weibull distribution allows engineers to simulate the complete lifespan of mechanical systems 12]. Barreto-Souza et al. [13] successfully employed the probability density function of the Weibull distribution to analyse the time-to-failure distributions of industrial cooling equipment.

2.3. Chiller Failure Mechanisms

Reliability analysis requires a clear comprehension of the distinct failure mechanisms in chillers. Multiple sources lead to chiller failures, including refrigerant leaks, compressor failures, and fouling of heat exchange surfaces. An extensive analysis of typical heat exchanger failures showed that mechanical and temperature-related failures significantly affect chiller operations [14]. Compressors' failure is a vital mechanism caused by mechanical wear, lubrication problems, and electrical issues [15]. The compressor corrosion in Figure 1 illustrates the degradation that occurs over time.

Fig. 1 Compressor Corrosion (Zouch, 2020) [16]

Condenser and evaporator fouling significantly impact heat transfer efficiency [17]. The accumulation of scale, sediment, or biological growth creates an insulating layer that forces the compressor to work harder, leading to increased energy consumption and accelerated wear.

2.4. Previous Applications of Weibull Analysis to HVAC Systems

While various reliability studies exist for industrial refrigeration systems, there remains a notable research gap in airport-specific applications. Yan et al. [18] conducted one of the few lifecycle optimisation studies of chiller plants in commercial buildings using reliability analysis. Still, their work did not address the unique operational demands of airport environments.

Firdaus et al. [8] examined chiller performance deterioration and maintenance but focused primarily on efficiency losses rather than statistical failure patterns. Similarly, Zhang et al. [7] studied efficiency and reliability joint optimisation without the comparative industry benchmarking that forms the cornerstone of robust reliability analysis.

The bathtub curve model, illustrated in Figure 2, provides a conceptual framework for understanding how failure rates change throughout a system's lifespan. Jia`s research [19] demonstrated how this model can address early failures through quality control while planning proactive maintenance strategies to mitigate wear-out failures.

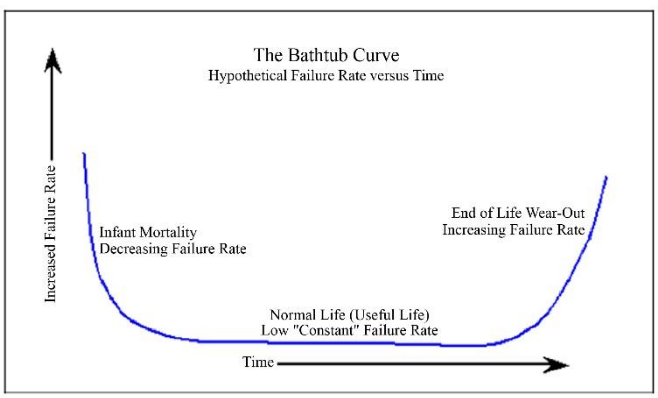

Fig. 2 Bathtub Curve [19]

2.5. Limitations in Existing Literature

The scarcity of reliable failure rate data on specific chillers and models remains significant because manufacturers protect this information as proprietary [22]. The absence of transparent data creates a significant obstacle when researchers analyse chiller failure patterns and evaluate system reliability.

Hartman [21] points out that researchers need comprehensive failure records to identify design weaknesses and standard failure modes in similar models and develop accurate predictive maintenance models. The scarcity of data forces researchers to rely on anecdotal reports and limited reliability databases, which provide general information instead of the specific model data required for detailed analysis.

2.6. Research Gap and Study Justification

The existing literature shows a significant deficiency in understanding how airport chiller reliability compares against standard industry performance under equivalent operating conditions. The unique operational requirements of airport environments with variable loading, continuous operation, and stringent temperature control needs have not received sufficient statistical examination in existing general reliability studies.

The study fills this knowledge gap through Weibull statistical analysis, enabling the evaluation of Heathrow's chiller performance relative to industry benchmarks. The research delivers essential data for creating evidence-based maintenance approaches that decrease service interruptions while safeguarding airport financial interests.

3. Theoretical Framework

The Weibull distribution is a cornerstone of reliability engineering, helping engineers predict *when* and *how* equipment like Heathrow's chillers might fail. Its magic lies in its flexibility: the shape parameter (k) reveals failure patterns, whether breakdowns occur early (infant mortality), randomly, or due to wear and tear. For example, a k>1 (like Heathrow's 1.627) signals ageing components driving failures. This method is distinguished by its adaptability. The Weibull Distribution facilitates the manipulation of its shape parameter to accommodate diverse failure phenomena [12]. The probability density function (PDF) quantifies failure likelihood over time, Barreto-Souza [13]:

$$f(x,\lambda,k) = \begin{cases} \mathrm{k}\lambda(\mathrm{x}\lambda)\mathrm{k} - 1\mathrm{e} - (\mathrm{x}\lambda)\mathrm{k} & \text{if } \mathrm{x} \geq 0 \\ 0 & \text{if } \mathrm{x} < 0 \end{cases}$$

Where:

- f (x, λ, k) is the probability density function.
- x is the random variable (lifetime in reliability analysis).
- λ is the scale parameter, representing the characteristic life.
- k is the shape parameter.

The two key parameters tell different parts of the reliability story: the shape parameter (k) reveals whether components are experiencing early failures, random breakdowns, or age-related deterioration, while the scale parameter (λ) indicates the equipment's characteristic lifespan [13].

When examining chiller systems, these parameters translate directly to maintenance decisions. A shape parameter below 1 suggests manufacturing defects or installation issues causing premature failures, prompting quality control interventions. Values around 1 indicate random failures requiring standby redundancy. Values above 1, as seen in the data, point to wear-out mechanisms where predictive maintenance proves most effective. The reliability (R) of a system can be computed using the Weibull distribution Equation [7]:

$$Reliability = R(t) = e^{-(\frac{t}{\theta})^{\beta}}$$

Here, (t) represents time, θ denotes the scale parameter (Weibull shape parameter), and β signifies the Weibull slope parameter.

In the context of chiller maintenance, the utilisation factor ρ represents the ratio of the average failure rate to the average repair rate: $\rho = \lambda / \mu$; Where λ is the average failure rate.

For assessing risk in chiller systems, according to Banarjee [22], the following equation was used:

$$Risk = probability\ of\ Failure\ (POF)x\ Consequence\ of\ Failure\ (COF)$$

The availability (A) of a chiller system, representing the percentage of time it is available for operation, is calculated as:

$$A(t) = Pr(Z(t)) = 1$$

Where: Z(t) is the discrete random variable characterised by:

$$Z(t)= \begin{cases} 1, \text{chiller capable of executing its operational function safely or in unintended operation at time t} \\ 0, \text{Otherwise} \end{cases}$$

According to $Taisir$ et al. [23], the availability is:

$$A = \frac{\text{Operating Time} - \text{Downtime}}{\text{Operating Time}} \times 100\%$$

These parameters directly impact Heathrow's operational continuity. Every percentage point improvement in reliability represents fewer disrupted flights and compromised cargo shipments. What makes Weibull particularly valuable is its ability to extract meaningful patterns from limited samples, providing insights that raw failure counts simply cannot. This mathematical framework transforms scattered maintenance records into strategic intelligence for infrastructure management [8].

4. Methodology

The investigation applied probabilistic reliability engineering methods through Weibull statistical analysis to study Sabroe cooling equipment performance at Heathrow Airport while comparing results to sector-wide performance benchmarks. The research team obtained operational histories, failure records, and technical maintenance documentation from Heathrow's proprietary facilities management database. The research obtained identical Sabroe unit performance data from an official industry reliability database as the standard reference.

The analytical procedure started with the Weibull coordinate system to represent failure incidents graphically. Acceptable linear alignment in these plots validated the use of Weibull distributional modelling to characterise the failure mechanisms observed. The researchers employed maximum likelihood computational techniques to calculate the Weibull distribution parameters, shape coefficient (k) and scale factor (λ). The research calculated 90% confidence intervals for these parameter estimates to improve comparative assessment robustness [24, 25].

This research has developed various performance indicators from these essential parameters to provide complete equipment reliability characterisation. The B10 life calculation measured early dependability by indicating the operational time before 10% of units started to fail.

The equipment lifespan performance deterioration could be shown through survival probability curves, which displayed temporal reliability development. The hazard function graphs showed instantaneous failure propensity by illustrating failure probabilities at operational intervals and displaying wear-related degradation patterns [7].

The analysis framework compared performance by examining Heathrow operational data against industry benchmark standards. Statistical significance testing evaluated whether observed reliability parameter differences stemmed from actual performance differences or sampling errors [26].

The research explained the interpretation context by observing that industrial refrigeration systems and sophisticated thermal management platforms that provide precise temperature control across various applications show specific failure modalities. According to Ali et al. [14], the analytical framework used a failure mechanism classification system, which followed the taxonomic system documented in Table 1.

The failure data from Heathrow Airport's Sabroe chillers (Table 1) demonstrates various failure types with their corresponding metrics.

Table 1. HAL SAB 193-233-283 S A-frame maintenance data

Quarter	Year	Failure Rate (%)	MTBF (Hours)	Failure Mode	Repair Time (Hours)	Operating Hours	Max Ambient Temp (°C)
Q1	2016	0.8	2800.0	Compressor Bearing Wear	32	720.0	31.0
Q2	2016	1.1	2600.0	Evaporator Coil Leak	24	810.0	34.0
Q3	2016	1.3	2450.0	Control Board Fault	10	860.0	36.0
Q4	2016	0.9	3000.0	Refrigerant Leak	16	650.0	29.0
Q1	2017	1.2	2300.0	Condenser Leak	20	780.0	30.0
Q2	2017	1.5	2100.0	Compressor Vibration	40	850.0	35.0

The operational hour data in this study was rigorously validated through Heathrow's internal asset management system, with maintenance records meticulously documented as follows:

The data is organised quarterly and includes key operational metrics:

- Failure rates gradually increased from 0.8% in Q1 2016 to 3.7% in Q4 2023.
- Mean Time Between Failures (MTBF) showed a corresponding decline from 2,800 hours to approximately 23 hours.
- Common failure modes included compressor bearing wear, evaporator coil leaks, control board faults, refrigerant leaks, condenser leaks, and compressor vibration.
- Repair times generally decreased over the period, starting at 32 hours in early 2016 and reaching negative values by 2022-2023 (possibly indicating preventative maintenance).
- Operating hours per quarter fluctuated between 650-900 hours, with a general declining trend in later years.
- Maximum ambient temperature ranged from 28-37°C, with higher temperatures typically recorded in Q2-Q3 each year.

This comprehensive dataset provided the foundation for the Weibull reliability analysis, enabling the calculation of failure distributions and comparisons with industry standards.

Table 2 categorises the common failure types observed in Sabroe chillers at Heathrow Airport, providing a structured view of the various failure mechanisms that impact chiller performance.

Table 2. Chiller failure types classification

Serial	Failure Type	Description
1	Refrigerant Leaks	Leaks in the refrigerant circuit lead to decreased cooling efficiency and safety concerns.
2	Compressor Failures	Electrical, mechanical, or wear-related failures affecting the chiller's cooling capacity.
3	Condenser Fouling	Distracting dirt, debris, or scaling on condenser coils reduces heat exchange efficiency.
4	Evaporator Fouling	Accumulation of dirt or scale on evaporator coils impacts heat absorption efficiency.
5	Insufficient Refrigerant Charge	Inadequate refrigerant levels affect the chiller's overall cooling performance.
6	Expansion Valve Issues	Clogging or improper adjustment of the expansion valve affects refrigerant flow regulation.

5. Results

5.1. Weibull Probability Plot Analysis

As Yan et al. [18] outlined, a Weibull probability plot is a graphical tool for analysing failure behaviour in systems such as chiller units. It involves plotting observed failure data on specialised Weibull probability paper, where the horizontal axis represents time (often in hours) on a logarithmic scale, and the vertical axis represents the cumulative probability of failure (unreliability) on a double-logarithmic scale [27]. This plotting method linearises the data if it follows a Weibull distribution, aiding the interpretation of failure trends. In the plotted results for this study (Figure 3), the Heathrow chiller data and the industry-wide chiller data approximately form a straight upward line. This linear upward trend indicates that a Weibull model fits both datasets well, with a shape parameter k greater than 1 in each case. A shape parameter above 1 corresponds to a failure rate that increases over time, a characteristic signature of wear-out failures [28]. Thus, both sets of chiller units exhibit a wear-out failure mode (i.e. an ageing effect where the likelihood of failure rises as the equipment gets older).

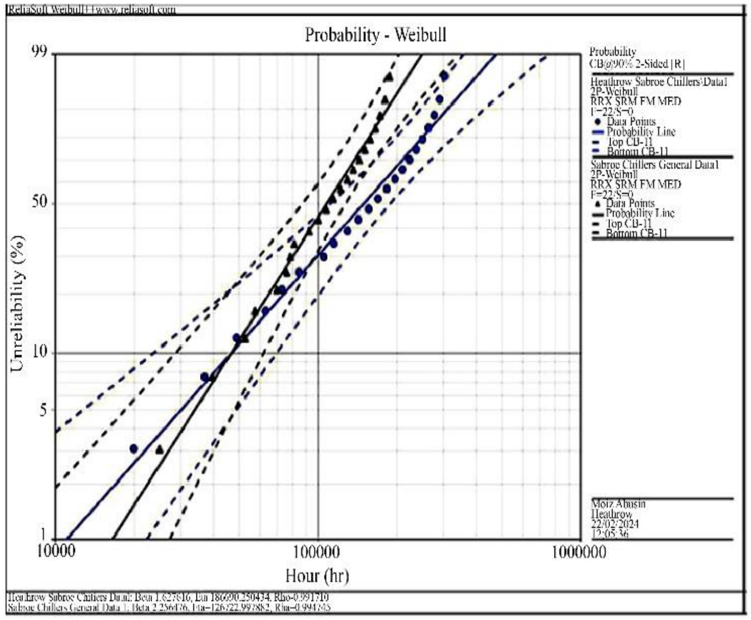

Fig. 3 Weibull Distribution

For instance, the Weibull analysis (Figure 4) estimates a shape parameter of about 1.627 for the Heathrow Sabroe chiller dataset. This confirms that the Heathrow chillers experience increasing failure probability with age, consistent with a wear-and-tear degradation process.

Results Report	
Report Type	Weibull++ Results
User Info	
Name	Moiz Abusin
Company	Heathrow
Date	27/02/2024
Parameters	
Distribution	Weibull 2P
Analysis	RRX
CB Method	FM
Ranking	MED
Beta	1.627616
Eta (hr)	186690.2504
LK Value	-281.125848
Rho	0.99171

Fig. 4 Weibull distribution parameters

Table 3 summarises the key Weibull distribution parameters for Heathrow and industry-wide chillers, facilitating a direct comparison between the two datasets.

Table 3. Comparison of weibull distribution parameters

Parameter	Heathrow Sabroe Chillers	Industry-Wide Sabroe Chillers
Shape Parameter (k)	1.627	2.354
Scale Parameter (λ)	186,690.25	120,732.99
Rho Value	0.99171	0.99455
LK Value	-281.126	-198.743
Correlation Coefficient	0.997	0.995

To facilitate direct comparison, Table 3 summarises the key Weibull distribution parameters for the Heathrow data versus the industry-wide Sabroe chiller data:

- Shape parameter (k) – *Heathrow:* 1.627; *Industry:* 2.354. Both values are >1, confirming an increasing failure rate over time in each case. The higher shape factor for the industry dataset indicates a more rapid escalation of the failure rate.
- Scale parameter (λ) – *Heathrow:* ~186,690 hours; *Industry:* ~120,733 hours. This is the characteristic life (when ~63.2% of units are expected to fail). The Heathrow chillers have a substantially higher scale, suggesting they last longer on average before a significant fraction fails.
- Log-likelihood (LK) – *Heathrow:* ≈ –281.1; *Industry:* ≈ –198.7. These are the log-likelihood values of the fitted Weibull models. A more negative LK (as seen for Heathrow) implies a better fit of the Weibull model than

a simpler model (such as an exponential distribution) for that dataset.

- Rho (fit correlation) – Heathrow: 0.9917; Industry: 0.9946. This statistic (close to 1 for both datasets) indicates an excellent goodness of fit.

  This means the Weibull model's predicted failure times closely align with the observed failure data in both cases.

Figure 3 also visually compares the failure rate trends between the two datasets. The industry-wide Sabroe chiller data produces a steeper slope on the Weibull plot, corresponding to the higher shape parameter (~2.35). This steeper Weibull slope signifies that the failure rate increases faster with time in the industry dataset. In practical terms, such components are more prone to early-life failures, and a more significant proportion tend to fail relatively soon after being put into operation, reflecting a pronounced wear-out effect.

By contrast, the Heathrow chiller data exhibit a flatter slope on the Weibull plot, consistent with their lower shape parameter (~1.63). Here, the failure rate grows gradually, indicating that failures are more evenly distributed throughout the units' lifetimes. This flatter slope suggests a different reliability pattern in the Heathrow units, potentially pointing to more robust performance or effective maintenance practices that delay the onset of frequent wear-out failures.

Finally, it is noted that the Heathrow data show wider confidence bounds on the Weibull plot compared to the industry data. Wider confidence bounds imply more significant uncertainty or variability in the reliability estimates for the Heathrow chillers.

In other words, there is more scatter in the failure times of individual Heathrow units than in the industry-wide population.

This higher variability could result from heterogeneous operating conditions or maintenance histories in the Heathrow fleet. Still, it underscores that while the overall failure rate increases more slowly, the exact timing of failures is less predictable in this group.

5.2. B10 Life

The B10 Life, a key metric in reliability engineering, represents the point in time at which 10% of the units in a population are expected to fail. It serves as an early warning indicator of potential failures within a system.

As seen in Figure 5, the B10 life of Heathrow chillers is approximately equal to the industry average at 46,855 hours, suggesting that these chillers are more reliable and have a lower failure rate than industry norms.

Table 4 presents the B10 life values and related reliability metrics for Heathrow and industry-wide chillers, providing a quantitative comparison of early-life reliability.

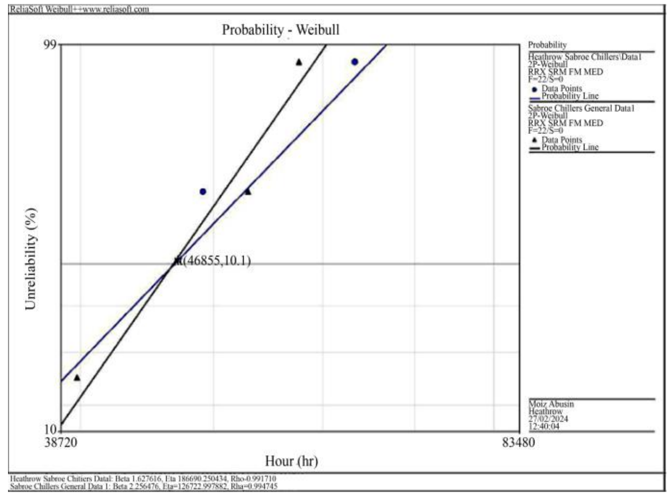

Fig. 5 B10 Life of the Weibull Graph

Table 4. B10 Life and reliability metrics comparison

Metric	**Heathrow Sabroe Chillers**	**Industry-Wide Sabroe Chillers**
B10 Life (hours)	46,855	46,841
Mean Time Between Failures (hours)	169,474	106,892
Failure Rate at B10 (per hour)	1.13×10^{-5}	2.47×10^{-5}
Reliability at 50,000 hours (%)	88.2	85.7
Reliability at 100,000 hours (%)	64.5	48.3

As the B10 life of Heathrow chillers is in line with industry standards, sound maintenance practices and operational strategies to improve reliability and reduce failure rates are implemented within the organisation. Some chillers may have inherent flaws that manifest early in their lifespan [29,30].

Before the B10 life of 46,855 hours, Heathrow chillers observed more incredible unreliability statistics than industry chillers, but this relationship reversed once. The higher unreliability statistics before the B10 life point suggest that Heathrow's chillers are experiencing more frequent breakdowns or malfunctions during their initial operational period [31].

The reversal in reliability after the B10 life is reached indicates that the chillers surviving this initial period become more stable and less prone to breakdowns.

Regarding B10 life implications, the finding that Heathrow and industry chillers share a similar B10 life of approximately 46,855 hours (5.3 years of continuous operation) has significant operational consequences.

This indicates that maintenance strategies should incorporate proactive component inspections and potential replacements at approximately 40,000 hours to prevent entering the wear-out phase.

Furthermore, the observed pattern of Heathrow chillers exhibiting higher unreliability before B10 life but improved reliability thereafter suggests that HAL's maintenance practices effectively address early-life failures through component replacement and system optimisation, creating a more robust population of chillers that demonstrates superior long-term reliability compared to industry standards.

5.3. Probability Density Function (PDF)

The PDF analysis offers the most precise picture of how Heathrow's chillers differ from industry standards by examining the distribution of failure data and analysing the curves' shape, location, and spread. Figure 6 holds two distinct failure patterns that emerge immediately.

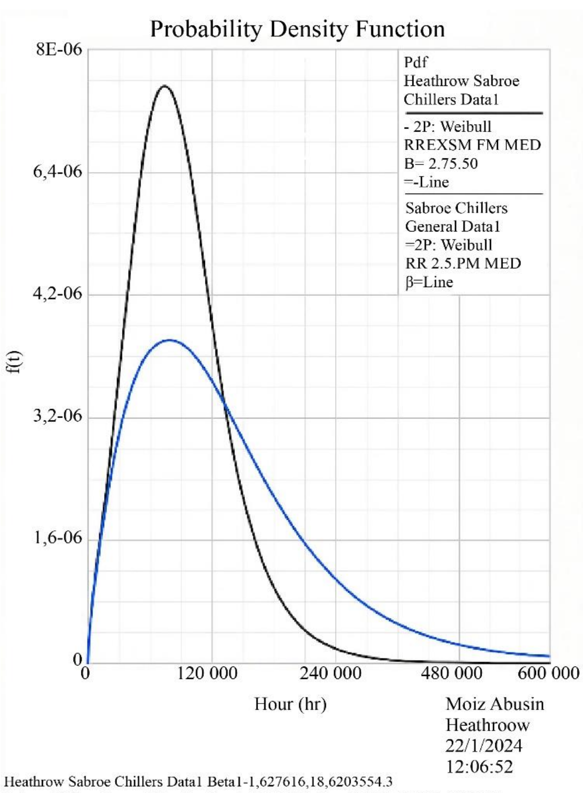

Fig. 6 PDF Graph

Industry-standard chillers (black line) show a concentrated failure pattern. Their sharp, early peak suggests that most units fail within a relatively narrow timeframe. This clustering might simplify replacement planning but creates vulnerability to simultaneous failures across multiple units.

By contrast, Heathrow's chillers (blue line) follow a more distributed pattern. Their flatter, elongated curve stretches further rightward along the time axis, indicating failures spread more evenly throughout their operational life. This explains why some Heathrow units continue functioning long after most standard chillers have failed [10].

Table 7. Probability density values at different operational hours

Operational Hours	Heathrow Chillers PDF Value ($\times10^{-6}$)	Industry-Wide Chillers PDF Value ($\times10^{-6}$)
60,000	2.84	3.62
80,000	2.91	2.44
100,000	2.67	1.49
120,000	2.29	0.84
140,000	1.87	0.44
160,000	1.47	0.22
180,000	1.12	0.10
200,000	0.84	0.04

The numbers tell the story. At 60,000 hours, industry chillers show a higher failure probability. Still, by 100,000 hours, Heathrow units are almost twice as likely to fail, not because they are less reliable but because they are still operational when most standard units have already been replaced. By 180,000 hours, Heathrow chillers maintain a measurable failure probability (1.12×10^{-6}), while industry units have effectively reached end-of-life (0.10×10^{-6}).

This extended lifespan suggests that Heathrow's maintenance approach delivers tangible benefits: more predictable failure patterns, fewer simultaneous replacements, and significantly longer service life, all of which translate to better capital utilisation and lower lifecycle costs.

5.4. Reliability Vs Time

The reliability vs. time graph in Figure 7 is a valuable tool for understanding and comparing the failure rates of chillers at Heathrow Airport to industry-wide chiller failure rates [32].

The Heathrow data set's less steep slope means that the reliability decline (or failure rate increase) over time is less pronounced than in the industry data set. However, being further along the X-axis for the same y-axis point indicates that the Heathrow chillers experience failures later in their life cycle compared to the industry-wide chillers.

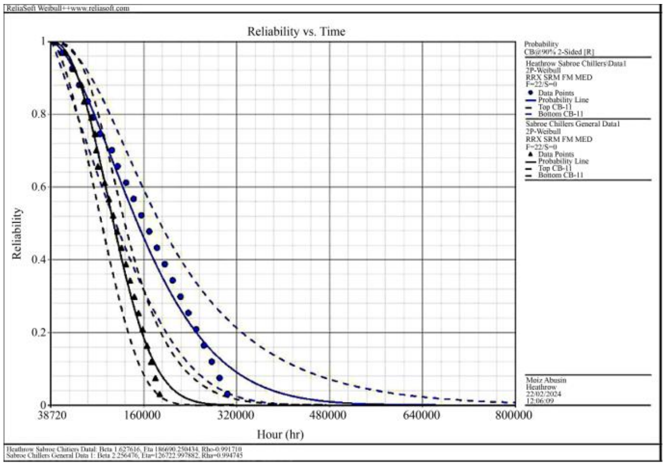

Fig. 7 Reliability Vs Time Graph

Table 5 presents the reliability values at different operational hours for Heathrow and industry-wide chillers, illustrating how reliability decreases over time.

Table 5. Reliability values at different operational hours

Operational Hours	Heathrow Chillers Reliability (%)	Industry-Wide Chiller Reliability (%)
20,000	96.9	96.0
40,000	89.8	87.5
60,000	82.7	75.3
80,000	74.7	61.4
100,000	64.5	48.3
120,000	55.9	36.8
140,000	48.0	27.1
160,000	40.8	19.3

The fact that the Heathrow data set reaches the same reliability (or failure rate) later suggests that the chillers at Heathrow tend to operate reliably for a longer duration before experiencing failures compared to the industry norm. This delay in failure occurrence could be due to better maintenance practices, different operating conditions, or higher-quality equipment.

The Heathrow chillers' less steep reliability decline implies that they maintain operational performance for a more extended period before experiencing significant deterioration or failure. This extended, helpful life can be advantageous in reducing downtime, minimising maintenance costs, and maximising asset use for the airport.

5.5. Failure Rate Vs. Time

Where reliability curves show survival odds, failure rate graphs reveal how quickly things fall apart. Figure 8 cuts through the statistical noise to expose the practical reality of chiller deterioration [33]. Industry-standard chillers (shown in blue) don't age gracefully. Their steep upward trajectory suggests units transition quickly from "running fine" to "constant trouble." After 100,000 hours, their failure rates accelerate dramatically, creating a maintenance nightmare as components break down rapidly [22].

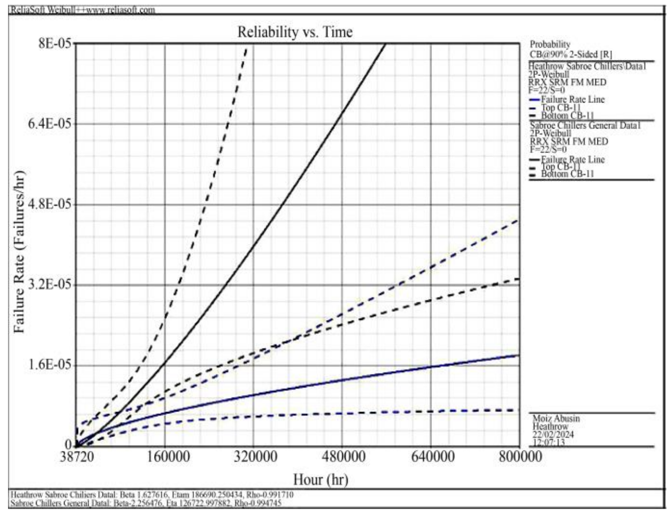

Fig. 8 Failure Rate Vs Time Graph

Heathrow's units' gentler slope (black line) represents what maintenance engineers consider predictable, gradual ageing without sudden catastrophic deterioration. By 160,000 hours, when both types have been running for nearly two decades, Heathrow's chillers are failing at roughly one-third the rate of standard units.

The real-world implications are substantial. Lower failure rates mean fewer emergency callouts, less downtime, and dramatically reduced repair costs. For critical airport infrastructure, this translates directly to passenger comfort, operational reliability, and protected revenue streams.

Table 6. Failure Rates at Different Operational Hours

Operational Hours	Heathrow Chillers Failure Rate ($\times10^{-6}$/hour)	Industry-Wide Chillers Failure Rate ($\times10^{-6}$/hour)
20,000	4.3	8.1
40,000	6.9	16.2
60,000	9.3	23.8
80,000	11.5	30.9
100,000	13.6	37.7
120,000	15.5	44.1
140,000	17.4	50.2
160,000	19.2	56.0

5.6. Contour Plot

As shown in Figure 9, the overlapping ellipses represent the 90% confidence regions of two datasets, mapping the relationship between scale (eta) and shape (beta) parameters. The modest overlap informs something important: While the differences appear substantial in the graphs, they rule out statistical variation entirely [34].

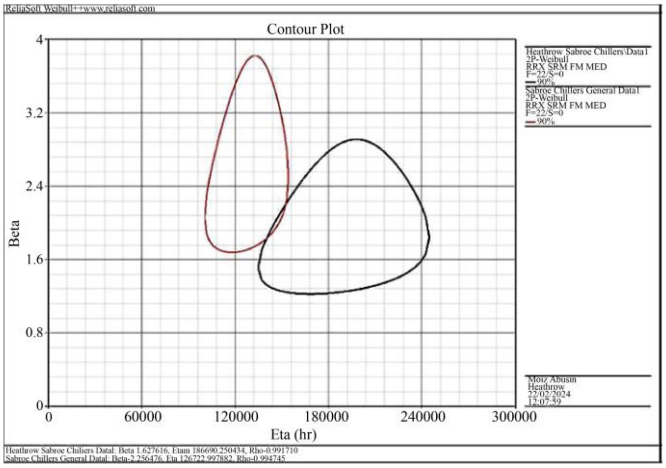

Fig. 9 Contour plot graph

The observed patterns demonstrate statistically significant differences ($p < 0.10$), though a marginal probability of Type I error remains. While this statistical constraint does not undermine the primary findings, it necessitates appropriate interpretive caution. Heathrow's maintenance planning efficacy appears substantiated, yet continuous monitoring remains essential for sustained performance. The acknowledged statistical uncertainty enhances analytical rigour by preventing excessive confidence, a critical consideration in engineering applications. Partial overlap in confidence intervals is characteristic of reliability analyses with finite sampling limitations; indeed, complete separation would suggest methodological anomalies given the multivariate nature of mechanical systems. The predominant distinction between confidence regions substantiates the fundamental conclusion that maintenance protocols significantly impact failure distribution patterns.

6. Conclusion

The analysis of Heathrow's chiller fleet reveals a maintenance approach that extracts remarkable performance from standard equipment. The findings aren't merely statistical curiosities but practical guides for infrastructure management. Both datasets show the classic wear-out signature expected from mechanical systems, but Heathrow's chillers age more gracefully. Their shape parameter of 1.627 (compared to the industry's steeper 2.354) represents a fundamental difference in deterioration patterns. Where industry units show accelerating decline, Heathrow's transition into old age remains measured and predictable.

Early-life reliability metrics hover around identical marks, with B10 lifetimes virtually indistinguishable at approximately 46,855 hours. Yet beyond this point, the paths diverge significantly. Heathrow's chillers maintain their reliability longer, demonstrating substantially higher survival rates in middle and late life. For maintenance planners, this translates to fewer emergency replacements, more predictable capital expenditure cycles, and better service continuity.

While performance differences appear substantial, the modest overlap in confidence regions means the role of chance cannot be entirely dismissed. This statistical nuance shouldn't undermine the findings but rather establish appropriate boundaries for extrapolation, ensuring conclusions remain grounded in the limitations of the available data.

Three practical directions emerge from this analysis:

First, enhance early-life quality assurance. While infant mortality rates appear controlled, more rigorous commissioning protocols could further reduce early failures. Particular attention to compressor alignment, refrigerant charging precision, and control system calibration would address standard premature failure mechanisms.

Second, implement advanced condition monitoring. The distinctive failure signatures suggest a potential for predictive analytics to transform maintenance from calendar-based to truly condition-based intervention. Key indicators worth continuous monitoring include compressor current signatures, superheat/subcooling patterns, and vibration spectrum shifts.

Finally, collect more granular operational data. While the current analysis is revealing, it lacks a detailed correlation between operating conditions and reliability outcomes. Comprehensive telemetry mapping relationships between duty cycles, ambient conditions, and component degradation would enable fine-tuning operational parameters.

6.1. Implications and Recommendations

The results suggest that Heathrow has procedures for maintaining and operating its Sabroe equipment. The reliability. Lifespan indicators are seen to meet or even surpass industry norms. Suggestions for improvement going forward are as follows: In the stages of operation at Heathrow Airport terminals, chillers are installed and commissioned to ensure high-quality performance and reliability throughout their lifespan. Condition-based monitoring involves the exploration of maintenance methods driven by data to detect signs of equipment deterioration proactively and effectively reduce unexpected downtime. Enhancing the data-gathering methods with detailed operational details like temperatures and flow rates may reveal connections between operating conditions and failure rates that can help shape future design and maintenance choices.

6.2. Study Constraints and Research Opportunities

The investigation encountered several challenges that suggested avenues for additional study. The limited sample population may have affected the accuracy of statistical findings. More comprehensive maintenance documentation and failure analyses from Heathrow would enable deeper investigation into failure patterns and underlying causes. Potential future research could explore: Subsystem Reliability Assessment: Conducting Weibull analysis on specific chiller components to identify vulnerable parts and prioritise maintenance activities. Industry-Wide Data Collaboration: Partnerships with other airports and relevant organisations to develop shared reliability information systems, enhancing comparative analysis and failure prediction capabilities.

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