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Through-life stochastic carbon emission assessment and optimisation for critical assets

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A R T I C L E I N F O

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A B S T R A C T

International governments and businesses are increasingly pledging more action to address human-induced climate change, including committing to the Paris Climate Agreement, which seeks to reduce global Greenhouse Gas Emissions (GHGE). Critical assets provide essential capabilities where failure could have catastrophic consequences. These assets have long service lives and are exposed to varying operational conditions and service requirements, which makes assessing through-life GHGE challenging. Current modelling techniques provide deterministic, single-point results, which provides a limited assessment of critical asset through-life GHGE where uncertainty can be significant. Furthermore, no modelling technique was identified that relates asset GHGE to Whole Life Cost (WLC) and operational effectiveness, which are both organisational priorities. This leaves decision-makers without robust information regarding the possible impacts of GHGE reduction strategies on the WLC and the operational effectiveness of their critical assets. This study develops a methodology framework to model critical asset GHGE with WLC and operational availability based on industry best practices and transferrable modelling techniques from other sectors. A model was created based on an in-service helicopter platform and was subjected to four test scenarios to demonstrate effects on WLC, GHGE and operational availability relative to baseline. Monte Carlo simulation was used to appropriately present modelling uncertainty.

1. Introduction

Human-induced Greenhouse Gas Emissions (GHGE) are causing global climate change and consequential events like extreme flooding, drought, rising sea levels and melting polar ice (International Panel on Climate Change, 2021). Increasing awareness of these effects has generated commitment from international governments to reduce GHGE via the Paris Climate Agreement to keep global temperatures within 2 °C of pre-industrial levels (Zhu et al., 2018).

National administrations and governments are setting targets, strategies, and requirements to reduce GHGE in line with the Paris Climate Agreement to reach net-zero GHGE (United States of America Government, 2021; The European Commission, 2018; Yang et al., 2020; Environment and Climate Change Canada, 2022; Department for Environment Food and Rural Affairs, 2019a). There are various processes, tools, and consultancy services available that can calculate GHGE at a corporate level and for engineering assets in a generic sense (Department for Environment Food and Rural Affairs, 2019a; United States Environmental Protection Agency, 2021; Ntziachristos et al., 2021; Greenhouse Gas Protocol; Department for Environment Food and Rural Affairs, 2019b; ThrustCarbon. Thrust Calculator; Carbon-Independent.org, 2022; United States Environmental Protection Agency, 2022; Carbon Trust, 2022) methodologies only provide single-point estimates with no indication of uncertainty or risk impact (Zhu et al., 2018; Hart and Jacobson, 2011).

Critical assets are defined with regards to asset-intensive industries where organisational performance depends heavily on complex and expensive physical asset reliability (e.g., aviation, transportation, manufacturing etc) (Moerman et al., 2020). Critical asset failure can have damaging consequences for an organisation regarding safety, cost and environmental factors which can cause reputational damage and further impacts to wider society. Critical assets commonly include complex “Major” assets with service lives lasting decades [18, p.3] which can create considerable risk and uncertainty to operational utilisation and associated GHGE. This is particularly pertinent when operational requirements and parameters are likely to change over the asset’s life cycle and demonstrates the key challenge related to GHGE quantification for critical assets.

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Furthermore, no standard methodology has been identified that demonstrates the effectiveness of GHGE reduction strategies/measures for critical assets in relation to effects on Whole Life Cost (WLC) and operational capability. This leaves critical asset owner/operators ill-equipped to model environmental impact optimisation in an affordable manner that ensures asset operational effectiveness.

This paper will fill this research gap by developing a novel and adaptable methodology that can be used by critical asset owners/operators to assess their GHGE and support decision-making. As such, the methodology must be able to calculate asset GHGE relative to WLC and operational effectiveness while meeting reporting requirements. A prototype model is created using an in-service helicopter platform as a case study. This demonstrates the effects of asset operational, design and/or supportability change scenarios to enable trade-off analysis and optimisation.

The novelty and originality of the developed methodology lie in the approach and modelling mechanics utilised to generate the results. Furthermore, the contribution of this paper enables critical asset owners/operators to better consider the environmental impact of their investment decision-making in a manner that currently is not possible.

2. Literature review

2.1. International commitment to reducing GHGE

Various international administrations have set legally binding GHGE reduction targets, including the United Kingdom (UK) (Climate Change Act, 2008, 2008), European Union (Regulation, 2021), Canada (Canadian Net, 2021), Japan (Act on Promotion of Global, 1998), South Korea (Grantham Research Institute on Climate Change and the Environment, 2021) and New Zealand (Climate Change Response, 2019). GHGE are quantified using the standard unit “CO2 Equivalent” (CO_2e) (Environmental Protection Agency (USA), 2014) which represents the amount of Carbon Dioxide required to cause the same atmospheric impact per unit of Greenhouse Gas (GHG).

A further demonstration of national commitment to GHGE reduction comes from the UK, where legal requirements were implemented in October 2013 for all quoted companies to report global GHGE in annual directors’ reports (Department for Environment Food and Rural Affairs, 2019b) via the Companies Act 2006 (The Companies Act, 2006, 2013). These requirements were broadened in 2019 (The Companies, 2018) to include:

- Global energy use and efficiency actions for quoted companies.
- UK energy use, GHGE and efficiency actions taken by large unquoted companies and Limited Liability Partnerships.
- Calculation methodologies.

The intent is to increase energy cost awareness, assist in planning GHGE reduction strategies and transparently present company green credentials to investors (Department for Environment Food and Rural Affairs, 2019a). Certain public sector bodies must also report GHGE in annual reports.

However, reporting commitments for unquoted small and medium companies remain voluntary (Department for Environment Food and Rural Affairs, 2019b), and certain public bodies are exempt (Department for Environment Food and Rural Affairs, 2019a), potentially creating sizable unreported GHGE. This calls into question the validity of reported UK GHGE.

2.2. GHGE reporting practices

Carbon accounting is considered one of the most promising ways of monitoring and reporting GHGE. Whilst different carbon accounting methods exist, it is broadly defined as quantifying, collating, measuring, and reporting GHGE and presenting costs of carbon offsetting (Stechemesser and Guenther, 2012). It applies financial accounting discipline and processes to quantifying company GHGE from direct and indirect operations (He et al., 2022). It is a commonly used mechanism to comply with reporting standards, including ISO14064 (Stechemesser and Guenther, 2012), GHG protocol (World Research Institute), ISO 14065 (British Standards Institute, 2021) and PAS 2050 (British Standards Institute, 2011).

Whilst this provides an emissions quantification platform, it does introduce questionable practices that demonstrate GHGE reductions without necessarily reducing emissions. Net GHGE are reported, which is total GHGE minus the GHGE removed from the atmosphere by other means (British Standards Institute, 2019). “Carbon offsetting” [28, p.30] is practised by companies that invest in programmes removing atmospheric GHGE, e.g. planting trees. Whilst effective in principle, this system is open to abuse because offsetting emissions may not address climate change impacts where emissions geographically occur. For example, sponsoring tree planting in Scotland will have a negligible effect on reducing local effects of emissions made by a company if their operations burn fossil fuels in Southern England.

“Greenwashing” (Edwards, 2022) occurs when companies publicise a commitment to carbon offsetting (featuring in their carbon account) that does not materialise. An example includes companies committing to planting trees where a considerable percentage died shortly after planting, which negates the carbon offset (Khadka, 2022) but will not feature in the companies’ carbon account.

Reducing GHGE to zero is impractical, and carbon offsetting will be required to some degree to negate residual GHGE (EquipmentSupport, 2021). Nonetheless, it is argued that reducing emissions at source is more effective because there is less uncertainty surrounding its effectiveness at removing atmospheric GHGs. Therefore, this study shall focus on enabling emissions reductions rather than using carbon offsetting to present more effective solutions.

2.3. GHGE modelling approaches

The academic literature review of relevant prior work and industry guidance provided an understanding of current GHGE modelling methodologies to identify transferrable techniques suitable for critical assets.

The United States Environmental Protection Agency utilise the “MOtor Vehicle Emission Simulator (MOVES)” [8, p.3] to model land vehicle GHGE. MOVES creates a bottom-up estimate using average empirical emissions rates for similar vehicles and applying different factors to replicate real-world scenarios. “COPERT” is the equivalent model adopted by the European Environment Agency and uses a similar approach based on average vehicle emissions factors depending on type, operational environment and activity (Ntziachristos et al., 2021). Wang et al. (2021) used processes from COPERT and MOVES to model GHGE for car parking and whilst their model is very specific, MOVES and COPERT principles can be applied to critical assets. Xu, Dong and Yan utilise a similar approach to model car GHGE on different road gradients by combining theoretical calculation with experimental results (Xu et al., 2020). The model proved effective but required detailed understanding of relevant physical and chemical processes being modelled which would be impractical for critical asset owners/operators to obtain.

Sun et al. applied an input-output model to analyse GHGE from Chinese urban areas (Sun et al., 2021). Their approach categorised different industry sectors emitting GHGs and modelled dependencies between each to calculate GHGE. Daryanto, Wee and Astani adopted a similar approach to model GHGE from different elements of a “Three-echelon supply chain” [40, p.368] throughout the asset lifecycle to enable cost and GHGE optimisation. Both approaches modelled GHGE for each operational element to identify where efficiencies were possible. Asset lifecycle GHGE are also considered by Luo and Chen who model GHGE for residential buildings by applying the “Life Cycle

Assessment method" [41, p.1].

Gao et al. utilised their "Novel fractional grey riccati model" [42, p.1] to model national scale GHGE, but this required complex mathematical processes and modelling, which may not be available to critical asset owners/operators.

2.4. Modelling uncertainty

The modelling approaches identified are generally utilised with minimal consideration of uncertainty regarding operational futures, and modelling outputs present a single data point. Hart and Jacobson, and Lee et al. compound this observation by stating that most GHGE models present the "Deterministic" output [16, p.1] based on linear models that multiply coefficients by specific units (Lee et al., 2020). Zhu et al. state that considering uncertainty generates more scientific results, and modelling using fixed rates (rather than ranges) creates unrealistic forecasts (Zhu et al., 2018). Smith and Mastorakos demonstrate the importance of presenting uncertainty by predicting that a hydrogen fuel cell-powered aircraft could fly between 415 and 4,571 km at 95% confidence (Smith and Mastorakos, 2019). This large range has considerable implications regarding future operational planning, and being informed of this uncertainty is impossible when only considering single data points.

This is acknowledged by the UK Ministry of Defence (MoD) via Joint Service Publication (JSP) 507 (Ministry of Defence, 2014). This publication governs MoD investment decision making and requires projects to demonstrate how risks affect WLC and asset operational effectiveness before investments are approved. JSP 507 recommends using Monte Carlo Simulation (MCS) to assess impacts of risk and uncertainty on WLC and operational effectiveness (Lindop, 1998).

This approach is further supported by the American Department of Defence (DoD) who recommend MCS for modelling Reliability, Availability and Maintainability (RAM) (The Department of Defence (USA), 2005).

2.5. Utilising MCS for GHGE modelling

Modelling through-life GHGE with MCS is not well established for critical assets, and Table 1 shows examples of prior MCS applications for modelling GHGE.

MCS versatility enables application for modelling critical asset GHGE, particularly when coupled with examples of scenario testing (Zhu et al., 2018; Lee et al., 2020; Huo et al., 2021; Tsiakmakis et al., 2016).

2.6. Research gap

Despite legally mandated GHGE targets and increasingly stringent reporting requirements, many countries are not predicted to meet Paris Climate Agreement targets (Climate Change Committee, 2021; United Nations, 2022). Furthermore, literature review could not identify any methodology that simultaneously models asset operational effectiveness, WLC and GHGE which also considers and presents uncertainty.

Table 1
MCS GHGE modelling summary.

Researcher(s)	MCS application
Hart and Jacobson (Hart and Jacobson, 2011)	GHGE for energy systems heavily reliant on renewables.
Huo et al. (Huo et al., 2021)	GHGE of residential buildings by considering possible future scenarios.
Lee et al. (Lee et al., 2020)	GHGE of cattle based on different feed types.
Sim (Sim, 2018)	Container shipping terminal GHGE.
Tsiakmakis et al. (Tsiakmakis et al., 2016)	GHGE impact by adopting new light-duty vehicle technologies.
Zhu et al. (Zhu et al., 2018)	Power generation sectors GHGE based on predicted government policies.

This study shall develop a modelling methodology and MCS prototype to fill this research gap to enable options analysis for optimisation and provide investment decision support to critical asset owner/operators.

3. Methodology

Fig. 1 demonstrates the adopted research methodology overall approach.

The means to calculate required modelling outputs were determined to identify data input requirements based on industry recommendations from (Institute of Chartered Accountants for England and Wales).

Ultimately, anticipated asset utilisation and operational use determine modelling processes and logical relationships between variables which depends on the considered asset lifecycle. The proposed solution considers the whole life of the critical asset, which is called the "Product life cycle" [54, p.9] It equates to the "CADMID cycle" [54, p.16] defined as Concept, Assessment (definition), Manufacture (development), In service (operation) and Disposal (termination).

For the prototype model, anticipated asset operational utilisation was determined by historical data, reviewing asset records and artifacts and consultation with a logistics and cost modelling expert. Mathematical formulae used for modelling was based on the requirements for deterministic and MCS simulation techniques identified in the literature review and were developed based on dependencies and logic between operational activities.

The developed methodology is tested for realism and practical application by using a case study to build a prototype model representing a suitable critical asset. For this study, an in-service helicopter platform is selected as a critical asset as it provides key operational capability to public interest operators (such as fire services, health operators and military), including logistical support, humanitarian aid, and surveillance. Asset failure could cause loss of such capability and result in operational failure, which could have severe consequences given the heightened hazard exposure risks associated with operations in sensitive locations. Furthermore, such failures are expensive to rectify and could easily cause public interest operator reputational damage given its public and political scrutiny.

The study aims to develop a methodology with practical applications; therefore, input modelling data must either be available or enable suitable assumptions to be made (NASA. Cost and Duggleby, 2020). Data availability was assessed via review of public resources and restricted information sources, including maintenance databases, contracts, asset performance metrics and risk registers. Uncertainties associated with input variables required three-point estimates for Minimum (optimistic), Most Likely (ML) and Maximum (pessimistic) conditions (Rogers, 2020). Where data did not exist, suitable assumptions were

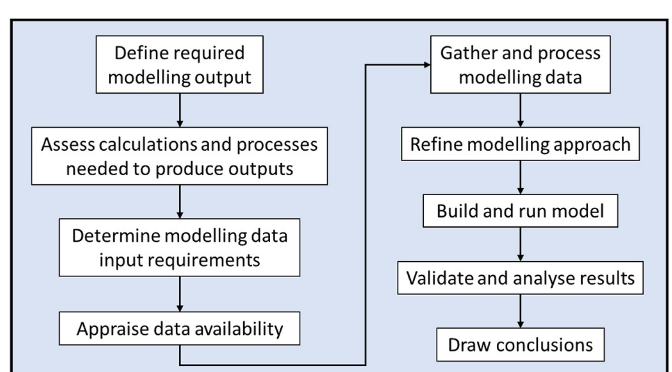


Fig. 1. Research methodology.

agreed upon and captured in collaboration with two industry experts.

Modelling logic and formulae were adjusted based on data availability analysis and a deterministic model representing asset baseline was created in Microsoft Excel with Excel plug-in software @Risk utilised to perform MCS. Probabilistic and deterministic outputs were compared to gauge impact of uncertainty.

Test scenarios were created to model the effects of potential GHGE reduction strategies which required adjusting modelling input parameters for each scenario based on predicted impacts. The deterministic calculation and MCS were executed for each scenario and outputs were compared to baseline to demonstrate each scenarios impact.

This enables trade-off assessment and optimisation to support key decision-making.

For the validation of the model, outputs were presented in conjunction with methodology and modelling mechanics to a group of experts (Table 2) associated with the case study. Semi-structured interviews were used to capture feedback. Validation is provided by gathering interview feedback regarding output usefulness for business areas, methodology suitability and value generation. In addition, modelling implementation challenges and areas requiring further development/research were captured.

4. Framework development and case study

4.1. Solution framework

The developed modelling methodology framework is presented in Fig. 2 and is based on guidance from the American National Aeronautical and Space Administration (NASA) (NASA. Cost and Duggleby, 2020), PAS2080 (British Standards Institute, 2016), Department for Environment, Food and Rural Affairs (Department for Environment Food and Rural Affairs, 2019a) and the American DoD (The Department of Defence (USA), 2005). A logical flow of activities was utilised that centres around first defining the model boundaries and understanding the required outputs. The mathematical formulae and relationships/dependencies between variables required to deliver the outputs were defined based on real-world interactions and planning assumptions. This ultimately dictated the data input requirements, and modelling mechanics were developed and refined based on available data gathered and processed to produce a deterministic baseline output.

Different scenarios were developed based on strategies to reduce asset GHGE. The impacts on modelling inputs caused by each scenario are defined and incorporated into the modelling mechanics to produce a deterministic output for each scenario. MCS was then performed for the baseline and each scenario to produce probabilistic outputs which were then reviewed and verified. A feedback loop is utilised which enables planning assumptions and modelling mechanics to be developed in cases where outputs were deemed unrealistic or unreasonable.

Table 2
Expertise summary.

Expert	Expertise
One	Helicopter integrated logistics support and cost modelling expert with extensive experience of RAM and WLC modelling techniques. Chosen because of in depth experience following similar methodologies to different helicopter platforms.
Two	Senior sustainability engineer within a UK government department. Chosen because they provide insight from the end user perspective regarding methodology realism and practical application.
Three	Leading military sustainability engineer responsible for creating and implementing sustainability policies. Chosen because they understand the challenges when planning and implementing net zero strategies and provides an informed assessment of the methodologies applicability and value offered.
Four	Senior cost modelling consultant, chosen because their experience building RAM and WLC models provides an informed assessment of modelling mechanics and techniques suitability.

Once content, the scenario modelling outputs were compared to the baseline to ascertain the impact each scenario has on cost, operational effectiveness and GHGE.

The relationship between cost and operational effectiveness is well established. This can be understood by using Operational Availability (A_o) (defined in section 4.3) as an example of operational effectiveness. In-service cost depends on asset utilisation rate and how often maintenance is required because items like fuel, spares and labour come at a cost. Availability is a function of reliability and maintainability (Blanchard, 2013) which defines asset failure rate (Stapelberg, 2009) and the probability that maintenance actions can return it to agreed levels of effectiveness (Smith, 2017). This defines maintenance duration and frequency, and cost modellers can use this information to predict resources and costs required to deliver different support solutions.

The proposed solution builds on this by calculating the assets GHGE relative to WLC and A_o. An in-service helicopter platform has been used as a case study to test the developed framework whereby mathematical relationships between RAM, WLC and GHGE are determined and fed into deterministic and MCS models. The platform is referred to as "Helicopter X" with RAM, operational and cost data being altered from source to ensure asset anonymity whilst also enabling a useful and realistic analysis.

4.2. Model boundaries

The guidance recommends defining organisational and system boundaries (Department for Environment Food and Rural Affairs, 2019a; Sim, 2018; NASA. Cost and Duggleby, 2020; British Standards Institute, 2016) to explicitly define model scope. An initial review was conducted of the software tool used by the operator to log helicopter maintenance actions to establish Reliability, Availability and Maintainability (RAM) asset data availability. It shall be referred to as "Maintabase" to protect its identity.

A Maintabase extract was obtained containing Preventive and Corrective Maintenance (PM and CM respectively) data for the helicopter fleet, including maintenance action duration and aircraft flight-hours when the action was required. PM is captured at platform level and CM is logged for each of the 40 aircraft systems. Acknowledging asset complexity and resources available for this study, a Paretos analysis is recommended by (Mokashi et al., 2002) and was performed to focus on the 11 systems (25%) that cause 74% of total aircraft CM to balance time efficiency and modelling effectiveness. These 11 systems are presented in Fig. 3 which shows the helicopter Product Breakdown Structure (PBS) (Weaver, 2014), categorised in terms of PM and CM. The system names differ from source data to protect their identity.

Maintabase also presents RAM data at sub-system level below that presented in Fig. 3, however, analysing to that level of detail increases complexity, delivers limited additional value and adds further data capture, processing and management burdens. Therefore, performing the analysis at the system level was deemed the optimal solution that could be developed in future work.

The cost elements contributing to Helicopter X's WLC are defined in the Cost Breakdown Structure (CBS) (Weaver, 2014) presented in Fig. 4.

Defining GHGE scope can be challenging as organisational responsibility is not always clearly defined (Department for Environment Food and Rural Affairs, 2019a). Emissions for which the organisation is responsible, affected by its operations or can influence environmental or social impacts should be included (Climate Disclosure Standards Board, 2022). GHGE are commonly categorised as per Table 3 [7, p.60]. These scopes inform the Helicopter X Carbon Breakdown Structure (CO_2BS) presented in Fig. 5. GHGE include any qualifying substance under the Kyoto Protocol (The United Nations, 1997) and quantified using $KgCO_2e$ (Environmental Protection Agency (USA), 2014).

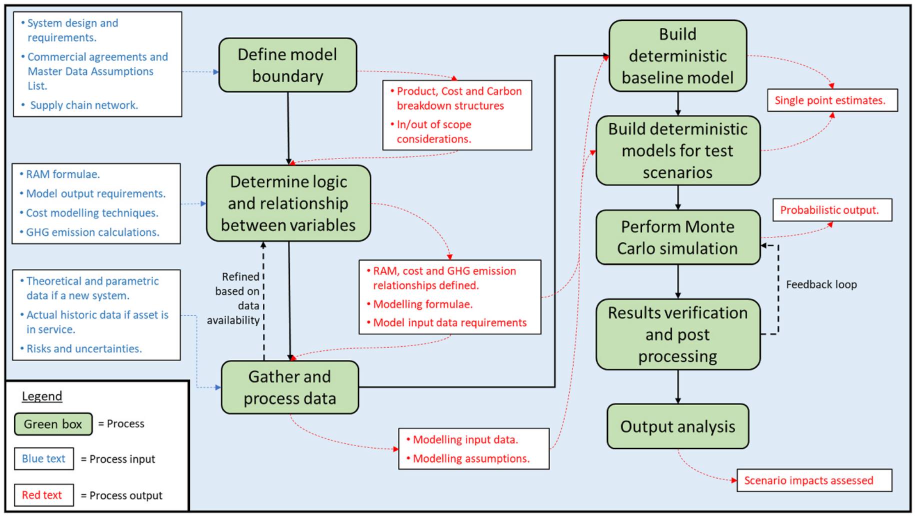


Fig. 2. Proposed solution framework.

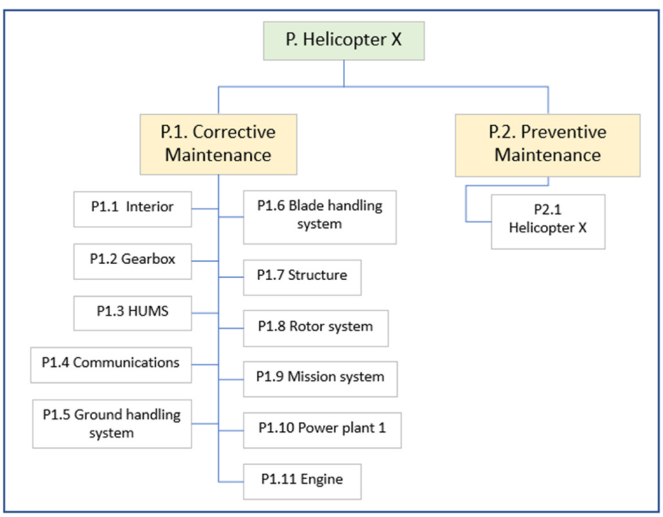


Fig. 3. Helicopter X PBS.

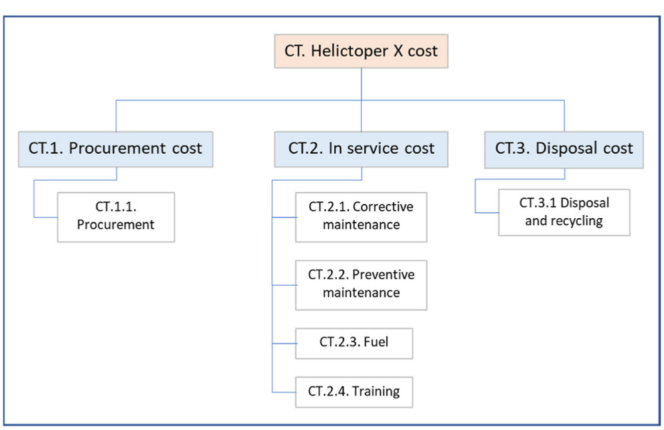


Fig. 4. Helicopter X CBS.

4.3. Determine model logic and gather and process data

It is important clarifying how Operational Availability (A_o), Whole life cycle (WLC) and GHGE are calculated based on data availability for

Table 3
GHGE categorisation.

Scope category	Associated GHGE emissions
Scope 1	Direct emissions resulting from organisational activities.
Scope 2	Indirect emissions from purchased energy consumption.
Scope 3	Other indirect emissions from consequences of organisational activities, e.g. supply chain, business travel etc.

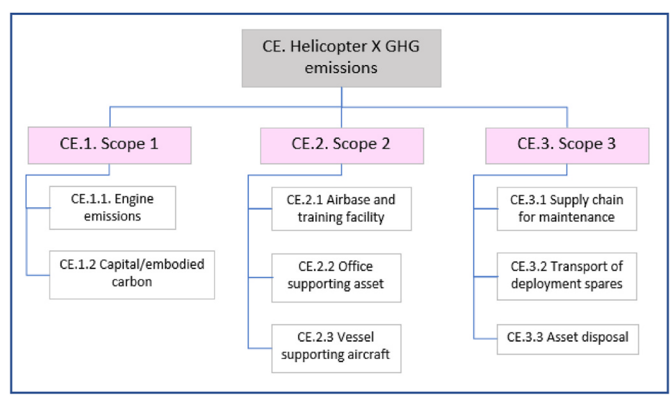


Fig. 5. Helicopter X CO_2BS.

developing the modelling logic. Data was captured from sources at different levels and processed into the format required to input into the model, including optimistic, ML and pessimistic estimates. Data unavailability was an issue and where data was not available, suitable estimates were made based on input from Subject Matter Experts (SMEs) (The Department of Defence (USA), 2005; Rodrigues et al., 2015). The modelling logic was refined in response to data availability to ensure the model was developed organically and had practical applications.

4.3.1. Operational availability

Helicopter X must be maintained at an agreed level of availability to the owner/operator and this a key driver of its operational effectiveness. Whilst there are multiple ways of calculating an assets availability, Operational Availability (A_o) was chosen for this model because of its similarity to a Helicopter X Key Performance Indicator and is calculated as [66, p.182]:

$$A_o = \frac{\text{Total Time} - \text{NMCT}}{\text{Total Time}} \quad \text{Equation 1}$$

Non-Mission Capable Time (NMCT) is the total time Helicopter X is unserviceable (i.e. its total downtime) which equates to Mean Corrective Maintenance Time (MCT) plus Mean Preventive Maintenance Time (MPT). Helicopter X's utilisation changes depending on operator priorities and its annual utilisation will vary each year. Therefore, the model shall calculate NMCT annually and each years NMCT will be summed up to calculate through-life NMCT. The model assumes a 20-year service life (similar to Helicopter X), therefore the Total Time through-life is the number of hours in 20 years and if y = number of in-service years [66, p.182]:

$$\text{NMCT} = \sum_{y=1}^{20} \text{MCT}_y + \text{MPT}_{y+}\text{ALDT} \quad \text{Equation 2}$$

Administrative and Logistics Delay Time (ALDT) is included within maintenance durations logged in Maintabase and does not need to be considered separately. PM for Helicopter X occurs after a specified number of flight-hours, therefore based on (Jones, 2006):

$$\text{MPT} = \frac{\text{Expected Annual Flight Hours}}{\text{MTBPM}} \times \text{MTPM} \quad \text{Equation 3}$$

Mean Time Between Preventive Maintenance (MTBPM) is measured in flight-hours because asset utilisation is the key driver for degradation (rather than age) and is the main factor considered when system manufacturers develop PM plans. Mean Time of Preventive Maintenance (MTPM) is measured in labour-hours because this dictates maintenance action duration and how long the aircraft is out of service. The ratio of Expected Annual Flight Hours to MTBPM calculates how many PM periods are expected per year and multiplying this by the MTPM estimates the average annual time spent undergoing PM, i.e. annual MPT.

Similar to PM, Corrective Maintenance (CM) occurs after a system failure which happens after a number of flight-hours as this is the key driver to system degradation. Therefore, if systems being considered are numbered 1–11 and equal n (Jones, 2006):

$$\text{MCT} = \sum_{n=1}^{11} \frac{\text{Expected Annual Flight Hours}}{\text{MTBF}_n} \times \text{MTTR}_n \quad \text{Equation 4}$$

Similar to PM, Mean Time Between Failure (MTBF) is average number of flight-hours between system failure and Mean Time To Repair (MTTR) is average labour-hours required for system repair (Jones, 2006). Therefore, the ratio of Expected Annual Flight-Hours to system MTBF calculates the annual number of system failures and multiplying this by the system MTTR calculates how long the aircraft is out of service per year whilst the system is repaired. The sum of each system MCT calculates the total annual time the aircraft is out of service undergoing CM.

MTBPM and MTBF three-point estimates were calculated using the Maintabase extract whereby the largest and smallest differences in flight-hours between maintenance actions provided optimistic and pessimistic values whilst the Mode value provided the ML. MTPM and MTTR were calculated similarly by considering maintenance action durations.

4.3.2. Whole Life Cost (WLC)

Actual WLC data relating to Helicopter X is commercially sensitive and access was denied. Therefore, estimates and assumptions were created for WLC based on SME input and data from public sources. Table 4 presents each cost element calculation, data capture and processing methods used.

Costs are calculated in £UK per year in-service (y) without applying future inflation. The costs are normalised to model year zero for historic exchange rates (OFX) and inflation (CPI Inflation Calculator, 2021), therefore:

Table 4
WLC calculation methods.

Cost Element	Calculation method	Data capture and processing method
CT.1 Procurement		
CT.1.1 Procurement cost	Parametric estimate based on similar helicopters.	Normalised per unit procurement cost of four similar helicopter platforms gathered from (Bhattacharya, 2018; UK Parliament, 2007; Department of Defence (USA), 2021; Defence Management, 2009) and use of the "PERT" calculation (Mochal, 2007) generated three point estimates.
CT.2 In Service cost		
CT.2.1. CM	Estimated system repair cost based on MTBF.	Each system repair cost is based on estimated labour costs (a function of MTTR and required workforce hourly rate) and material costs required for optimistic, ML and pessimistic maintenance scenarios.
CT.2.2. PM	Assumes same maintenance cost per flight-hour as CT.2.1 multiplied by estimated annual flight-hours.	CM cost comes from CT.2.1 and estimated annual flight-hours is based on operator historic records.
CT.2.3. Fuel	A function of estimated annual flight-hours, aircraft fuel consumption and predicted aviation fuel market rate.	Based on historic fuel rates from (IndexMundi, 2022; Jet-A1-Fuel, 2022) and aviation fuel specific gravity from (Measurement Canada, 2016) to provide three-point estimate.
CT.2.4. Training	Based on similar aircraft training cost.	Annual cost per aircraft was calculated based on normalisation of (EquipmentSupport, 2018; Newdick, 2020) which presents the contract price for a similar helicopter training solution.
CT.3 Disposal		
CT.3.1 Disposal	Based on similar aircraft disposal costs.	Two-point estimate based on normalised unit disposal cost of a Blackhawk helicopter from (Department of Defence (USA), 2021) and a predicted 10% of procurement cost CT.1.1 based on fixed wing jets (Zhao et al., 2016). The actual cost is likely in-between these values as a large number of Blackhawk units were disposed of and helicopters generally have smaller disposal cost than fixed-wing aircraft (Centre for Public and Environmental Oversight, 1998).

$$\text{WLC} = \sum_{y=1}^{20} \text{CT.1}_y + \text{CT.2}_y + \text{CT.3}_y \quad \text{Equation 5}$$

Where CT.X_y are the individual cost elements defined in Table 4 and summing up their modelled values per year Helicopter X is in service will ultimately calculate its WLC.

Through life greenhouse gas emissions

Table 5 demonstrates each GHGE element calculation and data capture methods. Annual GHGE for each scope are calculated per year in-service (y) and the through-life GHGE equates to the sum of the calculated GHGE for each year Helicopter X is in service thus:

Table 5
GHGE calculation methods.

GHGE element	Calculation means	Data capture and processing methods
CE.1 Scope 1		
CE.1.1. Engine emissions	Estimating GHGE per flight-hour based on engine efficiency, consumption and estimated annual flight-hours.	Two-point estimate based on two calculation methods. Method one uses historic annual fuel consumption, average flight-hours and engine emissions data from engine manufacturer. Method two uses (Rindlisbacher and Chabbey, 2015) based on helicopter shaft horsepower, number of engines, time spent in each flight mode and conversions from (Climate Change Connection, 2020).
CE.1.2. Embodied carbon	Multiplying each component weight by a suitable "Embodied Carbon" factor (Jones and Hammond, 2019).	Weights per helicopter component were not available, therefore (Demircan et al., 2017) was used to calculate component weight based on its percentage of the assumed total weight. Component material was approximated based on material conversion factors from (Jones and Hammond, 2019; Composites UK).
CE.2 Scope 2		
CE.2.1. Airbase and training facility CE.2.2. Office supporting asset	It is assumed that Helicopter X is stationed at an airbase and that there is an office building that provides administrative support in a different location (shown in Appendix). Estimated facility annual electrical consumption is multiplied by "Electricity factor" from (Department for Business Energy and Industrial Strategy, 2021) and reduced based on the proportion of Helicopters X's fleet size vs all aircraft stationed at the airbase.	Three-point estimates were created based on historic power consumption for comparable sites.
CE.2.3. Vessel supporting aircraft	When Helicopter X is deployed at sea, the ship supporting it produces GHGE via Marine Gas Oil (MGO) combustion when generating power for aircraft support. The power required equals that calculated for CE.2.1. and the GHGE is calculated by multiplying the amount of MGO required by the relevant GHGE factor from (Department for Business Energy and Industrial Strategy, 2021).	Data sources stated in calculation.
CE.3 Scope 3		
CE.3.1. Supply chain	Calculations vary depending on whether Helicopter X is stationed ashore or deployed at sea. Based ashore: All system spares are transported to the airbase from the Original Equipment Manufacturer (OEM) facilities via the aircraft operator logistics hub in a similar manner to the UK MOD (Ministry of Defence, 2013). GHGE are based on road and sea miles travelled for deliveries between sites (shown in Appendix A), the GHGE factors from (Department for Business Energy and Industrial Strategy, 2021) and the estimated number of annual journeys. Deployed at sea: Spares for most critical systems are transported via airfreight to ship location and GHGE are based on predicted number of annual flights required, airmiles flown and GHGE factor from (Department for Business Energy and Industrial Strategy, 2021).	Road and sea distances between locations were calculated using Google Maps and (Ports.com, 2022). Air miles between Helicopter X's airbase and typical seaport destinations for spares deliveries came from (Distance.to. Distance Calculator, 2022). The number of annual deliveries per system was based in its criticality whereby more critical systems require more annual deliveries. The number of deliveries was then estimated based on system failure rates and consultation with a helicopter supply chain SME.
CE.3.2. Transport of deployment spares	Spares required for sea deployment are transported by road the relevant embarkation port and GHGE is based on road distance travelled, emissions factor (Department for Business Energy and Industrial Strategy, 2021) and predicted number of journeys.	Road miles and emissions data sources are identical to CE.3.1. Number of journeys is based on $\%_{deploy}$.
CE.3.3. Asset disposal	Assuming 90% of Helicopter X can be recycled (Airbus, 2021a), GHGE are based on energy required to recycle 90% of each material mass from CE.1.2 with the remaining 10% going to landfill using relevant GHGE factors from (Department for Business Energy and Industrial Strategy, 2021).	Disposal GHGE factors came from (Department for Business Energy and Industrial Strategy, 2021) and were calculated using the masses of approximated component materials in CE.1.2.

$$\text{Through-life GHGE} = \sum_{y=1}^{20} \text{CE.1}_y + \text{CE.2}_y + \text{CE.3}_y \qquad \text{Equation 6}$$

The model assumes Helicopter X has maritime applications and is deployed onboard a ship at sea for a certain number of years based on the likelihood of deployment ($\%_{deploy}$). For each year Helicopter X is deployed at sea, the model calculates GHGE accordingly for that year and this is factored into the through-life GHGE.

4.3.3. Risk

Risk impacts can cause additional CM throughout Helicopter X's life resulting in additional cost and GHGE. Therefore, each risk probability and impact are determined in terms of additional NMCT, WLC and GHGE on a case-by-case basis. These are added onto the respective totals to demonstrate the impact on model outputs. The risks applied to the model are based on the Helicopter X risk register; the specific details being commercially sensitive cannot be presented; however the authors can be contacted should further information be desired.

4.3.4. Additional considerations

4.3.4.1. Asset degradation. Helicopter system deterioration accelerates in-service (International Air Transport Association, 2018) which is accommodated by assuming a 2.02% increase in CM and PM actions per year based on linear extrapolation of data from Wyndham (2017) which states maintenance cost increases by 40.4% over a 20-year service life. Whilst this relates to cost increases and fixed wing aircraft, it is argued that increasing maintenance actions drive the cost increase and helicopters are similar enough to fixed wing aircraft to make this assumption reasonable.

4.3.4.2. Annual flight-hours. Annual flight-hours are based on historic analysis of the Helicopter X fleet to create a three-point estimate.

4.3.4.3. Likelihood of deployment. Likelihood of deployment ($\%_{deploy}$) was set at 20% based on input from Expert One.

4.4. Building a deterministic baseline

Striking a baseline defining Helicopter X's current performance enables comparison with test scenario outputs and is recommended by (Zhu et al., 2018; Huo et al., 2021; Brander et al., 2021; UK Government, 2021). Historic data informs this case studies model because Helicopter X is currently in-service. SME judgement and theoretical data sources should be used for assets pre-manufacture (The Department of Defence (USA), 2005) including:

- Failure Mode, Effect and Criticality Analysis (Jun and Huibin, 2012).
- Fault Tree Analysis (Cepin, 2011).
- Reliability Block Diagram (Blanchard, 2013).
- Level of Repair Analysis (UpKeep, 2019).

The deterministic model generated single-point outputs based on mean averages and the PERT technique applied to two and three-point data inputs to create single-point inputs. Outputs dependant on $\%_{deploy}$ were calculated assuming the output applied to every year in-service and was then either reduced by or to $\%_{deploy}$ for shore or sea-based outputs respectively.

4.5. Build deterministic test scenarios

Test scenarios were developed based on input from industry experts and UK MoD environmental policies (EquipmentSupport, 2021; Ministry of Defence, 2021) (because the MoD are helicopter owner/operates) as this explores potential GHGE reduction strategies which could be implemented for helicopter platforms. Modelling assumptions for each scenario were created and impacts on input variables were determined so that each output demonstrates the comparative value each scenario releases relative to baseline.

4.5.1. Scenario one: switch to sustainable aviation fuels

Helicopter X immediately switches to 50/50% blend of Sustainable Aviation Fuels (SAF) (Airbus, 2021b) which increases to 75/25% at year three and then 100% at year 7. SAF costs 10 times more than regular aviation fuel (Ministry of Defence and Wigston, 2021) which is assumed to reduce by 10% per year from year 10 when producers can increase supply capacity (Goldstein, 2021). Using SAF reduces engine GHGE to net-zero (Huq et al., 2021) but increases risk of engine issues and a requirement for engine modification.

4.5.2. Scenario two: increased use of synthetic training

Assuming 30% of flight-hours are conducted in synthetic training simulators increases training cost by 30% and reduces flight-hours and supply deliveries by 30% as the aircraft requires less maintenance. This scenario increases risk of accidental aircraft damage due to reduced familiarity of pilots.

4.5.3. Scenario three: OEMs integrate supply chain

This scenario assumes OEMs can share delivery vehicles when sites are located on the route that one OEM uses to deliver to Purple Gate. This reduces overall deliveries required but introduces risk that OEMs will not effectively co-ordinate deliveries and increased urgent single journey deliveries are required as mitigation.

4.5.4. Scenario four: mid-life upgrade

Extending Helicopter X's service life to 35 years via mid-life upgrade in year 15 removes it from service for year 15 and is estimated to cost £15,000,000 based on the Merlin Life Sustainment Programme (Defence Equipment and Support, 2021). GHGE for the upgrade are assumed to be the same percentage of embodied carbon as the upgrade cost is of procurement cost (55%) and degradation rate resets to zero at year 15.

4.6. Perform Monte Carlo simulation

A MCS applies random numbers to determine input variables based on their two and three-point distributions to calculate outputs for that iteration (Kenton, 2021). This is repeated multiple times to generate a probability distribution of outputs which typically fits a bell-curve distribution (Caballero et al., 2018). MCS produces probabilistic outputs demonstrating percentage likelihood of a result occurring by using the prefix "Pxx," for example, the P50 and P75 values were not exceeded by 50% or 75% of iteration outputs (Caballero et al., 2018). The MCS was performed for 2,000 iterations as convergence occurred at approximately this point and this produced probabilistic outputs to demonstrate result uncertainty.

4.7. Results verification and post processing

The deterministic and probabilistic results were reviewed and sense-checked for realism which included sensitivity analysis (Kenton, 2020) to identify key results drivers. This also enabled results verification to ensure simulation was carried out with no errors.

A feedback loop was utilised where confidence in outputs was low to review model inputs and logic to determine if errors were present and re-run the model where appropriate. Comparison of deterministic modelling and MCS outputs, coupled with verification and post-processing enabled refinement of the proposed solution.

4.8. Output analysis

Scenario outputs were compared to baseline to demonstrate their impact and enable evaluation of scenarios to provide recommendations. This analysis enables the optimal solution to be identified by objectively demonstrating the differences in terms of A_o, WLC and GHGE.

5. Results and discussion

5.1. Model outputs

Results for baseline and each scenario were produced by implementing the proposed methodology and consolidated into dashboards to optimise data presentation rather than presenting results in their raw format (an example of such a dashboard is illustrated in Fig. 6, more results are presented in the Appendix). These present the results through-life and average per year in-service (equal to through-life result divided by total years in-service).

Probabilistic outputs P25, P50 and P75 were calculated because the difference between P25 and P75 is the Interquartile Range (IQR) which is suitable for skewed results and is less influenced by outliers (Bhandari, 2020). A_o is the same through-life and average per-year and shown in Table 6.

Table 7 and Table 8 show through-life and average annual GHGE and cost results.

Scenario four skews through-life results by having a longer service life which will naturally incur additional through-life cost and GHGE. Therefore, each scenarios average annual results were plotted onto

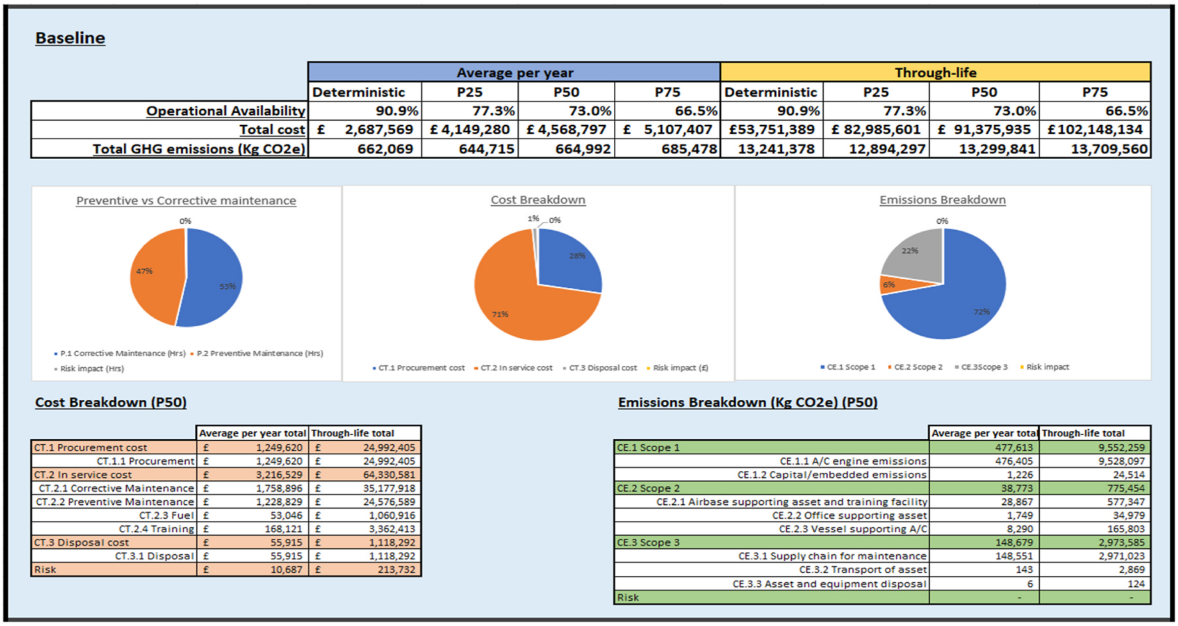


Fig. 6. Graphical dashboard for presenting modelling results.

Table 6
A_o results.

	A_o				
	Deterministic	P25	P50	P75	IQR
Baseline	90.9%	77.3%	73.0%	66.5%	10.8%
Scenario 1	90.9%	77.9%	73.6%	67.1%	10.8%
Scenario 2	93.4%	83.3%	80.1%	75.5%	7.8%
Scenario 3	89.8%	76.0%	71.2%	64.7%	11.3%
Scenario 4	91.1%	75.4%	71.5%	65.7%	9.7%

graphs for comparison (Figs. 7-9) with error bars equalling IQR.

The consolidated dashboards (shown in Appendix) compare Scenario P50 outputs with baseline for through-life and average annual results to demonstrate their relative value as presented in Table 9.

5.2. Analysis and discussion

5.2.1. Output analysis

The sensitivity analysis presented in Fig. 10 indicates annual flight-hours drive baseline GHGE which is logical considering engine emissions account for 72% of total GHGE.

This aligns with the model output which demonstrates the most effective means of reducing Helicopter X's GHGE is switching to SAF because it removes 8,722,393 $KgCO_2e$ through-life which is 2.4 times more effective than the second most effective solution (Scenario two). Also, switching to SAF does not impact A_o because impact on engine reliability is marginal and only costs £8.23 m more through-life (a modest increase) because fuel accounts for 8% of overall cost when using SAF whereas maintenance accounts for 61%.

A contrast is provided by considering increased synthetic training (Scenario two) which reduces GHGE via decreased asset utilisation rather than reducing its direct engine emissions. Scenario 2 proves less effective at reducing GHGE because only 3,600,366 $KgCO_2e$ are removed through-life. However, Scenario 2 has additional benefits of increasing A_o by 7% and reducing through-life cost by £16.75 m. This is because MTBPM drives baseline A_o and reduced Helicopter X utilisation causes fewer failures and, therefore, requires less maintenance. This reduces NMCT to increase A_o and reduces supply chain GHGE as demand for spares reduces due to less maintenance being required. Furthermore, sensitivity analysis of baseline indicates MTBF is the key cost driver, therefore reducing failure rate will drive considerable savings. Reduced flight-hours also reduces engine emissions and fuel cost. Scenario two presents a favourable option, however, it is vulnerable to changes in future circumstances because if increased operational deployment is required outside of modelling assumptions, the benefits of Scenario two are contradicted because increased asset use is not for training and cannot be performed in a simulator. Conversely, the benefits of using SAF, in this case, would not be undone which demonstrates the relative robustness of Scenario one.

Table 7
Model GHGE results.

	Average annual GHGE ($KgCO_2e$)				
	Deterministic	P25	P50	P75	IQR
Baseline	662,069	644,715	664,992	685,478	40,763
Scenario 1	236,481	220,307	228,872	237,077	16,771
Scenario 2	483,665	470,035	484,974	500,797	30,762
Scenario 3	638,300	617,413	637,805	658,652	41,239
Scenario 4	655,707	641,473	657,794	673,790	32,317
	Through-life GHGE ($KgCO_2e$)				
Baseline	13,241,378	12,894,297	13,299,841	13,709,560	815,263
Scenario 1	4,729,615	4,406,136	4,577,448	4,741,547	335,411
Scenario 2	9,673,300	9,400,706	9,699,475	10,015,945	615,238
Scenario 3	12,765,997	12,348,269	12,756,108	13,173,041	824,772
Scenario 4	22,949,762	22,451,570	23,022,789	23,582,649	1,131,079

Table 8
Model cost results.

	Average annual cost				
	Deterministic	P25	P50	P75	IQR
Baseline	£2,687,569	£4,149,280	£4,568,797	£5,107,407	£958,127
Scenario 1	£3,051,960	£4,518,449	£4,981,310	£5,572,798	£1,054,348
Scenario 2	£2,340,155	£3,415,104	£3,731,303	£4,148,218	£733,114
Scenario 3	£2,694,979	£4,169,354	£4,581,221	£5,090,907	£921,553
Scenario 4	£2,578,567	£4,073,187	£4,435,803	£4,885,063	£811,876
	Through-life cost				
Baseline	£53,751,389	£82,985,601	£91,375,935	£102,148,134	£19,162,534
Scenario 1	£61,039,190	£90,368,988	£99,626,201	£111,455,954	£21,086,966
Scenario 2	£46,803,102	£68,302,085	£74,626,063	£82,964,362	£14,662,277
Scenario 3	£53,899,589	£83,387,073	£91,624,416	£101,818,130	£18,431,057
Scenario 4	£90,249,847	£142,561,556	£155,253,110	£170,977,199	£28,415,643

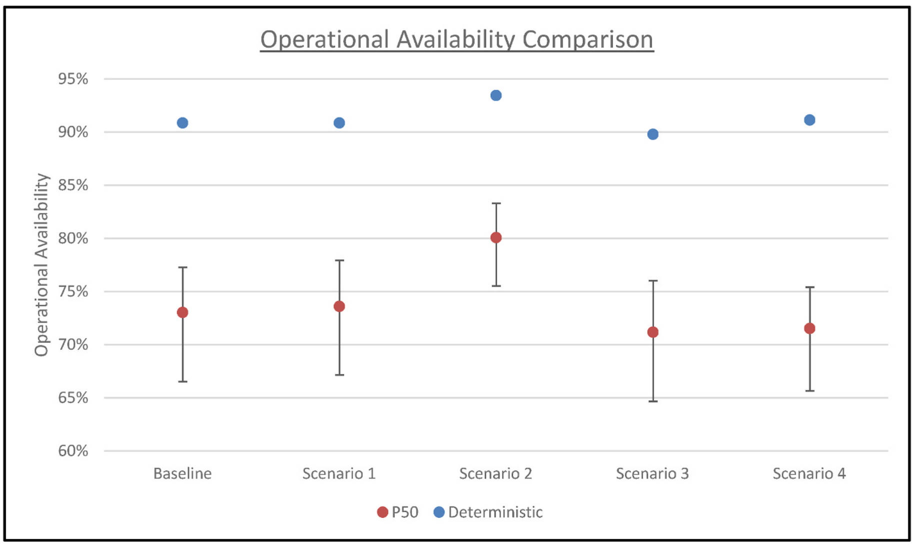


Fig. 7. A_o comparison.

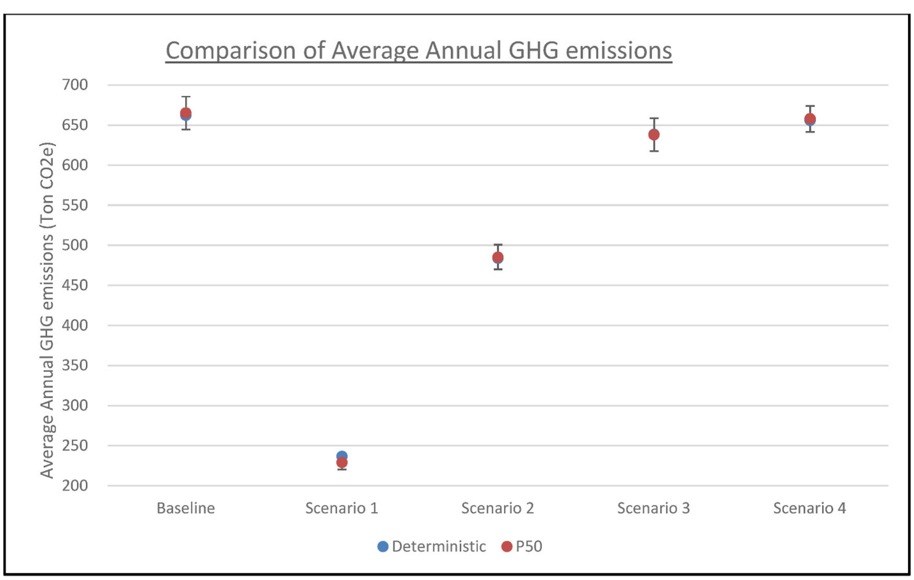


Fig. 8. Average annual GHGE comparison.

Integrating OEM supply chains (Scenario three) models the effects of attempting to reduce GHGE from the supply chain and reduces GHGE by 4.1% but also reduces A_o and increases cost. This is because the risk OEMs will not effectively integrate supply chains causes increased NMCT waiting for spares and cost more due to increased individual deliveries for critical spares being required. The modest reduction in

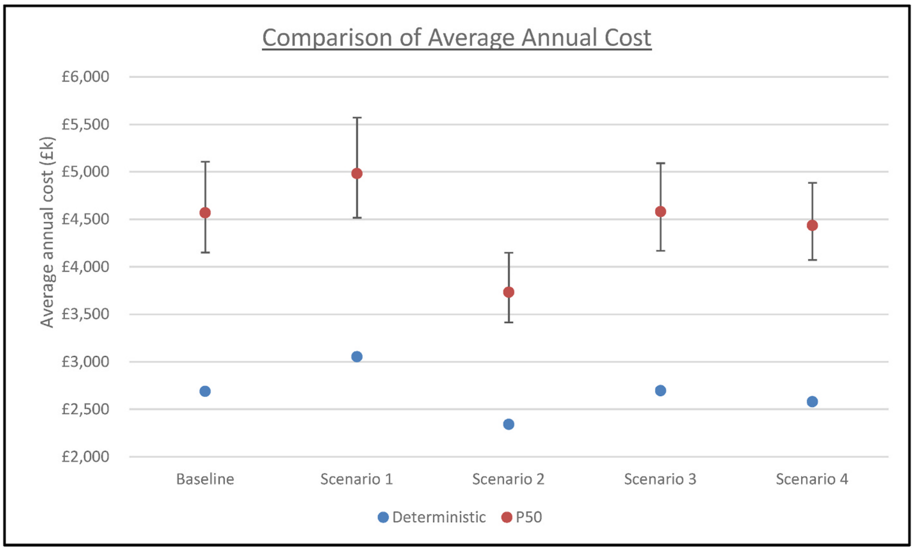


Fig. 9. Average annual cost comparison.

Table 9
Relative difference in Scenario and baseline P50 results.

Average Annual	Scenario 1	Scenario 2	Scenario 3	Scenario 4
A_o variation	+0.6%	+7.0%	−1.9%	−1.5%
GHGE variation ($KgCO_2e$)	−436,120	−180,018	−27,187	−7,198
Cost Variation	+£412,513	-£837,494	-£12,424	-£132,994
Through-Life				
A_o variation	+0.6%	+7.0%	−1.9%	−1.5%
GHGE variation ($KgCO_2e$)	−8,722,393	−3,600,366	−543,733	+9,722,948
Cost Variation	-£8,250,266	+£16,749,872	-£248,481	-£63,877,175

GHGE is because the supply chain is not the key GHGE driver and only reduces by 3% compared to baseline. Contrasted with the effectiveness of Scenarios one and two in reducing GHGE, it is argued the increased cost and reduced A_o caused by implementing Scenario three is not worth the marginal GHGE reduction.

Scenario four increases through-life cost and GHGE simply because Helicopter X is in service for more years and the through-life outputs are not comparable with other Scenarios. However, annual average results enable effective comparison and indicate an annual 1.1% and 2.9% reduction in GHGE and cost respectively which appears minor but is considerable when considering the additional 15 years in-service. This cost and GHGE reduction is caused by procurement cost and embodied carbon being spread over more years in-service. Interestingly, A_o reduces by 1.5% which is caused by Helicopter X requiring more maintenance due to increased degradation due to more years in-service. However, associated maintenance cost increases are offset by spreading procurement cost. Furthermore, there are cost savings associated with not needing to procure and support a replacement platform if Helictoper X left service after 20 years, but capturing such savings is outside the scope of this study.

5.2.2. *Deterministic vs probabilistic results*

There is circa 20–30% variance between P50 and deterministic values for A_o and total cost with deterministic values sitting outside the IQR. Total cost and A_o are heavily influenced by maintenance input data which all have large value ranges.

For example, the largest ML value for a systems MTBF and MTTR is 24.4 flight-hours and 13.7 labour-hours respectively whereas the largest pessimistic values are 678 flight-hours and 127 labour-hours. The same trend applies to planned maintenance and pessimistic values are generally much larger than single-point estimates feeding the deterministic model.

The large input data ranges calls their validity into question,

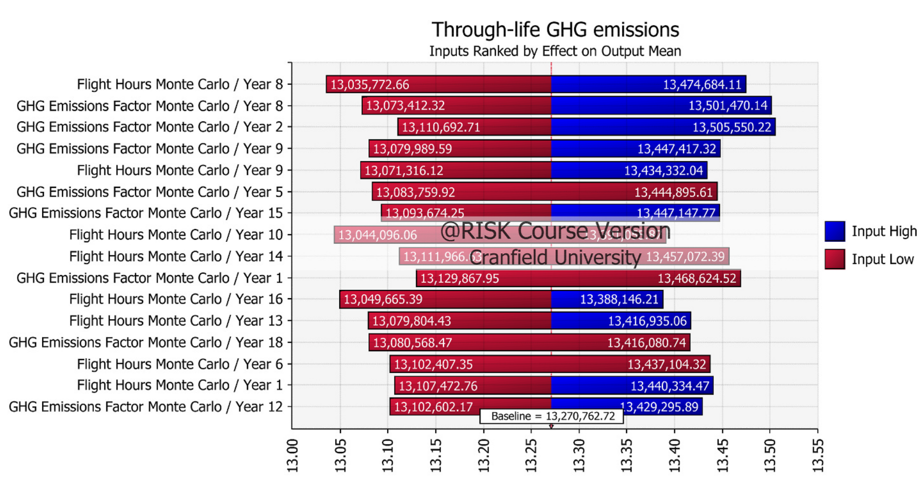


Fig. 10. Baseline GHGE sensitivity analysis.

however, it is argued these values are justified given they are based on historical records. A similar outcome was identified whereby deterministic outputs produced an overly optimistic result (Hart and Jacobson, 2011). Indeed, this demonstrates the benefits of MCS because it highlights data uncertainty and provides a more informed assessment than single-point deterministic models and justifies MCS for this study.

Furthermore, the MCS output predicts the environmental impact in terms of GHGE caused by each scenario throughout the lifecycle of Helicopter X in a more informed manner than the deterministic results. This would prove useful to owner/operator decision makers when weighing investment options as it enables them to better judge how the predicted environmental impacts of their decisions will align with prospective net-zero GHGE emissions targets. Whilst this study modelled an asset in service, the methodology could be applied during the early lifecycle stages to demonstrate how the predicted impact of engineering design solutions may or may not meet the required prospective carbon footprint needed to meet owner/operator net-zero targets.

5.3. Limitations

The following model limitations have been identified:

- No direct linkage between maintenance calculations and supply chain GHGE; demonstrated by relatively small GHGE uncertainty.
- Maintenance actions occurred in series as the model could not accommodate maintenance applied to multiple systems in parallel.
- Systems causing the remaining 26% of failures were not modelled.
- Assessment of individual system impact on outputs is not intuitive.

Areas of future research that could address these limitations are stated in 6.

5.4. Recommendations

Implementing a combination of Scenarios one and two is recommended because they predict considerable GHGE reductions and cost increases associated with using SAF could be offset by savings made implementing Scenario two. This also mitigates Scenario two's vulnerability and presents opportunities for future cost savings e.g. via "Carbon tax" implementation [108, p.665].

5.5. Validation

Modelling methodology and output validation was conducted primarily via semi-structured interviews with Experts One, Two, Three and Four who represent those that would execute the methodology and use outputs to justify decision making.

5.5.1. Methodology verification

Modelling critical asset GHGE is a relatively new discipline and the methodology adopted was based on data analysis of methods (Zhu et al., 2018; United States Environmental Protection Agency, 2021; Ntziachristos et al., 2021; Department for Environment Food and Rural Affairs, 2019b; Sun et al., 2021; Daryanto et al., 2019; Luo and Chen, 2020; Lee et al., 2020; Lindop, 1998; Tsiakmakis et al., 2016; British Standards Institute, 2016; Jones and Hammond, 2019; Department for Business Energy and Industrial Strategy, 2021; Department for Environment Food and Rural Affairs, 2013). Therefore, it is argued the methodology adopted broadly aligns to current practice, meets reporting standards and draws on other industry experience to add credibility.

Modelling GHGE utilises similar techniques to cost modelling, therefore the modelling mechanics were presented to Experts One and Four who believed the methodology was logical, thorough and justifications were valid. However, the following was raised:

- Assuming system MTBF is proportional to flight-hours introduces uncertainty as systems can be cycled (and therefore degrade) without the helicopter flying.
- Assuming asset degradation rate resets post mid-life upgrade requires further development as some components (e.g. the airframe) would not get replaced and would continue to degrade at the same rate as before the mid-life upgrade (also raised by Expert Three).
- The model excludes spares embodied carbon which could have a measurable impact given volume of maintenance Helicopter X requires, although it was argued this could double account suppliers Scope 1 GHGE.
- Maintenance input data is very skewed and investigation to justifiably remove outliers and experimentation with other distributions in @Risk may reduce uncertainty.
- Consideration of fuel quality variations (also raised by Expert Three) and the effect of Helicopter X carrying different payloads/role kits could benefit model outputs.

Furthermore, Expert Two had previously calculated company level GHGE for a large helicopter service provider based on Standard Industrial Classification codes to calculate a ratio of engine to supply chain GHGE of approximately 3:1. The proposed methodology presents a 3.2:1 ratio at baseline which provides further verification of calculations used.

5.5.2. Output validation

Expert Two believed model outputs would be useful for their business area because options analysis functionality would support enterprise and asset level decision making and enable analysis and prediction of through-life GHGE and cost of carbon.

Expert Three compounded this by asserting the output and methodology could have multiple applications across different assets and that it could satisfy part of the demand for a standardised, enterprise-wide tool. Expert Three said the proposed methodology provides the required functionality and provided a credible opportunity to influence owner/operator policy and process via implementation. Expert Two echoed this by believing the presented model outputs would complement current methodologies used and the changes created by the proposed methodology would produce an optimised solution.

Expert Three raised concerns regarding access to the required modelling data if this methodology were to be applied to other asset platforms (e.g. fixed wing aircraft) although this was deemed low risk for rotary wing assets.

Both Experts raised the following:

- Emissions of vehicles used to handle and manoeuvre helicopters around the airfield are not captured.
- Presenting cost of carbon and other carbon accounting outputs would be beneficial to integrate with carbon accounting practices.
- Double accounting supply chain emissions is a risk due to no standard approach of calculation.
- Presenting wider benefits of cutting GHGE would be beneficial (e.g. carbon tax savings, wider benefits to society etc) to enable a more holistic cost/benefits analysis.
- Demonstrating of impact/benefits of wider GHGE reduction strategies (e.g. increased use of renewables on airbases) would be beneficial.

6. Conclusions

Demand for reducing critical asset GHGE has never been higher but lack of a standard modelling approach demonstrating GHGE reduction strategy effectiveness at asset level makes planning and performance monitoring challenging.

The proposed solution provides such a methodology by integrating recognised techniques to create a modelling methodology that can be used for different critical assets and has been tested by using a helicopter platform case study. It was built using data currently available to the owner/operator and whilst assumptions were needed, the experts required for development were available. Therefore, the solution presented in this paper contributes a practical solution to the research community that models A_o, WLC and GHGE that can be used by critical asset owner/operators to objectively assess GHGE when considering investment options.

Limitations were identified which could mostly be addressed by dedicating further time to research and refinement. Utilising software packages and interactive output visualisations would greatly benefit the proposed solution by standardising a consistent format for modellers and end-users.

This study developed a methodology that provides a new approach to a relatively immature discipline. Presentation of modelling outputs to Experts Two and Three received a positive reception and both suggested possibly adopting the methodology to integrate with sustainability programmes in their business areas:

The following areas would benefit from future research to build upon model outputs based on limitations identified in 5.3 and 5.5:

- Research supply chain modelling and determine GHGE dependencies within maintenance calculations as this will provide a more complete modelling approach with reduced reliance on assumptions.
- Integrate carbon accounting outputs to enable setting of carbon budgets because this would make modelling outputs more relevant and useable for industry leaders and policymakers.
- Develop tools and techniques to measure GHGE of an asset through-life to enable performance measurement against carbon budgets/baselines. This enables industry leaders to assess adherence to GHGE reduction strategies, determine their effectiveness and mitigate issues where appropriate.
- Research the modelling of parallel system maintenance operations as this will enable the model to predict Ao more accurately.
- Application of proposed methodology to other assets and data sources as this will determine the unique challenges and modelling mechanics required when applying the methodology to different platforms. This will provide a unique insight and build the modelling knowledge base to enable methodology refinement.
- Implementation of software and interactive dashboard solutions to standardise modelling processes and enable more effective, in-depth assessment of input drivers.

Research data

Modelling input data and exact processes used for this paper's case study are commercially sensitive and cannot be included. Please contact the authors if further information is desired.

CRediT authorship contribution statement

Matt Townley: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Project administration. **Konstantinos Salonitis:** Conceptualization, Methodology, Validation, Writing – review & editing, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supply Chain Assumptions

The following image demonstrates the location of the airfield Helicopter X is normally based at, the operator logistics hub, the additional office that supports it, the assumed port of embarkation for sea deployments and locations of each sub-systems OEM.

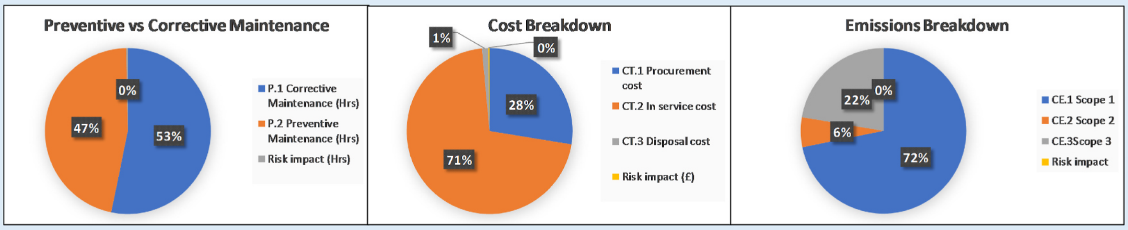
Fig. ure A-1. Location of Helicopter X support infrastructure

Appendix B. Model Results Dashboards

2.1 Baseline dashboard

Baseline

	Average per year				Through-life			
	Deterministic	P25	P50	P75	Deterministic	P25	P50	P75
Operational Availability	90.9%	77.3%	73.0%	66.5%	90.9%	77.3%	73.0%	66.5%
Total cost	£ 2,687,569	£ 4,149,280	£ 4,568,797	£ 5,107,407	£ 53,751,389	£ 82,985,601	£ 91,375,935	£ 102,148,134
Total GHG emissions (Kg CO2e)	662,069	644,715	664,992	685,478	13,241,378	12,894,297	13,299,841	13,709,560



Cost Breakdown (P50)

	Average per year total		Through-life total	
CT.1 Procurement cost	£	1,249,620	£	24,992,405
CT.1.1 Procurement	£	1,249,620	£	24,992,405
CT.2 In service cost	£	3,216,529	£	64,330,581
CT.2.1 Corrective Maintenance	£	1,758,896	£	35,177,918
CT.2.2 Preventive Maintenance	£	1,228,829	£	24,576,589
CT.2.3 Fuel	£	53,046	£	1,060,916
CT.2.4 Training	£	168,121	£	3,362,413
CT.3 Disposal cost	£	55,915	£	1,118,292
CT.3.1 Disposal	£	55,915	£	1,118,292
Risk	£	10,687	£	213,732

Emissions Breakdown (Kg CO2e) (P50)

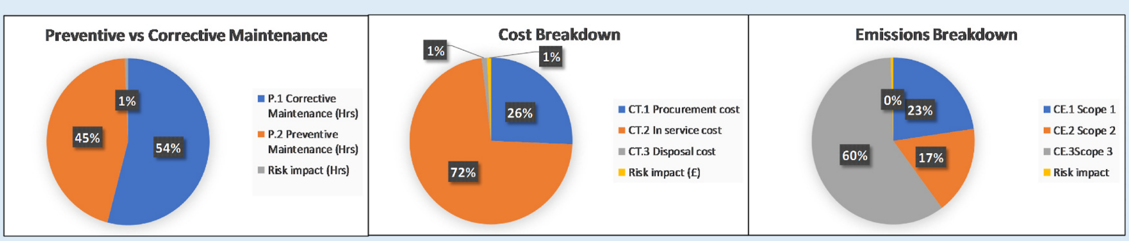
	Average per year total	Through-life total
CE.1 Scope 1	477,613	9,552,259
CE.1.1 A/C engine emissions	476,405	9,528,097
CE.1.2 Capital/embedded emissions	1,226	24,514
CE.2 Scope 2	38,773	775,454
CE.2.1 Airbase supporting asset and training facility	28,867	577,347
CE.2.2 Office supporting asset	1,749	34,979
CE.2.3 Vessel supporting A/C	8,290	165,803
CE.3 Scope 3	148,679	2,973,585
CE.3.1 Supply chain for maintenance	148,551	2,971,023
CE.3.2 Transport of asset	143	2,869
CE.3.3 Asset and equipment disposal	6	124
Risk	-	-

Fig. B-1. Baseline results dashboard

2.2 Scenario 1 dashboard

Scenario 1 - Use of sustainable fuels

	Average per year				Through-life			
	Deterministic	P25	P50	P75	Deterministic	P25	P50	P75
Operational Availability	90.9%	77.9%	73.6%	67.1%	90.9%	77.9%	73.6%	67.1%
Total cost	£ 3,051,960	£ 4,518,449	£ 4,981,310	£ 5,572,798	£ 61,039,190	£ 90,368,988	£ 99,626,201	£ 111,455,954
Total GHG emissions (Kg CO2e)	236,481	220,307	228,872	237,077	4,729,615	4,406,136	4,577,448	4,741,547



Cost Breakdown (P50)

	Average per year total		Through-life total	
CT.1 Procurement cost	£	1,323,120	£	25,139,273
CT.1.1 Procurement	£	1,323,120	£	25,139,273
CT.2 In service cost	£	3,739,890	£	71,057,911
CT.2.1 Corrective Maintenance	£	1,866,568	£	35,464,788
CT.2.2 Preventive Maintenance	£	1,277,008	£	24,263,156
CT.2.3 Fuel	£	403,570	£	7,667,823
CT.2.4 Training	£	176,969	£	3,362,413
CT.3 Disposal cost	£	54,213	£	1,030,043
CT.3.1 Disposal	£	54,213	£	1,030,043
Risk	£	41,285	£	784,409

Emissions Breakdown (Kg CO2e) (P50)

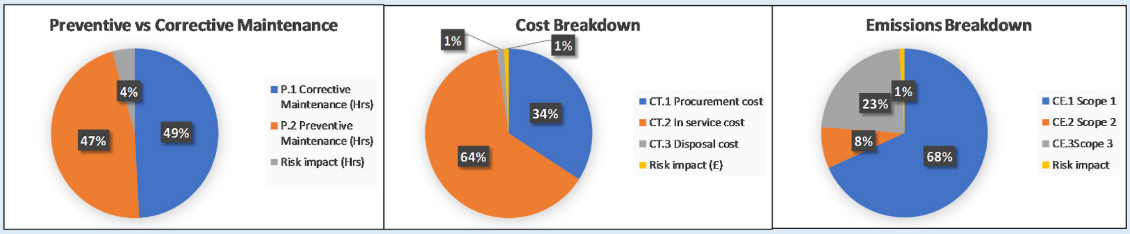
	Average per year total	Through-life total
CE.1 Scope 1	51,375	1,027,496
CE.1.1 A/C engine emissions	50,147	1,002,938
CE.1.2 Capital/embedded emissions	1,228	24,557
CE.2 Scope 2	38,785	775,699
CE.2.1 Airbase supporting asset and training facility	28,842	576,830
CE.2.2 Office supporting asset	1,749	34,988
CE.2.3 Vessel supporting A/C	8,295	165,900
CE.3 Scope 3	135,181	2,703,617
CE.3.1 Supply chain for maintenance	135,031	2,700,624
CE.3.2 Transport of asset	143	2,869
CE.3.3 Asset and equipment disposal	6	124
Risk	1,143	22,867

Fig. B-2. Scenario 1 results dashboard

2.3 Scenario 2 dashboard

Scenario 2 - Increased use of synthetic training and simulation

	Average per year				Through-life			
	Deterministic	P25	P50	P75	Deterministic	P25	P50	P75
Operational Availability	93.4%	83.3%	80.1%	75.5%	93.4%	83.3%	80.1%	75.5%
Total cost	£ 2,340,155	£ 4,169,354	£ 4,581,221	£ 5,090,907	£ 46,803,102	£ 68,302,085	£ 74,626,063	£ 82,964,362
Total GHG emissions (Kg CO2e)	483,665	470,035	484,974	500,797	9,673,300	9,400,706	9,699,475	10,015,945



Cost Breakdown (P50)

	Average per year total	Through-life total
CT.1 Procurement cost	£ 1,270,151	£ 25,403,022
CT.1.1 Procurement	£ 1,270,151	£ 25,403,022
CT.2 In service cost	£ 2,365,018	£ 47,300,367
CT.2.1 Corrective Maintenance	£ 1,240,875	£ 24,817,504
CT.2.2 Preventive Maintenance	£ 844,882	£ 16,897,633
CT.2.3 Fuel	£ 36,973	£ 739,456
CT.2.4 Training	£ 218,557	£ 4,371,137
CT.3 Disposal cost	£ 52,800	£ 1,056,003
CT.3.1 Disposal	£ 52,800	£ 1,056,003
Risk	£ 33,633	£ 672,660

Emissions Breakdown (Kg CO2e) (P50)

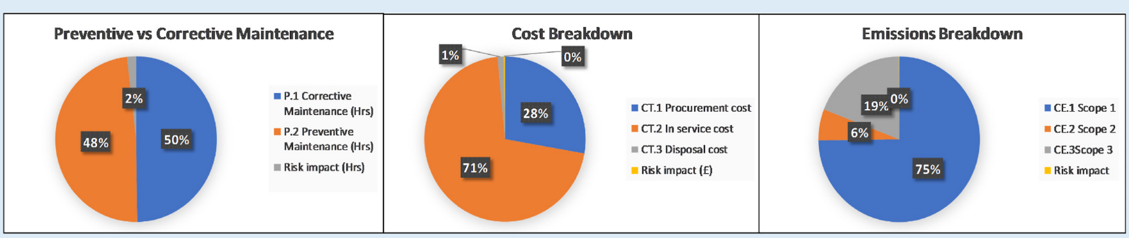
	Average per year total	Through-life total
CE.1 Scope 1	333,937	6,678,738
CE.1.1 A/C engine emissions	332,688	6,653,752
CE.1.2 Capital/embedded emissions	1,225	24,492
CE.2 Scope 2	38,785	775,697
CE.2.1 Airbase supporting asset and training facility	28,845	576,903
CE.2.2 Office supporting asset	1,750	34,992
CE.2.3 Vessel supporting A/C	8,294	165,879
CE.3 Scope 3	112,053	2,241,068
CE.3.1 Supply chain for maintenance	111,911	2,238,219
CE.3.2 Transport of asset	136	2,725
CE.3.3 Asset and equipment disposal	6	124
Risk	4,775	95,492

Fig. B-3. Scenario 2 results dashboard

2.4 Scenario 3 dashboard

Scenario 3 - OEMs integrate supply chain

	Average per year				Through-life			
	Deterministic	P25	P50	P75	Deterministic	P25	P50	P75
Operational Availability	89.8%	76.0%	71.2%	64.7%	89.8%	76.0%	71.2%	64.7%
Total cost	£ 2,694,979	£ 4,169,354	£ 4,581,221	£ 5,090,907	£ 53,899,589	£ 83,387,073	£ 91,624,416	£ 101,818,130
Total GHG emissions (Kg CO2e)	638,300	617,413	637,805	658,652	12,765,997	12,348,269	12,756,108	13,173,041



Cost Breakdown (P50)

	Average per year total	Through-life total
CT.1 Procurement cost	£ 1,264,132	£ 25,282,643
CT.1.1 Procurement	£ 1,264,132	£ 25,282,643
CT.2 In service cost	£ 3,216,729	£ 64,334,590
CT.2.1 Corrective Maintenance	£ 1,762,975	£ 35,259,502
CT.2.2 Preventive Maintenance	£ 1,218,327	£ 24,366,537
CT.2.3 Fuel	£ 53,062	£ 1,061,246
CT.2.4 Training	£ 168,121	£ 3,362,413
CT.3 Disposal cost	£ 54,282	£ 1,085,647
CT.3.1 Disposal	£ 54,282	£ 1,085,647
Risk	£ 12,642	£ 252,848

Emissions Breakdown (Kg CO2e) (P50)

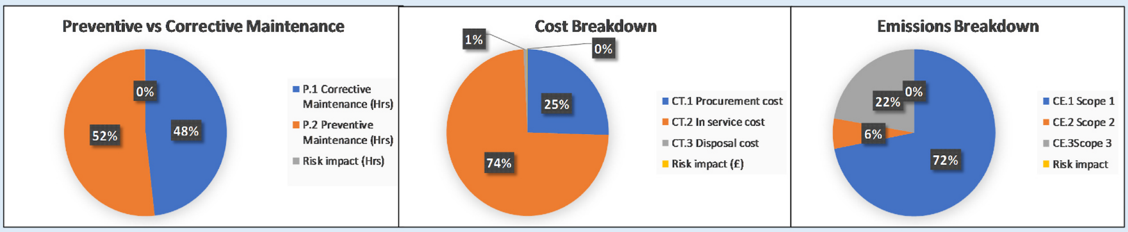
	Average per year total	Through-life total
CE.1 Scope 1	477,085	9,541,708
CE.1.1 A/C engine emissions	475,877	9,517,532
CE.1.2 Capital/embedded emissions	1,228	24,567
CE.2 Scope 2	38,794	775,880
CE.2.1 Airbase supporting asset and training facility	28,852	577,041
CE.2.2 Office supporting asset	1,749	34,989
CE.2.3 Vessel supporting A/C	8,308	166,152
CE.3 Scope 3	121,485	2,429,699
CE.3.1 Supply chain for maintenance	121,321	2,426,427
CE.3.2 Transport of asset	143	2,869
CE.3.3 Asset and equipment disposal	6	124
Risk	448	8,968

Fig. B-4. Scenario 3 results dashboard

2.5 Scenario 4 dashboard

Scenario 4 - Mid life upgrade

	Average per year				Through-life			
	Deterministic	P25	P50	P75	Deterministic	P25	P50	P75
Operational Availability	91.1%	75.4%	71.5%	65.7%	91.1%	75.4%	71.5%	65.7%
Total cost	£ 2,578,567	£ 4,073,187	£ 4,435,803	£ 4,885,063	£ 90,249,847	£ 142,561,556	£ 155,253,110	£ 170,977,199
Total GHG emissions (Kg CO2e)	655,707	641,473	657,794	673,790	22,949,762	22,451,570	23,022,789	23,582,649



Cost Breakdown (P50)

	Average per year total	Through-life total
CT.1 Procurement cost	£ 1,126,293	£ 39,420,242
CT.1.1 Procurement	£ 1,126,293	£ 39,420,242
CT.2 In service cost	£ 3,258,942	£ 114,062,967
CT.2.1 Corrective Maintenance	£ 1,821,604	£ 63,756,144
CT.2.2 Preventive Maintenance	£ 1,201,600	£ 42,055,983
CT.2.3 Fuel	£ 52,730	£ 1,845,543
CT.2.4 Training	£ 168,121	£ 5,884,223
CT.3 Disposal cost	£ 30,266	£ 1,059,323
CT.3.1 Disposal	£ 30,266	£ 1,059,323
Risk	£ 6,283	£ 219,913

Emissions Breakdown (Kg CO2e) (P50)

	Average per year total	Through-life total
CE.1 Scope 1	472,408	16,534,269
CE.1.1 A/C engine emissions	471,540	16,503,916
CE.1.2 Capital/embedded emissions	932	32,613
CE.2 Scope 2	38,559	1,349,566
CE.2.1 Airbase supporting asset and training facility	29,243	1,023,522
CE.2.2 Office supporting asset	1,789	62,609
CE.2.3 Vessel supporting A/C	7,314	256,006
CE.3 Scope 3	146,169	5,115,904
CE.3.1 Supply chain for maintenance	146,051	5,111,768
CE.3.2 Transport of asset	143	5,020
CE.3.3 Asset and equipment disposal	4	124
Risk	-	-

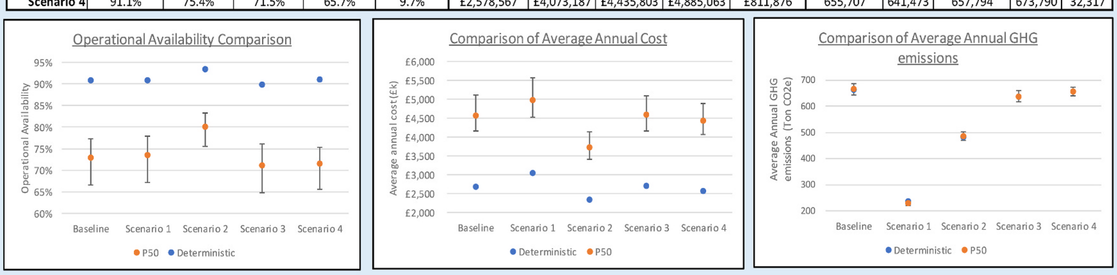
Fig. B-5. Scenario 4 results dashboard

2.6 Annual average consolidation dashboard

Scenario comparisons

Monte Carlo results

	Operational Availability					Average annual cost					Average annual GHG emissions				
	Deterministic	P25	P50	P75	IQR	Deterministic	P25	P50	P75	IQR	Deterministic	P25	P50	P75	IQR
Baseline	90.9%	77.3%	73.0%	66.5%	10.8%	£2,687,569	£4,149,280	£4,568,797	£5,107,407	£958,127	662,069	644,715	664,992	685,478	40,763
Scenario 1	90.9%	77.9%	73.6%	67.1%	10.8%	£3,051,960	£4,518,449	£4,981,310	£5,572,798	£1,054,348	236,481	220,307	228,872	237,077	16,771
Scenario 2	93.4%	83.3%	80.1%	75.5%	7.8%	£2,340,155	£3,415,104	£3,731,303	£4,148,218	£733,114	483,665	470,035	484,974	500,797	30,762
Scenario 3	89.8%	76.0%	71.2%	64.7%	11.3%	£2,694,979	£4,169,354	£4,581,221	£5,090,907	£921,553	638,300	617,413	637,805	658,652	41,239
Scenario 4	91.1%	75.4%	71.5%	65.7%	9.7%	£2,578,567	£4,073,187	£4,435,803	£4,885,063	£811,876	655,707	641,473	657,794	673,790	32,317



Baseline comparison

Figures in the below table are mesured realtive to the Baseline P50 values

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Change in Operational Availability P50	0.6%	7.0%	-1.9%	-1.5%	Red = Reduction in Ao, Green = Increse in Ao
Change in Average annual cost P50 (£)	£412,513	-£837,494	£12,424	-£132,994	Red = Increase in Cost, Green = Reduction in Cost
Change in Average annual GHG emissions P50 (Kg CO2e)	-436,120	-180,018	-27,187	-7,198	Red = Increase in GHG Emissions, Green = Reduction in GHG Emissions

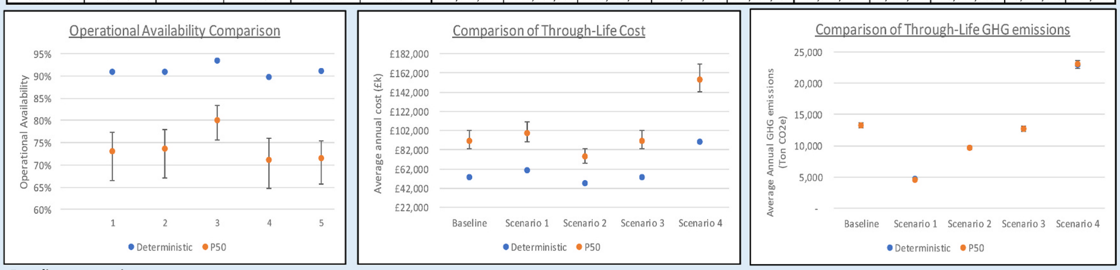
Fig. B-6. Annual average consolidation dashboard

2.7 Through-Life consolidated dashboard

Scenario comparisons

Monte Carlo results

	Operational Availability					Through-life cost					Through-life GHG emissions				
	Deterministic	P25	P50	P75	IQR	Deterministic	P25	P50	P75	IQR	Deterministic	P25	P50	P75	IQR
Baseline	90.9%	77.3%	73.0%	66.5%	10.8%	£53,751,389	£82,985,601	£91,375,935	£102,148,134	£8,390,334	13,241,378	12,894,297	13,299,841	13,709,560	405,544
Scenario 1	90.9%	77.9%	73.6%	67.1%	10.8%	£61,039,190	£90,368,988	£99,626,201	£111,455,954	£9,257,213	4,729,615	4,406,136	4,577,448	4,741,547	171,312
Scenario 2	93.4%	83.3%	80.1%	75.5%	7.8%	£46,803,102	£68,302,085	£74,626,063	£82,964,362	£6,323,978	9,673,300	9,400,706	9,699,475	10,015,945	298,769
Scenario 3	89.8%	76.0%	71.2%	64.7%	11.3%	£53,899,589	£83,387,073	£91,624,416	£101,818,130	£8,237,343	12,765,997	12,348,269	12,756,108	13,173,041	407,839
Scenario 4	91.1%	75.4%	71.5%	65.7%	9.7%	£90,249,847	£142,561,556	£155,253,110	£170,977,199	£12,691,554	22,949,762	22,451,570	23,022,789	23,582,649	571,219



Baseline comparison

Figures in the below table are mesured realtive to the Baseline P50 values

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Change in Operational Availability P50	0.6%	7.0%	-1.9%	-1.5%	Red = Reduction in Ao, Green = Increse in Ao
Change in Average annual cost P50 (£)	£8,250,266	-£16,749,872	£248,481	£63,877,175	Red = Increase in Cost, Green = Reduction in Cost
Change in Average annual GHG emissions P50 (Kg CO2e)	-8,722,393	-3,600,366	-543,733	9,722,948	Red = Increase in GHG Emissions, Green = Reduction in GHG Emissions

Fig. B-7. Through-Life consolidation dashboard

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