



Techno-Economic analysis of ceramic matrix composites integration in remaining useful Life Aircraft Engine Hot Section Components

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Abstract

Ceramic Matrix Composites (CMCs), specifically SiC/SiC composites, represent a significant innovation in aerospace material technology, offering superior performance over traditional nickel-based superalloys in high-temperature turbine blade applications. This study presents a novel techno-economic assessment, filling a critical gap in the literature by directly comparing the economic and technical viability of CMCs versus superalloys. Unlike previous studies, which primarily focus on technical performance or cost analysis independently, this work integrates both aspects, providing a holistic comparison across key economic metrics, including acquisition, machining, maintenance, and recycling costs. The results demonstrate that SiC/SiC blades offer a 15–20% higher Net Present Value (NPV) and a 17% greater Internal Rate of Return (IRR) over a 20-year lifecycle than superalloys. Despite higher initial costs, CMCs achieve an estimated 2 to 3 years reduction in payback period, mainly due to their superior thermal and creep resistance, leading to fewer maintenance interventions and longer operational lifetimes. Although machining costs for CMCs are higher, these are more than offset by the long-term savings achieved through improved fuel efficiency and lower maintenance costs. A comprehensive sensitivity analysis, incorporating fluctuations in discount rates and material costs, further validates the economic robustness of CMCs in various operational scenarios. This study is the first to compare CMCs and superalloys, offering new insights into the financial implications of material selection in aerospace manufacturing. The findings present critical engineering recommendations that empower aerospace manufacturers and decision-makers to optimise material selection for improved efficiency and cost-effectiveness in high-performance turbine applications.

Keywords Ceramic matrix composites · CMC · Aircraft engine components · Economic feasibility · Maintenance costs

1 Introduction

Recent research on advanced materials for aircraft engine hot sections has highlighted the potential benefits of integrating ceramic matrix composites (CMCs) due to their superior thermal and mechanical properties [1]. Previous studies demonstrate the potential of CMCs to improve engine efficiency and reduce emissions [1, 2], yet they need a comprehensive techno-economic analysis. Additionally, while significant advancements have been made in CMC processing techniques [3], there is a notable research gap in comparing the economic viability of these materials against traditional superalloys in turbine blade applications [4]. This study addresses this gap by providing a holistic techno-economic analysis, focusing on lifecycle costs and performance. Such influential factors highlight the industry's evolution, allowing for aerospace technological advancements and yielding more robust engines capable of increased thrust and efficiency. Consequently, the

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demand for materials exhibiting superior mechanical properties and higher heat resistance has intensified, given the progressively severe operational conditions [2].

The elaboration of composite techniques such as Resin Transfer Moulding (RTM), Filament Winding, and Autoclave Moulding has allowed manufacturers to create complex geometries with precise tolerances, meeting the stringent demands of modern aerospace applications. These techniques enable embedding continuous fibres (such as carbon or ceramic) into a polymer matrix, resulting in lightweight materials capable of withstanding extreme operational conditions. In addition to manufacturing, computational modelling techniques have also played a crucial role in optimising composite structures. Models based on Finite Element Analysis (FEA) and multi-scale simulations are frequently employed to predict the performance of composites under thermal, mechanical, and environmental loads, thereby reducing the need for expensive experimental testing [1, 2]. This integrated approach of manufacturing and modelling has significantly enhanced the application of composites in aerospace, where safety, performance, and durability are paramount.

The primary objective of this paper is to evaluate the economic and technical feasibility of replacing superalloy turbine blades with CMCs using detailed metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and lifecycle cost analysis. This study aims to offer actionable insights for material selection in aerospace applications by addressing both acquisition and maintenance costs. Furthermore, this research contributes to the existing body of knowledge by directly comparing the economic viability of oxide and non-oxide CMCs with conventional superalloys.

Rigorous environmental regulations requiring reductions in greenhouse gas emissions and noise pollution from aircraft engines have amplified the necessity for material innovation to bolster engine efficiency [5]. Adhering to these regulatory demands hinges on implementing advanced materials and technologies. Furthermore, the operational landscape, characterised by high-altitude flights, close to supersonic speeds, and prolonged journeys, necessitates materials that endure prolonged stress and thermal cycling, thus emphasising the need for more durable materials [6, 7].

Economic considerations also play a pivotal role in material selection for hot section components. Williams and Starke [8] underline that the significant impact of maintenance and operating costs on airline profitability underscores the importance of materials that curtail maintenance requirements and prolong component life. This strategic selection aids airlines in bolstering their competitive edge by optimising economic efficiency [9].

Evaluating maintenance requirements and associated costs in the context of hot section component material replacement assumes paramount importance in aviation operations [10–12]. Alsyouf emphasises that maintenance impacts both safety and economic facets within the industry [13]. For

instance, ensuring the safe and reliable operation of aircraft engines is essential; hence, careful assessment of maintenance requirements is imperative to avoid compromising safety standards or escalating the risk of in-flight failures [14].

Moreover, maintenance directly influences operational efficiency, with downtime significantly impacting airline operations. By reducing maintenance frequency and length, airlines improve aircraft availability and minimise interruptions to flight schedules [15]. Additionally, as maintenance costs constitute a substantial portion of an airline's operating expenses, evaluating these costs becomes instrumental in anticipating and controlling expenditures. Such an approach substantially enhances cost-efficiency and overall profitability within the airline industry [9, 16].

Hot section components in aircraft engines are pivotal in ensuring aerospace propulsion systems' safety, efficiency, and longevity. These components, often subjected to extreme temperatures and pressures, are essential for generating thrust and power, making them a critical aspect of aviation technology [17]. Research highlights that the relentless pursuit of innovation to enhance the performance and reliability of these components is crucial [18, 19]. Therefore, material replacement and upgrades in hot section components have become a pressing concern. While ceramic materials are known for their high-temperature performance and sustainability, their natural brittleness presents considerable challenges, particularly in the harsh environment of aerospace applications. Ceramics' brittle nature can result in unexpected and catastrophic failures under stress, making them unsuitable for aeronautical components that must withstand dynamic loads and stress concentrations [20]. Ceramic Matrix Composites (CMCs) have been effectively developed to overcome such restrictions by integrating ceramic fibres into a ceramic matrix. This unique structure improves fracture toughness and crack propagation resistance, which is crucial in aeronautics, where reliability and security are essential [20, 21].

The design of CMCs typically involves the use of continuous fibres or whiskers, such as silicon carbide, which are embedded into a ceramic matrix [10]. The fibres help bridge cracks that may form within the matrix, distributing stress more evenly and preventing the cracks from widening. This fibre reinforcement strategy not only enhances the toughness of the composite but also improves its structural integrity under operational conditions [10]. Moreover, constructing fibre orientations and volume fractions in CMCs allows for optimising mechanical properties to specific application needs, enhancing their performance in complex aeronautic environments.

Additionally, advancements in the processing techniques of CMCs, such as chemical vapour infiltration and matrix impregnation, have further improved their durability and thermal shock resistance [20, 22]. These processing improvements ensure that CMCs perform even under the extreme temperature gradients and high-speed impacts characteristic of aerospace hot engine Sect. [23]. As a result, CMCs fulfil the high-performance

criteria required in the aerospace sector and reduce the risk associated with the brittle behaviour of traditional ceramic materials, making them a viable and increasingly preferred choice in the design of critical aeronautic components.

Using CMCs and superalloys for turbine blade materials has been researched extensively [22]. However, a notable research gap exists in the direct comparative techno-economic analysis between such material classes for turbine blade manufacturing. The literature must capture a thorough techno-economic investigation of oxide and non-oxide CMCs. While numerous studies have separately investigated the economic viability, performance, and durability of superalloys [24], there needs to be more comprehensive comparative analyses with CMCs that holistically assess and contrast the economic competitiveness of these materials. Moreover, this study differs from previous research by incorporating specific financial benchmarks, such as NPV and IRR, and performing sensitivity analyses to address acquisition and maintenance cost uncertainties. The direct comparison between oxide and non-oxide CMCs and superalloys sets this work apart, providing insights not extensively covered in the existing literature.

Understanding the nuanced financial implications, such as Net Present Value (NPV), Cash Flow, and Internal Rate of Return (IRR), associated with CMCs and superalloys in turbine blade production is a critical gap that demands further exploration to aid in informed material selection decisions. This leads to the purpose of this research: to evaluate the economic impact of replacing metallic blades with CMC materials in aircraft engine hot section components. By evaluating maintenance requirements and associated costs, the study seeks to understand how this material change could affect the lifecycle and integrated systems. A risk assessment will also be presented to analyse potential risks associated with adopting CMC materials, such as thermal shock resistance and environmental sustainability. This analysis serves as a basis for cost comparisons. Investment cost analysis, utilising metrics like NPV and IRR, determines the economic

viability of transitioning to CMC materials. Sensitivity studies address uncertainties in acquisition and maintenance costs. The novelty of this study lies in its comprehensive techno-economic comparison between CMCs and traditional superalloys, which is a direct gap in the current literature. Unlike previous studies, this research not only focuses on the technical performance of CMCs but also provides a detailed economic analysis, including sensitivity studies that assess uncertainties in acquisition and maintenance costs. This integrated approach offers a more informed framework for decision-making in material selection for high-performance aerospace components.

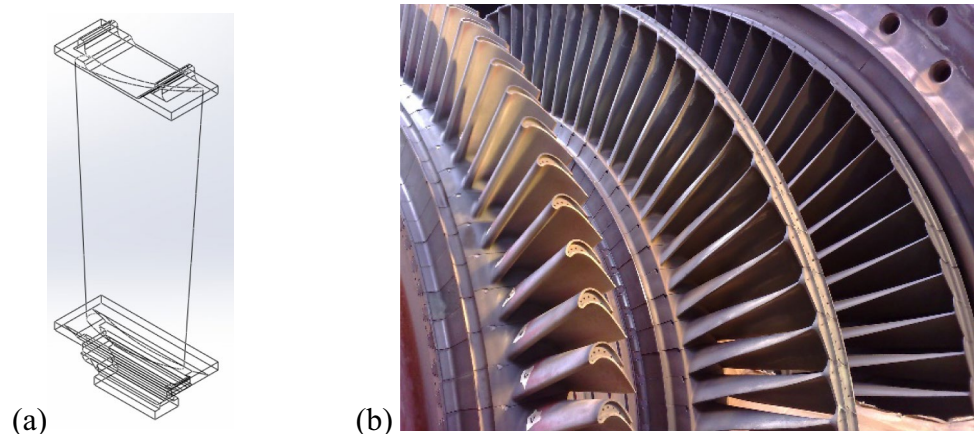
2 Research Methodology

The research assesses a case study where the specific CMC components and their metallic counterparts are identified, focusing on gas turbine blade applications. This involves defining their functionalities and critical roles within applications, notably in aero engines and gas turbines. Specifically, the case study explores the design and functionality of gas turbine blades in gas aerospace turbine engines, as shown in Fig. 1.

Gas turbine blades undergo a lifecycle from design to replacement, including routine maintenance checks every 400 to 600 h or 200 to 300 flights to ensure performance. With long-range widebody airliners aiming for 30,000 flight cycles and short-range narrowbody jets targeting 50,000 cycles, turbine blades are critical for gas turbine engine efficiency and safety [25, 26].

Furthermore, the blades endure harsh conditions like high temperatures and pressure changes during engine operation. To withstand these challenges, advanced materials like nickel superalloys, such as Inconel 625 and Hastelloy X are used for their strength and resistance to heat and corrosion. However, despite their durability, the blades degrade over time due to the intense thermal and mechanical strains they

Fig. 1 Turbine blade (a) schematic used in the analysis, (b) actual turbine blades in various engine Sect. [28]



experience. For this reason, the study focuses on assessing CMCs with high-temperature and creep-resistant properties to compare with the selected conventional metallic materials. The CMCs with the highest impact mechanical and thermal properties are addressed in previous literature research [24] and include both oxide and non-oxide CMCs, such as SiC/SiC, Al₂O₃/B₄C, and Al₂O₃/SiO₂. Such CMCs are compared with nickel superalloys in Figs. 2 and 3, using material properties from an existing database [27].

CMCs showcase much lower thermal expansion coefficient and conductivity than nickel superalloys, as shown in Fig. 2, which are essential requirements for such applications. The results show that the Nickel Superalloys have higher fracture toughness but similar fatigue strength with Al₂O₃/B₄C.

The manufacturability of turbine blades, whether crafted from nickel superalloys or CMCs, must satisfy the aerospace industry's criteria for safety and performance. Precision investment casting has been used for decades to produce blades with complex geometries and precise tolerances [28]. Superalloys additionally require

complicated heat treatment [29]. CMCs, including different types such as SiC/SiC, Al₂O₃/B₄C, and Al₂O₃/SiO₂, present unique production issues due to their brittleness and hardness. Ceramic fibres are embedded into a ceramic matrix using processes such as chemical vapour infiltration (CVI) and polymer impregnation and pyrolysis (PIP), which improves the material's toughness and resistance to operational stress [24, 30]. To achieve the specific requirements for aerospace components, specialised machining processes such as diamond grinding or laser machining are required [31].

Both material types need extensive quality testing to ensure the blades meet operational and performance standards. The ongoing research of CMC production intends to improve the scalability and cost-effectiveness of these methods, making CMCs a viable option to replacing superalloys, especially for high-temperature applications in aircraft turbines [32]. This research study achieves this by adhering to previously published research studies where the operating flight hours and costs are also considered.

Fig. 2 Thermal properties of selected CMCs and superalloys

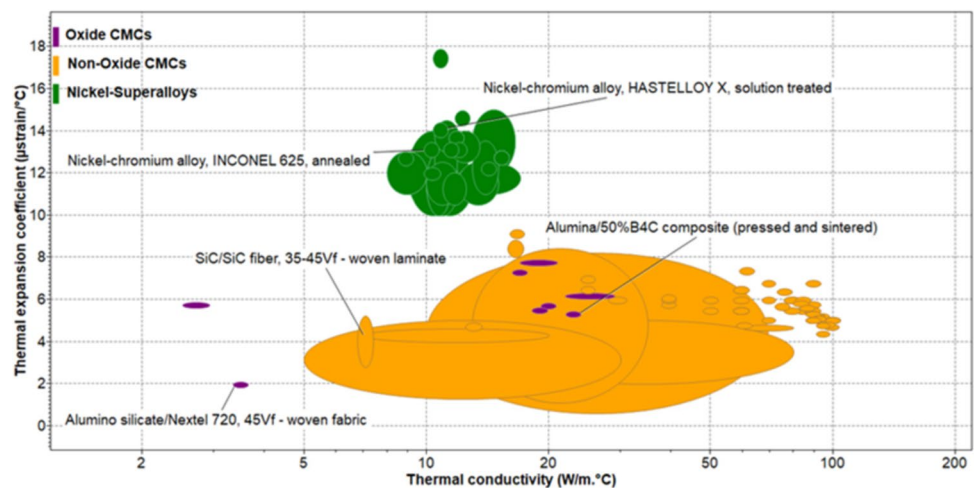
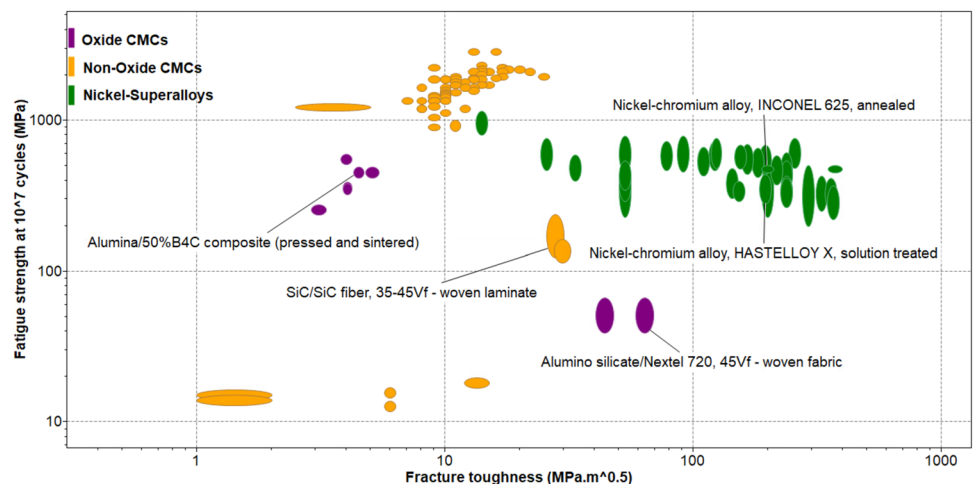


Fig. 3 Mechanical properties of selected CMCs and superalloys



3 Economic analysis approach and metrics

Economic considerations wield substantial influence in the aerospace industry, particularly in selecting materials for critical components like turbine blades [31, 32]. Applying various economic indicators is fundamental to understanding the financial implications of such material choices. This section delves into the critical economic analysis mechanisms used for evaluating the viability of turbine blade materials. The flowchart in Fig. 4 presents a systematic approach, capturing crucial input data, including material properties, cost estimates, and other pertinent information. Subsequently, a robust cost model is developed, incorporating various components such as acquisition, maintenance, and operating expenses. This model is the basis for evaluating the financial implications associated with different turbine blade materials over their lifecycle.

Leveraging a group of economic indicators, including NPV, cash flow analysis, IRR, discount rate, and maintenance costs, the analysis provides insights into each material's financial viability and efficiency for this application. This section includes a novel comparative analysis highlighting how advanced economic models and sensitivity analyses integrate to evaluate CMCs holistically versus superalloys. Unlike previous studies, this research provides a detailed examination of how specific CMC configurations with optimised fibre orientations influence the long-term economic viability of aircraft components. Specifically, NPV analysis clarifies the long-term attractiveness of investments [32, 33], while cash flow analysis offers

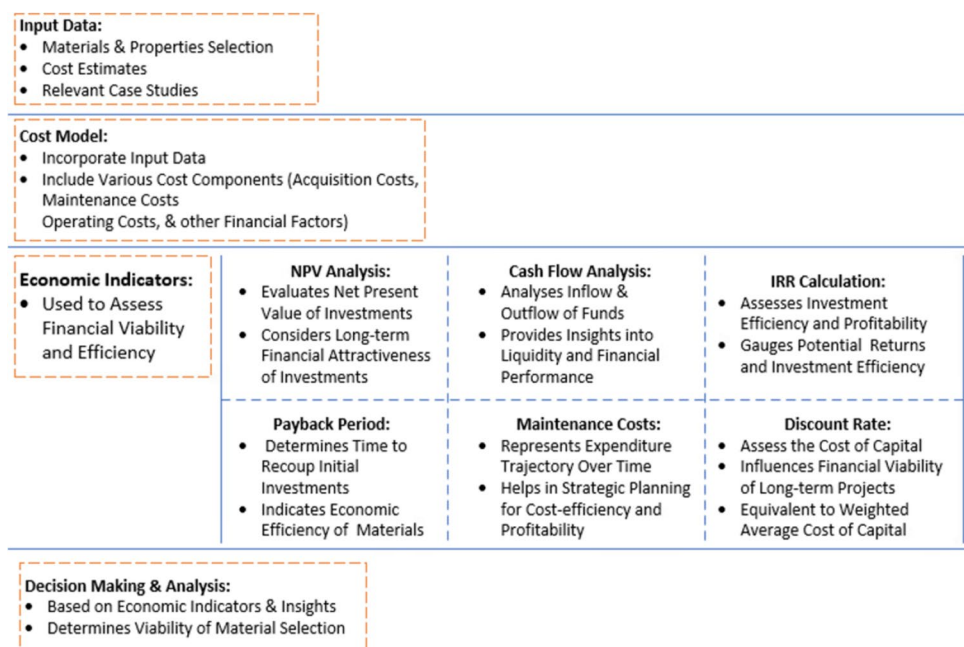
critical insights into liquidity and financial performance [34, 35]. Furthermore, IRR calculation aids in determining potential returns and investment efficiency [36, 37], whereas consideration of the discount rate sheds light on the influence of capital costs on economic feasibility.

Additionally, the trajectory of maintenance costs over time is examined to inform strategic planning and cost-efficiency [38]. The payback period indicates how swiftly initial investments can be recovered. A shorter payback period signifies quicker returns in turbine blade material selection, highlighting economic efficiency and aiding decision-making. Ultimately, informed decision-making is facilitated by synthesising insights gleaned from the economic analysis, enabling the selection of turbine blade materials that align with economic considerations and performance requirements in aerospace applications.

4 Economic assessment-case study

This case study evaluates and compares the financial feasibility of utilising CMCs and nickel-based superalloy materials for gas turbine blades in the aerospace industry. Similar assumptions implemented in previous techno-economic research studies are used to calculate the results in this research [32]. The financial analysis focuses on key investment decision criteria, assessing parameters like initial acquisition cost, annual maintenance, depreciation, assumed inflow, residual value, and the discount rate set at 7% [26]. This rate is pivotal as it reflects the opportunity cost of capital and serves as a benchmark for investor returns

Fig. 4 Economic analysis mechanisms flowchart



in the aerospace sector, where capital-intensive investments are typical.

The initial investment for 40 nickel superalloy blades is approximately \$600,000, including the first-year maintenance costs [39]. However, CMCs, particularly SiC/SiC composites, are more expensive, with a set costing about \$2.3 million due to their higher production costs [45]. Despite this higher initial investment, CMCs exhibit superior material properties such as enhanced thermal, creep, and oxidation resistance, which directly reduce operational and maintenance costs over time [20, 26]. This reduces total depreciation expense compared to superalloys, as CMCs experience less wear and tear over their lifecycle [40].

The blades' lifecycle is critical to financial projections. The usage assumptions for the case study predict 1,700 flight cycles or 3,300 flight hours annually, summing up to 6,600 flight hours over the turbine's operational life [25]. In contrast, CMC blades typically offer double the operational life of up to 20,000 cycles due to their higher resistance to extreme temperatures and mechanical stress, allowing for fewer replacements over time [26]. For example, the blades are expected to be replaced in year 10, which impacts cash flow during that year. However, CMCs extend the replacement period, reducing the frequency of these capital expenditures.

Net Present Value (NPV) and Internal Rate of Return (IRR) are essential metrics used in this analysis to assess the financial viability of the blades over a 20-year horizon [26]. The NPV of CMCs is significantly higher (by approximately

15–20%) than superalloys due to lower ongoing maintenance costs, fuel savings, and extended operational life [41]. These factors result in fewer outflows and improved cash flow stability. The NPV for the superalloys is lower, primarily because of their shorter lifespan and higher maintenance costs, which increase operational disruptions and expenses over the 20-year evaluation period [32].

Similarly, the IRR for CMCs reaches 62%, reflecting a desirable investment compared to 45% for nickel superalloys. The extended life of CMCs reduces the number of blade replacements required and cuts down on maintenance-related downtimes, which leads to better overall profitability.

As can be seen in Table 1 results, CMCs are lighter than superalloys but more expensive to produce in the case of SiC/SiC and Al₂O₃/SiO₂ compared to Al₂O₃/B₄C, Inconel 625, and Hastelloy X.

Using the values from Table 1 in Eq. 1, the annual material cost per blade is calculated. The cost per kg of CMCs such as SiC/SiC and Al₂O₃/SiO₂ is substantially higher than traditional materials like Inconel 625 and Hastelloy X. Despite this, the operational advantages such as reduced fuel consumption due to the lighter weight and lower maintenance costs due to improved durability help mitigate the initial higher acquisition costs [16, 17].

Material costs for CMC composites and nickel-based superalloys were obtained from the Granta Selector Material Library [27]. These values represent the latest data for aerospace materials and reflect the current market conditions.

$$\text{Annual Material Cost per Blade} = (\text{Cost of Material per unit} * \text{Material weight}) \quad (1)$$

Recent advancements in additive manufacturing and robotic automation have contributed to the higher machining costs for SiC/SiC composites than superalloys [3]. These

costs, however, are compensated by the reduced maintenance and operational costs throughout the lifecycle of the turbine blades.

$$\text{Annual Maintenance Cost} = \text{Maintenance cost per cycle} \times \text{Number of cycles per year} \quad (2)$$

$$\text{Total Maintenance Cost} = \text{Machining cost per hour} \times \text{Machining hours per unit} \quad (3)$$

Table 1 CMC and superalloy materials density, material weight, and cost per blade [27]

Material	Density (kg/m ³)	Material Weight (kg)	Material Cost Per kg (USD)	Embodied Energy (MJ/kg)	CO ₂ Footprint (kg)
Inconel 625	8,4	13.8	35	207	13
Hastelloy X	8,2	14.2	291	110	8
SiC/SiC	2,3	5.5	3,708	146	9
Al ₂ O ₃ /B ₄ C	3,3	3.4	69	148	12
Al ₂ O ₃ /SiO ₂	2,5	4.6	4,274	38	3

Maintenance cost data were sourced from the Rolls-Royce TotalCare program [46], reflecting updated costs for turbine blade lifecycle management using CMCs and nickel-based superalloys. These data provide insights into reducing maintenance intervals and the corresponding cost savings due to CMCs' improved material properties.

A sensitivity analysis was conducted to understand the influence of key variables such as maintenance costs, material costs, and discount rates on the economic outcomes. The study shows that CMC blades maintain a positive NPV across discount rates (5–10%) due to their operational advantages, including reduced fuel consumption and longer operational life. The results demonstrate that the payback period for CMC blades is reduced by 2–3 years compared to superalloy blades, primarily due to fuel savings and lower maintenance intervals. This makes CMCs a financially robust choice, even under fluctuating market conditions.

The technical properties of CMCs, such as thermal resistance, lightweight structure, and creep resistance, directly influence the economic viability of gas turbine blades in aerospace applications. These properties lead to lower maintenance costs, extended operational life, and improved fuel efficiency, resulting in higher NPV and IRR for CMCs than traditional nickel-based superalloys [16, 31]. Despite higher upfront costs, the long-term savings make CMCs a cost-effective solution for high-performance aerospace applications.

5 Results

5.1 Economic analysis

The calculations presented in the previous section allow estimating the maintenance costs attributed to turbine blades. Annual material costs per blade type allow for the calculation of replacement expenses while operating costs offer insights into ongoing expenditures concerning blade performance and maintenance. The annual depreciation cost, annual operating cost (AOC), cash flow, net present values, payback period, revenue, return of investment, gross margin, internal rate of return, and net cash flow are calculated using the equations below and are presented in Table 2. (Table 3)

$$\text{Annual Depreciation cost} = \frac{\text{Initial Cost} - \text{Residual Value}}{\text{Useful Life}} \quad (4)$$

$$\text{Annual Operating Cost} = \text{Maintenance Cost} + \text{Annual Depreciation Cost} \quad (5)$$

$$\text{Cash Flow}_t = \text{Cash Inflow}_t + \text{Cash Outflow}_t \quad (6)$$

$$\text{NPV} = \sum_{t=0}^n \frac{CF_t}{(1+r)^t} - \text{Initial investment} \quad (7)$$

$$\text{Payback Period} = \text{Number of full years} + \frac{\text{Initial Investment} - \text{Cumulative cash flow before recovery}}{\text{Cash flow during the year when recovery occurs}} \quad (8)$$

$$\text{Revenue/Savings} = \frac{\text{Quantity} \times \text{Price}}{\text{Value per unit}} \quad (9)$$

$$\text{Gross Margin (\%)} = \left(\frac{\text{Total Revenue} - \text{COGS}}{\text{Total Revenue}} \right) \times 100\% \quad (10)$$

Table 2 shows the sum of economic impact indicators for 20 years. This table presents financial metrics for five selected materials, with each row corresponding to different financial indicators, offering insights into the performance

Table 2 Material cost and average machining cost

Material	Cost Per Blade (USD)	Machining Cost (USD per hour)	Reference
Inconel 625	485.6	70	[3]
Hastelloy X	291.2	80	[42]
SiC/SiC	2,0393.8	110	[43]
Al2O3/B4C	234.3	93	[44]
Al2O3/SiO2	1,7737.1	100	[45]

and profitability of these materials. ROI measures the profitability of an investment relative to its initial cost. Al2O3/B4C and Hastelloy X demonstrate the highest ROI values, indicating higher returns than their initial investments. IRR represents the discount rate at which the net present value of cash flows equals zero. Silicon Carbide (SiC/SiC) and Alumina/Silica (Al2O3/SiO2) exhibit the highest IRR values, suggesting higher returns on investment over the project's duration. NPV measures the present value of future cash flows generated by an investment, discounted at a specified rate. Al2O3/B4C has the highest NPV, indicating its capacity to create significant value over 20 years. Gross Margin represents the percentage of revenue that exceeds the cost of goods sold (COGS). Alumina/Silica (Al2O3/SiO2) displays the lowest Gross Margin percentage, suggesting comparatively lower profitability from its sales revenue. Operating Costs reflect the expenses incurred in the production process, excluding depreciation. Alumina/Boron Carbide (Al2O3/B4C) and Silicon Carbide (SiC/SiC) show relatively higher operating costs, potentially impacting their profitability. The

Table 3 Economic impact values for the 20 years period

	Inconel 625	Hastelloy X	SiC/SiC	Al2O3/B4C	Al2O3/SiO2
Revenue (USD)	554	568	220	136	166
Return of Investment (USD)	6,580	10,970	156	13,636	180
Net Cash Flow (USD)	11,884,733	11,954,864	4,698,049	11,975,422	5,657,084
Net Present Value (USD)	330,560,804	332,662,562	115,182,553	333,278,656	143,923,938
Gross Margin (%)	20.86	20.91	14.95	20.93	15.74
Depreciation Cost (USD)	1,835,730	1,101,183	77,108,678	885,863	67,063,797
Operating Cost (USD)	2,455,151	1,712,832	78,524,429	1,495,235	68,373,281
Payback period (Years)	0.91	0.90	1.52	0.90	1.35
Internal Rate of Return (%)	906.65	1256.21	62.00	1447.90	69.86

payback Period represents the time required to recover the initial investment. Hastelloy X and Inconel 625 boast shorter payback periods, indicating faster returns on investment. The IRR was calculated using the Microsoft Excel IRR function, considering each material's Cash Flow results and initial investment cost. Following the results from Table 2, the annual operating cost of every selected material is plotted in Fig. 5.

Figure 5 portrays a 20-year trajectory of annual operating costs for both CMC and superalloy turbine blades, revealing a progressive rise in expenses starting at the acquisition cost of each material in the initial year and progressively increasing yearly. The yearly costs exhibit a consistent upward trajectory, which shows a continuous growth pattern, indicating a year-on-year cost escalation. It is observed that there are some nonlinearities between year 0 and year 2 because, after year 1, the maintenance cost is added to the operating expenses. In addition, in year 10, the blades will be replaced with spare parts, slightly spiking the operating costs. Furthermore, the cash flow comparison across the selected

materials over the 20 years shows an increasing linear scale for each material, as shown in Fig. 6 below.

Figure 6 indicates the change in cash flow from year 0 to year 1 due to the maintenance of the combustor liner, showing a decrease in cost, resulting in a negative cash flow. From year 1 to year 20, the cash flow remains impacted by ongoing cost depreciation of the materials, but the cash inflow increases yearly. Furthermore, Fig. 7 shows the NPV results from year 1 to year 20. Positive NPV indicates that the project generates more value than its costs, while negative NPV suggests it may not be financially viable, as seen in Fig. 7.

The results show significant variations in cash flow, NPV, IRR, and payback period among the different materials. These differences can be attributed to several factors, including the annual material cost, material properties, and specific case study parameters. Inconel 625 and Hastelloy X, due to having relatively low annual material costs compared to SiC/SiC and Al2O3/B4C, exhibit higher cash flows, NPV, and IRR. On the other hand, SiC/SiC and Al2O3/SiO2 have lower Cash Flow and NPV results. This

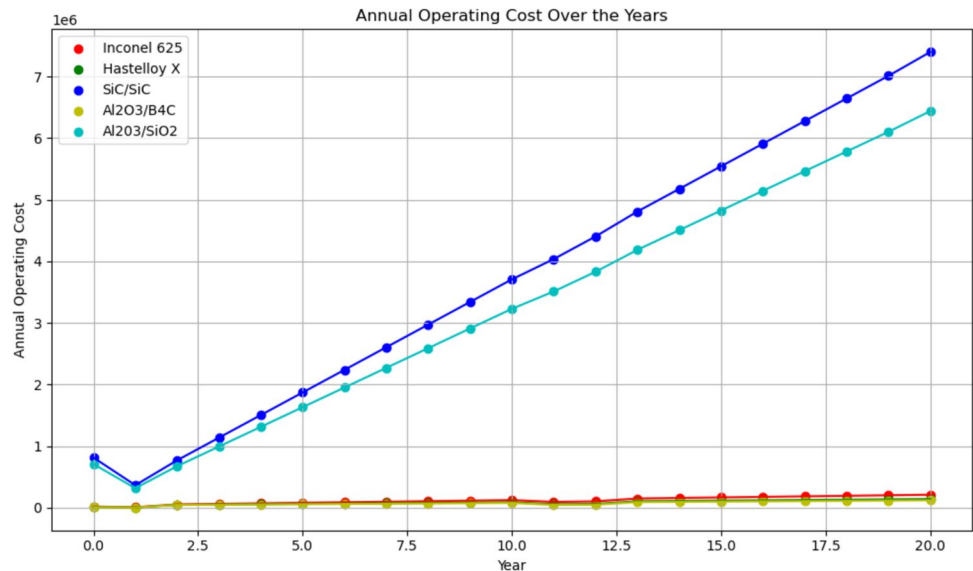
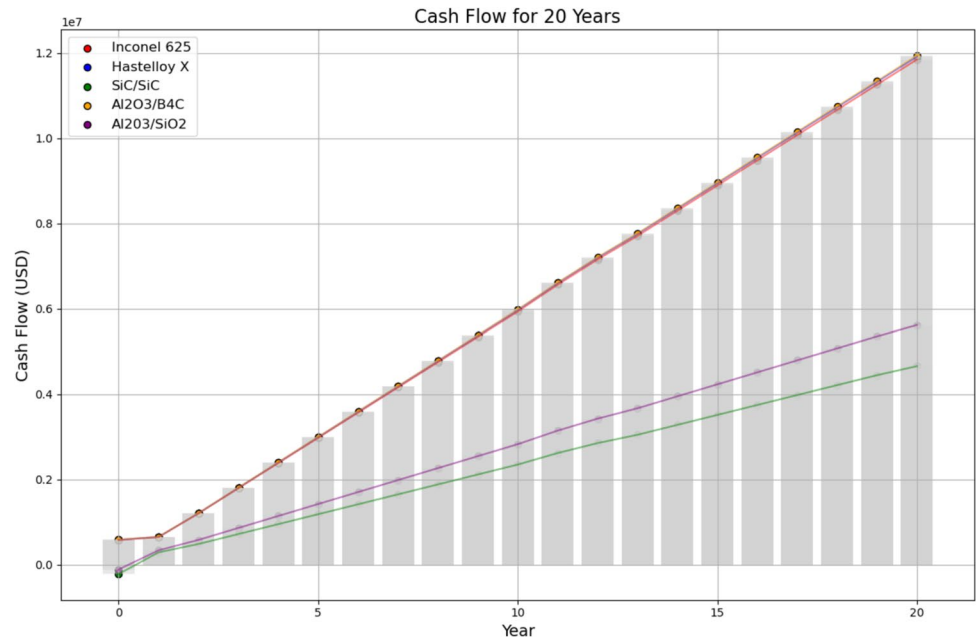
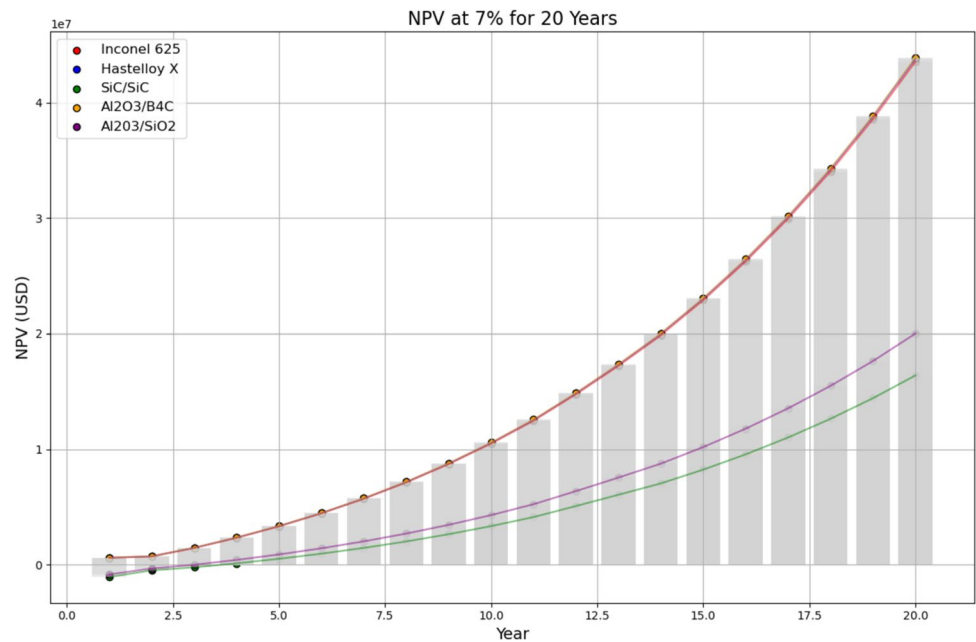
Fig. 5 Annual operating cost calculations

Fig. 6 Cash flow results from year 0 to year 20**Fig. 7** NPV results at 7% discount rate from years 1 to 20

is due to their higher initial investment and higher maintenance costs results. The more extended payback period suggests a slower return on investment for these materials, likely due to their higher expenses and possibly lower profitability than Inconel 625 and Hastelloy X. This suggests that superalloys and Al₂O₃/B₄C initial investment have higher returns over time. The lower payback period for these materials indicates a quicker recovery of the initial investment, which may be due to their higher profitability and potentially lower maintenance costs.

5.2 Sensitivity analysis

The sensitivity analysis was conducted to assess how fluctuations in discount rates and residual value impact the financial metrics, NPV, and Cash Flow, for six distinct turbine blade materials: Inconel 625, Hastelloy X, SiC/SiC, Al₂O₃/B₄C, and Al₂O₃/SiO₂. The analysis covered a range of discount rates and residual value percentages (-15%, -10%, -5%, 0%, 5%, 10%, 15%) to estimate the responsiveness of these

Fig. 8 NPV vs. discount rate sensitivity analysis of CMCs and Superalloys

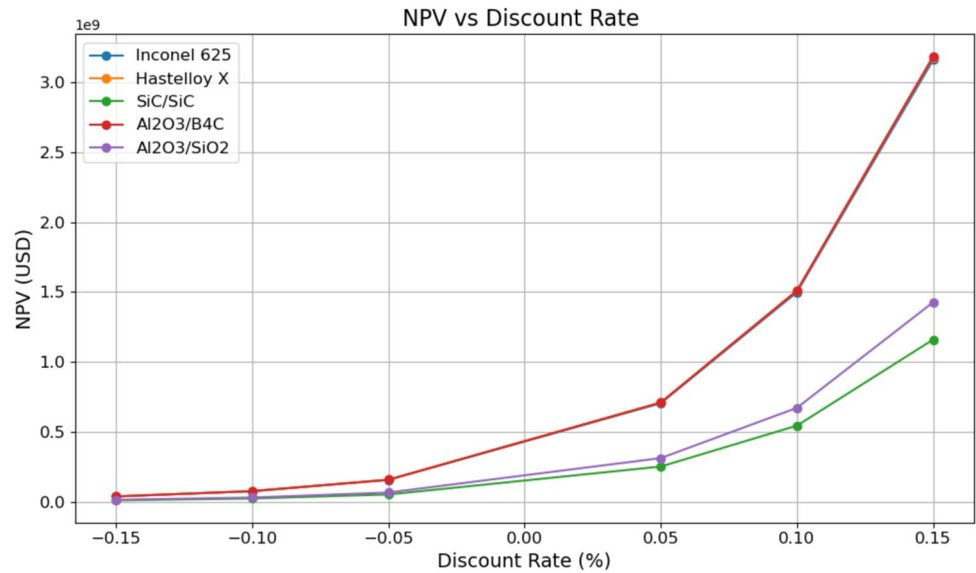
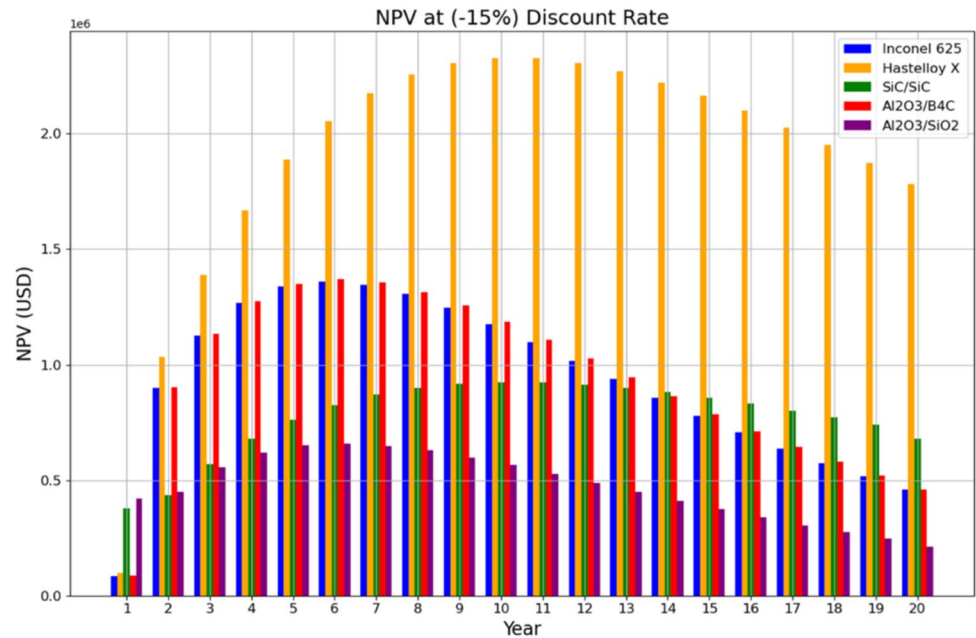


Fig. 9 NPV vs. discount rate sensitivity analysis of CMCs and Superalloys at (-15%)



metrics and their implications for material selection in turbine blade manufacturing. The selected metrics percentages are changed individually for each case scenario.

The findings highlighted substantial insights into the financial performance of these materials under varying cost scenarios. Lower acquisition and maintenance costs generally correlated with increased NPVs and improved cash flows, indicating favourable economic outcomes. Conversely, higher acquisition and maintenance costs had a corresponding adverse impact on NPV and cash flows, suggesting potential financial drawbacks. Additionally, the IRR exhibited sensitivity to fluctuations in acquisition costs, showcasing varied impacts on investment efficiency for each

material. Figures 8 and 9 illustrate the sensitivity analysis of NPV changes concerning different percentages of acquisition cost variations and discount rates.

The NPV vs. discount rate sensitivity analysis Fig. 8 provides insight into how changes in the discount rate impact the NPV of different materials. This sensitivity analysis is crucial because it helps assess the financial viability of the case study under different discount rate scenarios.

When decreasing the discount rate values (moving from right to left in the table), it is observed that the NPV tends to increase for all materials. This indicates that lower discount rates lead to higher NPVs, suggesting that the present

value of future cash flows increases when future earnings are discounted at a lower rate. Conversely, when increasing the discount rate values (moving from left to right in the table), the NPV decreases for all materials. This indicates that the present value of future cash flows decreases when future earnings are discounted at a higher rate.

Focusing on the lowest percentage (-15%) results of the discount rate, the NPV increases until the percentage of the discount rate becomes positive, as seen in Fig. 9 below. In contrast, all the other percentages have a linear incline in results, as presented in Fig. 8 above.

This occurs because the discount rate, often representing the cost of capital or the required rate of return, affects the present value of future cash flows. A lower discount rate results in less discounting of future cash flows, leading to higher present values and, consequently, higher NPV. On the other hand, a higher discount rate increases the discounting effect, reducing the present value of future cash flows and lowering NPV.

Discount rates below zero (e.g., -15%) reflect scenarios where investors place a lower cost on future cash flows, possibly due to lower perceived risk or higher confidence in future returns. In such cases, the present value of future cash flows increases, resulting in higher NPV. However, as the discount rate becomes positive, the opposite effect occurs, leading to a decrease in NPV.

After plotting the sensitivity analysis of NPV against the discount rate percentage, the sensitivity analysis of NPV at different residual value percentages but within the same percentage range was made. Figure 10 below shows the differences between the selected materials.

For materials like Inconel 625, Hastelloy X, and Al₂O₃/B₄C, as the residual value percentage increases from -0.15

to 0.15, the NPV increases. A higher residual value means the asset retains more value at the end of its useful life. Therefore, the depreciation expense decreases, leading to higher net cash flows in future periods. As a result, the NPV increases because the future cash flows are discounted less, making them more valuable in present terms.

On the other hand, materials like SiC/SiC show a similar trend in NPV with changes in residual value percentages, but the NPV values are significantly lower compared to Inconel 625 and Hastelloy X. That is because SiC/SiC has higher initial costs and lower residual values compared to the other materials, which means changes in the residual value have a lesser impact on the NPV compared to the other materials.

The change in NPV when plotting against different residual value percentages, as seen in Fig. 10 is primarily influenced by the impact on cash flows over time due to changes in the residual value. This change in residual value affects the calculation of depreciation expense, affecting the net cash flows and, ultimately, the NPV. Hence, it is essential to show the differences in cash flow results for each material at the compared residual value percentages to understand and evaluate the results that Fig. 10 demonstrates.

Figure 11 shows the sensitivity analysis of Cash Flow results at the same residual value variation compared to the previous NPV sensitivity analysis. The sensitivity analysis values in the cash flow reflect how residual value changes impact the materials' overall cash flow. When residual value decreases, materials tend to experience a decrease in cash flow. Similarly, reductions in depreciation costs lead to improved cash flow, as fewer expenses are incurred over time. Conversely, cash flow tends to decrease when acquisition or maintenance costs increase as more financial resources are required to acquire or maintain the materials.

Fig. 10 NPV against different residual value percentages

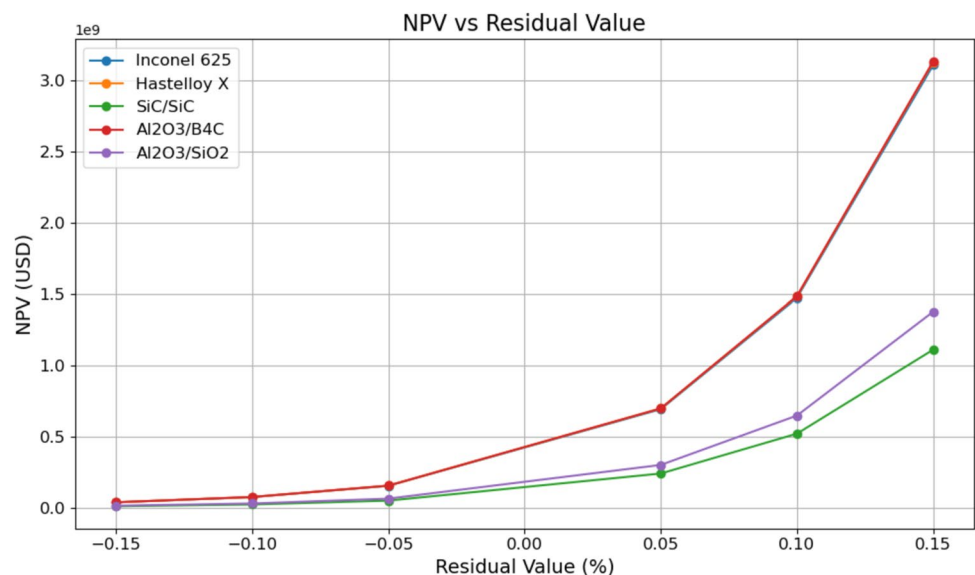
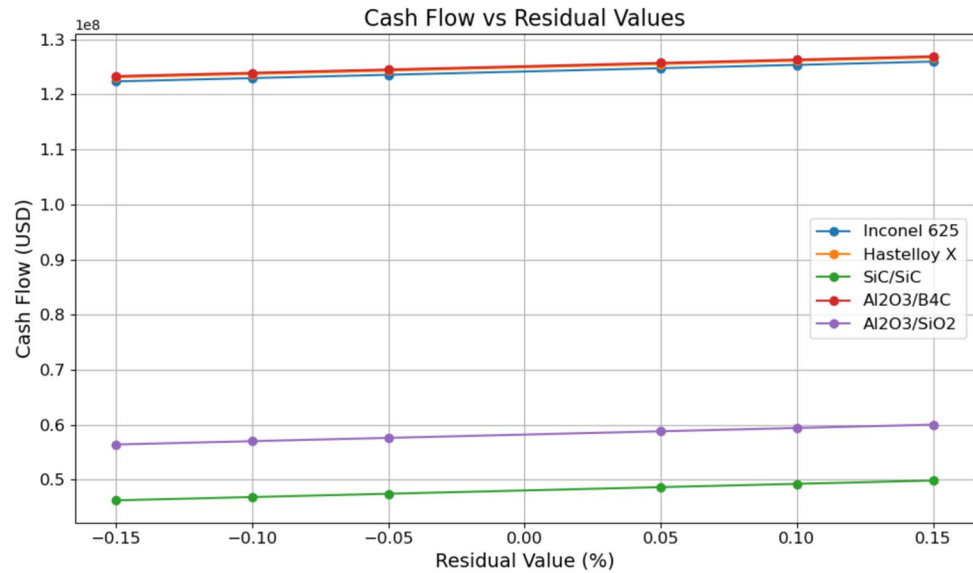


Fig. 11 Cash flow vs. range of residual values sensitivity analysis of CMCs and Superalloys



5.3 Risk assessment

Considering the technical implications of material substitution is vital in a techno-economic assessment. This assessment offers insight into the risks and benefits of adopting alternative materials, particularly in aerospace applications like turbine blades. By evaluating the engineering challenges, operational impacts, and environmental considerations, decision-makers can make informed choices that optimise performance and ensure long-term sustainability.

Several failure modes and mechanisms are identified for both CMCs and metallic materials in aerospace applications. These include thermal shock resistance, creep resistance, oxidation and corrosion resistance, fatigue strength, impact resistance, high-temperature capability, susceptibility to manufacturing defects, repairability and maintenance, cost implications, and environmental impact, as seen in Table 4 below.

Each failure mode presents specific risks to engine components, impacting reliability, integrity, and performance. CMCs exhibit lower thermal expansion coefficients, providing thermal shock resistance, but are less impact-resistant due to brittleness. Metallic materials offer better impact resistance but may suffer from structural failure and creep at high temperatures. CMCs demonstrate superior high-temperature stability but require stringent quality control and pose challenges in repairability, leading to higher maintenance costs than metallic counterparts. While CMCs entail higher initial costs, they offer potential long-term savings in lifecycle costs, with lower emissions aligning with environmental sustainability goals. Conversely, metallic materials have lower initial costs but may incur higher operational costs over their lifecycle.

6 Conclusions

This study offers a novel and detailed techno-economic analysis comparing Ceramic Matrix Composites (CMCs) with traditional nickel-based superalloys for gas turbine blades in the aerospace industry. The novelty of this research lies in its integrated approach, which combines a thorough evaluation of the material properties of CMCs, such as thermal resistance, creep resistance, and oxidation resistance, with a robust economic analysis. The work is among the first to link these technical properties directly to key financial metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR), offering a holistic assessment of the long-term economic viability of using CMCs in aerospace applications.

The results reveal that SiC/SiC composites exhibit a 15–20% higher NPV and a 17% greater IRR than traditional superalloys. These findings are primarily driven by CMC's ability to operate at higher temperatures, thereby reducing maintenance frequency and enhancing fuel efficiency, ultimately resulting in significant long-term savings. Moreover, the study shows that the payback period for CMCs is reduced by 2–3 years compared to superalloy blades, demonstrating their financial feasibility despite their higher initial costs. The sensitivity analysis further confirms that CMC blades maintain a positive NPV across various discount rates, making them a financially stable option even in fluctuating economic conditions. These key results make a strong case for adopting CMCs in critical aerospace components where performance and cost efficiency are paramount.

The findings of this research have direct applications in the aerospace industry, especially in the design and manufacturing of gas turbine blades, nozzles, and combustion chambers for both commercial and military aircraft. The study demonstrates that CMCs, particularly SiC/SiC composites,

Table 4 Comparative FMECA on using CMC vs. metallic materials [based on data collected from references [20–23]]

Material	Failure Mode/ Mechanism	Cause	Effect	Control Measures
CMCs	Thermal Shock Resistance	Lower thermal expansion coefficients	Reduced engine reliability and increased maintenance	Regular thermal inspections and stress analysis
Metallic		Higher thermal expansion	Cracks and structural failure	
CMCs	Creep Resistance	Better high-temperature stability	Possible engine failure due to shape distortion	Design modifications to reduce stress concentrations
Metallic		Susceptibility to creep at high temperatures	Deformation under stress at high temperatures	
CMCs	Oxidation and Corrosion Resistance	Higher resistance to oxidation and corrosion	Deterioration of engine components and reduced life span	Protective coatings and regular inspections
Metallic		Prone to oxidation and corrosion at high temperatures	Deterioration of engine components and reduced life span	
CMCs	Fatigue Strength	Lower fatigue strength	Potential for fatigue failure under cyclic loading conditions	Fatigue testing and life prediction models
Metallic		Higher fatigue strength in specific alloys	Potential for fatigue failure under cyclic loading conditions	
CMCs	Impact Resistance	Brittle nature, less impact-resistant	Risk of catastrophic failure upon foreign object damage	Impact-resistant designs and shielding
Metallic		Better impact resistance due to ductility	Risk of catastrophic failure upon foreign object damage	
CMCs	High-Temperature Capability	Superior performance at high temperatures	Enhanced engine performance and efficiency	Thermal barrier coatings for metallic components
Metallic		Limited high-temperature capability	Reduced engine efficiency	
CMCs	Manufacturing Defects	Sensitivity to manufacturing defects	Potential for early failure due to material inconsistencies	Strict quality control during manufacturing
Metallic		More forgiving to manufacturing variations	Potential for early failure due to material inconsistencies	
CMCs	Repairability and Maintenance	Difficult to repair	Higher maintenance costs and complexity	Specialized repair techniques for CMCs
Metallic		Easier to repair and weld	Higher maintenance costs and complexity	
CMCs	Cost Implications	Higher initial cost but potential long-term savings	Economic impact on lifecycle costs	Cost-benefit analysis considering total lifecycle costs
Metallic		Lower initial cost but higher operational costs	Economic impact on lifecycle costs	
CMCs	Environmental Impact	Lower emissions and fuel consumption	Impact on environmental sustainability goals	Adoption of greener materials and technologies
Metallic		Higher emissions and fuel consumption	Impact on environmental sustainability goals	

offer substantial advantages in fuel efficiency, reduced maintenance, and extended operational life. Therefore, aerospace manufacturers should consider integrating CMCs into their high-performance engine designs to optimise operational performance and lifecycle costs. Furthermore, the weight savings provided by CMCs offer the potential for improved payload capacity and reduced overall fuel consumption, which are critical factors for long-haul flights. These operational advantages provide clear recommendations for industry adoption, particularly in applications where higher

temperature resistance and longer component life are key to operational success.

While this study has provided significant insights into the economic and technical viability of CMCs, future research should focus on expanding the material scope by exploring the potential of emerging composite materials with even greater thermal and mechanical properties. Moreover, the environmental benefits of CMCs, particularly their lower carbon footprint compared to traditional superalloys, should be investigated in more detail. This would align with

the growing focus on sustainability in the aerospace sector. Additionally, the adoption of additive manufacturing techniques for CMC production promises to reduce production costs, which could further improve their economic feasibility.

Finally, as the aerospace industry transitions toward electrification and sustainable propulsion systems, future studies should explore the role of CMCs in electric propulsion engines, battery systems, and other energy storage components. The unique material properties of CMCs make them highly suitable for these next-generation technologies, and further research in this area could open new avenues for their application beyond traditional turbine engines.

This study's novel contribution lies in its comprehensive and integrated evaluation of CMCs, combining technical and financial perspectives. This work is among the first to establish a direct link between CMCs' material advantages and their economic performance in aerospace applications. By providing a holistic assessment of the long-term cost benefits, this research sets a new benchmark for evaluating the use of advanced materials in the aerospace sector, offering valuable insights for researchers and industry professionals.

Author contributions All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Georgios Karadimas, Anastasia Ioannou, and Athanasios Kolios. The first draft of the manuscript was written by Georgios Karadimas and all authors commented on previous versions of the manuscript. The final editing of the manuscript, the supervision and the funding acquisition were performed by Konstantinos Salonitis. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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