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Technology-Integrated Closed-loop Supply Chains and Sustainable Performance in Turkish Aviation Industry with Implications for Naval Aviation Arm

Teknoloji Entegreli Kapalı Döngü Tedarik Zincirleri ve Türk Havacılık Sektöründe Sürdürülebilir Performans: Deniz Havacılık Birimleri İçin Çıkarımlar

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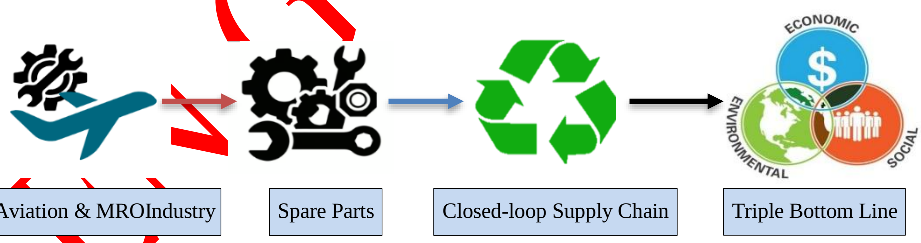
Highlights

PLS-SEM was used to examine the impact of technology-integrated closed-loop supply chains on sustainable performance in the Turkish aviation industry using data from 163 commercial aviation and MRO professionals. Adoption significantly improved all Triple Bottom Line dimensions, with the strongest effect on financial performance (β = 0.363), followed by environmental (β = 0.301) and social performance (β = 0.299). Positive Q^2 values confirmed predictive relevance despite modest R^2 values.

Grafiksel / Tablo Özet - Graphical / Table Abstract (Zorunlu)



Özet (Zorunlu)

Havacılık Havacılık platformlarının bakımı, hem ticari hem de askerî bağlamlarda kesintisiz yedek parça desteği gerektirmektedir. Bu çalışma, Teknoloji Entegreli Kapalı Döngü Tedarik Zincirlerinin finansal, sosyal ve çevresel performans üzerindeki etkisini Üçlü Sorumluluk (Triple Bottom Line) çerçevesinde incelemektedir. Türkiye'deki ticari havacılık ve bakım, onarım ve revizyon (MRO) firmalarında görev yapan 163 profesyonelden elde edilen veriler, SmartPLS 4.0 yazılımı kullanılarak PLS-SEM yöntemiyle analiz edilmiştir. Bulgular, benimsemenin tüm sürdürülebilirlik boyutları üzerinde anlamlı ve pozitif bir etkiye sahip olduğunu göstermekte olup; yaşam döngüsü uzatımı, sıkı güvenlik gereklilikleri ve operasyonel hazırlık düzeyinin kritik önemde olduğu deniz havacılığı tedarik zincirleri açısından dijital olarak etkinleştirilmiş tersine lojistik sistemlerinin gerekliliğini güçlendiren çıkarımlar sunmaktadır.

Abstract (Zorunlu)

Aviation platform maintenance requires uninterrupted spare parts support in commercial and military contexts. This study examines the impact of technology-integrated closed-loop supply chains on financial, social, and environmental performance under the Triple Bottom Line framework. Data from 163 professionals in Turkish commercial aviation and MRO firms were analyzed using PLS-SEM in SmartPLS 4.0. Results show a significant positive effect of adoption across all sustainability dimensions, with implications for naval aviation supply chains where lifecycle extension, strict safety requirements, and operational readiness strengthen the case for digitally enabled reverse logistics systems.

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1. INTRODUCTION

Giriş Globally, aviation industry operates at the forefront of technological and technical sophistication by operating state-of-the-art platforms which require extensive maintenance and technical precision support. Commercial Airlines as well as Maintenance, Repair, and Overhaul (MRO) companies are required to keep thousands of aircrafts flying safely each day, which requires uninterrupted flow of spare parts ranging from major engine components to small valves and pumps. These spare parts, once wear-out or become defective, are removed from the system, inspected, and often sent back for repair, refurbishment, or recycling. During this reverse flow, digital technologies play a significant role by enabling the tracking systems, automated testing, and data-driven decision-making. Resultantly, commercial aviation sector is transforming used parts inventory into valuable assets thereby saving money, reducing environmental footprints, and improving social well-being [1].

Similar to commercial aviation industry, military aviation setups face a very similar challenge. Military forces around the globe operate complex platforms that require regular upkeep and maintenance to ensure their operational availability at all times; this necessitates the availability of ample spare parts inventory [2]. In particular, the contemporary Naval aviation platforms involve substantial life-cycle planning and require uninterrupted spares supportability because they are often required to be kept operational across multiple decades. The naval and commercial aviation share similar operational nature of mechanical spare parts as both platforms have long operational life, high reliability requirements, and fixed maintenance routines and cycles. Among other systems, the spare parts and assemblies such as engine components, different kinds of pumps, gaskets, and valves have the highest consumption trends and require regular replacement due to wear and tear, failure, or leakage. Subsequently, these end-of-life items follow a predefined reverse path starting from the platforms to the central collection points designated by the Naval Headquarters. At these collection points, these returned parts and assemblies are segregated after inspection and are either condemned or sent to repair authorities based on their technical certification status. However, this reverse flow in naval aviation supply chains is largely not seen as a value-generating process but rather a protective obligation. Resultantly, a significant portion of mechanically recoverable end-of-life spare parts are either disposed of or end up resting on warehouse shelves as dormant inventories while in parallel, procurement agencies keep sourcing replacement items which adversely impacts already-budgetary-constraint supply chains [2]. Furthermore, low integration levels of state-of-the-art technologies in these reverse flows also results in restricted asset visibility and increased uncertainty.

The concept of closed-loop supply chains, also known as reverse logistics, refers to a systematic process of return, inspection, reconditioning, and reintegration of end-of-life mechanical spare parts from the point of consumption [3]. This concept has gained considerable prominence due to its associated financial, social, and environmental benefits [1,4,5]. In contrast to naval setups, closed-loop supply chain practices are comparatively more integrated in commercial aviation industry with airlines and Maintenance, Repair, Overhaul (MRO) companies increasingly focusing on reverse flow of spare parts. These spare parts when removed from the aviation platforms are carefully inspected and returned for recycling, refurbishment, or reintegration into the forward supply chains as certified-for-reuse items. Unlike the naval supply chains, commercial aviation sectors considers reverse logistics as an enabler of achieving cost-efficiency, strengthening corporate social image, and achieving sustainability targets. These companies are continuously looking to evaluate contemporary technologies, to enhance recovery potential and accuracy, in their reverse supply chains such as those related to parts traceability, inspection, and automated testing [6].

This study aims to empirically examine the relationship between technology-enabled closed loop supply chain practices and the three distinct performance dimensions based on triple-bottom-line theoretical framework. While data collection and subsequent analysis will be carried out in context of Turkish commercial aviation context; however, the insights form results will be analytically extended to naval aviation supply chains. This is because the empirical data from naval aviation setups is not publicly disclosed due to security and confidentiality concerns [2,7], hence, analyzing civil aviation industry provides a practical opportunity for exploring the subject. In this backdrop, this study aims to answer following research questions:

RQ1: What is the impact of adopting Technology-enabled Closed-Loop Supply Chains for Mechanical Spare Parts on Supply Chain Financial Performance in Turkish commercial aviation sector?

RQ2: What is the impact of adopting Technology-enabled Closed-Loop Supply Chains for Mechanical Spare Parts on Supply Chain Social Performance in Turkish commercial aviation sector?

RQ3: What is the impact of adopting Technology-enabled Closed-Loop Supply Chains for Mechanical Spare Parts on Supply Chain Environmental Performance in Turkish commercial aviation sector?

RQ4: What implications does the findings from commercial aviation sector have for naval aviation supply chains?

The study comprises of six main sections starting with Introduction, followed by Literature Review, Research Methodology, Data Analysis, Discussion and Implications, and Conclusion.

2. LITERATURE REVIEW

2.1 Conceptual basis of Closed Loop Supply Chains

The terms closed-loop supply chains and reverse logistics are used interchangeably in the literature. The recovery and reuse of materials and products is not a new phenomenon. Practices such as metal scrap trading, re-cycling of wastepaper, and soft-drink bottles deposit systems have been implemented across the world for decades. These practices persist because recovered products often retain significant amount of economic value making their recovery and reuse more viable than disposal at landfills. Further, this potential economic rationale has traditionally been the basic driver behind the early Reverse Logistics (RL) systems. Recently, the growing environmental and social awareness among masses has augmented the need of sustainable recovery and reuse systems [8].

The review of relevant literature reveals the use of numerous alternate terms like Reversed Logistics, Return Logistics, Retro Logistics, and Reverse Distribution [9,10]. Despite slight contextual differences, all these terminologies refer to the same concept of reverse flow of goods in a supply chain. However, it is important to understand the difference between RL and waste management. While waste management deals with collection and disposal of unwanted end-of-life products, RL focuses on value recovery by reintegrating them into supply chain operations [11]. Table-1 provides an overview of activities included in reverse flow of products in a supply chain.

Table 1: Reverse logistics activities

Materials	**RL Activities**
Products	Products returned to supplier
	Resell/ Sell via outlet
	Salvage
	Recondition/ Refurbish
	Remanufacture
	Reclaim materials
	Recycle
	Donate
	Landfill
Packaging	Packaging reuse
	Refurbish
	Recycle
	Salvage
	Landfill

2.2 Sustainable Supply Chain Performance (SSCP)

The idea of sustainability became popular around 1980 and ever since has become a topic of interest for scholars and practitioners. However, there is neither a single entirely accepted viewpoint for sustainability assessment, nor a fixed definition that captures its full scope. [13] defined sustainability as incorporation of social, environmental, and economic responsibilities in day-to-day business operations. Building on this idea of sustainability, the concept of sustainable development provides actionable goals to achieve social, environmental, and economic goals. The idea of sustainable development was given by the World Commission on Environment and Development (WCED) in Brundtland Report defining it as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [14]. Applying the concept of sustainable development in the context of supply chains, [15] argued that Sustainable Supply Chains (SSC) focus on interconnectedness among the supply chain activities, environmental wellbeing, and society. Scholars like [16,17] further confirmed three dimensional nature of integrating sustainability in supply chain operations by highlighting the need to reduce environmental impacts like resource depletion and emissions, address societal responsibilities like labor conditions and community wellbeing, and most importantly while maintaining economic profitability across firm and supply chain wide operations. This multi-dimensional approach to sustainability has led scholars to not only focus on the practices but also evaluate the tangible outcomes, giving rise to the concept of Sustainable Supply Chain Performance (SSCP).

Sustainable Supply Chain Performance (SSCP) refers to the measurable outcomes of supply chain activities that reflect progressive improvement across environmental, social, and economic dimensions of performance under the Triple Bottom Line (TBL) framework [15]. TBL framework theory was introduced by [18], which argued that an organization's overall performance should not only be gauged through its financial performance but also by its contribution towards environment and the society. Scholar also emphasized that sustainable supply chains must achieve a balance between all three dimensions of TBL rather than maximizing only one at the expense of others. These three dimensions of SSCP include:

- Economic Performance: The economic bottom-line refers to financial viability of supply chain activities like revenue growth, cost efficiency, and asset optimization. The economic profitability should be considered as the residual surplus after fulfilling the social and environmental obligations.

- Environmental Performance: The environmental bottom-line focuses on the responsible use of natural resources. Enterprises are expected to ensure ecological compliance through effective management of renewable and non-renewable energy, water resources, emissions, waste, and broader environmental concerns.

- Social Performance: The social bottom-line stresses that businesses should implement policies and practices that benefit employees, workers, and society. The social dimension is typically assessed through compliance with social accountability regulations, health and safety protocols, social integration, involvement, human rights standards, gender equality, and justice [19].

2.3 Tech-integrated Closed Loop Supply Chains for Recovery of Mechanical Spare Parts in Aviation Industry

In the aviation sector, various digital technologies are being integrated into the reverse supply chains to assist recovery, inspection, and reintegration mechanisms especially for the mechanical spare parts. These parts often include various pumps, actuators, valves, and components belonging to landing-gears. The mechanism of recovery and reverse flow of spare parts in aviation industry is different from the manufacturing sector due to strict flight safety protocols and certification requirements which makes the digital integration an operational necessity. Prior studies have highlighted that aviation sector players use RFID technology, digital maintenance records through computer-based management systems, condition-monitoring systems to assist in decision-making regarding the reuse, repair, or disposal of recovered parts. Few studies also highlight how recovered used parts are reintegrated into the inventory systems for reuse based on the technology enabled inspection systems in the reverse supply chains. In such cases, the technology enabled reverse flow practices allow standardized, data-driven routine which allows the aviation and MRO firms to recover used mechanical components more efficiently and ensure regulatory as well as safety compliance.

Reverse flow of end-of-life spare parts pertaining to aviation industry is a complex task due to enforcement of strict regulations and hazardous materials. Studies show that closed-loop supply chains in aviation industry require a careful mix of reuse, recycling, and disposal practices while focusing on sustainability and stakeholder needs. However, the lack of clear performance measures and high uncertainty rates make such practices very hard to implement when compared to other industries [1]. Other researchers like [2] also supported [20] stance by emphasizing that the reverse logistics solutions from other sectors cannot be directly applied to the commercial aviation industry because of its unique features like complexity, regulations, and supply chain relationships. Authors further proposed a framework to systematically evaluate opportunities and challenges of implementing sustainability focused reverse logistics in aviation industry. [3] examined recovery and recycling in aviation industry with a three-stage 3D approach (Decommissioning, Disassembly, Smart Dismantling) alongside the emerging technologies and processes such as mechanical recycling, fluidized bed process etc. Although authors' work documented the existing frameworks, the downside is that it treats recycling as a linear process rather than a data-driven loop connecting design, remanufacturing, and reverse logistics activities.

2.4 Reverse Logistics and Economic Performance

Review of literature revealed that several scholars have identified the significant positive association between RL adoption and an organization's economic performance. For example, [1] highlighted that RL adoption contributes to overall cost savings through asset recovery, inventory reduction, and reuse of the recovered products. Similarly, [4] identified specific economic benefits like enhanced profitability, increased labor productivity, reduced inventory costs, and value recovery from the returned products. Empirical findings from scholars like [23] further support the association between RL adoption and improved market share resulting in increased profitability. [5] argue that reverse logistics adoption strengthens the economic performance of the firms by optimizing productivity and lowering operational costs through material recovery and its subsequent reuse in the supply chain which in return aids wealth generation and higher profit margins. Thus, it is hypothesized that:

H$_1$: *Technology-integrated closed-loop supply chain adoption has a significant positive impact on supply chain economic performance in the commercial aviation sector.*

2.5 Reverse Logistics and Environmental Performance

The impact of RL on environmental performance has been vastly studied by scholars over the years. [1] argue that RL adoption acts as a fundamental environmental mechanism by facilitating recycling, reuse, and responsible disposal, thereby contributing towards waste reduction and environmental sustainability. While maintaining the similar viewpoint, [23] further explains that RL adoption helps businesses to reduce air and water pollution and reduce usage of toxic materials. Further, RL adoption also contributes to broader climate sustainability goals by reducing carbon footprints through its core activities like product returns and recycling. [5] note that reverse logistics adoption provides clear environmental gains by promoting responsible practices and encouraging maintenance of cleaner operational footprints. This results in achieving credible green image, complying with environmental regulations, and avoiding pollution and waste mismanagement related penalties.

H$_2$: *Technology-integrated closed-loop supply chain adoption has a significant positive impact on supply chain environmental performance in the commercial aviation sector.*

2.6 Reverse Logistics and Social Performance

The earlier literature focused primarily on economic and environmental dimensions of sustainability; however, recent studies have highlighted the emerging role of closed-loop supply chains adoption in optimizing social performance as well. The term 'social performance' in context of SSCP refers to a firm's responsibilities towards its workers and broader societal stakeholders [6]. RL activities contribute towards social performance by promoting safe working conditions for workers, providing them with requisite training in remanufacturing processes, and generating employment opportunities through returns management programs [11]. According to [1], a company's RL practices like product returns and recycling initiatives can significantly enhance customer satisfaction and stakeholders' trust. Complementing this view, [4] argued that RL improves social performance by supporting health and safety standards, ethical labor practices, and ensuring overall welfare of all stakeholders. [5] argue that reverse logistics adoption enhances the social performance by creating jobs and encouraging entrepreneurial activities in collection and recovery work. Further, it also improves firms' social responsibility profile and helps in maintaining public trust.

H$_3$: *Technology-integrated closed-loop supply chain adoption has a significant positive impact on supply chain social performance in the commercial aviation sector.*

2.7 Research Gap

Despite the increasing interest among researchers regarding closed-loop supply chains and reverse flow of end-of-life products, research work in aviation sector remains limited especially in the emerging economies context. Most of the prior research studies focus on manufacturing sector, construction sector, and packaging-intensive industries, however, the industries such as aviation where the recovery decision are affected but strict safety and certification protocols remain underexplored [9], [10], [11], [12]. The role of technologicalization is often discussed in literature in a broader perspective without actually examining the impact of these technologies on financial, environmental, and social performance outcomes in the supply chain [28,29]. Furthermore, there remains a notable methodological gap in existing literature wherein there is absence of empirical studies employing advanced statistical methods like PLS-SEM to assess closed-loop supply chain practices in aviation industry. Thus, there is limited available empirical evidence of how tech-integrated closed-loop supply chains work in aviation sector recovery systems and how these impacts can be translated into actionable implications for naval aviation-arm.

2.8 Conceptual Framework

Based on the reviewed literature and proposed hypothesis, Figure 1 illustrates the conceptual framework of the study. Independent Variable i.e. Technology-integrated closed-loop supply chain adoption (TCLSC) is expected to have positive effects on Dependent Variables i.e. supply chain financial performance (SCFP), supply chain social performance (SCSP), and supply chain environmental performance (SCEP).

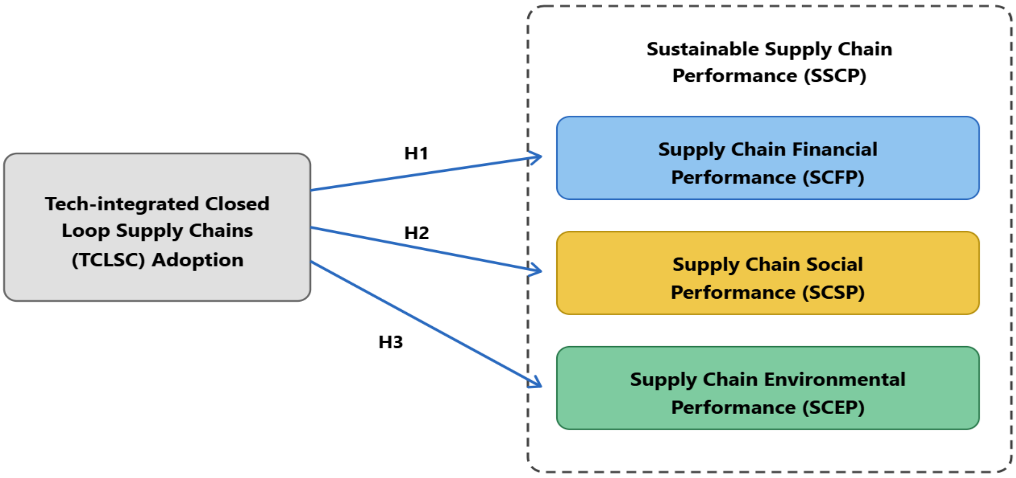

Figure 1. Conceptual framework

3. METHODOLOGY

3.1 Research Design

The research design of this study is grounded in positivist paradigm and requisite data for examining the relationship between constructs of conceptual model is collected through survey questionnaire which is widely regarded as appropriate tool for collecting organizational level perceptions and practices data [15]. In order to analyze the hypothesized relationships, this study employs Partial Least Square – Structural Equation Modeling (PLS-SEM) using latest SmartPLS4.0 software. PLS-SEM is a variance-based structural modeling technique which has the ability to simultaneously estimate both measurement and structural models. It is particularly suitable for present study for three main reasons:

- This study aims at explaining variance in the three TBL dimensions of performance rather than confirming an already established theory.
- As the sample size of this study is relatively small (n = 163), PLS-SEM is preferred choice as compared to Covariance-based SEM (CB-SEM)
- PLS-SEM does not require multivariate normality of collected data. This is particularly important as survey-based organizational data often violates normality.

Further analysis was conducted in a two-stage process. First, the measurement model was assessed for reliability and validity. In the second stage, the structural model was analyzed using path coefficients, significance testing (bootstrapping), and predictive relevance measures.

3.2 Population and Sampling

The target population of this study comprises commercial aviation and Maintenance, Repair, and Overhaul (MRO) firms operating in Türkiye. These firms offer a suitable setting for analysis due to their well-documented and structured maintenance systems, regulatory pressures, and integration of state-of-the-art digital technologies in inventory management. Data was collected using purposive non-probability sampling technique. While this sampling technique limits the generalizability of results, it enhances the validity of responses by focusing on key knowledgeable informants rather than randomly selecting participants who possess limited domain expertise [16]. Data were collected from the employees working at managerial and senior managerial positions such as Supply Chain Managers, Finance Managers, Production Managers, Sustainability Managers, and Operations Managers. These respondents were selected because they are directly involved in day-to-day reverse logistics processes and have the necessary knowledge to evaluate operational and performance outcomes [17]. For the purpose of calculating the sample size, multiple established criteria for PLS-SEM were evaluated. First, 10-time rule given by [31] recommends that the minimum sample size for PLS-SEM should be the greater of either ten times the largest number of formative indicators used to measure a single construct or ten times the maximum number of structural paths directed toward any latent construct in the model. Once applied to present study's model, 10-times rules yielded a minimum sample size of 10 observations. However, keeping in view the criticism and limitations of this rule, a more rigorous statistical power analysis using G*Power was also considered assuming significance level of 0.05, statistical power of 0.80, and medium effect size (i.e. $f^2 = 0.5$). Resultantly, minimum sample size for this study's model came out to be 55. In total a total of 187 questionnaires were distributed through personal visits and using online resources during October to December 2025, out of which 171 were returned and 163 were considered complete and suitable for further statistical analysis. The figure of 163 is more than three times of the minimum sample size calculated for this study which is considered ample to detect significant relationships.

3.3 Construct Measurement

The questionnaire (Appendix) used in present study was developed subsequent to a thorough review of prior literature. To ensure validity, measurement items for each construct of the model were adopted from highly cited and widely used scales. These adopted items were then adapted to the needs and scope of current study with minor contextual changes. The comprehensive questionnaire was first prepared in English and later translated into Turkish language by obtaining services of a certified translator. Afterwards, the questionnaire was reviewed by a panel of academicians and industry professionals to ensure content validity. All items in questionnaire were measured on a seven-point Likert scale ranging from "Strongly Disagree" to "Strongly Agree" and prior to full-scale deployment, pilot-testing was undertaken to establish clarity and contextual appropriateness of its contents.

Technology-Integrated Closed-Loop Supply Chains Adoption variable was measured using a five-items scale adapted from [23,34,35]. This construct captures not only the adoption of closed-loop supply chain practices but also the extent to which these practices are enabled and supported by digital and technological capabilities in commercial aviation industry. On the other hand, dependent variable Supply Chain Financial Performance was measured on a 5-item scale adapted from [36,37,38], Supply Chain Social Performance using 5-items scale adapted from [38,39], and Supply Chain Environmental Performance using 5-items scale adapted from [38,40,41]. This study relies on the perceptual measures for collection of data related to endogenous constructs due to limited availability of objective data on supply chain performance, especially the supply chain economic performance. This is because the impact of reverse flow practices is often indirect and many other organizational activities are happening simultaneously which makes it difficult to isolate the individual activities' effects [42,43].

3.4 Data Collection and Analysis

The data from the target respondents for this study was collected using a combination of online surveys and in-person visits. In order to address the ethical concerns, participation in the study was kept voluntary while also obtaining informed consent from respondents. Moreover, surety regarding the anonymity and confidentiality of identity and responses was also given to all participants in order to curb social desirability bias and to encourage honest answers. The statistical analysis of collected data was performed using SmartPLS4.0 by following a two-stage approach. In the first stage, the assessment of measurement model was carried out in order to evaluate the reliability and validity. The reliability of indicators was examined through outer loadings whereas internal consistency was assessed using Cronbach's alpha and composite reliability values. Subsequently, convergent validity was analyzed using average value extracted (AVE), and discriminant validity was assessed using Heterotrait-Monotrait (HTMT) ratio. In the second stage, the structural model was assessed to test the hypothesized relationships between the constructs of the study. The values of path coefficients, t-values, and corresponding significance levels were examined along with R^2 values in order to assess explanatory power as well as effect sizes (f^2) to evaluate the relative impact of exogenous constructs.

Keeping in view the single-source survey design of this study, certain procedural and statistical remedies were employed in light of instructions put forward by [44,45]. Procedurally, respondents were ensured about anonymity as well as questionnaire was carefully designed to reduce the response bias. On the other hand, full collinearity variance inflation factor (VIF) values were examined wherein all values were found to be below the recommended threshold of 3.3, which indicated that CMB was unlikely. Moreover, although Herman's single-factor test was conducted initially but it was not relied upon as a primary indicator due to its well-known limitations. Similarly, non-response bias was also assessed by comparing early and late respondents and no significant differences were found suggesting that non-response bias is unlikely to affects the results of this study.

4. DATA ANALYSIS

4.1 Demographic Analysis

Out of total 163 respondents, 48 respondents (29%) were between age 21-30, 57 (35%) between 31-40, and remaining 58 (36%) were above 41 years of age. In terms of professional experience, 13 respondents stated that they have less than 5 years of experience, 78 had between six and 15 years of experience, and remaining 72 had more than 15 years of experience working in the aviation industry. Moreover, 89 respondents (55%) belonged to MRO firms and 74 (45%) to commercial airlines. These demographics highlight a balanced representation of respondents from different age groups and professional experience.

4.2 Factor Loading and Reliability Analysis

The measurement model of this study was analyzed through Factor Loading, Internal Consistency and Convergent Validity. The results (Table-2) show appropriate outer loading values for all the indicators (> 0.70) indicating strong Indicator Reliability. Similarly, all values for Cronbach's alpha, composite reliability (CR), and convergent reliability were also found to be above the minimum recommended levels [46].

Subsequent to the validation of measurement model, the evaluation of structural model was conducted through collinearity diagnostics, explanatory power (R^2), effect size (f^2), predictive relevance (Q^2), and hypothesis testing. The results of collinearity assessment (VIF) (Table 3) reveal that all VIF values are well below the conservative threshold of 3.3 [32], which indicates that there is no threat of multicollinearity and minimal risk of common method bias (CMB) exists.

In order to assess the model's explanatory power, the coefficient of determination (R^2) was used. The results of analysis (Table 4) show that TCLSC explains only a limited proportion of total variance in the three TBL dimensions of supply chain performance. While these values of R^2 appear to be modest, they actually reflect the multi-determined nature of organizational performance which is impacted by a wide range of operational, technical, technological, and institutional factors which are beyond the scope of this study's model. This implies that TCLSC adoption should be interpreted as a contributing factor rather than sole driver of performance outcomes.

Table 2: Factor Loading and Reliability Analysis

Variable	Item	Ldg	α	CR	AVE
Technology Enabled Closed Loop Supply Chains (TCLSC)	TCLSC1	.868	.918	.938	.753
	TCLSC2	.891			
	TCLSC3	.886			
	TCLSC4	.868			
	TCLSC5	.825			
Supply Chain Financial Performance (SCFP)	SCFP1	.842	.902	.927	.719
	SCFP2	.815			
	SCFP3	.821			
	SCFP4	.872			
	SCFP5	.889			
Supply Chain Social Performance (SCSP)	SCSP1	.862	.898	.925	.711
	SCSP2	.905			
	SCSP3	.799			

	SCSP4	.861			
	SCSP5	.784			
Supply Chain Environmental Performance (SCEP)	SCEP1	.910	.938	.953	.801
	SCEP2	.910			
	SCEP3	.904			
	SCEP4	.920			
	SCEP5	.830			

The effect size was also assessed to determine the impact of TCLSC on each of the dependent variables in the model. The results (Table 5) indicate that TCLSC has the strongest impact on financial performance (f^2 = 0.168), whereas its impact on social(f^2 = 0.102) and environmental performance (f^2 = 0.112), although statistically significant, remains comparatively weaker.

Table 3: Collinearity Assessment

Path	VIF
TCLSC → SCFP	1.842
TCLSC → SCSP	1.765
TCLSC → SCEP	1.913

Table 4: Coefficient of determination (R^2)

Construct	R^2
SCFP	0.132
SCSP	0.089
SCEP	0.091

Table 5: Effect size (f^2)

Path	f^2	Size
TCLSC → SCFP	0.168	Medium
TCLSC → SCSP	0.102	Small
TCLSC → SCEP	0.112	Small

Stone–Geisser Q^2 statistic obtained via blindfolding was used to evaluate predictive relevance of the model. This is particularly important when values of R^2 are relatively small. The results (Table 6) show that all values of Q^2 are greater than zero, which confirms that this study's model possesses predictive relevance. Moreover, despite relatively low R^2 values, the results confirm that model maintains adequate out-of-sample predictive capability. This implies that TCLSC construct contributes meaningfully to the predicting TBL performance outcomes even if it fails to fully explain them.

Table 6: Stone–Geisser Q^2 statistics

Construct	Q^2
SCFP	0.247
SCSP	0.186
SCEP	0.205

Heterotrait-Monotrait ratio of correlations (HTMT) test was used to analyze discriminant validity among the constructs. Results (Table-3) show that all HTMT values remained below the recommended level of 0.85 which indicates an acceptable level of discriminant validity.

Table 7: Correlation and discriminant validity

Variables	SCEP	SCFP	SCSP	TCLSC
SCEP	1			
SCFP	0.460	1		
SCSP	0.530	0.502	1	
TCLSC	0.321	0.393	0.325	1

4.3 Hypotheses Testing

The results of hypothesis testing (Table-4) show that adoption of technology-integrated closed-loop supply chain practices (TCLSC) has a positive and statistically significant impact on all three dimensions of supply chain sustainability performance. Specifically, TCLSC shows a significant positive impact on supply chain financial performance ($\beta = 0.363$, $t = 10.825$, $p < 0.001$), with 95% bias-corrected and accelerated (BCa) confidence interval (obtained using 5,000 resamples) with ranges 0.299 and 0.423. Similarly, the effect of TCLSC on supply chain social performance is also positive and significant ($\beta = 0.299$, $t = 8.455$, $p < 0.001$), with BCa confidence interval ranges 0.232 and 0.368 excluding zero, thereby supporting H_2. On the other hand, TCLSC adoption also shows significant positive impact on supply chain environmental performance ($\beta = 0.301$, $t = 8.042$, $p < 0.001$), with a 95% BCa confidence interval of 0.234 to 0.372, thus supporting H_3. The absence of zero from all confidence intervals is clear indication of the robustness of the estimated relationships. Comparing the results of all three hypothesis tests, it is evident that TCLSC has the strongest impact on the financial performance, followed by environmental performance and social performance. This indicates that economic benefits of TCLSC-adoption may be more readily realized as compared to other two dimensions.

Table 8: Hypothesis testing results

Hyp	Path	β	t-Value	p-Value	Result
H_1	TCLSC → SCFP	.363	10.825	.000	Supported
H_2	TCLSC → SCSP	.299	8.455	.000	Supported
H_3	TCLSC → SCEP	.301	8.042	.000	Supported

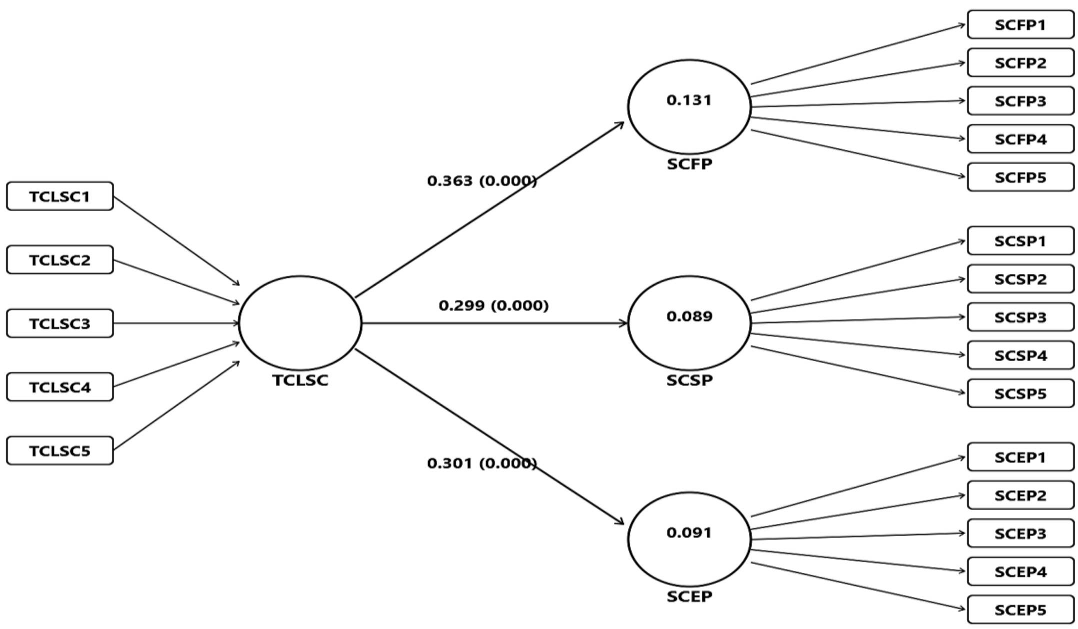

Figure 2. Structural model with results

5. DISCUSSION AND IMPLICATIONS

The findings of this study show a strong association in between Technology-integrated Closed-loop Supply Chains and the three dimensions of Sustainable Supply Chain Performance (SSCP) in commercial aviation and MRO industry in Türkiye. This implies that when firms adopt digital tracking and automated decision-support technologies to complement their existing backward flows of mechanical spare part, they achieve financial, social, and environmental benefits. The strong impact of IV of this study on Supply Chain Financial Performance indicates that when firms adopt technology-enabled reverse logistics they gain financial benefits by reusing recovered parts, reducing unnecessary procurement, and by future maintenance activities more effectively. The MRO firms, which already operate under tight margins, are able to reduce costs and improve overall efficiency by adopting these reverse logistics practices. Similarly, strong positive association between DV and Supply Chain Environmental Performance show that tech-based reverse logistics system reduce wastes, ensure proper disposal and better overall process control. This implies that the by adopting tech-enabled revers flows, the end-of-life mechanical parts which used to end up in landfills are now reintegrated into the forward supply chains for reuse or for value recovery purposes such as refurbishment. The results of social performance indicate overall improvements in the working environment of employees and the process reliability. The adoption of tech-enabled reverse flows support safer working conditions and enhance compliance with the enforced aviation standards and protocols. Overall, these findings significantly extend the prior closed-loop supply chain literature by quantitatively confirming that adoption of digital technologies in closed-loop supply chains not only enhance the operational efficiency but also impacts the multidimensional sustainability performance of companies. Furthermore, unlike the traditional closed-loop supply chain systems, technology-enabled systems facilitate proactive decision-making, improved asset visibility, as well as efficient resource utilization.

Overall, the results of this study provide a statistically significant, consistent but moderate explanatory model. Although TCLSC adoption significantly impacts all three dimensions of supply chain performance but low values of R^2 suggest that Supply Chain Performance is a multi-determined construct and is affected by some additional factors which are not captured in our model such as regulatory pressures, organizational capabilities, and market dynamics. However, the combination of results like significant path coefficients, acceptable effect sizes, and positive values of Q^2 suggest that our model is predictively relevant despite its limited explanatory powers.

5.1 Implications for Naval Aviation Supply Chains

The naval aviation supply chains as compared to commercial aviation companies operate under much stricter regulations and procedural adherence protocols. Naval aviation platforms are fitted with various kinds of state-of-the-art weapons and sensors alongside regular aviation spare parts and assemblies; these platforms are required to be kept operational over several decades. In this context, findings of this study suggest that adoption of technology-integrated reverse logistics practices may serve as a stabilizing mechanism for naval aviation platforms rather than a mere sustainability tool. The financial performance outcomes in naval aviation reverse supply chains are likely to be achieved through better visibility and control over high value used mechanical spare parts. Technology integrated closed loop systems of supply chains allow the naval aviation-arm and their sustainment partners to effectively recover, inspect, and reuse the end-of-life spare parts more systematically which reduces dependence on external supply chain networks which are considered more disruption-prone. This enables navies to better manage the life-cycle costs of their strategic aviation assets. On the other hand, the environmental performance gains are also relevant to naval aviation setups wherein the ensure sustainability is not the primary goal. Digitally enabled reverse supply chains reduce the material waste and unnecessary scraping of reusable spare parts. Thes social performance implications are closely related to safety of men and material and the procedural discipline. Since there is a lot of focus on workplace safety practices, technology integrated reverse channels standardize the handling, inspection and documentation functions related to returned spare parts which reduce human errors. This ultimately enhances the workplace safety culture and clearer accountability for technical workforce.

5.2 Managerial and Policy Implications

The results of this study imply that the managers and decision-makers should strive to comprehensively digitalize their operational reverse supply channels to gain multi-faceted advantages. Similarly, for policy and decision makers the findings advocate the integration of digital technologies enhances sustainability and the competitiveness in the aviation sector. Furthermore, these technologies also function as a strategic practical performance tool rather than a symbolic sustainability tool. Investments in RFID-enabled parts and component tracking, AI-assisted inspection, and integrated information systems for reverse logistics can yield significant results across all three dimensions of sustainability performance. Policy makers should prioritize offering incentives for technology-integration, especially for MRO firms which play a critical role on circular economy of the aviation industry.

5.2 Limitations and Future Research

Apart from significant contributions, this study has several notable limitations. First of all, the use of purposive non-probability sampling technique may limit the generalizability of findings as the selected sample may not be able to fully represent the complete population of firms operating in Turkish commercial aviation sector. Secondly, this study relies on self-reported perceptual measures in data collection which introduces common method and subjective biases and may inflate the relationships despite application of several procedural and statistical controls. Thirdly, implications identified regarding naval aviation setups are purely inferential and are required to be interpreted cautiously due to the absence of direct empirical data from naval aviation context. Finally, the cross-sectional design of this study limits the ability to infer the causal relationships between the constructs of this study over time. Future studies could improve on these limitations by analyzing the objective performance measures wherever possible. Moreover, by drawing cross-country comparisons between different contrasting sectors or countries, future studies can significantly enhance the existing body of literature. In order to increase the explanatory power of the model, future studies can also consider adding relevant mediator or moderating variables or explanatory variables in the model. This will also provide a more nuanced understanding of how and under what conditions TCLSC adoption contributes to overall sustainability outcomes.

6. CONCLUSION

This study analyzed the impact of technology-enabled closed-loop supply chain (TCLSC) adoption on supply chain financial, social, and environmental performance in Turkish commercial aviation sector including MRO firms. The overall findings confirm that TCLSC adoption has a positive significant impact on all three TBL dimensions of supply chain performance. However, it is pertinent to highlight that despite its statistical significance, the model possesses limited explanatory powers as evident from the low R^2 values across all endogenous constructs of the model. This implies that although TCLSC adoption does contribute meaningfully to enhance performance outcomes in supply chains, however, it only explains a small portion of total variance. This is possibly due to the fact that supply chain performance is often a multi-dimensional construct which is influenced by a broader set of organizational, technological, and institutional factors. The outcomes of this study also highlight that supply chain performance outcomes cannot be associated with a single organizational practice and rather emerge from the interaction of various distinct capabilities. From a practical perspective, the managers should avoid viewing the TCLSC adoption as a sole comprehensive solution for enhancing the supply chain performance.

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AUTHOR CONTRIBUTIONS

Muhammad Ahsan JAVED: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration.

CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript.

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APPENDIX A

Survey Questionnaire

Construct	Items

Technology Enabled Closed Loop Supply Chains Adoption (TCLSC)	Our firm uses digital systems to track and manage the return flow of aircraft components and materials across the supply chain
	Our firm utilizes advanced inspection and diagnostic technologies to assess returned components for reuse, repair, or remanufacturing
	Our firm employs integrated information systems to support disassembly, recovery, and reintegration of components in MRO operations
	Our firm leverages technology to coordinate with suppliers and partners for efficient return, recovery, and reuse of products and materials
	Our firm uses data-driven and standardized technological processes to facilitate lifecycle extension and closed-loop utilization of components
Supply Chain Financial Performance (SCFP)	Our firm's profits have improved
	Our firm's sales have grown
	Our firm's return on investment has increased
	Our firm's return on equity has grown
	Our firm's return on assets has increased
Supply Chain Social Performance (SCSP)	Our firm's operations have positively impacted the well-being of the surrounding community
	Our firm has enhanced occupational health and safety for employees in aviation/MRO activities
	Employees perceive higher job satisfaction due to the firm's operational practices
	Our firm has strengthened relationships with local communities and key stakeholders
	The firm actively promotes employee skills development related to supply chain and operational activities
Supply Chain Environmental Performance (SCEP)	Our firm has reduced emissions, wastewater, and solid waste from maintenance and operational activities
	Our firm has minimized the use of hazardous or toxic materials in MRO operations
	The frequency of environmental incidents has decreased in our operations
	Our firm has improved compliance with environmental and aviation-related regulations
	Our firm has reduced the environmental footprint of its supply chain and operational activities