33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

ICAS 2022 SWEDEN

A SCALABLE HYDROGEN PROPULSION SYSTEM FOR CIVIL TRANSPORT AIRCRAFT

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Abstract

The aim of this research was to explore the application of engineering systems evolvability analysis techniques in devising potential scalable hydrogen propulsion systems for future civil transport aircraft. Baseline and derivative aircraft concepts were generated for a medium-sized long-range aircraft, with the derivative options having different levels of hydrogen incorporated in a dual-fuel arrangement (with separate hydrogen and kerosene turbofans), as well as potential turboelectric propulsion with boundary layer ingestion. Commonality between each baseline-derivative pair was then estimated, which could be used to predict the derivative development cost savings that could potentially be obtained when working from a specific baseline. The performance and cost results enabled different future scenarios to be explored. It was shown that developing the future concepts based on an existing state-of-the aircraft as baseline can offer considerable cost savings, as opposed to designing a clean sheet version. The importance of the baseline configuration selection in reducing the development cost for the different hydrogen configurations was also highlighted.

Keywords: Hydrogen propulsion, scalability, evolvability, dual-fuel, boundary layer ingestion, electric propulsion.

1. Introduction

Hydrogen propulsion for civil transport aircraft is considered to be one of the most promising means to achieving zero-carbon emission flight [1,2]. However, there is considerable uncertainty inherent in the underlying technology itself (i.e., hydrogen-burning gas turbines, fuel cells, fuel pumps, fuel storage, and other supporting systems), as well as in the future production, distribution, and storage of hydrogen. Considering this, it is reasonable to expect that hydrogen supply and hydrogen aeronautical technology availability would increase only gradually. Predicting the rate at which this may happen is difficult and may be further complicated by the notion that the pace of growth of hydrogen-related infrastructure may also vary across different geographical locations.

Therefore, designers of the first generation of hydrogen-powered aircraft will need to account for different scenarios related to hydrogen supply and the availability and scale of the associated technology. One manner in which this can be done is to design aircraft incorporating hydrogen-related ‘evolvability’. This would mean that the design would be able to progressively incorporate hydrogen as the related technology matures and hydrogen supply increases. In other words, the designed aircraft would have a ‘scalable hydrogen propulsion system’, which would allow it to evolve in such a manner that it could maximise value across most of the potential hydrogen-related scenarios that could materialise.

‘Changeability’, which is an umbrella word for the terms such as the aforementioned evolvability, is a concept that has been receiving growing attention in the academic literature [3–6]. Changeability enables an engineering system to continue providing value for its stakeholders, despite potentially drastic changes in its environment (which could involve technology availability or other technical, social, political, or economic aspects). However, changeability usually comes at a cost [7–9], which could be both monetary and in terms of performance. This is because it often has to be actively designed for, which may increase development time and cost. It may also render the system heavier and larger than what it would otherwise have been, which would negatively affect performance. A careful balance must therefore be maintained between the level of changeability incorporated versus the impact on performance that this may produce.

Another important term related to changeability is ‘commonality’. Commonality can be considered to be the “sharing of components, processes, technologies, interfaces and/or infrastructure across a product family” [10]. One way in which the level of commonality between engineered systems can be measured is to take the mass of components and subsystems that they have in common divided by the sum of the total masses of these systems [11]. Higher commonality levels between a ‘baseline’ and a ‘derivative’ usually imply lower development cost for the derivative. It also usually offers benefits for operators of both versions, such as lower maintenance and training cost, because of the shared components and subsystems across the two versions. Large levels of commonality between a baseline and derivative are therefore seen as a successful result of designing for changeability. Therefore, in designing for changeability, aircraft manufacturers often attempt to maximise commonality but, again, must do so without penalising performance excessively.

Research efforts on evolvability in engineering systems have progressively included more aerospace applications (such as in Refs. [7,9,12]), but it appears that there is still a lack of evolvability studies focusing specifically on hydrogen aircraft. It is important to address this shortage, as doing so may highlight how the aviation industry could explore a more gradual, less risky means to transition to hydrogen aircraft, as opposed to suddenly starting to develop ‘clean sheet’ hydrogen designs, which may be a perilous undertaking.

Therefore, the aim of the study presented herein was to explore the application of evolvability design techniques in devising potential scalable hydrogen propulsion systems for future civil transport aircraft. More specifically, it was to demonstrate how the trade-offs in performance (i.e., CO_2 emissions and overall energy) versus development cost (also referred to as ‘Research, Development Testing, and Evaluation’ cost, or ‘RDT&E’ [13]), as obtained while considering commonality, could be explored between baseline kerosene aircraft concepts and derivative ‘dual-fuel’ (i.e., with different ratios of kerosene and hydrogen) and full hydrogen aircraft.

The class of aircraft considered in this study was the midsize, widebody, long-range airliner, as they may benefit particularly from dual-fuel systems, which will be relevant in scenarios where there is a disparity in hydrogen availability across different continents.

This introduction is followed by Section 2, in which the analysis approach is presented. In Section 3, the results are presented and discussed. Finally, conclusions are provided in Section 4.

2. Analysis approach

Fundamentally, the analysis involved developing kerosene-based aircraft concepts for a current or ‘near-future’ scenario, followed by developing a mix of kerosene and hydrogen concepts for a ‘far-future’ scenario, and subsequently determining which of the current or near-future options could most easily evolve to the most promising far-future aircraft.

An overview of the analysis approach followed is shown in Figure 1. As can be seen, the process is initiated by generating concepts for the near-future scenario, in which current state-of-the-art (CSA) technology is to be used. This was followed by generating concepts for the 2040 EIS timeframe (although this could be anything from 2035 to 2050), when different novel technologies may become available, including hydrogen-related technologies. In this timeframe, there may be different potential levels of availability in hydrogen supply. All the concepts were then sized, after which their performance could be predicted (i.e., determining the total block fuel consumed across the design mission). Note that the aircraft modelling was performed using the Boeing 787-9 as inspiration. The main reason for choosing this aircraft was that it is a current-state-of-the-art long-range medium-sized aircraft for which there is a relative abundance of data available.

From the sizing process, a ‘commonality’ assessment could be undertaken, which enabled the development costs to be predicted for the far future options as a function of the CSA concept selected as baseline. Using the results from both the cost prediction and performance analysis, a tradeoff exercise could be executed, which enabled the evolvability vs performance of the different concepts to be explored for different scenarios. Each of these steps is described in more detail in the subsections that follow.

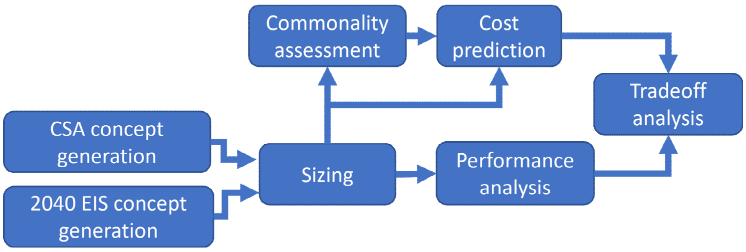

Figure 1: Overview of the analysis approach.

2.1 Current state-of-the-art (CSA) concept generation

The purpose of this step is to devise concepts for current or the 'near-future' generation. It is advisable here to generate as many concepts as can be handled in order to have a wide pool of candidates. This will allow a more detailed and useful evolvability analysis to eventually be undertaken. However, for this study, for the sake of simplicity, only two simple 'traditional' concepts were selected – a 'conventional' empennage twinjet with its turbofans attached under the wing (as in most large modern civil jets) and a T-tail trijet with two turbofans under the wing and the third embedded in the rear fuselage. These concepts are respectively referred to as 'CSA Twin' and CSA Tri and are depicted in Figure 2.

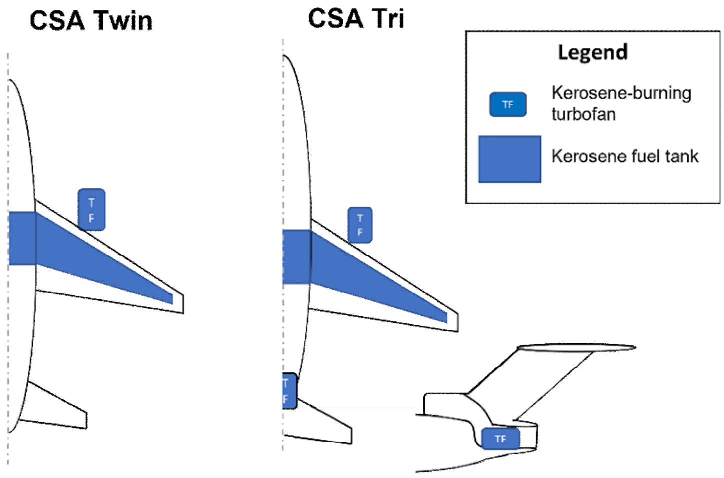

Figure 2: Current state-of-the-art (CSA) concepts.

It may seem unwise to pursue a trijet over a twinjet as it is now well known that trijets are significantly less energy-efficient than twinjets and more expensive to develop and maintain. However, as will be seen in later sections, in the context of evolvability, developing a trijet now may have some advantages in certain (albeit very limited) future scenarios. Regardless, the trijet serves as a good example to demonstrate the methodology. Also note that, from Figure 2, it can be seen that the rear engine is integrated into an S-duct. This is just for illustrative purposes, and it should be noted that the S-duct configuration may not be practical with future ultra-high bypass turbofans. Here it is assumed that a suitable geometry would be used as the intake. The turbofan engines to be employed on these concepts are based on CSA technology (e.g., the Rolls-Royce Trent 1000 for the 787).

2.2 EIS 2040 concept generation

For the 2040 EIS timeframe, concepts had to be generated that could be competitive or feasible in different technological and energy scenarios. For example, in one optimistic case, hydrogen supply may be abundant and inexpensive, and the related aeronautical hydrogen technology may be mature enough to be incorporated on civil aircraft. In such cases, the airframer would likely prefer to develop full hydrogen aircraft. In other scenarios, this might not at all be the case, and the airframer may therefore stick with the conventional kerosene. In this case, they may also use kerosene-like sustainable aviation fuels (SAFs), if these have become abundant by then. However, note that SAFs are not covered in this study. In other cases, some of the hydrogen technology may be mature, but it may be difficult to scale up or there might be a limited supply of hydrogen, or it may not be available at all potential destinations. In such cases, it may be of interest to develop aircraft that can employ a mixture of hydrogen and kerosene (or SAF). This could be done with some engines consuming hydrogen and the others kerosene, or engines that can consume both, i.e., 'dual-fuel' turbofans. Dual-fuel turbofans may be difficult to develop due to the different combustor topologies required for kerosene vs hydrogen and were not considered in this study. Note that, if any advanced propulsion concepts are introduced, such as boundary layer ingestion (BLI) with electrically driven fans, it would reflect an additional technical challenge, and may therefore also not be mature in the timeframes considered.

These considerations have led to the concepts presented in Figure 3 being devised. As can be seen, ten concepts were selected for this study. This is a limited number and was decided upon to best demonstrate the methodology. For real-world studies, as many concepts as can be managed should be studied. The different concepts can be described as follows:

- Conventional kerosene aircraft ('Twin KE 2040' and 'Tri 2040'). These would employ the same basic configurations as the CSA concepts and would not make use of hydrogen or any other 'unconventional' propulsion technology. They would however make use of more advanced (2030s technology) turbofans.
- Full H2 concepts (Twin H2 2040 and Tri 2040). These would employ the same major component layouts as the CSA kerosene concepts but would be powered fully by hydrogen using 2030s technology turbofans. The H2 tanks would be incorporated in the rear fuselage.
- Mixed kerosene/H2 concepts (Twin H2/KE 2040, Quad H2/KE 2040, Tri H2/KE 2040). In these aircraft, both kerosene and hydrogen would be used. In cases where lower levels of hydrogen are available and dual-fuel gas turbines are not mature yet, a smaller proportion of the total aircraft thrust would be provided by hydrogen propulsors. This would necessitate a trijet or quad to maintain thrust symmetry (Tri H2/KE 2040 and Quad H2/KE 2040). Aircraft with smaller levels of H2 thrust would also potentially be able to be used on outward journeys taken with both kerosene and H2 and return with kerosene only, or vice versa. However, in such cases, the engines would need to be designed for the return case, something which was not considered in this study. In cases where higher levels of H2 are available, larger proportions of the total thrust can be provided by H2 engines, in which a twin could be used. In this study, only H2-to-kerosene thrust ratios of a third (for the tri and quad) and a half (twin) were considered. The Twin H2/KE 2040 concept could either be powered by one H2 and one kerosene engine, or by dual-fuel engines. The former may be problematic from a redundancy/reliability point of view, whereas the latter would depend on the dual-fuel technology to be available.
- Boundary layer ingestion with superconducting electric propulsion (EBLI) concepts (EBLI KE 2040, EBLI H2/KE 2040, and EBLI H2 2040). These concepts are a manifestation of turboelectric propulsion. The two under-wing turbofans generate both thrust and electricity that powers an electric motor, which in turn drives a fan situated in the rear fuselage. The fan is employed in a boundary layer ingestion (BLI) configuration. The concept is therefore similar to the NASA STARC-ABL [14]). The electrical power distribution and large motors make use of superconductivity to limit waste heat production. For these concepts, all the technology related to the electric motor and inverters, cooling systems, and BLI would have to be mature enough for implementation. Also, the concepts again reflect the possible scenarios related to hydrogen. In EBLI KE 2040, no hydrogen is used (in this case, a cryocooler would need to be used for superconducting). In EBLI H2/KE 2040, like in Twin H2/KE 2040, hydrogen is used in one turbofan and kerosene on the other, or dual-fuel engines are used. In EBLI H2 2040, only hydrogen is used. For the concepts with hydrogen, the hydrogen could be used for superconducting.

With these concepts devised, the next step was to model them, which is described in the next subsection.

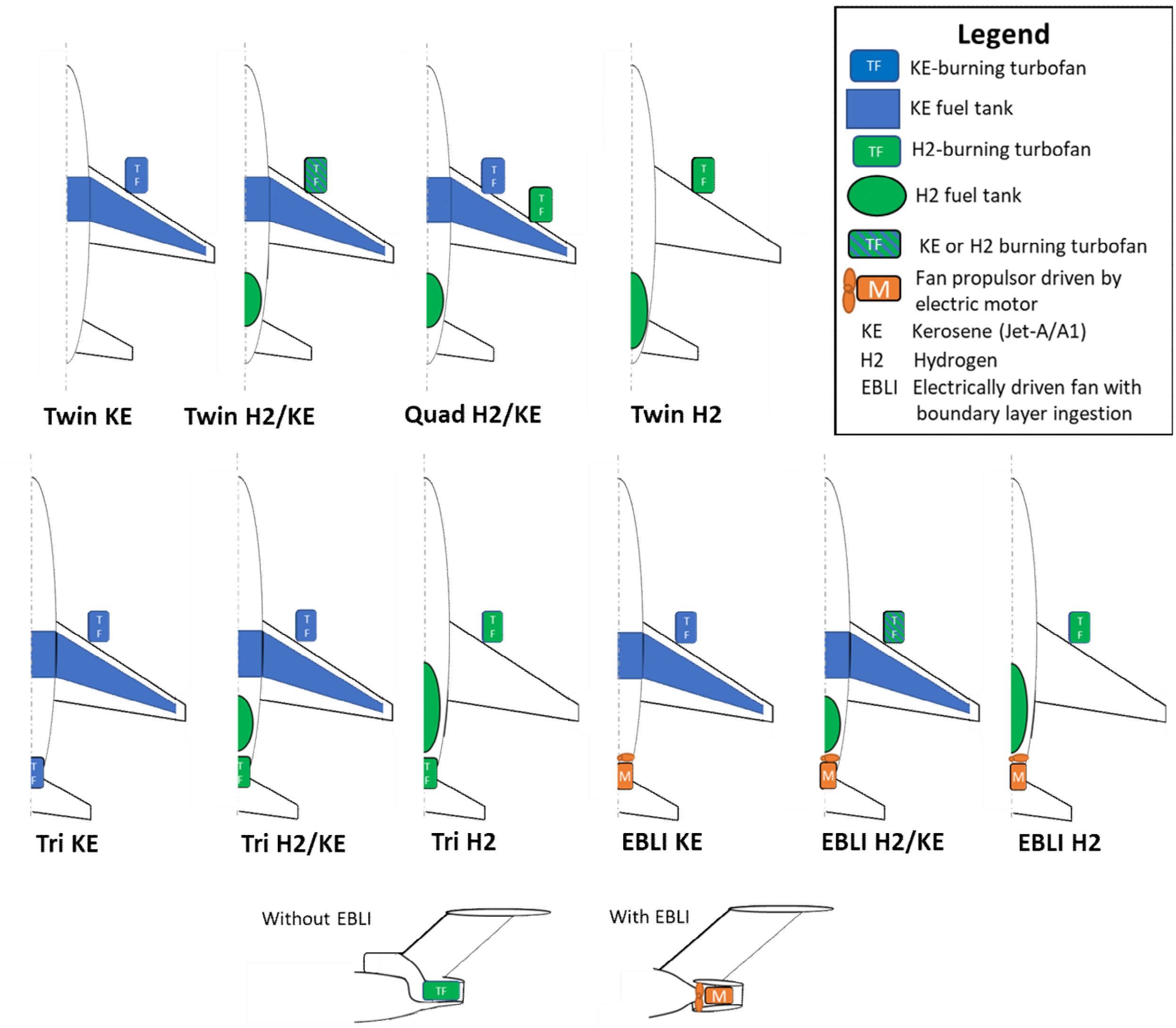

Figure 3: EIS 2040 concepts.

2.3 Sizing and performance analysis

This subsection focuses on the set of guidelines and assumptions followed to investigate the future concepts. The CSA aircraft selected to proceed with in the investigations was a hypothetical aircraft equivalent to the Boeing 787-9. The aircraft weight breakdown and drag polar were estimated using NASA FLOPS [15]. This was done using data from the airport planning manual for the 787-9 [16]. The fuel efficiency for the engines used by baseline aircraft was obtained from information in the public domain [17]. For the aircraft concepts involving the usage of LH_2, the weight of cryogenic tank storage and systems was estimated using the tank gravimetric efficiency formulation as follows:

$$\eta_{grav} = \frac{m_f}{m_f + m_t}$$

Where η_{grav} is the tank gravimetric tank efficiency/gravimetric index (GI), m_f is the mass of hydrogen fuel and m_t is the mass of the dry tank. A 60% tank gravimetric efficiency was assumed, in line with that suggested in Verstraete et al. [18]. The turbofan thrust-specific fuel consumption used by the CSA and 2040 concepts were taken for Mach 0.85 and are assumed as predicted from the public domain [19]. The LH_2 tanks are stored in the rear end of the fuselage and a maximum fuselage extension limit of 73m was imposed for aircraft modelling to limit unrealistic configurations arising from the concepts. In cases where this limit is exceeded, the passenger capacity is reduced accordingly to satisfy this limit. The drag penalty and additional weights due to the fuselage extension to realise LH_2 concepts were based on a database created from the FLOPS. The drag polar of concepts involving the tri- and quad-jets were also estimated using FLOPS.

For the concepts that utilise BLI, the Potential for Energy Recovery (PER) is a measure of the maximum amount of kinetic energy that may be harvested from the fuselage's boundary layer, by perfectly attenuating its wake contribution, and is usually found to be between 8-10% of the fuselage drag power [20,21]. Because this mechanism reduces dissipation in the aircraft's wake, it becomes convenient to rather represent it as a drag reduction in mission performance codes such as FLOPS. PER is an idealised figure, and after taking into account the various advantages and disadvantages of the installation effects, the benefit may be reasonably assumed to be equivalent to around a 4% reduction in overall drag [17]. This value was therefore used for drag reduction in the EBLI concepts.

The EBLI system consists of an electric fan driven by the power generated from the low-pressure shaft of the two turbofan engines. The electric fan produces a third of the thrust and consumes 13 MW of power at cruise. The electric powertrain weight is 2,500 kg assuming superconducting motors and generators and a 3,000 VDC voltage system. The thrust-specific fuel consumption of the under-the-wing turbofan engines improves by 5% from preliminary calculations due to improved core efficiency. This number is obtained by simulating a high bypass ratio engine with 2010s technology in Cranfield University's in-house engine performance software, Turbomatch [22].

To assess dual-fuel propulsion systems, the Breguet range equation needed to be modified. The original form of the Breguet range equation can be defined as:

$$R = \frac{LHV_{KE}}{g} \eta_{overall} \frac{L}{D} \ln\left(\frac{W_i}{W_f}\right)$$

Where R is the range, LHV is the lower heating value of the fuel used (note that the subscript KE is used for kerosene and H for hydrogen), g is gravitational acceleration, L/D is the lift-to-drag ratio, W_i is the initial mass (i.e., maximum takeoff weight [MTOW]), and W_f is the final mass of the aircraft at the end of the light. The efficiency term $\eta_{overall}$ can be defined as

$$\eta_{overall} = \frac{TV}{\dot{m}_f LHV_{KE}}$$

Where $\dot{m}_f$ is the mass flow rate of fuel consumed, T is the thrust, and V is the cruise true airspeed. If it is assumed that the hydrogen turbofan engine will have a thrust specific fuel consumption (C_{j_H}) lower than that of an equivalent kerosene engine C_{j_K}) by a factor equal to the ratio of the respective lower heating values of the two fuels, then

$$C_{j_H} = C_{j_{KE}} \frac{LHV_{KE}}{LHV_H}$$

Using the thrust split between hydrogen and kerosene engines (defined here as $r = T_{H_2}/T_{total}$) and the ratio of lower heating values (k $=LHV_H/LHV_{KE}$), a modified Breguet range equation can be deduced as follows:

$$R = V \frac{1}{gC_{j_{KE}}} \frac{L}{D} \left(\frac{k}{r+k-kr}\right) \ln\left(\frac{Wi}{W_f}\right)$$

The value of r can be varied between 0 and 1, which would reflect different scales of incorporated hydrogen. The EIS 2014 concepts Twin KE, Tri KE, and EBLI KE utilise only kerosene, so $r = 0$. Concepts Tri HE/KE and Quad H2/KE employ one and two hydrogen propulsion systems out of a total of three and four, respectively and $r = 0.33$ was selected for these. For concepts Twin H2/KE and EBLI H2/KE, $r = 0.5$. Finally, concepts Twin H2, Tri H2, and EBLI H2 are fully hydrogen-powered, so $r = 1$.

Note that R is the cruise-climb range and excludes climb and descent, which are not considered in this paper. This is reasonable as these aircraft are flown at a very long range.

All these aircraft concepts are assessed on the same range (6,236 nmi) to have a fair back-to-back comparison. A flowchart that illustrates the steps followed for calculating the performance of the future concepts is shown in Figure 4. The performance parameter of interest here is the fuel consumed per passenger per kilometre (both kerosene and hydrogen). As can be seen, the process is initiated with the engine SFC estimates, the drag polars (as obtained from FLOPS), and the thrust split as input. The initial maximum zero fuel weight is set equal to that for the current state-of-the-art aircraft (calculated by FLOPS for the twin, quad, or trijets) and is then updated to account for hydrogen tanks, weight due to fuselage extensions, passenger removal, and EBLI systems weights, while adhering to the original maximum take-off weight and maximum fuselage length as constraints. This process was iterated by updating the fuel weights until the range was met for each concept.

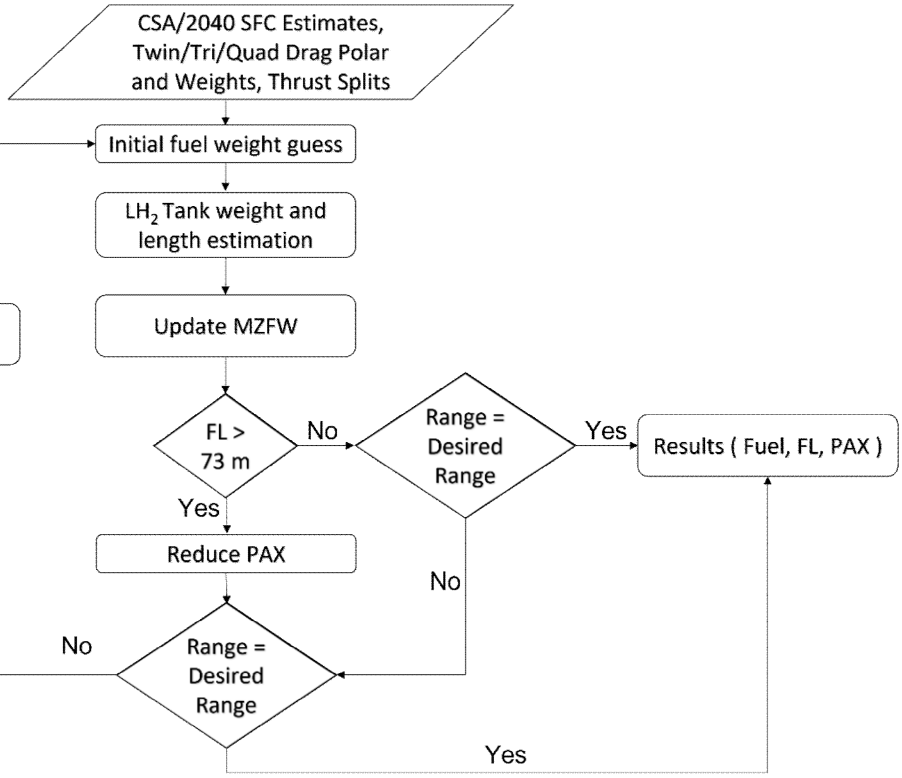

Figure 4: Performance prediction methodology (Note: PAX = passengers, FL = fuselage length, SFC = specific fuel consumption, and MZFW = maximum zero fuel weight).

2.4 Commonality assessment

For predicting commonality in aircraft during conceptual design, a minimum level of information about the geometry and mass distribution in the major components that would be shared across the baseline and derivatives would normally need to be generated in order to make initial estimates. For the current work, because the exact geometries were employed across all the concepts, and only limited changes were made to the rear of the fuselage and empennage, assumptions could be made for commonality across the major components and systems. This sufficed for demonstration purposes, but, for future work, a more detailed approach, as described above, would need to be followed to obtain more accurate results.

The assumptions made for the fractions of commonality for the 2040s concepts as derivatives are shown in Table 1 (with CSA Twin as baseline) and in Table 2 (with CSA Tri as baseline). Note that the values in these tables represent the fraction of mass of the component/system with the minimum mass (between the baseline-derivative pair) that is common with the other component/system. Therefore, the common mass $m_{i,cmn}$ of component/system i can be calculated as follows:

$$m_{i,cmn} = C_i \min\left(m_{i,BL}, m_{i,DR}\right)$$

where $m_{i,BL}$ and $m_{i,DR}$ are the total mass for component/system i for the baseline and derivative, respectively. The non-common mass would then simply be $m_{i,ncmn,BL} = m_{i,BL} - m_{i,cmn}$ for the baseline and $m_{i,ncmn,DR} = m_{i,DR} - m_{i,cmn}$ for the derivative.

As can be seen from the values in Table 1 and Table 2, it was generally assumed that the combinations of twin and twin, twin and quad, and tri and tri, or tri and EBLI would generally have higher levels of commonality, compared with other combinations. This is reasonable, as these pairs of concepts share the same layouts for their major components. It can also be seen that the more hydrogen is employed, the more commonality will be penalised. It was assumed that there would be no commonality across propulsion systems between the CSA and 2040 aircraft.

Fuselage commonality fractions were calculated based on the expected fuselage lengths that would be common across the baseline-derivative pairs. This was done using the following calculation:

$$Fuselage\ commonality\ fraction = \frac{0.95(2 \times common\ fuselage\ length)}{fuselage\ length\ of\ baseline + fuselage\ length\ of\ derivative}$$

The 0.95 factor is to allow for local modifications in the common sections. For the concepts considered in this study, the fuselages of the baselines were both assigned a length of 62.8 m (similar to the 787-9). From this, the values in Table 3 were subtracted to get the common length between the future derivatives and the baselines.

Table 1: Commonality fractions between CSA Twin as baseline and 2040 concepts as derivatives.

	Twin KE	Quad H2/KE	Twin H2/KE	Twin H2	Tri KE	Tri H2/KE	Tri H2	EBLI KE	EBLI H2/KE	EBLI H2
Wing	0.95	0.85	0.8	0.75	0.8	0.8	0.7	0.8	0.8	0.7
Empennage	0.95	0.95	0.95	0.95	0	0	0	0	0	0
Fuselage	0.95	0.6357	0.6268	0.6268	0.7987	0.6355	0.6268	0.7987	0.6268	0.6268
landing gear	0.95	0.95	0.95	0.9	0.5	0.5	0.45	0.5	0.5	0.45
Installed engines	0	0	0	0	0	0	0	0	0	0
Systems	0.75	0.5	0.5	0.25	0.65	0.4	0.15	0.55	0.3	0.05
Furnishings	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 2: Commonality fractions between CSA Tri as baseline and 2040 concepts as derivatives.

	Twin KE	Quad H2/KE	Twin H2/KE	Twin H2	Tri KE	Tri H2/KE	Tri H2	EBLI KE	EBLI H2/KE	EBLI H2
Wing	0.8	0.8	0.8	0.7	0.95	0.85	0.75	0.95	0.85	0.75
Empennage	0	0	0	0	0.95	0.95	0.95	0.95	0.95	0.95
Fuselage	0.7987	0.6357	0.6268	0.6268	0.95	0.6355	0.6268	0.7987	0.6268	0.6268
landing gear	0.5	0.5	0.5	0.45	0.95	0.95	0.9	0.95	0.95	0.9
Installed engines	0	0	0	0	0	0	0	0	0	0
Systems	0.65	0.4	0.35	0.15	0.75	0.55	0.25	0.65	0.45	0.15
Furnishings	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 3: Length of baseline fuselage [m] that is not common with derivative.

	Derivatives									
Baseline	Twin KE	Quad H2/KE	Twin H2/KE	Twin H2	Tri KE	Tri H2/KE	Tri H2	ELBI KE	ELBI H2/KE	ELBI H2
Twin 2030	0	18	18	18	10	18	18	10	18	18
Tri 2030	10	18	18	18	0	18	18	10	18	18

2.5 Cost prediction

Accurate prediction of development cost, normally referred to as ‘Research, Development, Test, and Evaluation’ (RDT&E) cost, is normally very difficult to perform. This is because of the considerable uncertainty that exists. In addition, airframers do not generally share their methods for calculating these costs. For this research, a simple RDT&E cost model, as described in Refs [13,23] was employed. This model gives a breakdown of the RDT&E cost per unit mass for each of the major components/systems listed in Table 1 and Table 2 (just note that these authors use the term ‘payloads’ instead of ‘furnishings’). The model also provides estimates for a reduction in cost for components/systems that are common with a baseline. Again, this is provided for the components and systems listed in 1 and Table 2. This cost model was deemed sufficient to demonstrate the methodology employed in this paper, but to obtain more accurate costs, improved models using up-to-date data would need to be employed.

The RDT&E cost per unit mass values provided in Refs [13,23] were updated to account for inflation (to get to 2022 values). They were also calibrated by multiplying by a constant factor so that the total cost of the baseline matched the estimated programme cost of the Boeing 787, which was deemed to be US$32 Billion in 2012 in Ref. [24] (again adjusted for inflation to 2022).

For this study, the CSA concepts were assumed to be clean-sheet designs and were therefore assigned to incur the full development expenses. For the 2040 concepts, the development cost (C_{RDTE}) for the component/system i were calculated as follows:

$$C_{RDTE,i} = m_{i,cmn}C_{RDTE,cmn,i} + m_{i,ncmn,DR}C_{RDTE,ncmn,i}$$

where $C_{RDTE,cmn,i}$ and $C_{RDTE,ncmn,i}$ are the RDT&E cost per unit mass for common and non-common components, respectively, as calculated using [24]. The total cost for the derivative could then be calculated by summing the costs of all the components and systems.

Note that any costs related to new technology (i.e., hydrogen and EBLI) were multiplied by a factor of 1.5, to reflect the additional efforts that may be needed to make these a reality. For the hydrogen and EBLI engines, this was done by taking the fraction of thrust produced by the new technology, multiplying it by the total propulsion mass given by FLOPS, and then multiplying the result by the cost per pound of new propulsion, times 1.5. Similarly, the tank mass was multiplied by the cost per pound for new systems, times 1.5.

2.6 Tradeoff analysis

This step simply involves plotting the results from cost prediction and performance analysis to explore the trade-offs between the predicted performance and evolvability/scalability of the concepts. The purpose is to help identify combinations of current state-of-the-art (CSA) and future (EIS 2040) concepts that collectively provide the best performance at the lowest total development cost. A 'combination' here refers to the baseline-derivative pair, where the selection of the baseline would influence the development cost of the derivative.

3. Results and discussion

3.1 CSA Concepts

The empty mass breakdowns for the two CSA concepts, as obtained from FLOPS, are summarised in Table 4. Note that FLOPS calculates the same wing mass for both the twinjet and the trijet. This is because it uses the same empirical relation for wings with attached engines for both but does not take into account the mass of these engines (which would be lighter for the trijet, which should lead to a slightly heavier wing, because of a decrease in load alleviation). Likewise, the mass for the empennage and furnishings are the same, as the empirical relations used to calculate these are the same for both configurations. The fuselage, installed engines, and systems of the trijet are all heavier than for the twin, because of the third engine on the centreline. The landing gear is slightly lighter, however, as the engine diameters for the tri are smaller, which enables shorter landing gear to be used. Note that it was assumed in this paper that the landing gear length of both versions would be sufficient to allow the fuselage extensions for hydrogen tank integration. This is an assumption that would need to be revisited in future work.

Table 4: Empty mass breakdowns (lbs) of the CSA aircraft concepts.

	Twin	Tri
Wing	65004	65004
Empennage	9100	9100
Fuselage	53043	55695
landing gear	25673	24235
Installed engines	31983	33154
Systems	22874	23543
Furnishings	31334	31334

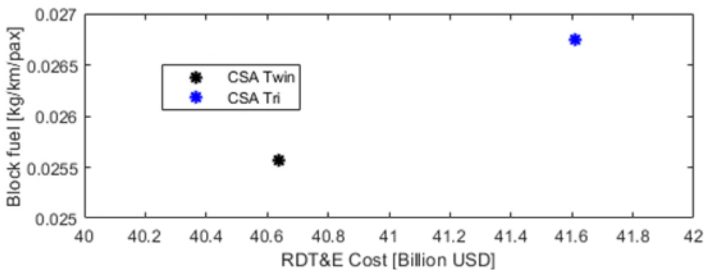

Figure 5: CSA concepts – performance (block fuel consumed) vs development cost.

The performance (in terms of block fuel per passenger per km) vs RDT&E cost for these concepts can be viewed in Figure 5. As can be seen, as is expected, CSA Tri is both less efficient and more costly to produce than CSA Twin. This result alone would appear to render CSA Tri completely undesirable, but as will be shown in the next subsection, there might be specific scenarios in which it may actually be a candidate worth considering.

3.2 2040 Concepts

Table 5 shows the empty weight breakdown summary for the 2040 aircraft. The weights for hydrogen tanks and the EBLI electric motor, cables, and converters are included under systems, whereas new engines are included under installed engines. As can be seen, many of the weights remain consistent with the CSA concepts. This is because it was assumed that these components/systems would be reused almost exactly as is on the derivatives. However, note that to get a more accurate reflection of the performance of clean sheet designs, any weight reductions due to advances in materials and structures would need to be accounted for. This should be kept in mind when considering the results for the clean sheet designs in the plots that follow.

Table 5: Empty weight breakdown (lbs) of the 2040 aircraft concepts.

	Twin KE	Quad H2/KE	Twin H2/KE	Twin H2	Tri KE	Tri H2/KE	Tri H2	ELBI KE	ELBI H2/KE	ELBI H2
Wing	65004	62712	65004	65004	65004	65004	65004	65004	65004	65004
Empennage	9100	9100	9100	9100	9100	9100	9100	9100	9100	9100
Fuselage	53043	62793	65067	65067	55695	65531	67719	55695	67719	67719
landing gear	25673	28250	25673	25673	24235	24235	24235	24235	24235	24235
Installed engines	31983	33930	31983	31983	33154	33154	33154	33154	33154	33154
Systems	22874	37189	42202	64004	23543	36860	66202	29055	47702	68400
Furnishings	31334	31334	30686	27444	31334	31334	27444	31334	30686	27444

Figure 6 shows the performance of the EIS 2040 concepts (in terms of the percentage reduction in CO_2 with respect to CSA Twin) vs the RDT&E cost as a function of different evolution/scaling strategies. Three of these strategies are shown: clean sheet (in which the aircraft are designed from 'scratch'), developed from CSA Twin as baseline, and developed from CSA Tri as baseline. Figure 7 shows the same strategies, but for the block fuel consumed over the mission in kg-equivalent kerosene per passenger per km flown vs RDT&E cost. This block fuel measure can be used as a proxy for the overall energy consumed by the different concepts.

In terms of the reduction in CO_2 emission per passenger per kilometre, it can be seen that (as expected) the full hydrogen concepts provide a 100% reduction, whereas the full kerosene concepts only provide marginal improvements over the CSA Twin (which are mainly due to their more efficient engines). The next best concept from the full hydrogen options is EBLI H2/KE 2040 (the turbo-electric/BLI concept with partial hydrogen), followed by TWIN H2/KE 2040 (which uses 50% H2 and 50% KE).

From the perspective of energy use per passenger per kilometre, the kerosene aircraft perform the best, whereas increasing levels of r correlate to increasing energy use. This is due to a combination of the drag and mass related to the longer fuselages of the hydrogen aircraft, but also because fewer passengers are carried on these aircraft. Also, the EBLI aircraft tend to perform better than those that do not have the technology.

As a summary regarding the performance results, if development cost were not a regard, the decision of which 2040 aircraft to develop would hinge on the desire to have a 100% hydrogen aircraft vs the costs incurred due to the total energy used per passenger per kilometre, with hydrogen aircraft providing 100% reduction on CO_2, but using more energy relative to aircraft having less hydrogen. Also, in general, for equivalent hydrogen-kerosene thrust-ratios, the tri-jets generally perform slightly worse than the twins and quads, whereas the EBLI concepts (which share the same major component layout with the tri-jet) generally perform the best.

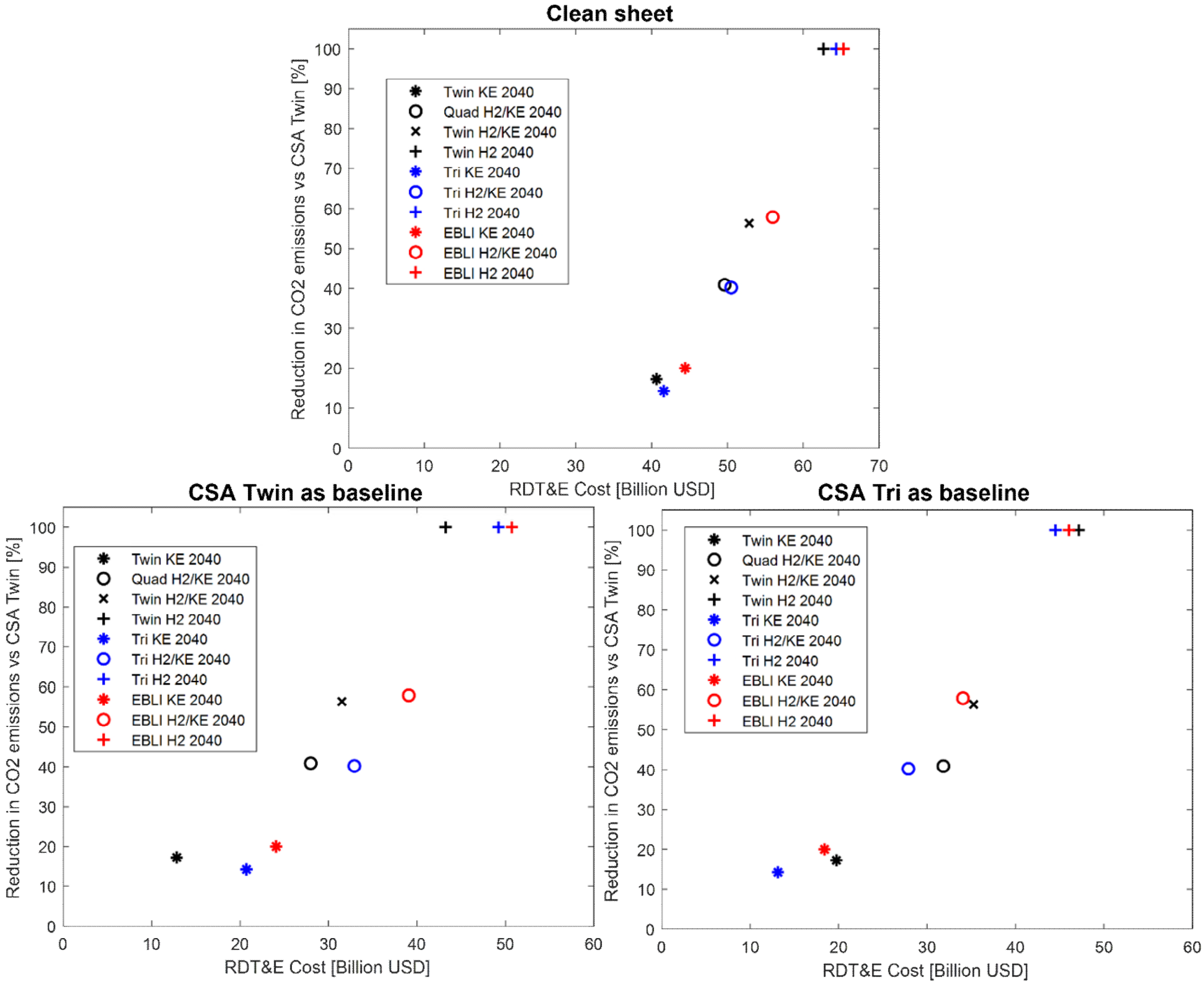

Figure 6: EIS 2040 concepts – performance (in terms of CO2 emissions reduction with respect to CSA Twin) vs development cost for different evolution strategies (Clean sheet, CSA Twin as baseline, and CSA Tri as baseline).

However, as highlighted in the context of this paper, the decision of which aircraft to go for if development cost were not a concern would also depend on the availability of the relevant technologies. In one scenario, hydrogen may be available in abundance and affordable, in which case all the different hydrogen options would be available, and the aforementioned trade-off between energy usage and fossil fuel reduction would be relevant. In other scenarios, the technology to introduce hydrogen would not be mature enough, or the hydrogen infrastructure would not exist on the scale required, in which case none of the hydrogen options will be available. In still other scenarios, the technology may be mature enough, but it may be difficult to scale up, or the supply of hydrogen may be limited. In this case, only the partial hydrogen options may be available along with the kerosene-only options. Whether to select Twin H2/KE or the EBLI H2/KE, which both use 50% hydrogen, over the concepts that make use of only a third of hydrogen for propulsion, would depend on the actual levels of hydrogen available or how much the technology could be scaled up.

Nonetheless, cost will of course be a concern, so this has to be considered. It can be seen from the results in the figures that, if the 2040 concepts were to be produced as clean sheet designs, for the same value of r, the twinjet (and the quad, if $r = 0.33$) options would be the least expensive. Based on the cost models used and the associated assumptions, an increase in hydrogen would impose a substantial related penalty on the expenses incurred.

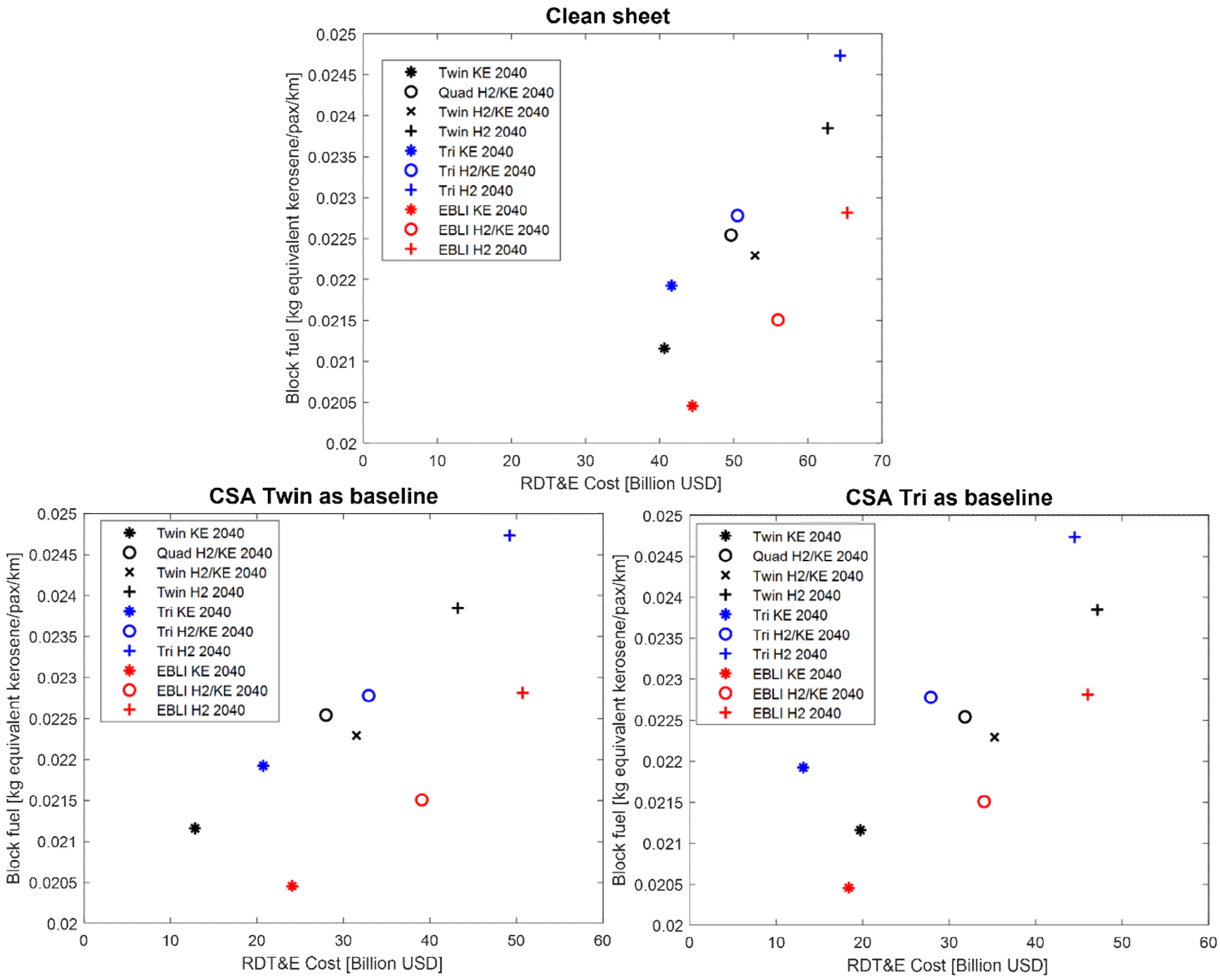

Figure 7: EIS 2040 concepts – performance (in terms of block fuel consumed in kg equivalent kerosene) vs cost for different evolution strategies (Clean sheet, CSA Twin as baseline, and CSA Tri as baseline).

It can also be seen from the figures that developing from a baseline offers generous benefits in terms of RDT&E cost, regardless of which baseline is chosen. This is the power of commonality. This power can be enhanced by choosing the right baseline. In other words, it can be seen that the choice of baseline becomes very important when considering the combination of the comparative performance benefits that can be obtained from the derivatives of a selected baseline vs the cost to develop them from that baseline. For example, consider a scenario where CSA Twin was selected as the baseline, a 'Pareto front' containing Twin KE, Quad H2/KE, Twin H2/KE, and Twin H2 develops on the 2040 reduction in CO_2 vs RDT&E cost plot (as can be seen in Figure 6), which would indicate that the airframer would likely adopt one of these, depending on the availability of hydrogen and maturity of the technology. If EBLI has not become a reality, these would be the best options and having chosen the twin, would have been the best choice, as the total development cost of the baseline and derivative would have been far lower than if CSA Tri were selected as baseline. Again, the exact choice of which concept on the Pareto front to develop would depend on the considerations deliberated upon earlier (considering both the quantity of hydrogen used vs energy usage).

Next, however, consider scenarios where EBLI does become a reality, and a competitor aggressively introduces successful EBLI designs. In such cases, if the manufacturer attempts to redesign CSA Twin to become one of the EBLI concepts, the total baseline-derivative cost would be more than if CSA Tri were selected as baseline. This could indicate that there are scenarios in which choosing a trijet may actually offer some benefits. However, the relatively unfavourable performance of the CSA Tri may make it difficult to sell, which would reflect a loss of revenue. In addition, the risk of EBLI not maturing enough in time may be too high. What would be needed to provide a more definitive answer on which baseline to pursue would be a more comprehensive study accounting for the revenue that the concepts may provide, as was done in Markish [13,23] for a blended wing body aircraft, across different future scenarios, while taking into account the probability that each scenario may materialise. This is planned as part of future work

4. Conclusions

In this paper, it was demonstrated how engineering systems evolvability analysis techniques could be employed in devising potential scalable hydrogen propulsion systems for a future medium-sized widebody long-range civil transport aircraft. Specifically, it was shown how the predicted performance and potential commonality between a set of concepts for current state-of-the-art kerosene aircraft and future dual-fuel aircraft with different levels of hydrogen-to-kerosene thrust ratios and potential turboelectric propulsion with boundary layer ingestion could be exploited to investigate future scenarios.

The performance results showed a trade-off emerging between carbon dioxide emissions reduction and the reduction in overall energy use per passenger per kilometre. Another clear trade-off was in development cost vs the level of hydrogen propulsion incorporated.

The results further illustrated the substantial potential cost reduction that could be obtained by developing the future aircraft from a baseline as opposed to a clean sheet. Using the twinjet as a baseline ensured higher levels of cost reduction for future derivatives that are also twins or quad jets, as opposed to those that have a tri-jet or EBLI configuration. The converse is obviously also true.

Furthermore, as would be expected, for the same levels of kerosene-hydrogen thrust split, the trijets were always outperformed by the twin jets and even the quad. They were generally also more expensive to develop. However, it was shown that there could be scenarios where there may be some benefit in developing a trijet as the baseline. These would involve a high likelihood that EBLI would be sufficiently mature to be incorporated. The benefit would arise from the combined development cost for the trijet baseline-EBLI derivative pair being substantially lower than that of the twinjet baseline-EBLI derivative pair. However, this does not account for the loss in revenue that the trijet may incur because of it being inferior to twinjet competitors. Because of this, the twinjet is likely still the best configuration to use as baseline. That being said, it is hoped that this paper demonstrated the importance of designing the baseline with evolvability very much in much such that the transition to incorporating higher levels of hydrogen would proceed affordably.

Future work would involve more detailed modelling, especially regarding performance, commonality, cost, and revenue predictions. More aircraft concepts and technologies will also be explored. Additionally, the concepts will be infused with different changeability enablers, to investigate in more detail how the actual changes could be performed. Finally, specific future scenarios with associated probabilities of occurring will be defined, such that an improved assessment could be made regarding the best baseline to pursue.

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6. Copyright Statement

7. References

[1] Khandelwal, B., Karakurt, A., Sekaran, P. R., Sethi, V., and Singh, R. “Hydrogen Powered Aircraft: The Future of Air Transport.” *Progress in Aerospace Sciences*, Vol. 60, 2013, pp. 45–

59.
[2] Huete, J., Nalianda, D., and Pilidis, P. "Propulsion System Integration for a First-Generation Hydrogen Civil Airliner?" *The Aeronautical Journal*, Vol. 125, No. 1291, 2021, pp. 1654–1665.
[3] Ryan, E. T., Jacques, D. R., and Colombi, J. M. "An Ontological Framework for Clarifying Flexibility-Related Terminology via Literature Survey." *Systems Engineering*, Vol. 16, No. 1, 2013, pp. 99–110.
[4] Ross, A. M., and Rhodes, D. H. "Towards a Prescriptive Semantic Basis for Change-Type Ilities." *Procedia Computer Science*, Vol. 44, No. 0, 2015, pp. 443–453. https://doi.org/10.1016/j.procs.2015.03.040.
[5] Niese, N. D., and Singer, D. J. "Assessing Changeability under Uncertain Exogenous Disturbance." *Research in Engineering Design*, Vol. 25, No. 3, 2014, pp. 241–258.
[6] Van Heerden, A. S. J., Guenov, M. D., Molina-Cristóbal, A., Riaz, A., and Bile, Y. Combined Airframe and Subsystems Evolvability Exploration during Conceptual Design. 2018.
[7] Van Heerden, A. S. J., Guenov, M. D., Molina-Cristóbal, A., and Riaz, A. Enhancing the Exploration of Aircraft Changeability during Conceptual Design. 2016.
[8] Fricke, E., and Schulz, A. P. "Design for Changeability (DfC): Principles to Enable Changes in Systems throughout Their Entire Lifecycle." *Systems Engineering*, Vol. 8, No. 4, 2005, pp. 342–359.
[9] Ross, A. M., and Hastings, D. E. Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration. No. 1, 2006, pp. 551–568.
[10] Boas, R. C. *Commonality in Complex Product Families: Implications of Divergence and Lifecycle Offsets*. Massachusetts Institute of Technology, Cambridge, MA, U.S.A., 2008.
[11] Johnson, M. D., and Kirchain, R. E. Developing and Assessing Commonality Metrics for Product Families. In *Advances in Product Family and Product Platform Design*, Springer, 2014, pp. 473–502.
[12] van Heerden, A. S. J., Guenov, M. D., and Molina-Cristóbal, A. "Evolvability and Design Reuse in Civil Jet Transport Aircraft." *Progress in Aerospace Sciences*, Vol. 108, 2019, pp. 121–155. https://doi.org/10.1016/j.paerosci.2019.01.006.
[13] Markish, J. *Valuation Techniques for Commercial Aircraft Program Design*. Massachusetts Institute of Technology, 2002.
[14] NASA. Single-Aisle Turboelectric Aircraft with Aft Boundary-Layer Propulsion. https://sacd.larc.nasa.gov/asab/asab-projects-2/starc-abl/. Accessed Oct. 23, 2020.
[15] McCullers, L. A. Aircraft Configuration Optimization Including Optimized Flight Profiles. 1984.
[16] Boeing Commercial Airplanes. 787 Airplane Characteristics for Airport Planning (D6-58333). https://www.boeing.com/resources/boeingdotcom/commercial/airports/acaps/787.pdf.
[17] Rolls-Royce PLC. Powering the Dream. https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-1000.aspx#section-overview. Accessed Jun. 1, 2022.
[18] Verstraete, D., Hendrick, P., Pilidis, P., and Ramsden, K. "Hydrogen Fuel Tanks for Subsonic Transport Aircraft." *International journal of hydrogen energy*, Vol. 35, No. 20, 2010, pp. 11085–11098.
[19] Rolls-Royce. Advance and Ultrafan. https://www.rolls-royce.com/media/our-stories/innovation/2016/advance-and-ultrafan.aspx. Accessed Dec. 10, 2020.
[20] Sanders, D. S., and Laskaridis, P. "Full-Aircraft Energy-Based Force Decomposition Applied to Boundary-Layer Ingestion." *AIAA Journal*, Vol. 58, No. 10, 2020, pp. 4357–4373.
[21] Mutangara, N. E., Smith, L., Craig, K. J., and Sanders, D. S. "Potential for Energy Recovery of Unpowered Configurations Using Power Balance Method Computations." *Journal of Aircraft*, Vol. 58, No. 6, 2021, pp. 1364–1374.
[22] Cranfield University. *The TURBOMATCH Scheme*. 1999.
[23] Markish, J., and Willcox, K. A Value-Based Approach for Commercial Aircraft Conceptual Design. 2002.
[24] Nolte, P., Apffelstaedt, A., and Gollnick, V. Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency. In *Air Transport and Operations*, IOS Press, 2012, pp. 514–531.