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Analyzing Boeing's Supply Chain, Quality Control, and Certification Issues: Lessons from the 787 Dreamliner and 737 MAX

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Abstract

This study analyzes the impact of Boeing's outsourcing strategy on aircraft safety and production efficiency, focusing on the 787 Dreamliner program. The intended benefits of cost reduction and accelerated production are examined against the realities of risk-sharing arrangements and documented issues like faulty materials from suppliers such as Kobe Steel. The study investigates how these outsourcing practices, coupled with Boeing's self-certification license from the Federal Aviation Administration (FAA), contributed to lapses in regulatory oversight and quality control. Applying a risk analysis to Boeing's supply chain, its risk treatment and monitoring processes are assessed. This study delves into the complexities and associated problems of Boeing's risk-sharing supplier partnerships. Based on the findings, this study suggests enhancing supply chain resilience, ensuring regulatory adherence, and bolstering quality management systems to rebuild trust in Boeing's manufacturing processes and support long-term sustainability.

Keywords: 737 MAX, 787 Dreamliner, Boeing, quality control, supply chain

1. Introduction

Boeing stands as a global leader in aerospace, renowned not only for its dominance in commercial jetliner manufacturing but also for its significant role in producing military aircraft, helicopters, and space vehicles. The company's influence in the industry was further strengthened by key acquisitions. These included the purchase of Rockwell International Corporation's aerospace and defense divisions in 1996. Another key event was the landmark merger with McDonnell Douglas Corporation in 1997. By 2022, Boeing commanded an impressive 51% share of new airplane orders, attesting to its leadership in the aerospace industry [1].

The debut of the 787 Dreamliner marked a transformative chapter for Boeing and set a new standard for the commercial aviation industry. Launched with great fanfare, the Dreamliner was heralded to bring about revolutionary changes. This aircraft distinguishes itself from conventional yet innovative designs featuring low-sweep-back wings and engines mounted on pylons underneath. This design emerged after Boeing discontinued the Sonic Cruiser program and refined many of its forward-thinking concepts. The Dreamliner's construction relies heavily on cutting-edge materials, blending lightweight, high-strength composites with advanced aluminum alloys to deliver exceptional performance and durability. Its wings, for example, utilize state-of-the-art carbon fibers, epoxy composites, and titanium graphite laminate, enhancing structural integrity and efficiency [2].

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To accelerate the Dreamliner's development, Boeing set an ambitious goal to reduce the typical six-year timeline to four years. Achieving this required a bold shift from traditional, vertically integrated manufacturing to a more globalized outsourced model. Boeing opted to partner with firms around the world, not simply as a cost-saving measure, but as a comprehensive strategy to optimize its supply chain. This approach required precise coordination of raw materials and skilled labor across continents, ensuring that each component met Boeing's stringent standards for quality and efficiency. By manufacturing parts internationally, Boeing aimed to avoid substantial procurement costs and navigate the complexities of global logistics, all while tapping into the specialized expertise and resources of its partners. This strategy enabled the company to leverage innovations and efficiencies from its subcontractors, ultimately reducing overhead and enhancing the Dreamliner's value proposition [2].

Boeing is committed to remaining a leader in the aerospace industry by consistently pushing the boundaries of innovation, development, and maintenance of aerospace products, thereby improving safety, efficiency, and sustainability. Fig. 1 is an overview of the international supply chain for the Boeing 787 Dreamliner aircraft. This illustrates the various parts of the airplane and their countries of origin [3]. For instance, wing tips originated from South Korea, wings from Japan, and tail fins from the United States. The center fuselage and other parts come from Italy, whereas the doors come from France. Fig. 1 highlights the globalized nature of modern aerospace manufacturing, showcasing how Boeing has sourced components from around the world to assemble the Dreamliner. The illustration reflects the company's strategy of optimizing its supply chain by using the resources of its international partners. The effect of Boeing's supply chain issues, regulatory oversight, and cost-cutting strategies concerning safety and quality is analyzed in this study, as illustrated in Fig. 2.

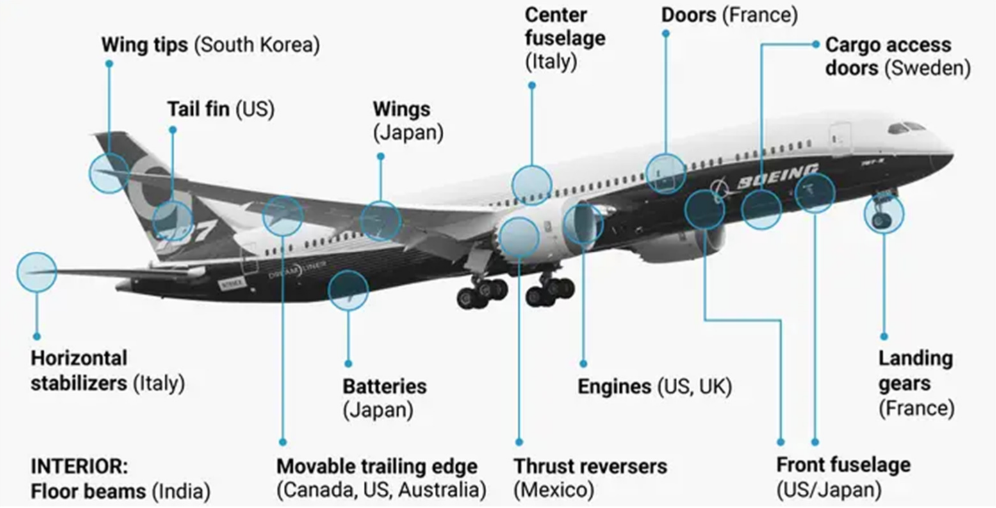

Fig. 1 The global origins of the Boeing Dreamliner [3]

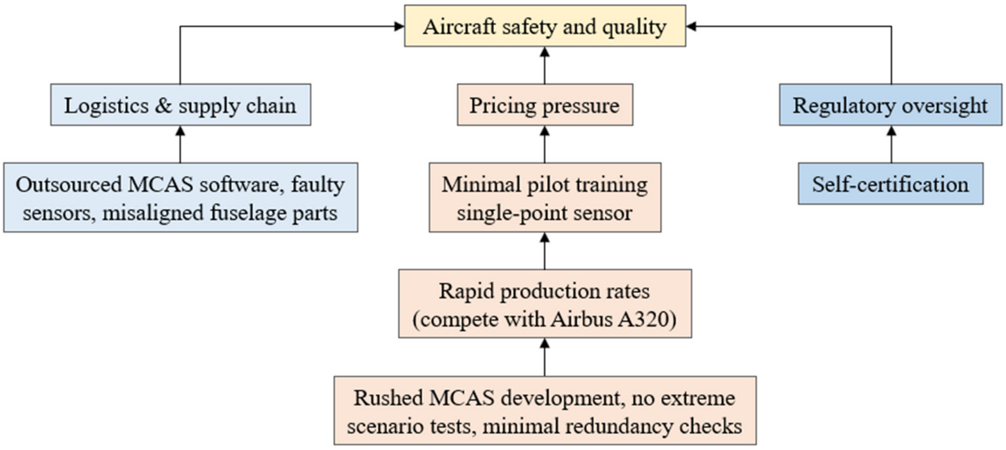

Fig. 2 Impact of supply chain breakdown on aircraft safety

The Air India crash on June 12, 2025, represents a tragic and significant moment in aviation history as the first fatal accident involving a Boeing 787 Dreamliner. The aircraft went down just minutes after takeoff, claiming the lives of 241 people on board. This marks a sobering break in the Dreamliner's previously unblemished safety record since its 2011 debut, a record that had held despite concerns over manufacturing defects, thanks largely to its robust design and operational protocols. However, this tragedy cannot be isolated from the broader and long-standing concerns surrounding the 787 program, including quality-control lapses, whistleblower reports, questionable maintenance practices, and increased regulatory scrutiny. While the exact cause of the crash remains under investigation, the event underscores the urgent need for stringent safety protocols and transparent oversight in the design, manufacturing, and operation of commercial aircraft. In light of Boeing's broader safety culture, the incident could be a case study in pilot training, maintenance standards, and operational pressures within low-cost carriers.

This study is driven by critical safety and quality control issues within Boeing's 787 Dreamliner program, especially in light of the 737 MAX accidents. Key motivators include:

(1) Safety and quality concerns: Incidents involving manufacturing defects, substandard materials, and regulatory failures have raised significant questions about Boeing aircraft safety and integrity.
(2) Fragmented supply chain impact: This study addresses how a highly fragmented supply chain has compromised quality control, leading to delays, integration issues, and reduced quality.
(3) Balancing cost, production, and risk: It investigates the tension between Boeing's drive for cost reduction and accelerated production through outsourcing and risk-sharing versus documented issues like faulty materials from suppliers.
(4) Regulatory oversight and self-certification: The self-certification delegation of the Federal Aviation Administration (FAA) to Boeing is scrutinized for its role in regulatory lapses and undetected safety issues.
(5) Rebuilding trust and ensuring sustainability: A core motivation is to restore confidence in Boeing's manufacturing by recommending ways to enhance supply chain resilience, regulatory compliance, and long-term sustainability.

The methodology in this study, as shown in Fig. 3, depicts how Boeing aircraft safety and product quality are affected. This study investigates the supply chain and supplied materials in Section 3, the effects of self-certification in Section 4, supply chain risks in Section 5, and Boeing's risk-sharing supplier-partnership model in Section 6. Section 7 discusses the findings, followed by the conclusion in Section 8.

Fig. 3 Proposed methodology

2. Literature Review

Make-to-order (MTO) supply chains in aerospace are complex, with sustainability as a key long-term challenge. Barbosa et al. [4] propose a hybrid, hierarchical performance assessment model using system dynamics, discrete event simulation, and agent-based simulation. Applied to an aerospace manufacturer, it evaluates sustainability across alternative supply chains without compromising manufacturing representation. Guerra et al. [5] explore aerospace supply chain risk management using surveys and interviews, identifying key risks, mitigation strategies, and ten critical supply chain risk management dimensions.

Unlike previous studies focused on process steps, it provides a holistic view of industry-specific challenges, emphasizing resource allocation, role clarity, and integration in emerging markets. Along the same lines, the resource interaction approach is investigated in Bygballe et al. [6]. Their study claims that supply chain disruptions can be better managed than with traditional risk management methods by emphasizing resource interdependence and collaborative strategies.

The transaction cost economics (TCE) framework proposed by Williamson [7] offers a structured approach to subcontracting decisions, assisting firms in determining whether to outsource or retain activities internally. By leveraging TCE, manufacturers can strategically weigh production costs against transaction costs, ensuring optimal economic efficiency and operational flexibility. The TCE framework offers valuable insight into aircraft safety and quality control. It highlights how supply chain structure, regulatory oversight, risk assessment, and partnership design shape the costs and challenges of compliance and reliability. It predicts that fragmented supply chains and loosely governed risk-sharing partnerships raise transaction costs.

Regulatory oversight is meant to serve as a safeguard, but as contracts and relationships become more complex and global, policing and enforcement costs rise, and the risk of safety lapses grows if governance is weak or information is incomplete. When these structures are misaligned with the characteristics of the transactions, the result can be delays, quality lapses, and ultimately compromises to safety. The Dreamliner’s challenges and the recent Air India crash highlight the consequences of misaligned governance in high-risk environments that prioritize safety by effectively addressing these transaction cost dilemmas. Williamson [7] suggests that for safety-critical systems, more hierarchical or tightly integrated governance structures can reduce coordination costs and limit opportunism. These structures can also better protect quality and safety, whereas market-based or hybrid models may fall short.

Employing a case study approach and TCE, Ronchini et al. [8] analyzed how original equipment manufacturers (OEMs) strategically integrate additive manufacturing (AM) into their upstream supply chains (make, buy, hybrid, or vertical integration). The study highlighted the influence of experience, application, and control needs, as well as the constraints of cost and skill gaps, on shaping supply bases and buyer-supplier relationships. Nazeer et al. [9] examined sustainability in South Asia’s aviation sector. They discovered that agility and alignment drive overall sustainability, while adaptability’s impact is limited to environmental, operational, and social aspects, excluding economic sustainability.

This study contributes to filling several research gaps:

(1) Outsourcing’s impact on safety and efficiency: Limited analysis exists on how risk-sharing and global partnerships affect safety and quality control in aerospace manufacturing, beyond just cost and speed benefits.
(2) Assessment of Boeing’s risk management: The study specifically applies a risk analysis methodology to Boeing’s supply chain to assess its actual risk treatment and monitoring processes.
(3) Effectiveness of regulatory oversight and self-certification: The consequences of the FAA’s self-certification program on quality assurance and incident prevention have not been thoroughly examined.
(4) Supplier quality control and material traceability: Research on ensuring material quality and traceability in complex global supply chains remains insufficient, especially concerning issues with sub-suppliers and faulty materials.
(5) Specific recommendations for aerospace supply chain resilience: The study provides tailored recommendations for enhancing supply chain resilience, regulatory adherence, and quality management within Boeing’s global, outsourced model, including specific proposals for FAA and Tier-I supplier auditing.

This study aims to advance understanding of global outsourcing’s impact on aerospace manufacturing safety and efficiency, with a focus on Boeing’s supply chain model. Key contributions include:

(1) In-depth analysis of outsourcing risks: It will examine how Boeing’s risk-sharing and global partnerships affect safety and production, moving beyond typical cost and speed considerations.

(2) Empirical risk evaluation: By applying a risk analysis to Boeing's supply chain, the study investigates real-world risk treatment and monitoring practices.
(3) Review of regulatory oversight: It will assess the consequences of FAA self-certification on quality assurance and incident prevention, addressing critical oversight gaps.
(4) Insight into multi-tier supply chain challenges: The study will explore specific risks in global, multi-tiered MTO models, including traceability issues and material defects.
(5) Practical recommendations and restoring trust: The study will present actionable strategies, such as enhanced supplier audits, to improve resilience, regulatory compliance, and long-term quality to rebuild confidence in aerospace manufacturing by addressing core safety and governance issues.

3. Supply Chain and Materials

Boeing's current crises primarily stem from a financialized corporate culture that prioritizes profit maximization over engineering excellence. This pivotal shift commenced with the 1997 merger with McDonnell Douglas, moving Boeing away from its traditional engineering-led ethos. Airbus, on the other hand, has managed to maintain stronger engineering governance [1].

Boeing's difficulties began in October 2018 with the tragic crash of Lion Air Flight 610, a Boeing 737 MAX 8, which fell into the Java Sea soon after taking off from Jakarta. Initially, Boeing deflected blame, suggesting a pilot error and inadequate response to the system's failure. However, the narrative shifted when Ethiopian Airlines Flight 302, a Boeing 737 MAX 8, suffered a similar fate on March 10, 2019, for identical reasons. This second disaster brought intense scrutiny upon Boeing for misleading communication with its customers and concealing critical information. Consequently, on November 26, 2019, the FAA withdrew Boeing's Organization Designation Authorization (ODA), stripping it of the discretion to certify the airworthiness of its MAX Airplanes independently.

On January 5, 2024, a Boeing 737 MAX 9 incident provoked safety concerns after part of the aircraft detached mid-flight, echoing concerns stemming from previous crashes. Following the event, the FAA grounded similar models for inspections, focusing on door plugs, such as those that failed, prompting scrutiny of Boeing's quality control and the FAA's oversight mechanisms. This incident highlighted the challenges in ensuring aircraft safety and maintaining public trust.

In the wake of these incidents, Boeing was faced with relentless scrutiny. Every manufacturing imperfection was rigorously investigated, with the FAA meticulously overseeing the delivery of Boeing aircraft to ensure rigorous compliance with safety standards. The 787 Dreamliner encountered significant issues attributed to lapses in supply chain management, leading to a series of quality control failures. These incidents have led to increased regulatory oversight and prompted a reevaluation of Boeing's supply chain strategies and quality assurance protocols, highlighting the need for more robust and transparent manufacturing processes.

In short, the company's struggles are multifaceted: (1) outsourcing and supply chain management issues compromising quality control; (2) production pressures and a skilled labor shortage prioritized output over quality improvements; (3) the lack of effective transparency procedure hindering proactive problem-solving; (4) ineffective quality management system within Boeing's facilities may have compounded these issues; (5) supply chain disruptions, exacerbated by the 737 MAX production challenges, significantly impacted the company's operations.

3.1. Supply chain issues with 787 Dreamliner

The 787 Dreamliner's extensive reliance on a global supplier network has sparked considerable debate. While a diversified supply chain yields clear benefits, mismanagement can lead to serious setbacks. The Dreamliner's assembly showcases international collaboration, weaving together expertise and components from around the world. Boeing has rationalized its strategy by emphasizing its role as a master integrator of complex systems, rather than a specialist in every individual part. Outsourcing components can be a shrewd strategy, enabling the company to focus on final assembly and system integration.

Nonetheless, the 787 program also exposed the risks of overreliance on external partners for the design and manufacture of critical elements. These challenges highlight the importance of a thoughtful outsourcing strategy, one that carefully considers not only which components to outsource but also how to manage relationships and processes effectively. The Dreamliner's experience illustrates the fine line between achieving cost efficiencies and maintaining rigorous quality control, a balance that is essential for the success and safety of advanced aerospace projects. Table 1 details several key components of the 787 and their countries of origin, further illustrating the truly global nature of Boeing's supply chain [3].

Table 1 787 Dreamliner parts and their sources

No.	Part	Source	No.	Part	Source
1	Wings	Mitsubishi, Japan	11	Wing-body fairings	Boeing, Canada
2	Batteries	GS Yuasa, Japan	12	Thrust reversers	Mexico
3	Wingtips	KAA, South Korea	13	Engines	US or UK
4	Floor beams	India	14	Engine nacelles	Goodrich, US
5	Front fuselage	Sprit, US; Kawasaki, Japan	15	Movable trailing edge	US, Canada, and Australia
6	Centre fuselage	Alenia, Italy	16	Fixed trailing edge	Kawasaki, Japan
7	Rear fuselage	Boeing, US	17	Centre wing box	Fuji, Japan
8	Landing gear	Messier-Dowty, France	18	Horizontal stabilizer	Alenia, Italy
9	Doors	Latecoere, France	19	Wing-to-body fairing panels	Hafei Aviation, China
10	Cargo doors	Saab, Sweden			

Sourcing components from a diverse group of vendors can yield significant advantages, such as reducing reliance on any single supplier, increasing operational flexibility, and lowering inventory risks. However, this strategy also introduces new complexities. Managing relationships with multiple suppliers demands greater oversight and coordination, and can strain resources. One of the main challenges is ensuring efficiency and maintaining consistent quality across all suppliers. The process of vetting and selecting partners becomes more rigorous, as companies must carefully weigh cost against quality to uphold their standards. Boeing's heavy reliance on third-party suppliers for essential aircraft parts, for example, later exposed the company to serious quality control issues.

Driven by a desire to accelerate production, Boeing set an ambitious timeline for the 787 Dreamliner, aiming to shorten development time from the six years required for the 777 down to four years [1]. The company hoped to slash development costs from an estimated \$10 billion to \$6 billion by outsourcing large subassemblies to Tier-I suppliers, thereby speeding up the final assembly process [2]. The vision was bold. Boeing intended to assemble a new 787 in as little as six days, and eventually reduce that to three days per aircraft. While this drive for speed and efficiency was groundbreaking, it also highlighted the inherent challenges and risks of managing a complex, global supply chain with numerous vendors.

Boeing's recent manufacturing issues predominantly stem from its distinct supply chain governance, which contrasts with Airbus's approach. While both rely on global suppliers, they differ in outsourcing depth, supplier control, and vertical integration [10]. Boeing's 'light-touch' model, evident in its partnership with Spirit AeroSystems on the 787, precipitated coordination failures. In contrast, Airbus enforces stricter oversight, including mandatory use of its digital quality tools.

The TCE principles provide a crucial framework for understanding the supply chain failures that plagued Boeing's Dreamliner program. The program's extensive reliance on global outsourcing inherently generated significant transaction costs due to factors such as asset specificity, potential for opportunism, and bounded rationality. While Boeing's strategic pivot from vertical integration to a decentralized “system integrator” model aimed to lower production costs, it inadvertently introduced critical governance failures, evident in recurring quality issues such as fuselage gaps and inspection oversights. Williamson [7] suggests that these problems stemmed from an imbalance between market coordination and hierarchical control. Boeing’s adoption of a “light-touch” outsourcing approach, rather than greater vertical integration or robust relational governance, ultimately escalated transaction costs and hindered production efficiency, representing a clear departure from core TCE principles.

In summary, Boeing’s 787 Dreamliner program grapples with significant supply chain challenges, affecting production rates and deliveries. Recent examples include [10]:

(1) Boeing is experiencing delays in scaling up 787 Dreamliner production but aims to achieve a monthly production rate of 10 units by 2026. As a result of these delays, Riyadh Air, Saudi Arabia’s new national carrier, has postponed its launch to the third quarter of 2025 due to deferred deliveries of its ordered 787s.

(2) Leonardo, the Italian aerospace firm responsible for supplying fuselage sections and horizontal stabilizers for the 787, has instituted rolling furloughs at its Grottaglie plant since July 2024. These furloughs are expected to persist through the end of 2025, reflecting the reduced pace of 787 production and delivery.

3.2. Unreliable materials and parts

After the tragic Boeing 737 MAX accidents, concerns about the safety of the 787 Dreamliner gained traction in April 2021. Workers at Boeing’s North Charleston facility voiced alarm over the relentless pace of the assembly line, arguing that the pressure to meet tight deadlines sometimes led to risky shortcuts. Their feedback revealed a growing tension between production speed and adherence to safety protocols. This cast doubt on the integrity of the assembly process and raised questions about whether operational efficiency was being prioritized over product safety.

In August 2019, KLM Royal Dutch Airlines publicly criticized the quality control at Boeing’s production site, describing standards as “way below acceptable.” Their Dreamliners arrived with a range of defects, from loose seats and missing pins to improperly tightened nuts and bolts, and even unsecured fuel line clamps. United Airlines also reported 20 separate issues, including dented panels, on a 787-10 delivered in April 2019 [11]. These incidents pointed to deeper problems within Boeing’s quality assurance processes and highlighted inconsistencies in manufacturing standards.

By late August 2020, Boeing grounded eight 787 Dreamliners after discovering two manufacturing issues related to fuselage shimming and inner skin surfacing at its South Carolina plant. These flaws compromised the structural integrity of the jet’s carbon fiber composite framework. Boeing acknowledged that “two distinct manufacturing issues in the joining of certain 787 aft body fuselage sections” did not meet their design standards [12]. Left unchecked, such defects could exacerbate material wear and even result in structural failure under stress, underscoring the importance of manufacturing precision, especially with advanced composite materials.

On September 7, the Wall Street Journal reported that the FAA had launched an investigation into Boeing’s quality control practices, which had faced scrutiny since the Dreamliner’s debut in 2011. Boeing disclosed a “nonconforming section of the rear fuselage” that failed to meet engineering standards, prompting the FAA to recommend inspections for up to 900 Dreamliners [11]. Soon, Boeing announced another issue, this time with the horizontal stabilizers, affecting nearly 900 aircraft. Excessive clamping forces during manufacturing in Salt Lake City had potentially caused inaccuracies in gap measurement and shimming. Boeing assured customers that the issue was being addressed in undelivered aircraft and posed no immediate flight risk [12], but the string of disclosures underscored persistent challenges in Boeing’s production process and the ongoing need for rigorous quality controls.

Just days later, Boeing entered talks with U.S. safety regulators about a manufacturing defect in the 787's vertical tail fin, which could affect as many as 680 aircraft. Excessive gaps within the tail fin's structure raised concerns about the long-term durability and safety of the jets. In July 2021, Boeing slowed 787 production to address a new flaw in the forward pressure bulkhead, where gaps failed to meet company standards.

Early in 2021, Boeing notified the FAA of an issue identified by Mitsubishi Heavy Industries, the contractor responsible for the Dreamliner's carbon-composite wings. During manufacturing, contamination from polytetrafluoroethylene (PTFE, commonly known as Teflon) compromised the strength of the epoxy bonds, which are crucial for wing integrity. This incident highlighted the challenge of maintaining material purity and the critical importance of strict manufacturing protocols.

In December 2021, Italian prosecutors launched an investigation into two small firms, MPS and Processi Speciali, after discovering that over 4,000 flawed parts had been produced for Boeing between 2016 and 2021 [11]. These sub-suppliers, working for Leonardo (which manufactures sections of the 787 fuselage), had supplied components made from "grade 2 titanium" instead of the specified titanium alloy [10]. The inferior material properties raised serious concerns about the reliability and safety of the affected aircraft. Prosecutors ordered the seizure of suspect components, emphasizing the need for unwavering quality control and strict adherence to material standards, especially in a global supply chain.

The problems didn't stop there. In June 2024, Boeing found improperly installed fasteners on numerous undelivered 787 Dreamliners [13], triggering further inspections and potential rework. Simultaneously, the FAA proposed new inspection rules for seat-track splice fittings on certain 787s due to concerns over incorrect titanium alloys, which could undermine structural integrity. To add to the scrutiny, Boeing's inability to produce records related to a previous "door plug" incident alarmed lawmakers and raised serious questions about the company's record-keeping practices [14].

3.3. Issues with Kobe Steel, Japan

Kobe Steel Ltd., known worldwide as Kobelco, has a legacy that stretches back over a century. However, in October 2017, the company's reputation took a major hit. It admitted to falsifying quality data for several materials, including aluminum sheets, aluminum components, copper products, and iron powder. These materials, falsely certified as meeting specific standards such as tensile strength, were subpar. The fallout was significant: more than 200 customers across various industries, including automotive giants like Toyota, Nissan, and General Motors, train manufacturers such as Hitachi, and aerospace leaders like Boeing, were affected. The scandal deepened when, just days later, Kobe Steel revealed that over 500 companies had received materials with falsified data, highlighting the widespread nature of the deception [15].

A four-month independent investigation uncovered even more instances of non-compliance, bringing the total number of affected entities to 602, including 222 international clients. This revelation exposed how a large volume of inferior products had entered the market, disrupted global supply chains, and shaken customer confidence. The scandal also revealed deep-rooted issues within Kobe Steel's corporate culture. Improper practices were not isolated, but rather widespread and carried out with the knowledge and sometimes participation of senior executives.

The company's investigative report, released in November 2017, shed light on a curious aspect of Kobe Steel's operations. Some facilities set internal quality standards even higher than those required by customers, hoping to enhance product quality by catching flaws early. While the intention was to exceed expectations, this approach backfired when customer demands became more stringent and Kobe Steel's benchmarks proved unattainable. Instead of reassessing production capabilities or negotiating standards, employees manipulated test results for products that failed to meet these lofty internal criteria. This not only violated customer trust but also reflected a fundamental misunderstanding of quality control and customer relations. Although Boeing does not buy directly from Kobe Steel, it does source components from several of Kobe's customers, including Mitsubishi Heavy Industries, Kawasaki Heavy Industries, and Subaru Corp.

This connection doesn't mean that every Boeing part contains suspect materials, but it does highlight the complexity of tracing material origins in a vast supply chain. Japanese suppliers play a vital role in Boeing's operations, providing about 20% of the components for the 777 and 35% for the 787 Dreamliner, which relies heavily on advanced composites [16]. This intricate network underscores the importance of transparency and reliability to maintain the integrity of the final product.

Kobe Steel, much like Boeing, has confronted intense competition, particularly from Chinese steelmakers flooding the market with surplus steel [15]. This pressure led to a shift in priorities, with profitability taking precedence over transparency. Analysts suggest that this focus on financial performance came at the expense of ethical standards, ultimately undermining the company's reputation and reliability.

Many of Kobe Steel's clients, such as the French conglomerate Safran, which supplies landing gear to both Airbus and Boeing, are themselves key players in the aerospace industry. The impact of Kobe's substandard materials has been detected in aircraft like the Airbus A350, specifically in its titanium landing gear. This demonstrates how a single supplier's quality issues can ripple through the entire aerospace supply chain, affecting multiple manufacturers and aircraft models. It also highlights the critical need for rigorous quality checks at every stage to ensure the safety and dependability of aerospace components.

In summary, the 2017 Kobe Steel scandal exposed serious vulnerabilities in Boeing's supply chain, even though Boeing did not purchase directly from Kobe. The need for extensive inspections and traceability led to delays and increased costs, accentuating the significance of stronger oversight, especially at the sub-tier supplier level [2]. Ultimately, this incident reinforced the importance of diversifying suppliers and maintaining strict quality standards to safeguard the reliability of complex, global manufacturing networks.

4. Boeing's Ability to Self-Certify

On August 18, 2009, the FAA granted Boeing's manufacturing and engineering teams the authority to perform certification tasks on its behalf, including issuing certificates and approving new aircraft designs. Even before this change, Boeing had an internal inspection system in place, with over 400 company employees designated to act for the FAA. Under the new arrangement, these internal inspectors, now reporting directly to Boeing, assumed expanded responsibilities: evaluating new designs, overseeing compliance tests, and authorizing certifications [17].

To provide oversight, the FAA also established the Boeing Aviation Safety Oversight Office, which audits Boeing's internal inspection process and reviews company-generated reports. This marked the beginning of Boeing's self-certification program, a major shift intended to streamline approvals while upholding safety standards.

The U.S. uniquely delegates significant aircraft certification tasks to manufacturers, a practice more extensive than in other major aviation markets like Europe or China. While some delegation exists globally, the FAA's reliance on manufacturer self-certification has been exceptionally high historically, and remains so despite ongoing reforms [18]. Most other regions prioritize direct regulatory oversight.

Aircraft certification requires compliance with the Federal Air Regulations (FARs), which set basic airworthiness requirements but don't always reflect the latest technological advances. This often puts manufacturers in a dilemma, as they strive to introduce innovations that may not fit neatly within existing regulations. Through self-certification, a manufacturer can obtain ODA from the FAA, allowing an appointed representative to endorse Airworthiness Certificates. This arrangement is particularly advantageous for manufacturers. Once granted, Type and Production certificates have no expiration date, provided that no major changes emerge that would require a new certificate. Consequently, companies can continue producing and certifying aircraft as airworthy for years without additional regulatory hurdles.

The Boeing 737, a mainstay in the commercial aviation market, set the stage for the 737 MAX 8. However, flight tests revealed that the larger engines added to the Max 8 increased its propensity to stall. To address this, Boeing introduced the Maneuvering Characteristics Augmentation System (MCAS) software system, but argued that this did not constitute a significant design change. This position allowed Boeing to avoid the lengthy and costly process of obtaining a new aircraft certification, maintaining that the 737 MAX was similar enough to its predecessor.

Leveraging its self-certification privileges, Boeing sped up the approval and production process, staying competitive with Airbus's A320neo. The company assured that pilots familiar with the previous 737 models would not encounter any significant differences in the cockpit of the Max 8. FAA test pilots, tasked with identifying any unique handling or performance characteristics of the Max 8, reported none [17]. While this approach offered financial and competitive benefits, it raised serious concerns about the depth of the certification process and the adequacy of pilot preparation.

Typically, one Boeing engineer tests a system, while another, acting as an FAA representative, certifies that it meets federal safety standards. At the start of the 737 MAX's certification, the FAA's safety team outlined which technical assessments would be handled by Boeing and which would remain under direct FAA oversight [19]. The imperative to accelerate certification shifted responsibilities, raising concerns about oversight and conflicts of interest. These concerns were heightened by the two fatal 737 MAX 8 crashes, which prompted calls for a comprehensive review of the certification process.

Even before the 737 MAX 8 disasters, the FAA's oversight was facing scrutiny. The Transportation Department's Office of Inspector General had already criticized the agency's supervision of manufacturers, pointing out inefficiencies and gaps in the self-certification process [17]. In 2011, the Inspector General released a series of reports highlighting problems with how the FAA assessed safety risks and managed the delegation of certification tasks. The reports also noted that company employees responsible for identifying deviations from safety standards often lacked adequate training.

A crucial part of the inspection process is determining whether pilots need comprehensive training on new aircraft features. However, flaws in the evaluation process meant that critical systems, such as MCAS, were not properly addressed. As a result, no additional pilot training was required for the 737 MAX 8, a decision that left crews unprepared for the MCAS system and contributed to the loss of two commercial aircraft and 346 lives. These failures underscore the urgent need for stronger oversight within the FAA, particularly regarding the delegation of certification tasks. Most recently, on January 17, 2025, Boeing requested temporary exemptions from the FAA for the stall-management yaw damper system on its 737 MAX 7 and MAX 10 models, citing regulatory challenges following a reclassification of the system [18].

The TCE framework proposed by Williamson [7] provides a powerful framework for analyzing Boeing's self-certification program under the FAA's ODA. It highlights the trade-offs between efficiency and control. Applying TCE, Boeing's self-certification aims to reduce transaction costs due to the specialized nature of aircraft manufacturing and the frequency of certification requirements. That said, ongoing oversight failures and recent incidents suggest that the ODA program hasn't adequately mitigated opportunism, a substantial concern within TCE. To optimize the ODA, stronger hierarchical controls are needed to realign with the governance principles proposed by Williamson [7], balancing the pursuit of efficiency with the paramount need for safety.

To summarize, several key issues under scrutiny are:

(1) Boeing engineers certifying aircraft safety are employed by the company, which could potentially compromise their independence.
(2) Boeing ODA staff feel pressured to approve items rapidly, potentially compromising safety.
(3) The FAA's oversight of Boeing's ODA is ineffective, failing to mitigate risks. The agency has yet to implement a risk-based approach to ODA oversight, despite recommendations dating back to 2015.

(4) Poor coordination within the FAA and with Boeing led to critical system changes going unnoticed.
(5) The FAA has faced a shortage of skilled engineers and difficulties in training and supervision, undermining its ability to effectively oversee Boeing's certification processes.
(6) Boeing exerted undue pressure on ODA-certified employees during the 737 MAX development.
(7) Mixed perceptions of improvement: A recent survey found that only 45% of ODA unit members perceive progress in addressing improper company interference.

To address ongoing concerns about certification, regulatory oversight, abysmal coordination, and inordinate corporate influence over inspection processes, the FAA is implementing significant initiatives. These initiatives aim to strengthen its ability to conduct independent evaluations and enhance its regulatory capacity.

5. Supply Chain Risks and Their Assessment

The Boeing 787 supply chain, with 70% of its parts outsourced and 30% supplied by foreign entities [3], embodies the complexities and challenges of managing a project with an ambitious scope. Integrating innovative composite materials into an aircraft's structure introduces a layer of complexity. This necessitates stringent oversight across all processes entailed in these composites. The global nature of the supply chain meant that Boeing faced significant risks. These included ensuring the consistency of material grades from diverse suppliers, coordinating timelines across various suppliers to facilitate a seamless assembly process, navigating political challenges that could impede deliveries, and managing inventory levels to avoid excesses or shortages.

Boeing's heavy reliance on outsourcing for critical components and software development has created significant challenges. This decentralized approach has led to fragmented quality and safety oversight, reduced control over design and production, and increased complexity with communication gaps between Boeing and its suppliers. Critical safety information is often ineffectively communicated or inadequately addressed. This is evidenced by multiple incidents and an FAA audit identifying 97 instances of alleged noncompliance with manufacturing control requirements.

Furthermore, due to poor planning and inaccurate data, Boeing faces supply chain vulnerabilities [5], leading to inefficiencies, material shortages, and manufacturing disruptions. These issues, coupled with safety concerns and increased regulatory scrutiny, have forced Boeing to significantly slow down 737 MAX production. A comprehensive risk assessment aimed at developing preemptive strategies to mitigate potential adverse outcomes is presented below. The vulnerabilities are identified to prevent or minimize the impact of these risks.

5.1. Risk identification

The risk assessment process hinges on the initial identification of potential risks, particularly when dealing with innovative systems or processes that are not well understood [18]. Boeing's venture into global outsourcing of its supply chain represents a bold and innovative approach. This makes a thorough risk assessment even more crucial to prevent avoidable delays and additional costs. The key challenges inherent to managing a global supply chain include maintaining visibility over suppliers, ensuring the quality of parts and materials, and preventing delays in shipments.

Once identified, each identified risk must be scrupulously analyzed to understand its root causes, the probability of its occurrence, and the magnitude of its potential impact. Factors contributing to delays include scarcity of raw materials, insufficient labor, failure to pass quality audits, suppliers underestimating the time required for production, and unpredictable events such as conflicts or economic downturns. Quality issues can arise from several factors, including incorrect calibration of manufacturing equipment, use of counterfeit materials, employment of workers lacking necessary training, and pressure to meet tight deadlines, causing compromised standards. Ineffective internal audits and inadequate oversight by the manufacturer further exacerbate these issues. Addressing these risks requires a proactive approach, beginning with early identification, followed by a detailed analysis. This approach enables the development of targeted strategies to mitigate risks, facilitating the progression of the supply chain and safeguarding the project against unnecessary setbacks and expenses.

5.2. Risk analysis

The causes of quality issues are then examined to analyze the causes and the likelihood of subsequent consequences. For instance, improper equipment calibration can result in dimensional errors in the parts. As these parts enter a much larger assembly, the tolerance (T) limits are exceeded if the tolerance of the individual components is out of range. This can lead to an entire batch being scrapped, imposing significant costs to the company. This is illustrated using the tolerance stacking method, which predicts how dimensional variations in individual components combine and impact the overall size, fit, and functionality of an assembly. Mathematically, this is described as a linear sum, as a worst-case analysis, in the following equation:

$$T^{Assembly} = T_{Part-1} + T_{Part-2} + T_{Part-3} + \cdots + T_{Part-n} \tag{1}$$

where $T^{Assembly}$ refers to the total tolerance of an assembled component, and $T_{part\text{-}1}$, $T_{part\text{-}2}$, and $T_{part\text{-}3}$ represent the tolerance of part 1, part 2, and part 3, respectively, and so on. This linear regression method quantifies risks by modeling a linear relationship between supply chain variables and the likelihood or impact of a risk event. Linear regression functions as a component of supply chain risk analysis. A hybrid approach integrating both quantitative and qualitative techniques, sometimes leveraging advanced statistical and machine learning models, may also be beneficial.

As an example of supply chain in the aerospace industry, the variables include supplier reliability, transportation bottlenecks, and raw material price fluctuations. Thus, delay (as a risk) can be calculated as:

$$Delay = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 \tag{2}$$

where x_1, x_2, and x_3 represent supplier reliability, transportation bottlenecks, and raw material price fluctuations, respectively, and α_0, α_1, α_2, and α_3 are coefficients indicating how much each factor contributes to the 'Delay'.

Previously, Boeing provided detailed plans and drawings to its suppliers [20]; however, for 787, it only provided detailed requirements to approximately 50 of its Tier-I (direct) suppliers. Moreover, detailed planning is the responsibility of these Tier-I suppliers, as pre-integrators. In this instance, Boeing has limited influence on decisions involving Tier-II (secondary) or Tier-III (tertiary) suppliers in the hierarchical supply chain. Consequently, owing to the lack of the manufacturer's oversight of the supplier, shimming problems emerged with matching composite parts from different suppliers [20]. Although other risk assessment methods are employed in aircraft manufacturing, the risk-reporting matrix offers a straightforward, visual, and effective tool for prioritizing safety-critical risks, enhancing communication, and ensuring regulatory compliance.

In a risk-reporting matrix, the likelihood of an event against its consequence to determine the overall risk is plotted as shown in Fig. 4. Risk is principally calculated by multiplying these two factors. This means that as one moves diagonally across the matrix, the risk level increases. For instance, events with both low likelihood and low consequence (on a scale of 1 to 5) will fall into the "lowest risk" category, often represented by lightly shaded areas in Fig. 4. Conversely, the darkest shaded areas signify "high risk," indicating events that are highly likely to occur and would result in severe consequences. For clarity, different events in the Boeing 787 supply chain are labeled (e.g., A, B, C, D, E, F, G, H), as shown on the right side of Fig. 4. Once these events have a likelihood and consequence score available, their risk can be calculated. The high-risk events at the end of the diagonal line demand immediate and prioritized attention. Based on Fig. 4, supply chain events A, D, E, F, and H have been identified as high-priority events that require effective strategies to mitigate or avoid them.

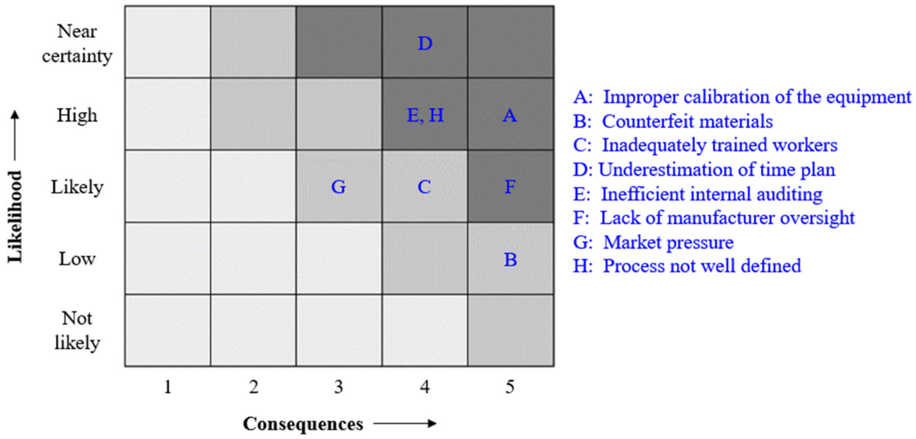

Fig. 4 Risk reporting matrix

Linking the supply chain issues discussed in Section 2 to the risk-reporting matrix reveals that Boeing's evaluation of the 737 MAX system during development relied on an oversimplified testing process that failed to consider the complexity of real-world scenarios. The company's flight tests were conducted under conditions significantly simpler than actual emergencies, and critical factors were underestimated, including the impact of the MCAS system and pilot response assumptions. This was exacerbated by a single point of failure due to reliance on a single angle-of-attack (AOA) sensor, resulting in a lack of redundancy [18]. Additionally, inadequate change management, such as changes to the MCAS system's power, insufficient use of key risk indicators, and a lack of board oversight undermined checks and balances on the company's risk appetite and tolerance.

As a prime aerospace contractor, Boeing relies upon a global network of subcontractors for components, systems, and services. TCE serves as a valuable analytical tool to assess Boeing's subcontracting choices and the governance mechanisms it employs. The Boeing case exemplifies the consequences of disregarding TCE principles, such as outsourcing core capabilities and failing to adequately govern high-specificity transactions, which contributed to operational failures. Airbus, on the other hand, better aligns with TCE by maintaining control over critical functions and fostering strong supplier relationships [18]. Boeing's recent steps, like considering the reintegration of Spirit and overhauling quality control, signal recognition of these issues. TCE provides a useful lens for understanding Airbus's resilience and guiding Boeing's recovery.

While implementing TCE-based solutions, like better oversight of outsourcing, would certainly prove advantageous, these must be combined with deeper cultural and structural reforms to fully re-establish engineering discipline. Real cultural transformation goes beyond simply adjusting structures or complying with regulations [18]. Airbus, despite its imperfections, offers a valuable contrast, as it has institutional safeguards that prevent similar dysfunctions.

5.3. Risk treatment

Following the identification of risks and the assessment of their potential impacts, strategies for mitigating those deemed unacceptable were developed. Boeing embraced a "risk-sharing" model through extensive outsourcing, distributing the responsibility for various aircraft components among different suppliers. This approach meant that the quality assurance of each part became the responsibility of the respective supplier under agreements established with Boeing. However, Boeing initially underestimated several factors, which resulted in quality issues and subsequently caused delays in aircraft delivery. The risk management strategies that should be implemented include the development of a comprehensive preventive plan aimed at minimizing the likelihood of these risk factors and mitigating their impacts [20].

In response to the significant delays experienced in their initial aircraft deliveries, Boeing implemented a contingency measure by establishing a Production Integration Center (PIC) to address and prevent future delays and quality problems [21]. To further ensure the integration of supply chain quality, Boeing deployed engineers and production staff across various countries to monitor the performance of its suppliers directly [22]. Ideally, PIC should serve as a proactive, preventive measure rather than a reactionary contingency plan. The deficiency of critical analysis of the identified risks necessitated PIC implementation only after substantial costs had been incurred by the company. This underscores the importance of early risk identification and the application of preventive measures to avoid the escalation of manageable risks into significant financial and operational challenges.

Boeing's risk treatment during the development of the 737 MAX was fundamentally flawed, prioritizing speed and cost-cutting over safety, which resulted in catastrophic consequences. Key missteps comprised the flawed design of the MCAS system, its omission from operations manuals and checklists, and an aggressive production schedule that emphasized deadlines over thorough testing. Additional cost-cutting measures included excluding an MCAS indicator light in the cockpit. Furthermore, Boeing failed to address critical concerns raised by engineers regarding the MCAS system, including the risks of erroneous AOA sensor data. It also made compromises, such as relying on limited iPad-based training due to contractual pressures from airlines such as Southwest [23]. These failures in risk treatment contributed to the tragic crashes of Lion Air Flight 610 and Ethiopian Airlines Flight 302, resulting in the global grounding of the 737 MAX fleet.

5.4. Monitoring and review

To verify the effective application of risk-mitigation strategies, Boeing needed to establish robust monitoring frameworks to oversee the implementation of these measures. Given the oversight of treating certain risks with the requisite level of seriousness, the adoption of digital audits to supervise supplier activities was initiated somewhat later. To enhance oversight, Boeing installed cameras at various supplier sites to facilitate digital audits [21]. These digital audits represent a significant advancement in maintaining diligent oversight of suppliers and reducing the likelihood of suppliers concealing issues [24].

The efficiency of such a system was underscored by the incident involving Kobe Steel, in which greater transparency and monitoring of supplier operations could potentially forestall fraudulent activities. Digital audits offer a continuous, real-time oversight mechanism, enabling companies such as Boeing to detect and address non-compliance or discrepancies in supplier practices promptly. This approach enhances the integrity of the supply chain and contributes to building trust and accountability between manufacturers and their supplier networks.

The Boeing 737 MAX development, extensive monitoring and review notwithstanding, suffered from significant shortcomings. FAA oversight was insufficient, and Boeing's internal processes, including safety assessments and post-certification monitoring, exhibited critical flaws. Notably, Boeing delayed crucial safety risk assessments related to the MCAS system until late in the certification process, failing to classify system-level risks as catastrophic. This led to the MCAS system relying solely on data from a single aircraft sensor, neglecting crucial redundancy measures.

6. Risk-Sharing Supplier-Partnership Model

Proposing to integrate the prescribed risk assessment protocols into the frameworks of Risk-Sharing [25] and Integrated Supplier [26], partnerships offer a strategic avenue for achieving effective resolutions supporting Boeing in surmounting its hurdles. The "risk-sharing supplier partnership model" encapsulates a collaborative approach in which both entities mutually undertake risks and responsibilities within the partnership, aiming for shared advantages and success. The key benefits of collaboration include enhanced communication, risk management, stability, and competitive advantage [27]. To improve collaboration, companies are advised to carefully select partners, maintain regular communication, aim for supply chain visibility beyond Tier-I suppliers, and prioritize long-term planning. It offers a supplier collaboration portal to facilitate communication and contractual information sharing, strengthen relationships, and achieve mutual success within the supply chain. By incorporating this model into its risk management steps, Boeing stands to gain numerous advantages in confronting supply chain challenges:

A. Enhanced risk identification

(1) Close collaboration with suppliers enables Boeing to identify potential risks by leveraging its collective expertise.
(2) Transparent communication between Boeing and its suppliers enables timely risk reporting and identification.

B. Improved risk assessment

(1) Sharing data with suppliers enhances the risk assessment accuracy, providing a holistic view of potential threats.
(2) Joint assessment of risks allows Boeing to consider interconnectedness within the supply chain.

C. Effective risk analysis

(1) Collaborative risk analysis with suppliers identifies root causes and consequences by leveraging their combined expertise.
(2) Shared risk analysis tools and methodologies ensure consistency, thereby improving the accuracy of risk evaluation.

D. Strategic risk treatment

(1) Collaborative risk treatment ensures efficient responsibility and liability sharing based on each party's strengths.
(2) Risk-sharing agreements foster mutual investment in risk management and a sense of shared responsibility.

E. Continuous monitoring and review

(1) Risk monitoring and review allow real-time tracking of treatment effectiveness and emerging risks.
(2) Joint reviews and lessons learned in sessions drive risk management improvement and strengthen collaboration.

Additionally, the early identification of potential risks and formulation of mitigation strategies is of paramount importance, particularly in the aerospace industry, which is characterized by its complex and heavily regulated nature. This necessitates the execution of thorough risk assessments, establishing contingency plans, and vigilance for emerging risks as projects evolve. The implementation of rigorous quality control measures is fundamental to ensuring the dependability and safety of aerospace network systems and involves the setting of quality standards and procedures, regular quality evaluations, and compliance with the stringent standards and best practices of the aerospace industry. Furthermore, fostering a culture of continuous improvement is crucial, necessitating regular reviews of project processes, outcomes, and team performance to identify opportunities for refinement. This involves a dedication to learning from each endeavor and applying the insights gained to enhance future project management practices.

In principle, integrating the risk-sharing supplier partnership model with risk management was expected to help Boeing build a more resilient and collaborative supply chain, mitigate risks more effectively, and enhance its ability to achieve shared objectives with suppliers. By fostering closer collaboration and shared responsibility, Boeing can address supply chain challenges more proactively, ultimately improving its operational efficiency and reducing the likelihood of disruption.

Boeing's risk-sharing supplier partnership model has encountered a range of challenges and has drawn substantial criticism [25]. Key issues are:

(1) Incentive misalignment: The model inadvertently created an incentive trap. It encouraged suppliers, who were covering the initial research and development (R&D) costs, to protract the development process and inflate expenses, directly contradicting Boeing's goals. This is a good example of how misaligned incentives can lead to significant cost overruns, delays, and quality problems.
(2) Delayed payments: The risk-sharing model included a payment structure that exposed suppliers to the risk of program delays. The payment was contingent upon certification and delivery, placing a significant financial burden on suppliers.
(3) Loss of control: By heavily relying on the risk-sharing model, Boeing delegated the selection and management of sub-tier suppliers to their partners, leading to reduced oversight and control over the supply chain, particularly at lower tiers. This approach had significant implications for Boeing's overall control over the production process.

(4) Development disasters: The 787 program, beset by substantial delays and cost overruns, highlights the unforeseen challenges of integrating complex systems developed by multiple partners. The first flight was delayed by 26 months and the initial delivery by 40 months, with cost overruns exceeding $11 billion. This suggests that Boeing may have overestimated the capacity of suppliers to manage the increased responsibilities and risks associated.

(5) Reputation risk: The risk-sharing model exposes Boeing to reputational harm, even if liability for delays or quality issues can be shifted to the partner.

(6) Intellectual property concerns: The risk-sharing model, which granted suppliers intellectual property rights, could potentially reduce Boeing's control over critical technologies.

The TCE framework proposed by Williamson [7] offers an explanation for challenges in Boeing's risk-sharing partnerships for the 787 Dreamliner program. These partnerships, where suppliers co-invested in production in exchange for long-term contracts, created high asset specificity, opportunism, and bounded rationality. The risk-sharing agreements, without sufficient hierarchical oversight or safeguards, led to quality control issues and delays. This revealed a misalignment with TCE's recommendation for more integrated or relational governance when dealing with strategically important and interdependent suppliers. This case exemplifies the insight proposed by Williamson [7] that an efficient organizational structure must match the complexity and risk of the transaction to minimize overall costs and inefficiencies.

To summarize, the experience with Boeing's risk-sharing model serves as a valuable lesson. While the intent was to distribute risk and foster innovation, the outcome included significant delays, cost overruns, and a loss of control over the development process. This underscores the need for careful consideration of incentive alignment, robust oversight mechanisms, and a realistic appraisal of supplier capabilities when undertaking complex aerospace projects.

Boeing continues to contend with production and supply chain issues, causing significant delivery delays that are disrupting airline operations and financial planning [28]. Major carriers such as Ryanair and Emirates have adjusted their financial forecasts and reported losses owing to late aircraft deliveries [29]. Similarly, American Airlines has had to suspend routes and delay upgrades due to delayed 787 Dreamliner deliveries. These persistent challenges underscore the ongoing weaknesses in Boeing's global supply chain management and their widespread impact on airline customers. Furthermore, safety concerns, e.g., the incident involving Alaska Airlines flight, remain high, with recent incidents bringing renewed scrutiny to Boeing's quality control practices.

The incidents point to systemic shortcomings in Boeing's oversight and quality assurance processes, further eroding trust among airlines and passengers. Moreover, reports suggest deeper systemic issues within Boeing's operations, such as misaligned priorities favoring cost-cutting over safety and quality [28]. These challenges are compounded by fragmented supplier relationships, leading to inefficiencies and reduced control over production processes. These developments reinforce the need for Boeing to adopt more robust risk management strategies, enhance supplier oversight, and prioritize transparency and quality assurance across its global operations. The company must also address organizational reforms to rebuild trust and ensure long-term operational resilience.

7. Discussion on Key Research Findings

This study undertook a comprehensive and in-depth examination of the systemic issues that have plagued Boeing's supply chain management, quality assurance protocols, and aircraft certification processes. The following discussion delineates the salient findings uncovered during this thorough investigation. Boeing's shift to a highly outsourced, risk-sharing supply chain for the 787 was intended to reduce costs and speed up development by utilizing global expertise. However, this strategy proved counterproductive, resulting in fragmented oversight, loss of direct control, and increased vulnerability to quality and delivery issues. Numerous suppliers struggled to meet standards and deadlines, exposing the risks of this model. The negative consequences of this strategy became evident through delays in parts delivery [28], problems on the assembly lines [14], and lapses in manufacturing quality [13].

The ODA program, which allowed Boeing to self-certify, significantly expedited approvals but also resulted in critical lapses. This issue was exacerbated by the FAA's ineffective delegated oversight and internal pressure on Boeing engineers to prioritize speed over safety. The adverse effects were evident in issues such as the MCAS software being implemented without adequate pilot training [17] and the financial pressures Boeing faced in competing with Airbus's A320neo model [18].

Intense cost-cutting at Boeing eroded its safety culture, particularly evident in the controversial iPad-based pilot training for the 737 MAX. Poor communication with suppliers exacerbated defects, such as loose seats reported by KLM. These misaligned incentives within Boeing highlight significant systemic gaps. The lack of integrated supply chain visibility and insufficient supplier collaboration directly caused costly delays [11], widespread quality problems [21], and severe production bottlenecks [18]. The Dreamliner's issues demonstrate that even advanced IT systems like Exostar are unable to overcome poor supplier integration and oversight without strong visibility and proactive engagement.

Following logistical and safety failures, Boeing revised its outsourcing strategy, repatriating integral operations and enhancing supplier controls. This decision is consistent with TCE's assertion that firms adjust governance structures to minimize transaction costs. However, Boeing still faces challenges, e.g., addressing manufacturing lapses, that must be resolved to fully recover and restore trust [22].

This study quantifies the impact of factors like supplier reliability, transportation delays, and material quality on overall supply chain performance through the application of structured risk analysis methods, such as risk matrices. The 737 MAX crashes and the 787 Dreamliner development process exposed significant shortcomings in risk analysis methods [21]. This quantitative, systems-based approach advocates for such tools to prioritize risks and guide effective mitigation strategies.

Boeing's risk-sharing contracts for the 787, which linked supplier payments to final delivery, unintentionally incentivized some suppliers to delay work, increasing the risk of program delays [25-26]. This case illustrates how poorly designed contracts can worsen supply chain risks, as Boeing attempted to shift development and production risks without proper oversight or safeguards.

Boeing's reactive risk management [23] failed to anticipate supply chain fragmentation and the MCAS single-point-of-failure. Primary interventions (such as acquiring suppliers or deploying engineers) occurred only after delays and cost overruns materialized. This underscores the critical need for proactive management, rigorous supplier selection, clear communication, and ongoing risk assessment in aerospace supply chains.

Over the decades, Boeing's safety record has steadily improved, with significantly fewer passenger fatalities from 2018 to 2022 compared to the 1968 to 1977 period [2]. This improvement continues even with recent quality-control problems on the 787 Dreamliner and 737 MAX, which arise from different systemic issues. But these setbacks emerge within a larger aviation safety system that has many layers, e.g., advanced technology, strict regulations, and a strong safety culture. These layers are designed to reduce risk and manage problems from individual manufacturers.

As a result, overall long-term safety continues to improve even amid occasional high-profile incidents. To understand aviation safety, the public should examine standard numbers like the global accident rate (accidents per million flights), the fatal accident rate (deadly accidents per million flights), and the fatality rate per 100 million people on board [2]. Minor issues that are not directly associated with fatalities, such as small cracks, rough landings, or electrical glitches, might indicate quality control concerns, but they are not necessarily indicative of an increased risk of a crash. Ultimately, long-term accident rates are the most reliable way to gauge aviation safety.

Boeing's recovery depends on internal reforms and U.S. government policy. Despite production improvements and a strong order book, the company faces significant challenges and growing competition from Airbus. Boeing is considered too big to fail due to its strategic importance, national security role, and economic impact. The U.S. government is highly unlikely to countenance the collapse of Boeing, as this would enable Airbus to attain a near-monopoly and have severe geopolitical consequences.

The government intervention that repeatedly shields Boeing from the consequences of its failures, such as through subsidies, procurement favors, or relaxed oversight, creates a moral hazard. This safety net can foster complacency and risk-taking within the company, as executives benefit from favorable outcomes without facing the full repercussions of poor decisions. Such unconditional support risks delaying necessary reforms, increasing the potential for regulatory capture, and promoting short-term fixes over fundamental improvements. Without stringent conditions, such as mandatory safety overhauls, leadership changes, strong oversight, and enforceable accountability, a guaranteed lifeline inadvertently exacerbates Boeing's underlying issues, reducing the crucial pressure on Boeing to change.

8. Conclusion

This study examined how Boeing's outsourcing practices, particularly when combined with its self-certification license from the FAA, precipitated significant lapses in both regulatory oversight and internal quality control. Based on this analysis, the main conclusions are summarized as follows:

(1) Boeing's risk management frameworks, although theoretically sound, faltered in practice due to a confluence of deep-seated cultural, operational, and regulatory weaknesses.

(2) The findings underscored the importance of supply chain visibility, robust collaboration, and proper incentive alignment as critical factors for effectively managing the inherent risks within a complex, globally outsourced aerospace supply chain, highlighting areas where Boeing's operations were deficient.

(3) The 787 and 737 programs illuminate the urgent necessity for aerospace companies to adopt integrated, transparent, and flexible supply chain strategies, which Boeing conspicuously failed to implement adequately.

(4) Tier-I suppliers must rigorously audit their own Tier-II suppliers to ensure product quality is never compromised, emphasizing the need for proactive oversight.

(5) While innovative operational models can enhance efficiency, they must be unequivocally supported by strong, proactive risk management and robustly structured contracts to prevent costly failures, protect brand reputation, and safeguard lives.

Conflicts of Interest

The authors declare no conflict of interest.

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