

Incident Reduction Associated with Safety Culture Interventions in Large Infrastructure Projects

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Abstract

The construction and management of large infrastructure projects present complex challenges related to occupational health and safety. Despite significant advancements in engineering controls and regulatory frameworks, incident rates in megaprojects remain a critical concern. This paper investigates the efficacy of safety culture interventions through the novel application of Lifecycle Assessment methodologies. Traditionally utilized for environmental impact evaluations, Lifecycle Assessment provides a robust, longitudinal framework for measuring the sustained impact of behavioral and cultural safety programs across the planning, execution, and operational phases of infrastructure development. By analyzing longitudinal data from multiple large-scale public works, this study aims to quantify incident reduction attributable to specific cultural interventions, such as leadership commitment programs, peer-to-peer observation mechanisms, and continuous safety training. The research synthesizes quantitative incident reports with qualitative cultural maturity assessments to offer a comprehensive view of safety performance over time. Findings suggest that safety culture interventions exhibit a delayed but compounding effect on incident reduction, with the most significant improvements materializing during the peak construction and early operational phases. The integration of Lifecycle Assessment principles into safety management enables project stakeholders to allocate resources more effectively, ensuring that cultural interventions are not merely reactive but serve as proactive, enduring mechanisms for risk mitigation.

Keywords: Safety Culture; Lifecycle Assessment; Incident Reduction; Infrastructure Projects; Applied Engineering

1. Introduction

1.1 Background and Context

Large infrastructure projects, encompassing expansive transportation networks, energy generation facilities, and complex urban development systems, serve as the backbone of modern economic and social development. However, the sheer scale, complexity, and extended duration of these projects introduce unparalleled occupational health and safety challenges. The dynamic nature of construction environments, characterized by high-risk activities, multifaceted supply chains, and transient workforces, makes them inherently susceptible to accidents and near-misses. Historically, the approach to mitigating these risks has been heavily reliant on physical engineering controls, stringent regulatory compliance, and reactive safety management systems [1]. While these traditional paradigms have undoubtedly contributed to a baseline reduction in catastrophic failures and severe injuries, the plateauing of incident rates in recent decades suggests that procedural and mechanical interventions alone are insufficient. This realization has precipitated a paradigm shift within the industry, redirecting focus toward the human element of safety, specifically the organizational psychology and behavioral dynamics collectively known as safety culture.

Safety culture represents the shared values, beliefs, and attitudes toward safety held by individuals within an organization. It dictates how safety protocols are perceived, prioritized, and executed on the ground, often serving as the invisible architecture that supports or undermines formal safety management systems. In large infrastructure projects, where multiple contractors and subcontractors converge, establishing a cohesive and

resilient safety culture is both exceptionally difficult and critically important [2]. Interventions designed to enhance safety culture range from executive leadership alignment and localized safety champion programs to psychological safety initiatives that empower workers to halt operations without fear of reprisal. Despite the widespread adoption of these cultural interventions, assessing their tangible impact on incident reduction remains a complex methodological challenge. Traditional safety metrics, such as the Total Recordable Incident Rate or the Lost Time Injury Frequency Rate, are predominantly lagging indicators. They measure failures after they occur and offer limited insight into the preventive efficacy or the temporal sustainability of cultural interventions.

1.2 The Role of Lifecycle Assessment in Safety Management

To address the limitations of traditional, snapshot-based safety metrics, this paper proposes the integration of Lifecycle Assessment methodologies into the evaluation of safety culture interventions. Originating in environmental science to quantify the ecological footprint of a product or process from cradle to grave, Lifecycle Assessment offers a structured, temporal framework that is remarkably well-suited for evaluating long-term safety performance [3]. When adapted for occupational health and safety in large infrastructure projects, a safety-focused Lifecycle Assessment evaluates the cumulative impact of cultural interventions across distinct project phases: conceptual design, detailed engineering, procurement, active construction, commissioning, and long-term operation.

This longitudinal approach acknowledges that the manifestation of safety culture is not instantaneous. Interventions introduced during the early planning stages require time to permeate the organizational hierarchy and alter entrenched behavioral patterns. By mapping incident data and cultural maturity indicators against the project lifecycle, researchers can identify delayed correlations, phase-specific vulnerabilities, and the compounding benefits of sustained safety initiatives [4]. Furthermore, a lifecycle perspective facilitates the identification of safety leakage, a phenomenon where safety performance deteriorates during transition periods between project phases, such as the handover from primary construction contractors to operational management teams. Through the systematic tracking of safety inputs and incident outputs over time, this paper aims to provide empirical evidence on how and when safety culture interventions exert their maximum influence on incident reduction, thereby guiding future resource allocation and strategic safety planning in megaprojects.

2. Literature Review and Background

2.1 Evolution of Safety Culture in Infrastructure

The concept of safety culture gained international prominence in the aftermath of catastrophic industrial failures in the late twentieth century, most notably the Chernobyl disaster, which highlighted how organizational deficiencies and normalized deviance could compromise highly engineered systems. Within the context of large infrastructure construction, the evolution of safety culture has transitioned through several distinct phases. Initially, the industry operated under a compliance-driven model, where safety was viewed primarily as a legal obligation and a domain relegated to specialized safety officers [5]. This approach often resulted in a punitive environment that discouraged the reporting of near-misses and masked underlying systemic risks.

As research in organizational psychology advanced, the industry began to embrace a behavioral-based safety model. This era was characterized by interventions targeting the unsafe acts of frontline workers through observation, feedback, and reinforcement programs. While behavioral-based safety yielded measurable improvements in incident reduction, critics argued that it disproportionately placed the burden of safety on the individual worker while neglecting latent organizational factors, such as aggressive scheduling pressures and inadequate resource allocation [6]. Consequently, contemporary literature advocates for a holistic, systems-thinking approach to safety culture. This modern perspective emphasizes leadership commitment, transparent communication, organizational learning, and psychological safety. In large infrastructure projects, a mature safety culture is now understood as one where safety is integrated into core business operations, where workers at all levels are actively engaged in risk identification, and where continuous improvement is prioritized over assigning blame [7].

2.2 Traditional Metrics and Their Limitations

The measurement of safety performance in infrastructure projects has long been dominated by lagging indicators. Metrics such as the incidence of fatalities, lost-time injuries, and medically treated injuries are universally standardized and easily quantifiable, making them attractive for regulatory reporting and inter-organizational benchmarking [8]. However, an extensive body of literature highlights the inherent limitations of relying exclusively on lagging indicators to assess the effectiveness of safety culture interventions. Lagging indicators are retrospective; they record the culmination of a chain of failures but provide little diagnostic value regarding the root causes or the efficacy of preventive measures. Furthermore, in environments characterized by low frequency but high consequence risks, a zero-incident rate over a specific period can create a false sense of security, masking a deteriorating safety culture that may suddenly manifest in a catastrophic event.

To counterbalance these limitations, safety researchers and practitioners have increasingly advocated for the adoption of leading indicators. Leading indicators are proactive measures designed to predict and influence future safety performance. Examples include the frequency of safety training hours, the number of hazard observations reported, the completion rate of preventive maintenance tasks, and the outcomes of safety climate surveys [9]. While leading indicators provide valuable insights into the activities that drive safety, establishing a direct, causal relationship between these proactive measures and ultimate incident reduction remains methodologically challenging [10]. The complex, multi-variable environment of large infrastructure projects means that safety outcomes are influenced by a myriad of confounding factors, including environmental conditions, changes in project scope, and workforce turnover, making it difficult to isolate the impact of specific cultural interventions using traditional cross-sectional analysis.

2.3 Applying Lifecycle Assessment to Occupational Safety

Lifecycle Assessment is traditionally defined as a systematic procedure for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. The conceptual leap of applying Lifecycle Assessment principles to social and organizational metrics, such as occupational health and safety, represents a significant innovation in construction management research [11]. The Social Lifecycle Assessment framework provides a theoretical foundation for this approach, expanding the traditional environmental focus to include the well-being of stakeholders, including the workforce, local communities, and society at large.

When specifically tailored to assess safety culture interventions in infrastructure projects, the Lifecycle Assessment framework requires the establishment of a defined system boundary encompassing all project phases from inception to final decommissioning. The functional unit of analysis shifts from a physical product to the delivery of the infrastructure asset under specific safety parameters. Within this framework, safety culture interventions are treated as inputs introduced at various stages of the lifecycle [12]. The outputs are measured not only in terms of lagging incident rates but also through longitudinal tracking of cultural maturity indices and leading performance indicators. This temporal analysis allows researchers to account for the latency period between the implementation of a cultural intervention, such as a comprehensive safety leadership development program, and its observable impact on frontline incident rates [13]. By conceptualizing safety as a dynamic, continuous process rather than a series of isolated events, the Lifecycle Assessment approach offers a more nuanced and accurate evaluation of how organizational culture influences risk mitigation over the extended duration of large-scale infrastructure projects.

3. Methodology for Assessing Safety Interventions

3.1 Research Design and Framework

This study employs a longitudinal, mixed-methods research design anchored in the principles of Lifecycle Assessment to evaluate the impact of safety culture interventions on incident reduction. The research framework is structured around four primary phases of large infrastructure projects: Planning and Design, Procurement and Early Works, Main Construction execution, and Commissioning and Initial Operation. The core objective of this design is to transcend traditional cross-sectional safety evaluations by continuously monitoring the interplay between cultural inputs and safety outputs over an extended temporal baseline, which in the context of megaprojects can span several years.

The methodology integrates quantitative incident data analysis with qualitative assessments of organizational safety maturity. This dual approach ensures that the study captures both the objective reality of safety performance, as evidenced by incident frequencies, and the subjective perceptions of the workforce, which are indicative of the underlying safety culture [14]. To facilitate a robust Lifecycle Assessment, a standardized data collection protocol was established and implemented across all participating projects. This protocol required the synchronization of safety reporting systems, ensuring that definitions of recordable incidents, near-misses, and leading safety activities were consistent across different contractor organizations and geographical locations.

The analytical framework utilizes a time-series approach to map specific cultural interventions against fluctuations in safety performance metrics. Cultural interventions were categorized into three primary domains: Leadership and Management Commitment, Workforce Engagement and Empowerment, and Organizational Learning and Communication. Each intervention was assigned a temporal marker indicating its initiation, duration, and intensity, allowing the research team to evaluate the latency and persistence of its effects on incident reduction.

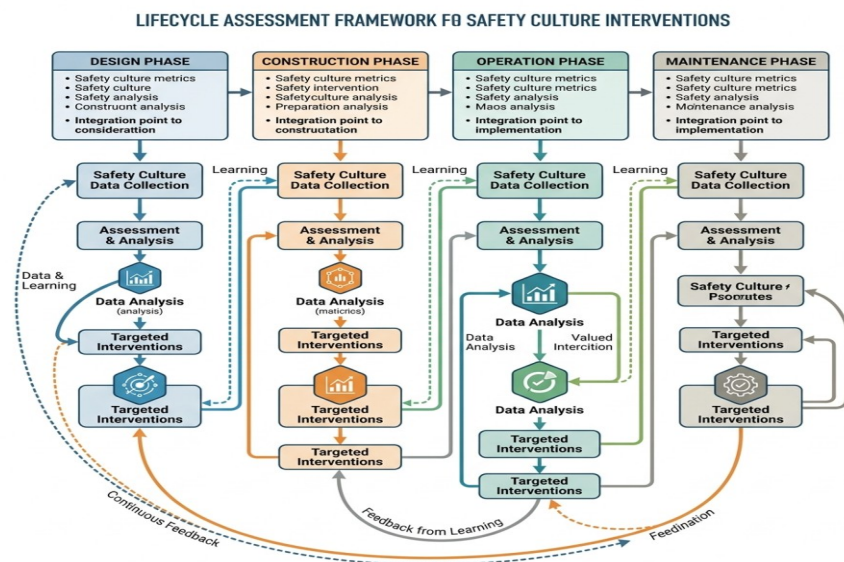


Figure 1: Comprehensive Schematic of Lifecycle Assessment Framework for Safety Culture Interventions

3.2 Data Collection and Case Selection

The empirical foundation of this study is derived from a purposive sample of three large-scale public infrastructure projects, collectively representing a capital investment exceeding five billion dollars and encompassing over twenty million total continuous workforce hours. The selection criteria for these projects required that they be multi-year endeavors, involve complex engineering challenges, utilize diverse contractor supply chains, and, crucially, have a documented commitment to implementing structured safety culture interventions throughout their lifecycle.

Data collection spanned a period of forty-eight months, capturing the transition of the projects through their various developmental phases. Quantitative data was extracted directly from the centralized safety management software systems of the primary contractors. This data included detailed logs of Total Recordable Injuries, Lost Time Injuries, First Aid cases, and High-Potential Near-Miss events. To normalize the data and allow for accurate comparative analysis across different project phases with varying workforce sizes, incident rates were calculated on a standardized basis of per one million hours worked.

Qualitative data regarding safety culture maturity was gathered through a series of structured surveys and semi-structured interviews administered at six-month intervals. The surveys utilized a validated diagnostic tool designed to measure workforce perceptions of management commitment, peer support, safety communication, and the usability of safety procedures [15]. A stratified random sampling technique was employed to ensure

that survey respondents accurately reflected the demographic composition of the project workforce, encompassing executive leadership, middle management, frontline supervisors, and direct labor personnel.

Table 1: Project Characteristics and Safety Intervention Baseline Metrics

Project Designation	Primary Infrastructure Type	Total Duration (Months)	Peak Workforce Volume	Baseline Cultural Interventions Implemented
Alpha Corridor	Rail Transportation Network	52	3400	Executive Safety Tours, Anonymous Hazard Reporting, Peer Mentorship
Beta Terminal	Maritime Port Facility	46	2100	Behavioral Observation Programs, Subcontractor Safety Alignment
Gamma Aqueduct	Water Distribution System	60	2800	Psychological Safety Workshops, Daily Micro-Training Modules

Table 1 outlines the fundamental characteristics of the three infrastructure projects selected for this study, detailing the primary infrastructure type, project duration, workforce volume, and the core cultural interventions introduced during the early phases of the project lifecycle. These baseline metrics provide the necessary context for interpreting the longitudinal safety performance data.

3.3 Implementation of the Lifecycle Assessment Model

The application of the Lifecycle Assessment model to the collected data involved a multi-stage analytical process. The first stage required the establishment of a baseline safety profile for each project during the Planning and Design phase. While active construction risks are minimal during this phase, decisions made regarding design for safety, procurement standards, and initial contractor selection significantly influence the safety trajectory of the entire project. The cultural interventions implemented during this period primarily targeted the project management teams and lead engineering consultants.

As the projects transitioned into the Main Construction phase, the Lifecycle Assessment model tracked the influx of the direct labor workforce and the corresponding escalation of occupational hazards. During this critical period, the frequency and intensity of safety culture interventions, such as frontline leadership training and behavioral observation cycles, were quantitatively mapped against the weekly and monthly incident rates. A time-lag statistical analysis was employed to identify correlations between proactive safety activities and subsequent reductions in lagging indicators [16]. This statistical approach was essential for isolating the impact of cultural interventions from the general background noise of construction operations and varying environmental conditions.

The final stage of the Lifecycle Assessment model focused on the transition from construction to the Commissioning and Initial Operation phase. This handover period is notoriously vulnerable to safety regressions due to the demobilization of the construction workforce, the introduction of specialized commissioning teams, and the energization of complex mechanical and electrical systems. The model evaluated how effectively the safety culture established during the construction phase was transferred to the operational teams and whether the cultural interventions demonstrated sufficient resilience to maintain low incident rates during this high-risk transition.

4. Results and Analysis of Incident Reduction

4.1 Temporal Evaluation of Incident Reduction

The longitudinal analysis generated through the Lifecycle Assessment framework reveals a distinct, non-linear trajectory of incident reduction across the lifespan of the infrastructure projects. Contrary to the expectation of immediate safety improvements following the introduction of cultural interventions, the data indicates a significant latency period. During the initial six to eight months following the implementation of core programs, such as comprehensive behavioral observation and leadership engagement training, the Total Recordable Incident Rate remained relatively static, and in the case of the Alpha Corridor project, experienced a marginal, temporary increase.

This initial plateau can be attributed to the organizational friction inherent in adopting new behavioral paradigms and the increased reporting of minor incidents and near-misses fostered by a developing culture of psychological safety. As workers became more comfortable reporting hazards without fear of reprisal, the volume of recorded data increased, masking the underlying improvement in actual safety conditions. However, as the projects progressed beyond the twelve-month mark, a consistent and statistically significant downward trend in incident rates emerged across all three case studies. This delayed impact underscores a fundamental finding of the Lifecycle Assessment approach: safety culture is not a mechanical switch that can be flipped, but an organic system that requires time to mature and manifest in tangible incident reduction.

Table 2: Longitudinal Incident Rates Across Lifecycle Phases

Lifecycle Phase	Average Total Recordable Incident Rate	Average High-Potential Near Miss Reporting Rate	Cultural Maturity Index Score (0-100)
Phase 1: Planning and Early Works	4.2	1.8	45
Phase 2: Initial Construction Ramp-up	4.5	3.5	58
Phase 3: Peak Main Construction	2.1	8.4	76
Phase 4: Commissioning and Handover	1.3	6.2	82

Table 2 illustrates the dynamic relationship between lagging incident rates, proactive reporting, and overall cultural maturity across the four designated project phases. The data clearly demonstrates that as the Cultural Maturity Index Score increases sequentially through the project lifecycle, the Total Recordable Incident Rate decreases dramatically during the peak construction and commissioning phases. Furthermore, the inverse relationship between the increase in High-Potential Near Miss Reporting during Phase 3 and the sharp decline in recordable incidents highlights the efficacy of a proactive, culturally driven reporting environment.

4.2 Effectiveness of Specific Cultural Interventions

Beyond general trends, the Lifecycle Assessment framework allowed for the granular evaluation of specific cultural interventions and their unique contributions to incident reduction. The data indicates that interventions categorized under Workforce Engagement and Empowerment, particularly peer-to-peer observation programs and anonymous hazard reporting systems, yielded the most substantial long-term benefits. These programs directly altered the daily behavioral patterns of the frontline workforce, creating a pervasive environment of mutual accountability.

However, the analysis also revealed that the success of these frontline programs was fundamentally dependent on the antecedent implementation of Leadership and Management Commitment interventions. Projects that prioritized executive safety tours and mandatory management participation in safety risk assessments during the early Planning and Procurement phases demonstrated a much faster assimilation of frontline safety programs during the construction execution phase [17]. The qualitative data derived from workforce surveys strongly corroborated this finding; frontline workers consistently cited visible leadership commitment as the primary factor influencing their own willingness to participate in proactive safety behaviors.

Conversely, the study identified limitations in the effectiveness of purely communicative interventions, such as safety posters, generic safety alerts, and passive digital dashboards. While these tools served as necessary baseline communication mechanisms, the time-series analysis showed no discernible correlation between the frequency of these passive communications and meaningful reductions in incident rates. This suggests that passive information dissemination is insufficient for driving cultural change in complex infrastructure environments, reinforcing the necessity for interactive, participatory interventions that require active cognitive engagement from the workforce.

The Lifecycle Assessment model also provided critical insights into the resilience of safety culture during the volatile Commissioning and Handover phase. Despite the rapid demobilization of the primary construction workforce and the influx of new operational personnel, projects that had achieved a high Cultural Maturity Index Score (exceeding 75) during the peak construction phase successfully maintained low incident rates during commissioning. This phenomenon suggests that a robust safety culture, once deeply embedded within

the project management structure and operational protocols, acts as an organizational buffer, mitigating the safety leakage typically associated with high-turnover transition periods.

5. Conclusion

5.1 Summary of Findings and Implications

This paper has demonstrated the significant analytical advantages of applying a Lifecycle Assessment methodology to evaluate the efficacy of safety culture interventions in large infrastructure projects. By shifting the evaluation paradigm from cross-sectional, lagging metrics to a longitudinal, phase-based analysis, the research provides compelling empirical evidence that safety culture fundamentally dictates long-term occupational health outcomes. The findings clearly establish that cultural interventions exhibit a delayed but compounding effect on incident reduction. The initial stagnation of incident rates following the introduction of cultural programs is not an indicator of failure, but rather a reflection of the organizational adaptation period necessary for profound behavioral shifts to take root [18].

The extensive tracking of both quantitative incident data and qualitative cultural maturity indices across project phases revealed that maximum incident reduction occurs during peak construction, contingent upon the successful establishment of leadership commitment and psychological safety during the early planning stages. Furthermore, the resilience of a mature safety culture proved vital in mitigating risks during the complex handover from construction to operations. Ultimately, this research underscores the necessity for project stakeholders, including government clients, primary contractors, and regulatory bodies, to view safety culture interventions not as short-term operational expenses, but as strategic, lifecycle investments. Integrating these interventions thoughtfully across all phases of infrastructure development is essential for achieving sustainable incident reduction and safeguarding the health and well-being of the global construction workforce.

References

1. Kuo, C.-C.; Zhu, Y.-J.; Wu, Y.-Z.; You, Z.-Y. Development and application of a large injection mold with conformal cooling channels. *Int. J. Adv. Manuf. Technol.* 2019, 103, 689–701.
2. Li, Y.; Zhang, Y.; Wei, Y.; Tao, L. Preparation of chitosan-based injectable hydrogels and its application in 3D cell culture. *J. Vis. Exp.* 2017, 127, e56253.
3. Singh Farwaha, H.; Deepak, D.; Singh Brar, G. Design and Performance of Ultrasonic Assisted Magnetic Abrasive Finishing Combined with Electrolytic Process Set up for Machining and Finishing of 316L Stainless Steel. *Mater. Today Proc.* 2020, 33, 1626–1631.
4. Beam, A.L.; Kohane, I.S. Big Data and Machine Learning in Health Care. *JAMA* 2018, 319, 1317–1318.
5. Laskowska, D.; Szada-Borzyszkowska, M.; Balasz, B.; Szada-Borzyszkowski, W.; Bukala, I. Application of Laser and Cryogenic Surface Treatment for the Evolution of Surface Morphology in Additively Manufactured Ti-6Al-4V Alloy Samples. *Materials* 2025, 18, 5315.
6. Zhang, R.; Lv, Q.; Li, J.; Bao, J.; Liu, T.; Liu, S. A reinforcement learning method for human-robot collaboration in assembly tasks. *Robot. Comput.-Integr. Manuf.* 2022, 73, 102227.
7. Li, G.; Gao, Y.; Huang, W.; Shi, Z. The Formation Mechanism and Influencing Factors of the Sawed Surface of ZTA Nanocomposite Ceramics in Diamond Wire Sawing. *Mater. Sci. Eng. B* 2025, 316, 118159.
8. Mahmoudi, N.; Simchi, A. On the biological performance of graphene oxide-modified chitosan/polyvinyl pyrrolidone nanocomposite membranes: In vitro and in vivo effects of graphene oxide. *Mater. Sci. Eng. C* 2017, 70, 121–131.
9. Romanello, M.; Walawender, M.; Hsu, S.-C.; Moskeland, A.; Palmeiro-Silva, Y.; Scamman, D.; Ali, Z.; Ameli, N.; Angelova, D.; Ayeb-Karlsson, S.; et al. The 2024 report of the Lancet Countdown on health and climate change: Facing record-breaking threats from delayed action. *Lancet* 2024, 404, 1847–1896.
10. Abowd, G.D.; Mynatt, E.D. Charting Past, Present, and Future Research in Ubiquitous Computing. *ACM Trans. Comput.-Hum. Interact.* 2000, 7, 29–58.
11. Wu, L.; Xu, R.; Zhang, J.; Yu, H.; Jiao, Z. Study on Fatigue Behavior and Life Prediction of Laser Powder Bed Fused Ti6Al4V Alloy at 400 °C. *Materials* 2025, 18, 5678.
12. Fang, Y.; Zhang, T.; Song, Y.; Sun, W. Assessment of various crosslinking agents on collagen/chitosan scaffolds for myocardial tissue engineering. *Biomed. Mater.* 2020, 15, 045003.
13. Jin, R.; Lin, C.; Cao, A. Enzyme-mediated fast injectable hydrogels based on chitosan–glycolic acid/tyrosine: Preparation, characterization, and chondrocyte culture. *Polym. Chem.* 2014, 5, 391–398.
14. Leborgne, F.; Champion, D.; Danty, P.; Pascaud-Mathieu, P.; Grandidier, J.-C. Quantitative analysis of the geometric fidelity of human bone twins produced by additive manufacturing in hydroxyapatite and Ti-6Al-4V alloy. *Materialia* 2026, 45, 102641.
15. Singh, S.; Shah, P.L. Safe and Efficient Practice of Bronchoscopic Sampling from Mechanically Ventilated Patients: A Structured Evaluation of the Ambu Bronchosampler-Ascope 4 Integrated System. *Respiration* 2021, 100, 27–33.

16. Nguyen, H.-L.; Holderbaum Do Amaral, R.; Lerouge, S.; De Roo, A.-K.; Zehtabi, F.; Vikkula, M.; Soulez, G. Injectable chitosan hydrogel effectively controls lesion growth in a venous malformation murine model. *Diagn. Interv. Imaging* 2024, 105, 430–438.
17. Smesseim, I.; Daniels, J.M.; Annema, J.; Bonta, P.I.; Slebos, D.-J. Disposable Versus Reusable Bronchoscopes: A Narrative Review of Cost-effectiveness, Risk of Cross-contamination and Environmental Impact. *Arch. Bronconeumol.* 2024, 60, 250–252.
18. Mirjalili, S. Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm. *Knowl. Based Syst.* 2015, 89, 228–249.