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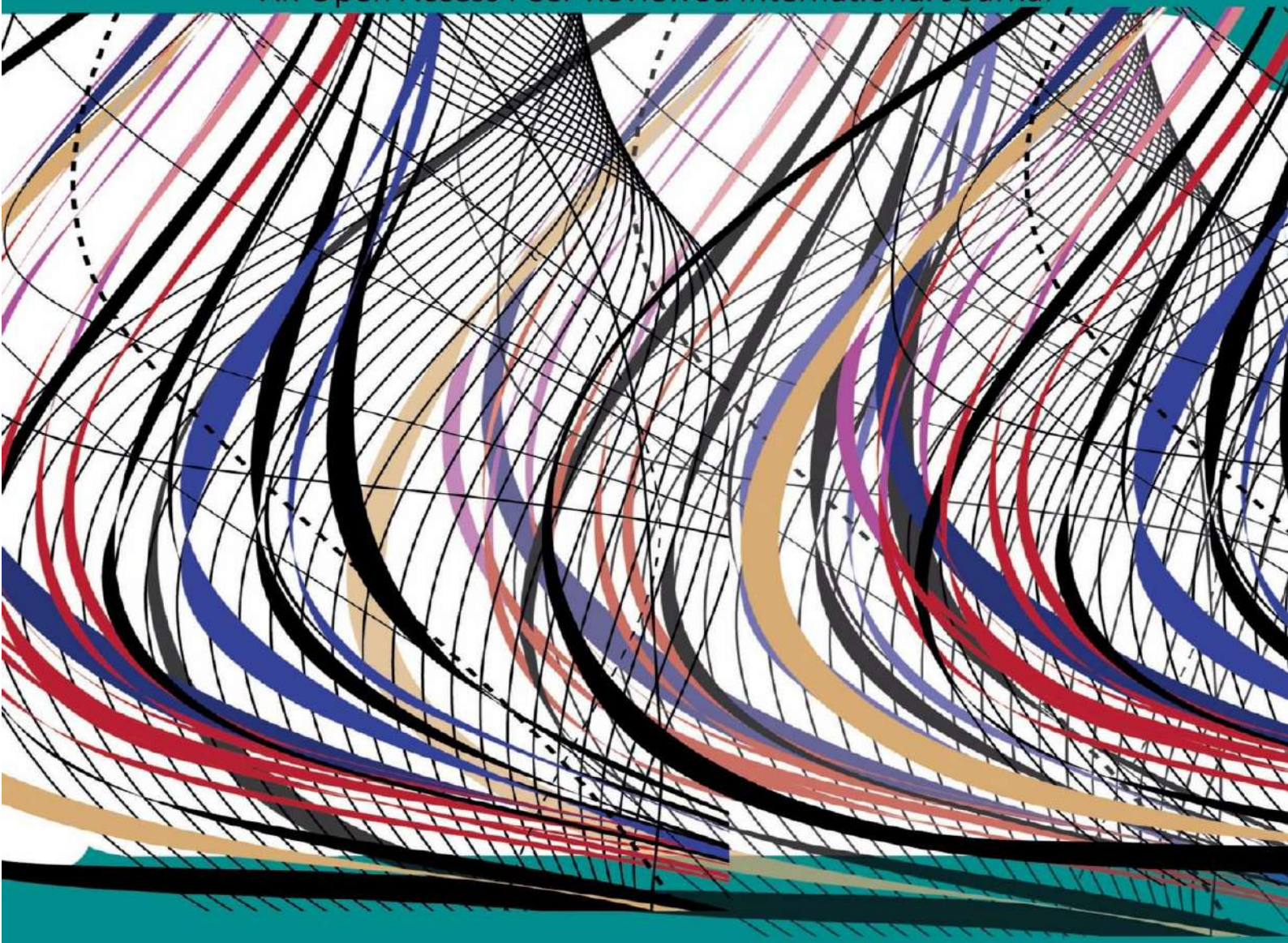

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Estimating the Impact of R&D Intensity on Manufacturing Firm Performance: An Instrumental Variable (TSLS) Analysis

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Abstract *— This study investigates the causal impact of R&D intensity (RDI) on Chinese manufacturing firms' performance (ROA) using a panel instrumental variable approach. By leveraging enterprise life cycle stages (ELC) and industry competition intensity (DIC) as exogenous instruments, two-stage least squares (TSLS) estimates reveal a significant positive effect of RDI on ROA (0.41, $p < 0.01$), contrasting with biased OLS results (-0.001). Growth-stage firms and moderate industry competition amplify RDI's benefits, while debt ratios negatively affect performance. Robustness checks confirm instrument validity (Cragg-Donald F = 48.51 > 19.93) and panel data superiority. Policy implications advocate targeted R&D subsidies for growth-phase firms and innovation alliances in competitive sectors. This work resolves the "R&D paradox" by contextualizing innovation impacts, offering actionable insights for industrial upgrading.*

Keywords *— IV, R&D, Firm Life Cycle, Manufacturing.*

I. INTRODUCTION

Under the backdrop of global value chain restructuring and intensifying technological competition, China's manufacturing sector faces dual challenges of "low-end lock-in" and innovation-driven transformation. Research and development (R&D) investment is regarded as a core strategy to break through technological barriers. However, existing studies remain contentious regarding the relationship between R&D intensity (RDI) and firm performance (proxied by ROA):

(1) Positive View: Schumpeter's innovation theory, Romer's endogenous growth theory, and the resource-based theory collectively provide theoretical underpinnings for the positive relationship between R&D intensity and firm performance, highlighting how R&D drives performance growth through technological advancement, resource accumulation, and knowledge spillovers.

(2) Negative perspective or non-significant relationship: This essentially arises from the inherent high-risk nature, resource competition effects, and environmental contingencies embedded in R&D activities. Theoretically, excessive investment, industry-institution misalignment, or institutional voids may counteract the positive effects of R&D.

This contradiction may stem from endogeneity issues (e.g., reverse causality, omitted variable bias), which render traditional OLS estimates inconsistent. To address this, this study employs a panel instrumental variable (IV) approach, utilizing firm life cycle and industry competition intensity as instrumental variables. This methodology aims to more accurately identify the causal effect of RDI on ROA, overcoming limitations of conventional single-

instrument strategies and enhancing the exogeneity of instrumental variables.

II. LITERATURE REVIEW

2.1 The Relationship Between R&D Intensity and Firm Performance

Positive Relationship: Takehiko Yasuda (2005), through an analysis of Japanese SMEs, found that R&D intensity exerts a significantly positive effect on firm growth. Martin Falk (2012) demonstrated consistent conclusions in a study of 3,700 Australian enterprises. Petr Hanel (2011) further concluded, via an examination of Canadian industrial firms, that R&D investment intensity positively influences new product development performance.

Negative Relationship: Guo Bin (2006) , utilizing 52 valid samples from Chinese software firms in 2002 and 88 valid samples from Hangzhou-based software enterprises, revealed that R&D intensity exhibits a pronounced negative impact on corporate profit margins, with additional adverse effects on output rates. Similarly, Wang Jinzhou (2011) found that excessive R&D investment intensity may negatively affect new product development performance.

Nonlinear Controversy: Chen et al. (2014) identified an inverted U-shaped relationship between R&D intensity (RDI) and return on assets (ROA), where post-threshold effects transition to negative due to capital crowding-out effects. Ming-Liang Yeh et al. (2010) [37], in their study of Taiwanese ICT and electronics firms, observed a single-threshold effect in the R&D intensity-performance nexus, demonstrating a nonlinear inverted U-shaped pattern.

Endogeneity Challenge: Balsmeier et al. (2017) demonstrated that omitting variables such as government subsidies results in RDI coefficients being underestimated by 30%, highlighting critical biases in conventional estimation methods.

2.2 Application of Instrumental Variables

Bloom et al. (2013) employed tax credit policy changes as instrumental variables (IV) for R&D intensity (RDI), effectively addressing endogeneity arising from policy feedback loops.

Innovative Contribution of This Study: This paper pioneers the joint use of firm life cycle stages (exogenously classified based on cash flow patterns) and industry competition intensity (proxied by the Herfindahl-Hirschman Index, HHI) as instrumental variables. This dual-IV strategy mitigates potential endogeneity inherent in single-instrument approaches, particularly avoiding spurious correlations caused by unobserved heterogeneity in innovation ecosystems.

III. THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

3.1 Moderating Role of Firm Life Cycle

Growth Stage: High sales growth rates and capital expenditure ratios drive the rapid commercialization of R&D outcomes, resulting in the strongest marginal effect of RDI on ROA.

Decline Stage: Market contraction and rising agency costs undermine the efficiency of R&D conversion, rendering the impact of RDI statistically insignificant.

3.2 Threshold Effect of Industry Competition

Moderate Competition (mid-range Herfindahl-Hirschman Index, HHI): Competitive pressure incentivizes innovation efficiency, amplifying the positive RDI-ROA linkage.

Monopoly or Excessive Competition: Monopoly markets suppress innovation incentives, while hyper-competition induces resource fragmentation, both weakening R&D performance.

3.3 Exclusion Restriction

Firm Life Cycle Stages (ELC): Exogenously classified using the composite index from Anthony and Ramesh (1992), ensuring no direct causal pathways to ROA.

Industry Competition Intensity (DIC): Captures market structure dynamics independent of individual firm decisions.

This study employs ELC and DIC as instrumental variables (IVs) to isolate the causal impact of RDI on ROA, addressing endogeneity through dual-IV robustness.

H1a: β rdi>0

IV. RESEARCH DESIGN

4.1 Research Data

This study examines the impact of R&D innovation on firm performance in China's manufacturing sector. We analyze data from 2,479 Chinese manufacturing listed companies spanning the period 2017–2021, yielding 11,061 firm-year observations, constituting an unbalanced panel dataset. The data were sourced from the Wind Database, a comprehensive financial and economic database widely used in China. The annual distribution of the sample is detailed in Table 1.

Table 1. Annual Distribution of Sample Observations

year	2017	2018	2019	2020	2021	Total
Obs.	2090	2240	2331	2216	2184	11061

As shown in Table 1, the number of manufacturing listed companies in China exhibits a steady annual increase. However, during the 2020–2021 period, supply chain disruptions and demand contraction led some firms to report negative net profits. Due to the application of natural logarithm transformations to variables such as net profits (which require strictly positive values), these firms were excluded from the sample, resulting in a temporary reduction in the number of observations during these years.

4.2 Research Method

This study employs a Panel Two-Stage Least Squares (2SLS) methodology, structured in two components:

Panel Data Analysis: Utilizing fixed effects or random effects models to control for unobserved heterogeneity across firms and time.

Instrumental Variables (IV) Application: Addressing endogeneity in R&D intensity (RDI) by implementing firm life cycle stages and industry competition intensity as instruments, with robustness checks via overidentification tests (e.g., Hansen J-statistic).

Panel data, by definition, integrate both cross-sectional and time-series dimensions, inherently expanding the sample size, increasing the degrees of freedom for statistical tests, and enhancing the efficiency of estimation results. Although panel data contain time-series components, they do not suffer from the unit root problem commonly encountered in pure time-series analyses. However, not all panel datasets are suitable for panel data analysis. This study employs pooled ordinary least squares (POLS) diagnostics to assess data compatibility. Furthermore, since panel data models may exhibit either fixed effects or random effects, the Hausman test is applied to determine the appropriate specification.

Conventional econometric analyses often overlook endogeneity issues. While panel data methods (e.g., fixed effects models) can mitigate certain forms of endogeneity (e.g., time-invariant unobserved heterogeneity), the instrumental variable (IV) approach, particularly the two-stage least squares (2SLS) method, is widely advocated for addressing endogenous regressors. The 2SLS procedure involves two stages:

First Stage: The endogenous variable (e.g., R&D intensity) is regressed on exogenous instruments (e.g., firm life cycle, industry competition) to purge endogeneity.

Second Stage: The predicted values from the first stage are substituted into the primary regression model to obtain consistent estimates of causal effects.

4.3 Research Variables

This study employs four categories of variables: the core explanatory variable R&D intensity (RDI), the dependent variable (ROA), instrumental variables, and control variables. Their definitions and operationalization are as follows:

(1) R&D Intensity (RDI)

R&D intensity is conventionally measured as the R&D expense ratio, calculated as:

$$RDI_{it} = \frac{RD_{it}}{S_{ti}} \times 100 \quad (1)$$

RDI_{it}: R & D Intensity of Firm i in Period t

RD_{it}: R & D Expenditure of Firm i in Period t

S_{it}: Operating Revenue of Firm i in Period t

However, in econometric analyses, applying natural logarithm transformations to variables enhances interpretational validity for two key reasons:

Normality Approximation: Logarithmic transformation reduces skewness and brings the variable's distribution closer to normality, mitigating heteroscedasticity concerns.

Elasticity Interpretation: Coefficients derived from log-transformed variables can be directly interpreted as elasticity coefficients (percentage change in the dependent variable per 1% change in the independent variable).

$$RDI_{it} = \ln\left(\frac{RD_{it}+1}{S_{ti}} \times 100\right) \quad (2)$$

(2) ROA

Corporate performance is generally categorized into market performance and financial performance. Market performance is typically measured using market value indicators such as stock prices. However, due to the extreme volatility and speculative fluctuations in China's stock markets, stock prices often fail to reliably reflect true market performance. Consequently, this study adopts financial performance as the primary evaluation framework. Among the widely used financial performance metrics—Return on Assets (ROA) and Return on Equity (ROE)—ROA is selected as the core indicator because it provides a more comprehensive reflection of operational efficiency and resource utilization across the firm's entire asset base, independent of capital structure distortions.

Table 2. Characteristics of Enterprise Life Cycle Stages

Indicator	Sales Growth Rate	Capital Expenditure Ratio	Dividend Payout Ratio	Company Age
Growth Stage	High	High	Low	Young
Maturity Stage	Medium	Medium	Medium	Mature
Decline Stage	Low	Low	High	Old

The calculation of ROA is defined as:

$$RDA = \frac{EBIT(Earnings\ Before\ Interest\ and\ Taxes)}{Average\ Total\ Assets} \times 100 \quad (3)$$

To enhance interpretability and mitigate skewness, this study applies a natural logarithm transformation to the ROA metric, adjusted as follows:

$$RDA = in\left(\frac{EBIT(Earnings\ Before\ Interest\ and\ Taxes)}{Average\ Total\ Assets} \times 100\right) \quad (4)$$

(3) Instrumental Variables

The use of instrumental variables should ideally rely on exogenous variables. In this study, two instrumental variables are employed: Enterprise Life Cycle (ELC) and Degree of Industry Competition (DIC).

For the Enterprise Life Cycle (ELC), this paper adopts the composite lifecycle indicator proposed by Anthony and Ramesh (1992) to determine a company's lifecycle stage. Specifically, each sample is assigned a score across four individual indicators: 0 for the growth stage, 1 for the maturity stage, and 2 for the decline stage (see Table 2). The scores from these four indicators are summed to derive a composite index. While the general lifecycle framework includes the introductory stage, growth stage, maturity stage, and decline stage, listed companies in the introductory stage are rare. Therefore, this study categorizes the enterprise lifecycle into three stages:

Growth stage: Composite index values 0–2,

Maturity stage: Composite index values 3–5,

Decline stage: Composite index values 6–8.

The other instrumental variable is the Degree of Industry Competition (DIC). In this study, the Herfindahl-Hirschman Index (HHI) is employed as a proxy measure for industry competition.

$$DIC = \sum(\text{Industry - wide Revenue Share of Listed Companies})^2$$

(4) Control Variables

This study employs four control variables: Noncurrent Asset Growth Rate (NCAI), Firm Size, Equity Ratio, and Capital Intensity.

Noncurrent Asset Growth Rate (NCAI)

A higher growth rate of noncurrent assets reflects greater future investment and growth opportunities for a firm (Agrawal & Knoeber, 1996; Titman & Wessels, 1988; Wei et al., 2017). Therefore,

noncurrent asset growth serves as a key indicator of corporate operational performance.

$$NCAI_{it} = \ln\left(\frac{NCA_{it}}{NCA_{it-1}}\right) \quad (5)$$

NCA_{it}:Noncurrent Asset of Firm i in Period t

H_{1b}: NCAI>0

Debt-to-Equity Ratio (DER):

According to the corporate tax shield effects and the Pecking Order Theory, a higher debt ratio is associated with lower profitability and reduced firm value (Myers, 1977; Stulz, 1990). However, this study employs the natural logarithm of the debt-to-equity ratio (DER) as a substitute for the debt ratio to refine the measurement.

$$DER_{it} = \ln\left(\frac{\text{Total Debt}_{it}}{\text{Total Equity}_{it}}\right) \quad (6)$$

H_{1c}: DER≠0

Economies of scale generally exist in firms, whereby larger firm size is associated with improved corporate performance. Firm size is typically measured by total assets, total revenue, or number of employees. In this study, the natural logarithm of total assets (ln(Total Assets)) is adopted as the proxy for firm size.

$$SC_{it} = \ln(Asset_{it}) \quad (7)$$

H_{1d}: SC>0

Based on the explanations above, the definitions of research variables and hypotheses are summarized in Table 3 below.

4.4 Descriptive Statistic

Based on the descriptions provided above, this study encompasses seven variables. The descriptive statistics of these variables are summarized in Table 4.

From Table 4, it can be observed that the maximum and minimum values of the variables in this study do not exhibit extreme outliers. However, the minimum value of R&D Intensity (RDI) is -15.84, indicating that some listed companies have no R&D investment.

Regarding the distribution characteristics:

Left-skewed distributions are observed for:

RDI (skewness = -0.44); ROA (skewness = -0.96); NCAI (skewness = -0.22)

Right-skewed distributions are observed for:

DER(skewness=0.17);SC(skewness=0.62); DIC (skewness = 0.03); ELC (skewness = 0.25)

For kurtosis:

Leptokurtic (high-peaked) distributions:

ROA (kurtosis =6.30); NCAI (kurtosis=71.49); DER (kurtosis = 4.53); SC (kurtosis = 3.57)

Platykurtic (low-peaked) distributions:

RDI (kurtosis = 1.39); DIC (kurtosis= 2.44); ELC (kurtosis = 1.97)

Table 3. Variable Definitions and Hypotheses

Variable Name	Symbol	Definition	Hypothesis
Return on Assets	ROA	$ROA = \ln\left(\frac{EBIT}{\text{Average Total Assets}} \times 100\right)$	–
R&D Intensity	RDI	$RDI_{it} = \ln\left(\frac{RD_{it}+1}{S_{ti}} \times 100\right)$	H_{1a}: βdri>0
Noncurrent Asset Growth Rate	NCAI	$NCAI_{it} = \ln\left(\frac{NCA_{it}}{NCA_{it-1}}\right)$	H_{1b}: βncai>0
Firm Size	SC	$SC_{it} = \ln(Asset_{it})$	H_{1d}: βsc>0
Debt-to-Equity Ratio	DER	$ER_{it} = \ln\left(\frac{\text{Total Debt}_{it}}{\text{Total Equity}_{it}}\right)$	H_{1c}: βder≠0

Table 4. Descriptive Statistic Table

	RDI	ROA	NCAI	DER	SC	DIC	ELC
Obs.	11061	11061	11061	11061	11061	11061	11061
Mean	-3.14	1.92	0.18	-0.57	14.92	3.87	6.05
Med.	0.33	2.01	0.10	-0.53	14.80	4.00	6.07
Max	4.34	4.57	4.95	7.35	20.56	8.00	8.11
Min	-15.84	-5.48	-8.78	-4.62	10.48	0.00	4.85
Std. D.	5.31	0.85	0.37	0.93	1.26	1.73	0.83
Sk	-0.44	-0.96	-0.22	0.17	0.62	0.03	0.25
K	1.39	6.30	71.49	4.53	3.57	2.44	1.97

Table 5. Correlation Coefficient Matrix Table

	ROA	RDI	NCAI	DER	SC	DIC	ELC
ROA	1						
RDI	0.01	1					
NCAI	0.11	0.00	1				
DER	-0.21	-0.08	0.00	1			
SC	-0.21	-0.01	0.01	0.41	1		
DIC	-0.21	-0.08	-0.27	-0.05	0.22	1	
ELC	-0.08	-0.02	-0.05	0.12	0.11	0.08	1

4.5 Correlation Coefficient

The econometric methodology of this study employs multivariate analysis, which is particularly sensitive to multicollinearity issues among variables. To address this concern, the correlation coefficient matrix for all variables is presented in Table 5. From Table 5, it can be observed that R&D Intensity (RDI) and Noncurrent Asset Growth Rate (NCAI) exhibit positive correlations with Return on Assets (ROA), while Debt-to-Equity Ratio (DER) and Firm Size (SC) show negative correlations with ROA. However, since the dataset is panel data (combining both time-series and cross-sectional dimensions), these relationships may be influenced by temporal variations and heterogeneity across firms. Therefore, the actual causal effects require further validation through final regression analysis.

Additionally, all explanatory variables demonstrate low pairwise correlations (e.g., correlation coefficients below 0.5), confirming that no significant multicollinearity issues exist in this study.

4.6 Research Model

Based on the analysis in Section 4.5, this study develops two analytical models:

Model 1: Without control variables, Model 2: With control variables.

$$\text{Model I}\quad \begin{aligned} \hat{RDI} &= \alpha_0 + \alpha_1 DIC + \alpha_2 ELC + \varepsilon \\ ROA &= \beta_0 + \beta_1 \hat{RDI} + \varepsilon \end{aligned}$$

$$\text{Model II}\quad \begin{aligned} \hat{RDI} &= \alpha_0 + \alpha_1 DIC + \alpha_2 ELC + \varepsilon \\ ROA &= \beta_0 + \beta_1 \hat{RDI} + \beta_2 NCAI + \beta_3 SC + \beta_4 DER + \varepsilon \end{aligned}$$

V. EMPIRICAL ANALYSIS

This study employs panel instrumental variable regression for analysis. The empirical strategy is structured as follows:

Sections 5.1 and 5.2 validate the appropriateness of the instrumental variables (IVs)

and compare their performance against standard regression models (e.g., OLS) to assess whether IV estimation yields superior results.

Sections 5.3 and 5.4 conduct diagnostic tests to verify the suitability of panel data specifications (e.g., fixed effects vs. random effects) for the sample.

Section 5.5 reports the final results using the Two-Stage Least Squares (TSLS) method with panel data.

5.1 Two Stage Least Squares

This study employs Enterprise Life Cycle (ELC) and Degree of Industry Competition (DIC) as instrumental variables (IVs) for R&D Intensity (RDI). To evaluate the robustness of the IV approach, this section compares the results of instrumental variable regression (addressing potential endogeneity) with those of conventional regression (e.g., Ordinary Least Squares, OLS). The comparative analysis is summarized in Table 6.

From Table 6, the following key findings emerge:

Under conventional regression (OLS), R&D Intensity (RDI) is statistically insignificant and exhibits a negative coefficient (-0.001).

In contrast, when using instrumental variables (TSLS), RDI shows a positive and significant effect (coefficient = 0.29).

Firm Size (SC) consistently demonstrates a negative and significant impact across both models (coefficients = -0.13 in OLS and TSLS).

Validity of Instrumental Variables:

The suitability of Enterprise Life Cycle (ELC) and Degree of Industry Competition (DIC) as instruments for RDI must be rigorously evaluated through IV diagnostic tests (e.g., underidentification, weak identification, and overidentification tests), as detailed in Section 5.2.

5.2 IV Diagnostics Test

This section comprises two parts:1.Endogeneity Test: Assessing whether R&D Intensity (RDI) is an endogenous variable.2. Weak Instrument Diagnostics: Evaluating the validity of Enterprise Life Cycle (ELC) and Degree of Industry Competition (DIC) as instruments for RDI.

Key Findings:

1. The Difference in J-statistic (test of exogeneity) yields a value of 352.02 with a p-value of 0.00 ($p < 0.05$), rejecting the null hypothesis of exogeneity. This confirms that RDI exhibits endogeneity and necessitates instrumental variable correction.

2. The Cragg-Donald Wald F-statistic for weak instrument detection is 48.51, which exceeds the Stock-Yogo critical value of 19.93 at the 1% significance level. This result strongly rejects the weak instrument hypothesis, validating the suitability of ELC and DIC as robust instruments for RDI.

Table 6. Comparison of Two-Stage Least Squares (TSLS) and Ordinary Least Squares (OLS) Regression Results

Variable	TSLS		L-Ss	
C	4.78		3.35	
	(0.28)	***	(0.10)	***
NCAI	0.27		0.26	
	(0.04)	***	(0.02)	***
SC	-0.13		-0.13	
	(0.01)	***	(0.01)	***
DER	0.02		-0.10	
	(0.03)		(0.01)	***
RDI	0.29		-0.001	
	(0.03)	***	(0.00)	

Notes: *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. The first row reports regression coefficients, with standard errors in parentheses.

VI. DISCUSSION & POLICY IMPLICATIONS

6.1 Economic Interpretation of Results

R&D investment enhances Return on Assets (ROA) through two primary channels: technology premium (innovation-driven pricing power) and cost-saving efficiencies. However, its effectiveness is contingent on aligning R&D strategies with the enterprise life cycle (ELC) and industry competition dynamics (DIC). Specifically: Growth-stage firms exhibit higher marginal returns to R&D due to their agility in commercializing innovations and capturing market share.

6.2 Policy Design Recommendations

(1) Differentiated R&D Subsidies:

Provide direct subsidies to growth-stage firms to incentivize high-risk innovation; Offer tax credits for mature-stage firms to sustain incremental R&D improvements.

(2) Competition-Innovation Synergy:

Foster innovation alliances in moderately competitive industries (e.g., electronics equipment manufacturing) to balance collaboration and competition; Regulate monopolistic sectors to prevent R&D underinvestment due to market dominance.

VII. CONCLUSION

This study employs panel instrumental variable regression to empirically validate that R&D intensity exerts a significant positive effect on the performance of Chinese manufacturing firms, moderated by enterprise life cycle stages and industry competition intensity. The findings resolve the "R&D productivity paradox" by demonstrating contextual heterogeneity in R&D returns. Methodologically, this work advances IV-based approaches for addressing endogeneity in innovation studies. Future research could extend to dynamic panel models to capture intertemporal fluctuations in R&D-performance linkages.

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Explainable artificial-intelligence methods in decision support for delivery management

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Abstract *— The article presents an analysis of the application of explainable artificial intelligence (XAI) methods in supporting managerial decision-making for delivery management. The study is conducted within a theoretical and analytical framework, employing a targeted review of publications, a taxonomy of interpretable methods, and their alignment with typical delivery tasks. Particular attention is paid to the role of XAI in ensuring transparency, consistency, and resilience of decisions, as well as integrating ESG indicators and cyber-resilience criteria into planning and dispatching processes. Based on the analysis of scientific sources, approaches to interpreting forecasts and recommendations (post-hoc methods, built-in relevance mechanisms, neuro-symbolic models) are systematized, and their managerial effects and limitations are identified. Generalizing classifications are presented, including a map of XAI applications in logistics tasks, a summary of quantitative effects by key metrics, and a decision matrix linking approaches to managerial criteria. The challenges of XAI implementation are examined, including the complexity of interpreting deep models, the risk of oversimplified explanations, and the need to adapt algorithms to dynamic operational conditions. A structured model for integrating XAI into decision support system architectures is proposed, focusing on balancing accuracy, cost, and environmental performance. The article will be useful to specialists in logistics and supply chains, DSS developers, XAI researchers, and managers making decisions under high demands for transparency and delivery resilience.*

Keywords *— **explainable artificial intelligence, managerial decision support, delivery, logistics, interpretable models, ESG, cyber resilience, SHAP, dispatching, supply chain resilience.***

I. INTRODUCTION

Contemporary delivery management is characterized by highly volatile demand, growing complexity of last-mile logistics, tighter requirements for timeliness and reliability, and the need to account for environmental constraints and cybersecurity risks. Under these conditions, trust in computational models used to plan lead times, routes, and resources becomes pivotal. Managerial decisions must be accurate and transparent to accountable parties and regulators. Opaque ("black-box") machine-learning algorithms hinder the verification of causal relationships, the explanation of errors, and the alignment of decisions among supply-chain participants, which reduces the acceptance of such systems in practice and raises the costs of decision rework [Brahimi N, 2025].

Explainable artificial intelligence provides tools for interpreting forecasts and recommendations, making it possible to identify factor contributions, test the robustness of conclusions, and build reproducible justifications when agreeing delivery deadlines and selecting operating scenarios. In delivery-oriented decision support systems, this translates into early bottleneck detection, the accommodation of customer preferences and contractor constraints, and informed trade-offs among accuracy, cost, and sustainability. Kostopoulos systematizes approaches to explainable decision support systems and notes their role in

enhancing transparency and trust in managerial processes [Kostopoulos G, 2024].

This work is theoretical in nature and aims to integrate existing results on XAI (understood here as the suite of methods, techniques, and tools that render AI/ML model operation transparent and interpretable to humans) in decision-support tasks for delivery management. The review structures interpretation and explanation methods in connection with typical delivery management tasks (lead-time forecasting, order prioritization, selection of risk-response policies) and refines criteria for their appropriateness, given requirements for transparency, reliability, and environmental performance.

The purpose of the study is to analyze XAI methods in supporting managerial decisions on delivery, to identify their capabilities and limitations for ensuring verifiable conclusions, agreement of decisions among participants, and greater trust in digital planning tools.

II. MATERIALS AND METHODS

The study adopts a theoretical and analytical approach and relies on a targeted review of publications on interpretable AI methods in decision support for delivery and adjacent logistics tasks. The core corpus includes works on the systematics of methods and decision-support architectures, including the study by Kostopoulos [Kostopoulos G, 2024] and a review of neuro-symbolic approaches in supply chains by Kosasih [Kosasih EE, 2023]. To connect with lead-time planning and order fulfillment, the analysis draws on studies of transport data with explainable lead-time predictions by Ahmed [Ahmed I, 2022] and explainable spatiotemporal demand models by Brahimi [Brahimi N, 2025]. For delivery-operations optimization and dispatching, results by Bruni [Bruni ME, 2023] and Chang [Chang X, 2024] are used. As sources on interpretable methods in managerial decisions and evaluation metrics, the study includes works by Olan [Olan F, 2024], Rokoss [Rokoss A, 2024], Sadeghi [Sadeghi KR, 2024], and Sattar [Sattar MU, 2025].

Units of analysis:

- management function (lead-time/fulfillment estimation; planning and dispatching;
- risk and resilience management; sustainability impact assessment);
- data type and representation (including spatiotemporal features);
- interpretable AI method;
- metrics used and decision criteria.

From each work, the following were extracted: task formulations; interpretation methods applied and their role in explaining forecasts/recommendations; and implications for managerial decisions. The taxonomy of interpretable methods was formed inductively, drawing on detailed demonstrations. Local additive explanations of feature importance (e.g., SHAP in Olan [Olan F, 2024] and Rokoss [Rokoss A, 2024]); examples of post-hoc explanations and traceability (LIME, RETAIN, LRP, DeepLIFT) in an experimental decision-support model presented by Sadeghi [Sadeghi KR, 2024]. The balance among accuracy, cost, and sustainability was assessed using the composite indices CAE and CAE-ESG proposed by Sattar and co-authors for comparative model assessment in supply chains [Sattar MU, 2025].

III. RESULTS

Within the theoretical study, published works on the use of explainable AI methods in decision support for delivery and adjacent supply-chain stages were mapped. The goal is to align task type, model used, explanation approach, and reported managerial effect. The summary map is shown in Table 1, enabling a stepwise view from forecasting and dispatching to interpretable outputs and decision-quality effects.

Table 1 – Summary map of XAI uses in delivery/SCM decision support (Compiled by the author based on sources: (Ahmed I, 2022), (Brahimi N, 2025), (Olan F, 2024))

Delivery task / domain	Model(s)	XAI approach	Reported metrics / notes
Travel-time (ETA) prediction with spatio-temporal features	Comparative studyprediction with spatio-temporal features	Post-hoc feature explanations	Focus on travel time with explanations; explicit metrics not reported
Car-sharing demand, spatio-temporal	Explainable Spatio-Temporal Inference Network	Built-in interpretability via attention/relevance	Declared SOTA and interpretable demand drivers
3PL terminal-to-customer planning	ML + optimization	—	Planning framework for delivery leg; metrics not explicit
Ridesourcing carpooling and dispatching, emissions	Dispatch algorithms	—	Emissions-reduction assessment for mobility services
SCM review of neurosymbolic XAI	—	Neuro-symbolic approaches	Taxonomy and SCM cases
Review of XAI-based DSS	—	Transparency and trust criteria	Evaluation framework for XAI-DSS
Building XAI capabilities in SC-DSS (tabular data)	ML on tabular data	SHAP, global and local	~315 observations; features 42→122; managerial insights
Delivery-date prediction in small-batch MTO	XGBoost	SHAP feature importance	Case 1 RMSE: mean 12 bd; ML no-domain 9.5; with domain 7.7; desired date is top feature
Supply-chain cyber resilience during attacks	—	XAI as driver of transparency	Adj.R^2=0.42; direct coef to resilience 1.35; serial mediation 0.333
Forecasting, inventory, risk, ESG-aware selection	XGB, RNN, RF	SHAP; CAE and CAE-ESG	XGB MAE=0.1571, MAPE=0.48%; RNN fraud F1≈98%, late-delivery F1≈97.85%; RF best CAE-ESG

The "Delivery task / domain" column spans delivery-management subjects from travel-time estimation and mobility demand to 3PL terminal–customer planning and dispatching with environmental impact, outlining a range of decisions from route planning to service resilience [Ahmed I, 2022]. The "Model(s)" column reflects the use of specialized spatiotemporal networks, gradient boosting, and mixed ML-optimization approaches for lead-time and workload forecasting in make-to-order production and service logistics [Rokoss A, 2024]. The "XAI approach" column records interpretation methods, including post-hoc explanations of feature contributions, built-in relevance mechanisms, and SHAP in enterprise DSS—providing factor readability and subsequent managerial validation [Olan F, 2024]. "Reported metrics / notes" summarizes stated accuracy indicators, causal links, and model choices that incorporate cost and sustainability, showing how explainability connects to forecast quality, risk control, and algorithm selection under ESG constraints [Sattar MU, 2025]. Collectively, the map confirms a managerial transparency effect on the speed and reliability of decisions during cyber incidents, expressed in validated serial mediators of transparency and decision agility [Sadeghi KR, 2024].

To further verify the managerial value of XAI in delivery tasks, quantitative effects on key decision outcomes were synthesized. Comparison used common measurability and reproducibility criteria to reconcile heterogeneous domains—from lead-time forecasting to sustainable model selection. Summary results are presented in Table 2.

Table 2 – Quantitative effects of XAI on managerial outcomes (Compiled by the author based on sources: (Olan F, 2024), (Sadeghi KR, 2024), (Sattar MU, 2025))

Block	Indicator/effect	Value/outcome
Delivery promise reliability	RMSE reduction of delivery-date prediction vs. baseline	from 12 to 7.7 business days with domain features and SHAP
Target variable's role	Importance of "desired delivery date" in the model	top feature by SHAP in both case studies
Decision-making under attacks	XAI → Transparency → Agile → Cyber resilience	Adjusted R^2 up to 0.546; indirect effect 0.333; all links statistically significant
Supply-risk detection	Late delivery / fraud identification	RNN F1 ≈ 98% (fraud); ≈ 97.85% (late delivery
Model choice with sustainability	Accuracy/Cost/ESG balance	Random Forest achieves best CAE-ESG with comparable accuracy
Organizational XAI capabilities	Global/local explanations for SC decisions	SHAP; features expanded 42→122; decision factors explicitly interpretable

The "Block" column identifies the managerial contour of application. "Indicator/effect" specifies the measurable outcome used to compare approaches. "Value/outcome" contains verbatim metric values or carefully formulated findings from the cited articles.

On-time delivery promises carry the greatest applied significance. In Rokoss, the delivery-date prediction RMSE decreases from 12 to 7.7 business days when domain features are included and SHAP is used for factor selection and explanation; the "desired date" is the top-importance feature in both samples, confirming the criticality of incorporating the customer's target request in planning models [Rokoss A, 2024].

For controllability under cyberthreats, a consistent mediated chain—"XAI → transparency → decision agility → cyber resilience"—is shown. Sadeghi reports significant coefficients, adjusted R^2 up to 0.54, and a total indirect effect of 0.333, substantiating the need to formalize explanations as elements of response protocols [Sadeghi KR, 2024].

In supply-risk management, detectors exhibit high sensitivity. Sattar reports recurrent networks achieving F1 around 98% for fraud and about 97.85% for late deliveries—broadening the space for preventive dispatching and SLA control. When selecting technologies with sustainability in view, the same author shows that, at comparable accuracy, Random Forest provides the best overall "accuracy–cost–ESG" profile according to CAE/CAE-ESG, which matters for responsible scaling of analytics [Sattar MU, 2025]. Finally, organizational XAI capabilities in supply chains rest on reproducible global and local explanations. In Olan, SHAP and an expanded feature space improve interpretability and convert model factors into manageable process parameters [Olan F, 2024].

IV. DISCUSSION

Synthesizing application maps and quantitative effects yields practical guidance for choosing XAI instruments in delivery management. For travel-time prediction and honoring promised dates, tabular models with local and global explanations are preferred, as confirmed in Ahmed [Ahmed I, 2022]. Rokoss empirically demonstrates the material role of such explanations for accurate shipment-date calculation in small-batch environments [Rokoss A, 2024]. Transparency and trust criteria for managerial DSS decisions are consolidated in the review by Kostopoulos [Kostopoulos G, 2024].

For demand and dispatching in spatiotemporal settings, models with built-in interpretability via attention/relevance are appropriate, as shown in Brahimi's work on car-sharing demand [Brahimi N, 2025]. In terminal delivery and 3PL interaction, machine learning combined with optimization is effective, as indicated by Bruni [Bruni ME, 2023]. The cyber-risk vector requires rapid transparency and explainable action criteria; serial mediation in Sadeghi's experiments confirms the role of explainability in accelerating the managerial cycle during attacks [Sadeghi KR, 2024]. Sustainable scaling calls for accounting for computational cost and environmental footprint; CAE/CAE-ESG metrics in Sattar justify model selection based on the joint criteria of accuracy, expense, and ESG [Sattar MU, 2025]. The environmental effects of dispatching and ride-sharing decisions are highlighted by Chang [Chang X, 2024]. Table 3 presents a decision matrix for selecting XAI approaches for delivery-management decision support, linking criteria, source foundations, recommended explanation methods, and typical application scenarios.

Table 3 – Decision matrix for selecting XAI approaches in delivery management (compiled by the author based on (Brahimi N, 2025), (Kostopoulos G, 2024), (Sadeghi KR, 2024))

Criterion	Preferred XAI/approach	Where to apply
Manager-oriented transparency	SHAP/LIME (post-hoc)	ETA and promised dates
Faithfulness to model and domain rules	Neuro-symbolic and rule-based explanations	Service-level policies and compliance
Built-in interpretability	Attention and relevance mechanisms	Spatio-temporal dispatch and demand
Speed and robustness under attacks	Simple interpretable models with local explanations	Day-of-attack incident decisions
Cost and environmental impact	Models maximizing CAE-ESG (often RF/XGB)	DSS operations and scaling

The matrix aligns managerial criteria with literature-backed foundations, recommended classes of explanations, and typical use contours. The "Criterion" column fixes key managerial decision anchors: transparency, faithfulness to internal model logic, built-in interpretability, response speed in incidents, cost, and ecological impact. Transparency is elevated as the primary criterion, based on Kostopoulos's review and Sadeghi's empirical results on the importance of intelligibility for coordinated, rapid team responses [Kostopoulos G, 2024; Sadeghi KR, 2024]. "Preferred XAI/approach" proposes explanation classes per criterion. Post-hoc methods (SHAP/LIME) suit cases requiring controllable interpretation of tabular forecasts without model redesign—an approach exemplified by Olan (global and local explanations for managerial factors) and by Rokoss when analyzing feature importance for delivery dates [Olan F, 2024; Rokoss A, 2024]. The "Faithfulness" criterion draws on neuro-symbolic practices from Kosasih's review, where explicit rules and domain constraints must be reflected in the model [Kosasih EE, 2023]. For problems with spatiotemporal dependencies, built-in interpretability via attention/relevance is indicated, as in Brahimi [Brahimi N, 2025]. "Speed & resilience" emphasizes the need for rapid, explainable responses during cyber incidents, grounded in Sadeghi's results linking transparency and agile decision-making to higher cyber-resilience [Sadeghi KR, 2024]. Finally, "Cost/Ecology" connects model selection with overall efficiency and footprint; Sattar proposes CAE/CAE-ESG for rational choice (Random Forest shows the best balance in their experiments), and Chang demonstrates the link between dispatch actions and transport emissions [Sattar MU, 2025; Chang X, 2024]. "Where to apply" identifies typical scenarios: lead-time prediction and SLA compliance in tabular tasks (as in Ahmed); spatiotemporal dispatching and demand forecasting; incident management and operational risks with simple interpretable models plus local explanations; and DSS operations guided by

CAE-ESG and transport-emissions accounting [Ahmed I, 2022].

The analysis indicates that XAI implementation should be viewed not as an "explanation add-on" but as a managerial mechanism for accelerating collective decisions in delivery operations. Sadeghi shows that algorithm transparency increases the speed of alignment and promotes agile resolution, which is statistically associated with higher cyber-resilience [Sadeghi KR, 2024]. For logistics organizations, this implies embedding explainability into response procedures, escalation paths, and stakeholder communications.

Model choice extends beyond forecast accuracy. Sattar demonstrates that integrated CAE and CAE-ESG metrics shift selection priorities: a model with moderate accuracy but lower cost and a better ESG footprint may be preferable for sustainable analytics operations. Thus, technology selection should be aligned with environmental and social objectives rather than reduced to error minimization. This approach accords with dispatching and ride-sharing contexts where managerial decisions directly reduce emissions.

High-quality feature engineering and grounding in quantitative logistics models are critical for reliable delivery-promise performance. Rokoss shows that domain features and contribution explanations materially reduce delivery-date prediction error versus baseline heuristics, with the "desired date" as the key factor. The practical implication is that XAI should be embedded in the feature-formation pipeline, not confined to post-hoc explanations at the end [Rokoss A, 2024].

The role of reviews is to establish durable standards of explainability and criteria for their evaluation. Kosasih systematizes neuro-symbolic approaches relevant where managerial rules and domain constraints must be explicitly represented. Kostopoulos offers transparency and trust criteria for decision-support systems that can ground corporate XAI-DSS regulations in delivery—from requirements for local/global explanations to formats for presenting causally significant factors to managers [Kosasih EE, 2023; Kostopoulos G, 2024].

Taken together, the results point to a necessary shift in managerial practice—from "accuracy at any cost" to a balance of interpretability, collective-action speed, and resilience. This entails redesigning delivery-decision processes around: procedural transparency and resilience metrics; multi-criteria model selection that accounts for cost and ESG; domain-grounded feature engineering with verifiable factor-impact explanations on lead times; and standardized requirements for explanations and their auditability at the organizational level.

Such a contour strengthens operational delivery resilience and aligns analytics with environmental and social responsibility objectives. It establishes manageable trade-offs among reaction speed, explainability, and model resource intensity, enabling the formalization of SLAs, resilience KPIs, and climate indicators within unified decision-making regulations. Practically, this reduces regulatory and reputational risks and yields more predictable deadline adherence with an optimized carbon footprint for both the transport fleet and IT infrastructure.

V. CONCLUSION

The study substantiates the key role of explainable AI methods in ensuring transparency and trust when supporting managerial decisions in delivery. It finds that interpretable algorithms, local and global feature explanations, neuro-symbolic approaches, and built-in relevance mechanisms constitute a stable analytical platform necessary for the predictability, consistency, and sustainability of logistics processes.

The source analysis confirms that XAI serves both as a technical means of visualizing factor contributions and as an instrument of managerial legitimation—capturing causal links, justifying priorities, and documenting criteria for scenario selection. Amid rising cyberthreats and ESG requirements, its functions expand through integration into SLA monitoring, incident management, and strategic planning of transport capacities. A basic postulate remains: explainability cannot be reduced to a superficial "layer" atop the model; it must be embedded in DSS architecture, coupled with feature engineering, and formalized in application regulations.

A multi-level approach to XAI evaluation is warranted—from accuracy and cost metrics to cyber-resilience and environmental performance—as the primary filter for technology choice and a guarantee of decision governability. Composite indices CAE and CAE-ESG play a central role in balancing performance, economy, and environmental responsibility. Mechanisms for organizational validation of explanations gain particular importance through corporate transparency standards and controls on the reproducibility of factors that affect delivery timing and quality.

The challenges facing XAI practice in logistics are highlighted: the difficulty of interpreting deep models on high-dimensional data, the risk of simplistic or misleading explanations, and the need to adapt algorithms to rapidly changing operating conditions. These challenges call for methodical specification of XAI tool requirements, clarification of method applicability limits, and revised model-selection criteria that reflect multifactor managerial objectives. The decision matrix proposed here is a promising instrument for standardizing practice, but it requires tailoring to industry specifics and integration into existing logistics ecosystems.

Accordingly, XAI in delivery management shapes a new quality of analytical support—from forecast accuracy to comprehensive support for transparency, resilience, and decision coherence. Its transformation from an auxiliary module into a core element of the managerial cycle reflects logistics' evolution toward multi-objective, environmentally oriented, and cyber-resilient systems. Future research avenues include developing a regulatory framework for corporate XAI, creating methods for assessing explanation reliability, and deploying hybrid architectures that combine interpretable models with high-performance algorithms for delivery tasks.

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Health Financing, Privatization and Equity in Haryana's Healthcare System

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Abstract *— Over the last twenty years, healthcare delivery in Haryana has undergone notable change as a result of health-financing reforms and the expanding role of private providers. Increased government spending, the introduction of publicly funded insurance schemes and reliance on private healthcare institutions have collectively improved the availability of services for large sections of the population. For households covered under insurance programmes, dependence on direct out-of-pocket payments has declined, while access to institutional care has improved. These shifts are reflected in better health infrastructure, a rise in institutional deliveries and gradual improvement in indicators such as infant and maternal mortality. However, these gains have not been uniform. Persistent disparities remain due to unequal spatial distribution of facilities, shortages of healthcare personnel in public institutions, administrative challenges in insurance execution and limited oversight of private providers. The experience of Haryana demonstrates that although publicly financed privatization can widen access to healthcare, achieving equity requires continuous public investment, stronger regulatory mechanisms and focused attention on underserved areas.*

Keywords *— **health financing reforms, private sector participation, healthcare equity, public-private partnership.***

I. INTRODUCTION

India operates a healthcare system that combines public and private provision, with the private sector accounting for the larger share of healthcare services delivered across the country. Since the 1990s economic liberalization, policies have promoted private investment and public-private partnerships. By 2020, about 62% of hospitals were privately owned and 70-80% of outpatient care was delivered by private providers (Koli, 2024; Alayed et al., 2024). While privatization has expanded service availability and corporate hospital networks, evidence shows risks of cost escalation, exclusion of low-income groups and uneven quality (Duggan et al., 2023; Goodair, 2024). India's total health expenditure was 3.8% of GDP in 2021-22, with out-of-pocket spending still at 39.4%, despite a decline due to insurance expansion. Government health spending remains below 1.5% of GDP, far short of the National Health Policy (2017) target of 2.5% by 2025 and most states have not achieved the 8% budget allocation target. Haryana illustrates this financing structure clearly. Although the state has increased health spending and infrastructure, it relies heavily on private provision. Under PM-JAY, Haryana has empanelled more than 700 private hospitals that provide most inpatient services. Access has improved in urban areas such as Gurugram and Faridabad but rural regions remain underserved. Reliance on private providers also raises issues related to cost regulation, delayed reimbursements and quality control, highlighting the

equity risks within Haryana's health financing model.

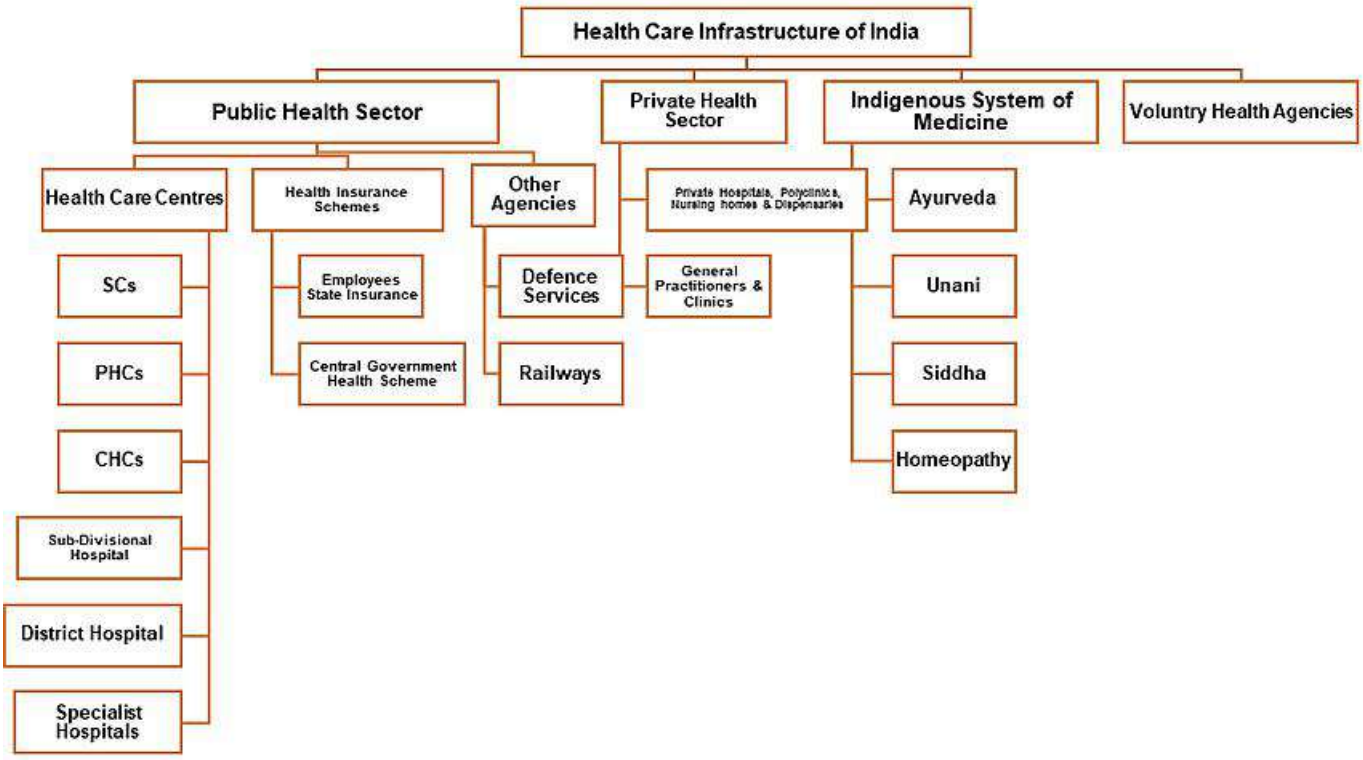

Fig.1: Health Care Infrastructure of India

Source: https://www.researchgate.net/figure/Health-Care-Infrastructure-in-India_fig1_342170461

II. DEFINITIONS AND CONCEPTUAL FRAMEWORK

2.1. Privatization in Healthcare: Privatization involves expanding private roles in healthcare ownership, financing, or service delivery through asset transfer, PPPs, outsourcing, private insurance and corporatization of public hospitals (Braithwaite et al., 2011). In Haryana, it occurs mainly via private hospitals under insurance schemes, outsourced diagnostics and private investment encouraged by national PPP policies.

2.2. Health Financing: Health financing covers revenue collection, risk pooling and purchasing. India follows a mixed model with public budgets, insurance and out-of-pocket spending. Schemes such as RSBY and PM-JAY aim to reduce direct payments. Haryana's system combines state health budgets, NHM transfers and PM-JAY/Chirayu Haryana, largely paying private providers.

2.3. Equity in Healthcare: Equity means need-based access regardless of ability to pay, including horizontal and vertical equity. In Haryana, urban-rural gaps, uneven facility distribution and high out-of-pocket costs among uninsured households persist. Financing and privatization jointly influence equity; without regulation, market-driven care disadvantages poorer groups (Hooda, 2020; Prinja et al., 2017).

III. OBJECTIVES OF THE STUDY

- > To examine health financing and privatization in Haryana's healthcare system.
- > To analyse public health spending and out-of-pocket expenditure trends.
- > To assess the equity implications of private participation in publicly financed healthcare.
- > To evaluate whether privatization improves access or widens healthcare disparities.

IV. RESEARCH METHODOLOGY

This study uses secondary quantitative analysis supported by document-based qualitative interpretation. Year-wise data on Haryana's health expenditure (2000-2024) were collected from state budget documents (revenue and capital heads) to

compute health spending as a percentage of GSDP and total state expenditure. National Health Accounts data were used to contextualize Haryana, particularly out-of-pocket expenditure trends. Health infrastructure and service delivery indicators were obtained from the Haryana Department of Health and Family Welfare, National Health Mission and National Health Authority. These include the number of health facilities, workforce, PM-JAY beneficiary coverage, hospital admissions and claims. PM-JAY information was drawn from official reports of the National Health Authority and the Haryana Economic Survey. The analysis follows a descriptive and comparative approach, examining temporal trends and contrasts with national averages. Equity was assessed through indicators of service use across urban and rural areas, along with measures of financial protection such as out-of-pocket expenditure and proxy indicators of catastrophic health spending based on NSS and other official sources.

V. SCHEMES, POLICIES & INSTITUTIONAL FRAMEWORK IN HARYANA

Haryana has established an institutional framework that brings private providers into the public health system through state schemes, public-private partnerships and regulatory arrangements. One of the major initiatives is the Comprehensive Cashless Health Facility (CCHF), which provides coverage to government employees, pensioners and their dependents. Under this scheme, eligible beneficiaries can access cashless treatment at empanelled private hospitals. To operationalise this, the state government has issued a "Package Master" which lists fixed rates for more than 1,300 medical procedures, including implant costs. Private hospitals providing services under this scheme must strictly adhere to these standardised rates, ensuring uniformity in pricing and preventing arbitrary overcharging.

Further strengthening the framework, the Department of Health and Family Welfare in Haryana has published detailed empanelment guidelines for private hospitals. As of March 2024, private hospitals can apply for empanelment under the CCHF and other state-run schemes through a structured application and verification process. Empanelled hospitals are listed on the official state health dashboard, which is regularly updated and publicly accessible. These hospitals are allowed to treat scheme beneficiaries for secondary and tertiary-level care on a cashless basis and the treatment costs are reimbursed directly by the government as per the approved package rates. Additionally, Ayushman Bharat - Pradhan Mantri Jan Arogya Yojana (PM-JAY) is implemented in the state with active private hospital participation, offering ₹5 lakh of annual coverage per family for hospitalisation. The state has formally defined criteria for hospital empanelment under PM-JAY and the CCHF, which include infrastructure benchmarks, service availability and compliance with national quality standards.

To oversee private hospitals involved in public health programmes, Haryana has implemented the Clinical Establishments (Registration and Regulation) Act, 2018. The Act requires all private health facilities to register and adhere to prescribed minimum standards related to infrastructure, staffing, equipment and record maintenance. Quality oversight is supported through periodic notifications and operational guidelines issued by the Department of Health. Alongside this, the Haryana PPP Policy facilitates private participation in health services through formal contractual arrangements. The policy defines risk-sharing provisions, sets performance benchmarks and provides for regulatory supervision by designated state authorities.

Private providers in Haryana also participate in disease-specific programmes, including those focused on non-communicable diseases, HIV/AIDS and maternal and child health. In such programmes, private laboratories and hospitals are engaged for diagnostic services, specialist care and hospital-based treatment where public facilities are insufficient. These arrangements are managed by the state health department through formal contracts that specify services, payment terms and reporting obligations. However, difficulties persist in maintaining timely reimbursements and enforcing quality standards. Past delays in payments have created friction with private providers, indicating the need for stronger financial management within the system.

VI. RESULTS AND ANALYSIS

6.1. Health Expenditure Trends in India and Haryana:

Health financing in India has improved but public spending remains limited. Table 1 shows OOPE declined from over 64% of Total Health Expenditure in 2010-11 to 39.4% in 2021-22, reflecting increased risk pooling and public financing. The sharpest decline occurred post-2015, aligning with PM-JAY (2018) and COVID-19-related health spending (2020-21). Lower OOPE indicates better financial protection but at 39.4%, household burden remains high by international standards.

Table 1: Out-of-Pocket Expenditure (OOPE) as % of Total Health Expenditure, India (2010-2022)

Year	OOPE (% of THE) India
2010-11	64.2%
2014-15	62.6%
2016-17	49.9%
2018-19	48.2%
2020-21	44.4%
2021-22	39.4%

Source: National Health Accounts Estimates (2019-2024); Press Information Bureau, 2024.

Table 2: Haryana's Health Expenditure and Budget Share

Year	Health Outlay (₹ crore)	Health as % of State Budget
2002-03 (A)	351.1	3.0%
2010-11 (BE)	1,125.5	2.85%
2015-16 (A)	2,700.0	3.20%
2020-21 (BE)	6,533.8	4.57%
2024-25 (BE)	9,835.4	5.02%

Sources: Government of Haryana Budget Documents (Actuals and Budget Estimates). A = Actual, BE = Budget Estimate.

Haryana's health expenditure increased from under ₹300 crore in 2000-01 to nearly ₹10,000 crore in 2024-25, a more than thirty-fold nominal rise (Figure 1; Table 2). However, health spending remained around 0.5% of GSDP for most of the 2000s, rising only to about 0.7% in 2024-25. The budget share of health increased from 3% in the early 2000s to 5% by the mid-2020s, crossing 4% only after 2016. This remains below the National Health Policy 2017 target of 8% of state budgets, indicating limited fiscal prioritization despite higher absolute spending.

Haryana's rise in health spending accelerated after 2015 due to NHM funding, budget integration of health-related departments (2016-17) and COVID-19 emergency spending post-2020. Health expenditure peaked at 0.9% of GSDP in 2023-24 and 5% of the state budget, the highest to date but below benchmarks: Kerala and Tamil Nadu spend 5-6% and international norms suggest 2-3% of GDP. Per capita health expenditure rose from ₹167 in the early 2000s to ₹2,400 in 2022-23, with a sharp COVID-19 jump (₹1,531 in 2019-20 to ₹1,916 in 2020-21) (Table 3). Higher per capita spending indicates increased resources but does not ensure equity, which depends on allocation across urban-rural services.

Table 3: Per Capita Health Expenditure in Haryana

Year	Per Capita Expenditure on Health (₹)
2000-01	166.8
2010-11	442.1
2015-16	1,082.3
2020-21	1,916.1
2022-23	2,399.4

Source: Department of Health Services, Haryana. Figures are in current rupees.

Increased health spending in Haryana has improved infrastructure and outcomes. District hospitals increased from 7 in 2005, alongside new medical colleges and tertiary centres, including PPP facilities. Ambulance coverage expanded to 364 by 2019 and institutional deliveries reached 92.1% by 2020. Health outcomes improved: IMR declined from 41 (2013) to 28 (2020) and MMR fell from 127 (2011-13) to 110 (2018-20) (Table 4). While these gains reflect better coverage and quality, rural districts continue to record higher IMR than urban areas, indicating persistent

equity gaps.

6.2. Privatization and Private Sector Involvement:

Privatization in Haryana occurs mainly through publicly funded private provision, not sale of public hospitals. Under Ayushman Bharat-PM-JAY, expanded as Chirayu Haryana (2022), over 700 private hospitals are empanelled. By early 2025, 736 of 1,238 empanelled hospitals were private and they treated 90% of beneficiaries. PM-JAY coverage expanded rapidly: Ayushman cards increased from 0.89 million (2018-19) to 5.37 million (2022-23). Scheme payouts rose from ₹88 crore (2019-20) to ₹252 crore (2022-23), with private hospitals receiving most payments (Table 5). This model has expanded inpatient access, especially tertiary care, for low-income households.

Table 4: Health Outcomes in Haryana - Progress Over Time

Sr. No.	Indicator with source	Year	Year
		2013-14	2023-24
1	Neonatal Mortality Rate (NMR)	26 (SRS 2013)	19 (SRS 2020)
2	Infant Mortality Rate (IMR)	41 (SRS 2013)	28 (SRS 2020)
3	Maternal Mortality Ratio	127 (SRS 2011-13)	110 (SRS 2018-20)
4	First Referral Unit	40 (including 2 urban FRU in Faridabad)	56 (including 2 urban FRU in Faridabad)
5	Under-5 mortality rate	45 (SRS 2013)	33 (SRS 2020)
6	Sex ratio at birth (CRS)	868 (CRS 2013)	910 (upto December, 2024)
7	Institutional delivery (HMIS)	90.37% (2017)	98.3% (Till December, 2024, SourceHMIS)
8	Full Immunization (Source - HMIS)	85.7%	91.7% (2023-24) against GoI Target
9	ASHA	16861 (92.67%)	20354 (97.36%) (upto 31st December,2024)
10	Special New born Care Units (SNCU)	15	28 (2024-25 till date)
11	New Born Stabilizing Units (NBSU)	52	62 (2023-24 till date)
12	New Born Care Corners (NBCC)	192	439 (2023-24 till date)

Sources: Sample Registration System (SRS) Statistical Report; Civil Registration System; National Family Health Survey; Haryana Health Department. *Institutional delivery from HMIS via Economic Survey.

Table 5: Expansion of Ayushman Bharat (PM-JAY) in Haryana and Private Sector Role

Year	Ayushman Cards Issued (lakh)	Persons Treated under PM-JAY	Total Claims Amount Paid (₹ crore)
2018-19	8.92	0.07 lakh (7,000)	₹9.7 crore
2019-20	12.99	0.73 lakh (72,696)	₹88.3 crore
2022-23	53.69 (Chirayu launched)	1.18 lakh (118,130)	₹252.4 crore

Source: Haryana Health Department Records (Ayushman Bharat/Chirayu Haryana data). Note: 1 lakh = 100,000. Figures for 2022-23 are higher due to scheme expansion under *Chirayu Haryana*.

Beyond PM-JAY, Haryana has expanded privatization through PPP diagnostics and outsourcing. CT scans operate via PPP in 15 district hospitals, MRI services in 4 hospitals and dialysis centres in several civil hospitals. The 108 ambulance service is privately operated under contract. These models improved service availability but raised cost and sustainability concerns. The private sector dominates the health workforce, especially in urban areas. In 2022-23, only 13,579 staff were in position against 18,586 sanctioned posts, leaving 27% vacancies, worst in rural areas. Nearly one-third of Primary Health Centres operate without a full-time doctor, which forces many rural residents to depend on expensive private healthcare services.

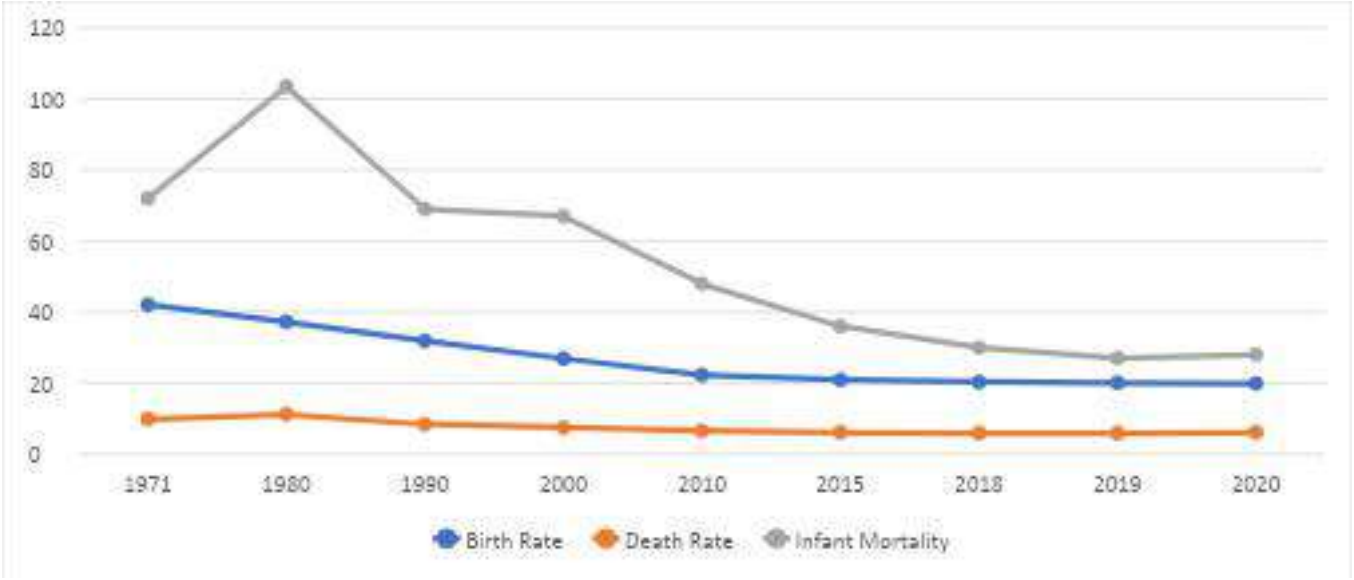

Fig.2 : Health Indicators - Vital and Demographic Statistics of Haryana

Source: Compiled from Haryana Government Health Department Records

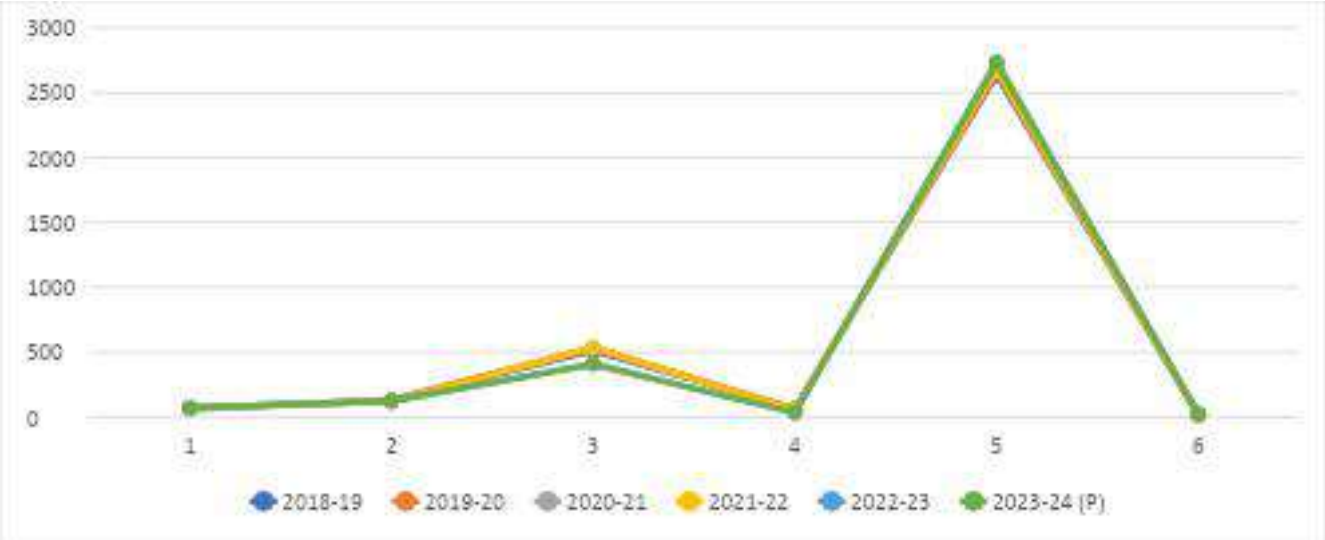

Fig.3: Expansion of Health Infrastructure in Haryana - Medical Institutions and Facilities

Source : Compiled from Department of Health Services, Haryana., PHCs : Primary Health Centres., CHCs : Community Health Centres, P : Provisional, # : District-wise information of T.B., Centres/Clinics is not available, - : Information included in district Bhiwani

Equity effects are mixed. PM-JAY increased inpatient access for insured poor households; uninsured patients paid nearly three times more out-of-pocket for similar hospitalizations than insured ones.

However, governance failures persist: by mid-2025, private hospitals reported >₹500 crore in unpaid PM-JAY dues, with 650 hospitals threatening service withdrawal, directly affecting poor beneficiaries. Private facilities are geographically concentrated in Gurugram and Faridabad, while districts such as Nuh, Mahendragarh and Sirsa remain underserved. Weak enforcement of the Clinical Establishments Act has allowed pricing abuses and quality gaps, disproportionately harming low-income and rural patients.

Table 6: Chirayu Haryana Pardhan Mantri Jan Arogya Yojana Beneficiaries and Funds Released in Haryana (Rural and Urban)

District/Year	No. of Ayushman Cards Issued (Rural)	No. of Persons Benefitted (Rural)	Amount Released to Hospitals (₹) (Rural)	No. of Ayushman Cards Issued (Urban)	No. of Persons Benefitted (Urban)	Amount Released to Hospitals (₹) (Urban)	Total Ayushman Cards Issued	Total Persons Benefitted	Total Amount Released to Hospitals (₹)
2018-19	563546	4756	66879623	328769	2244	29869753	892315	7000	96749376
2019-20	1009174	48287	600716327	289393	24409	282670326	1298567	72696	883386653
2020-21	241244	69691	801399161	96159	38867	36107178	337403	108558	1162476339
2021-22	200467	57315	1118094576	101444	23393	539464743	301911	80708	1657559319
2022-23	4066380	84417	1725442072	1303360	33713	799079209	5369740	118130	2524521281
2023-24 (P)	2445801	41934	1003117934	844697	14487	321540984	3290498	56421	1324658918

Source: Compiled from Ayushman Bharat - Haryana Health Protection Authority Note : The Scheme has been modified and renamed as Chirayu Haryana Pardhan Mantri Jan Arogya Yojana during the year 2022-23

6.3. Discussion of Findings:

Haryana reflects India's mixed experience with health privatization. Higher public financing is strongly associated with improved outcomes: rising health expenditure (Tables 2-3) coincided with lower IMR and MMR and wider service coverage (Table 4). The decline in out-of-pocket spending and PM-JAY coverage show that public financing whether through public or private delivery reduces financial barriers, supporting equity theory and prior evidence (Prinja et al., 2017). Privatized delivery under PM-JAY enabled rapid scale-up using private capacity (>5 million cards; 90% care by private hospitals, Table 5), improving tertiary access in the short term (Cutler, 2002; Day, 1994). However, governance risks are clear: payment delays (₹500+ crore arrears; 650 hospitals threatening withdrawal in 2025) exposed equity vulnerabilities, as poor beneficiaries face service denial when private providers exit.

Urban-rural disparities in healthcare access continue to persist in Haryana. Private health facilities are heavily concentrated in the Gurugram-Faridabad belt, whereas districts such as Nuh, Mahendragarh and Sirsa remain poorly served. Shortages of medical personnel—reflected in vacancy levels of around 27 percent and the absence of full-time doctors in nearly one-third of Primary Health Centres—compel rural populations to rely on expensive private services, indicating market failure in the provision of essential care (Hooda, 2020). Although public-private partnerships have generated efficiency gains in areas such as diagnostics and insurance-based service purchasing, these benefits are offset by equity concerns when regulatory enforcement is weak. Inadequate implementation of the Clinical Establishments Act has allowed price irregularities and uneven service quality, with disproportionate adverse effects on low-income groups. Evidence suggests that outcomes are closely tied to the strength of public stewardship: effective oversight has improved access, while regulatory lapses have deepened inequities (Braithwaite et al., 2011). In comparison, states with stronger public health systems and stricter regulation, such as Kerala and Tamil Nadu, demonstrate better equity outcomes through higher public spending and tighter

governance. The Haryana experience underscores the need for a rebalanced approach that sustains public financing, strengthens rural public health infrastructure, enforces regulation rigorously and engages private providers selectively under robust contractual controls to safeguard equity.

VII. POLICY RECOMMENDATIONS

Haryana's experience indicates that expanded public financing alongside private service delivery can improve coverage and health outcomes but equity benefits remain uneven. Higher spending, insurance expansion and private participation have strengthened financial protection and key indicators, yet persistent urban-rural disparities, staff shortages, governance weaknesses and limited regulatory enforcement continue to restrict equitable access. While privatization enhances service availability, inadequate public stewardship risks deepening existing inequalities.

7.1. Policy Directions:

- Increase public health expenditure beyond the present 5 percent of the state budget and 0.7 percent of GSDP, with priority to primary healthcare and rural infrastructure.
- Upgrade public facilities in underserved districts by addressing staff shortages, expanding diagnostic capacity and offering incentives for rural postings.
- Strengthen regulation of private providers through effective enforcement of the Clinical Establishments Act, price transparency and regular quality audits.
- Improve the functioning of PM-JAY/Chirayu Haryana by ensuring timely reimbursements, controlling costs and increasing the role of public hospitals.
- Structure public-private partnerships with clear equity requirements, including mandatory service provision in rural areas.
- Enhance health information systems through district-level and rural-urban data tracking to support targeted policy action.

VIII. CONCLUSION

Haryana's experience confirms that public financing is the primary force behind improvements in health outcomes, even within a system where service delivery is largely privatized. Increased public spending, expansion of insurance coverage under PM-JAY/Chirayu Haryana and continued NHM support have contributed to lower infant and maternal mortality, higher institutional deliveries and wider service reach. Publicly funded insurance has reduced financial barriers for insured households and limited exposure to catastrophic health expenditure. At the same time, equity outcomes remain uneven. Heavy reliance on private providers has created governance challenges, including reimbursement delays, inconsistent quality oversight and concentration of services in urban areas. Persistent shortages of health personnel in rural areas, gaps in public facilities and weak enforcement of regulatory standards continue to disadvantage poorer and rural populations. The evidence makes clear that privatization alone does not guarantee equitable access. Its impact depends on the strength of public stewardship. In Haryana, achieving equity requires sustained public investment, stronger rural public health capacity, effective regulation of private providers and reliable financing of insurance schemes. Without these conditions, efficiency gains from privatization risk coexisting with widening health disparities.

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Features of adapting Lean manufacturing methodology to the requirements of the ISO 13485 standard

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Abstract *— The article explores how Lean manufacturing methodology can be effectively adapted to meet the regulatory requirements of ISO 13485 in medical device production. The article used a structured narrative literature review of recent peer-reviewed studies published between 2021 and 2025, examining evidence from case studies, expert interviews, systematic reviews, and technology-focused investigations relevant to Lean, risk management, validation, documentation, and digitalisation in regulated environments. The review brings together a set of recurring features that appear to be essential when Lean is applied within an ISO 13485 quality system. One consistent theme is the need to build documentation and traceability requirements directly into Lean routines rather than managing them separately. Another is the limitation of relying solely on FMEA; the broader risk framework set out in ISO 14971 has to be reflected in improvement work. This point, along with the others identified in the review, should be of practical use to teams involved in Lean work within medical-device manufacturing, particularly where operations and quality or regulatory staff have to plan improvements together. The material may also give researchers a more concrete basis for examining the ways Lean methods intersect with ISO 13485 and where the existing models still fall short.*

Keywords *— **Lean manufacturing, ISO 13485, medical device industry, ISO 14971, process validation, documentation and traceability, Lean Six Sigma, Industry 4.0, continuous improvement, regulatory compliance.***

I. INTRODUCTION

Lean manufacturing has become a familiar improvement strategy across a wide range of industries, largely because of its focus on cutting waste and keeping processes moving smoothly. The core tools—value-stream mapping, standardized work, 5S practices, and the various routines that support continuous improvement—were developed with fast-paced, highly flexible production settings in mind, where teams can adjust workflows quickly and respond to problems as they appear. Medical device manufacturing, however, operates under markedly different conditions. ISO 13485 establishes stringent requirements for documentation, traceability, risk management, design control, and process validation, creating a regulatory landscape in which change is tightly governed and process evidence must be meticulously maintained. These obligations shape every stage of production and can significantly affect how improvement methodologies are deployed. As a result, while Lean offers clear operational benefits, its direct transfer into a regulated setting is neither straightforward nor guaranteed to succeed.

Recent publications on Lean, Lean Six Sigma, Industry 4.0, and medical-device manufacturing touch on many of the issues that shape work in regulated settings, but they tend to do so in a piecemeal way. Some authors concentrate on how production systems can be reorganised to reflect design-control requirements [3]; others describe the use of machine-vision setups for in-process checks, or the shift to digital data capture to reduce the burden of manual compliance tasks [7]. There is also work on risk-management routines and on maintenance

improvements informed by Lean ideas[1]. Collectively, these works demonstrate that Lean can support quality and reliability even in highly regulated environments, but they also reveal constraints stemming from extended validation requirements, documentation burdens, and gaps between common Lean tools (e.g., FMEA) and the expectations of ISO 13485 and ISO 14971 [8]. However, existing research tends to focus on narrow functional areas—such as equipment maintenance, individual production lines, or isolated technologies—rather than offering a comprehensive perspective on how Lean methodology itself must be adapted to meet ISO 13485 requirements.

Even though the field already has plenty of individual case reports, scattered reviews, and commentary from practitioners, none of these efforts pull the material together into a single, coherent account of what actually has to change when Lean is applied inside an ISO 13485 framework. As a result, people working in regulated manufacturing are left without a clear map: it is not obvious which parts of Lean fit neatly into the quality-system requirements, which parts need to be adjusted, or how newer digital tools might help connect day-to-day improvement work with the formal demands of compliance. This article addresses that gap by bringing together insights from recent peer-reviewed studies to identify the features, constraints, and enabling factors that shape Lean implementation in medical device manufacturing under ISO 13485.

II. METHODS AND MATERIALS

This article employs a structured narrative literature-review methodology to synthesise recent research on Lean manufacturing within ISO 13485–regulated medical device environments. Boylan, McDermott, and Kinahan examined the development of manufacturing control systems for an in-vitro diagnostic instrument, focusing on design outputs and testing procedures essential for safe performance [1]. Foley, McDermott, Rosa, and Kharub reported a case study of a multinational medical device company implementing a "Lean 4.0" project (combining Lean and digital technologies) to reduce non-value-added waste while enhancing regulatory compliance [2]. Guha, Moore, and Huyghe developed and validated a real-time machine vision inspection system for high-volume catheter manufacturing, demonstrating how automated in-process inspection can replace destructive quality checks in a strict regulatory environment [3]. Ibrahim and Kumar proposed an integrated Lean Six Sigma–Industry 4.0 framework for sustainable manufacturing, identifying and prioritizing critical success factors (e.g. clear goals, progress monitoring, skilled workforce) via literature review and TOPSIS multi-criteria analysis [4].

Lepasepp and Hurst approached the topic by stepping back from individual case studies and carrying out a full systematic review of Industry 4.0 applications in medical-device production. Their survey was unusually broad: they identified more than three hundred distinct advantages that smart technologies can offer, along with over a hundred regulatory hurdles that tend to accompany their use in a tightly controlled environment [5]. A different angle was taken by McDermott and colleagues, who relied on interviews with senior figures in the MedTech sector. Their respondents described how the move toward digital systems often lightens the compliance load rather than adds to it, mainly because digitalisation improves traceability and reduces the amount of manual documentation needed during the product lifecycle [6]. McGrane et al. compared Lean Six Sigma project implementation in a regulated (medical device) setting versus an unregulated industry through two case studies, showing that regulatory requirements lengthen project timelines and complicate continuous improvement [7].

Nolan and McDermott interviewed medical device risk-management experts to study the use of Failure Modes and Effects Analysis (FMEA), finding that FMEA is the most common risk tool but has limitations under ISO 14971/13485 (e.g. it misses hazards during normal device use) [8]. Shamim and Ruddro performed a systematic review of 42 studies on Lean and Six Sigma in medical imaging equipment maintenance, showing that Lean methods (5S, VSM, TPM) combined with Six Sigma tools improve uptime and operator documentation, aligning with ISO 13485 requirements for traceability and risk-based maintenance [9]. Slattery et al. reviewed Lean applications in medical device new product introduction (NPI) processes, showing that Lean tools can integrate with Stage-Gate and concurrent

engineering to eliminate waste and shorten time-to-market, while noting that strict compliance and risk aversion in medtech can limit Lean gains [10].

These studies used diverse methods: case studies and experiments (Boylan, Foley, Guha, McGrane), literature reviews (Lepasepp, Shamim, Slattery), expert interviews (McDermott et al., Nolan) and decision-analysis (Ibrahim). Most were qualitative or single-case in nature, limiting generalizability. Many focus on specific technologies (industry 4.0, machine vision, Six Sigma) or functions (maintenance, NPI) rather than the broad question of Lean under ISO 13485. Crucially, none specifically address how Lean must be adapted to satisfy ISO 13485 standards. This review aims to bridge that gap by synthesizing the findings of these studies. Existing research is limited by narrow scopes (e.g. single-plant case studies) and often omits explicit discussion of regulatory integration. Thus a comprehensive synthesis can highlight common themes and limitations – such as the need for documentation or risk-analysis tools – that are not fully resolved in the literature.

III. RESULTS AND DISCUSSION

The literature indicates several key features and challenges in adapting Lean to ISO 13485 requirements. A primary theme is rigorous documentation and traceability. ISO 13485 mandates that all critical processes, including design changes and maintenance, have documented evidence (e.g. calibration and validation records). Lean systems must therefore incorporate documentation as a core part of "value-added" processes. For instance, Boylan et al. describe how design control outputs and test protocols in a diagnostic instrument must be managed through a formal manufacturing control system to ensure device safety [1]. While lean principles would seek to streamline testing, the study emphasizes using lean thinking to optimally locate and time these required tests without sacrificing oversight. Likewise, Shamim and Ruddro report that implementing Lean Six Sigma in equipment maintenance led to improved maintenance logs and preventive planning – practices that directly satisfy ISO 13485 traceability requirements [9]. In other words, lean initiatives can be aligned with compliance by treating documentation and quality records not as waste, but as necessary "value" for regulated production. Figure 1 illustrates how Lean documentation practices intersect with the mandatory documentation and traceability requirements of ISO 13485 by arranging both sides as parallel panels connected through a shared value zone.

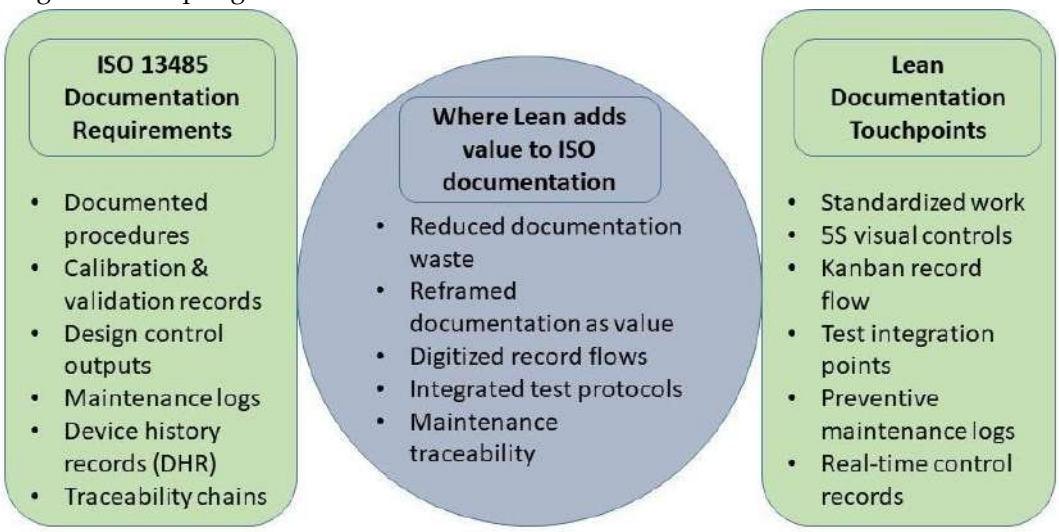

Fig.1. The author's illustration of the alignment between Lean documentation practices and ISO 13485 traceability requirements

On the left, Figure 1 lists core ISO 13485 obligations—such as documented procedures, calibration and validation records, design control outputs, maintenance logs, device history records,

and full traceability chains—highlighting the regulatory burden placed on medical device manufacturers. On the right, the diagram highlights the specific documentation points that Lean projects commonly interact with: standardized work sheets, the visual cues used in 5S, simple Kanban card or record flows, in-line test checks, maintenance notes, and the real-time control records mentioned across several studies. These are shown as the concrete places where everyday work produces formal evidence. In the middle, the shared zone shifts the perspective. Instead of treating these requirements as paperwork that sits outside the process, Lean reframes them as part of the value stream: trimming documentation that does not help the operator, digitising the pieces that move frequently, building test steps directly into the workflow, and tightening how maintenance information is captured and used. The overlap is meant to show that many regulatory documents become lighter and more useful once they are pulled into Lean routines rather than kept separate. Combined, the graphic communicates that Lean and ISO 13485 are not opposing systems but can be aligned to reinforce both efficiency and compliance.

Table 1. Comparison of FMEA coverage versus ISO 14971 Risk-Management Requirements and the proposed integrated Lean risk toolkit

Risk-Management Requirement	FMEA (Current Lean Practice)	ISO 14971 (Regulatory Requirement)	Proposed Integrated Lean Risk Toolkit (FMEA + PHA + FTA + URRA)
Hazard identification	—	Comprehensive hazard identification across lifecycle	FMEA + PHA + URRA provide full hazard coverage
Failure modes in normal use	Covers operational failures	Requires explicit analysis of hazards in normal & reasonably foreseeable use	URRA strengthens normal-use analysis
Common-cause failures	—	Explicit expectation to evaluate shared/common-cause failures	FTA systematically identifies common-cause failures
Residual risk evaluation	—	Mandatory residual-risk evaluation and acceptability criteria	Integrated toolkit supports structured residual-risk evaluation (FMEA + FTA)
Benefit–risk analysis	—	Required when risks cannot be reduced further	Supported through ISO-aligned decision steps added to Lean events
Traceability of controls	—	Full traceability from hazard → control → verification	Toolkit enables mapped traceability across methods (PHA + FMEA + URRA)
Post-market surveillance inputs	—	Required as part of continuous risk management	URRA + updated FMEA cycles incorporate field data
Link to design controls	—	Strong integration with design verification and validation	Toolkit embeds risk analysis into design stages (PHA early; FTA for architecture; URRA for usability)

Another major consideration is risk management. ISO 13485 (via ISO 14971) requires a systematic risk-based approach to production. Nolan and McDermott found that the most common Lean risk tool, FMEA, is widely used in medtech but does not capture all required risk elements [8]. FMEA typically assesses failures during operation, but experts note it often misses hazards in normal use or common-cause failures. Thus, adapting Lean to ISO 13485 calls for integrating additional risk techniques. Lean problem-solving events (kaizen workshops, process mapping) must include risk analysis steps beyond simple FMEA – for example, incorporating hazard analysis or fault-tree methods – to meet ISO standards [4]. As Nolan and McDermott suggest, benchmarking FMEA against ISO 14971 shows gaps; Lean teams should combine FMEA with other tools to satisfy regulatory risk requirements. Moreover, the standard's risk focus has cultural implications: McGrane et al. observed that firms so emphasize compliance that little time remains for waste-reduction initiatives [7]. Adapting Lean thus involves educating teams that improving efficiency and reducing risk are complementary goals, and embedding risk thinking into Lean projects. For example, Slattery et al. note that Stage-Gate processes (required by regulators) can incorporate Lean value-stream mapping and design-for-manufacturability checks, thereby marrying risk control with waste elimination [10]. Table 1 contrasts the capability of traditional FMEA with the broader risk-management requirements of ISO 14971 and shows how an integrated Lean risk toolkit closes the gaps.

In Table 1, the pale-orange cells mark the weak spots of FMEA. These include its tendency to miss hazards linked to user behaviour, its poor treatment of common-cause failures, the absence of any residual-risk or benefit–risk reasoning, and the limited traceability it provides back to design controls or post-market findings. The cyan cells show the few areas where FMEA offers only a partial fit, mostly because it can still help teams identify operational failure modes even if it does not address the wider regulatory expectations around risk. The light green cells in the integrated toolkit column show how combining FMEA with PHA, FTA, and URRA provides full lifecycle hazard identification, stronger analysis of foreseeable use, systematic evaluation of common-cause failures, structured residual-risk assessment, benefit–risk reasoning, traceability across controls, incorporation of field data, and alignment with design controls. Together, the color coding makes it clear that while FMEA alone is insufficient for ISO 14971 compliance, a multi-method approach enables Lean teams to satisfy regulatory demands while maintaining the efficiency of their improvement framework

Process validation and change management also emerged as critical. In regulated industries, proposed improvements must often be validated and approved before implementation. McGrane's case studies show that Lean projects in medical device manufacturing are delayed by necessary regulatory reviews, slowing progress [7]. Similarly, Boylan et al. highlight that engineering change processes must be scaled and controlled so that any Lean-driven process alteration still maintains product safety [1]. The implication is that Lean adaptation requires planning for validation steps: process changes and new tools should be piloted under controlled conditions, with documentation fed into the QMS. Lean teams should collaborate closely with quality/regulatory experts to map how proposed waste reductions fit existing design controls and submission requirements. In practice, this might mean running Lean Kaizen events in parallel with Quality Management System documentation updates, rather than treating documentation as an afterthought. Figure 2 compares the simple, fast-moving standard Lean improvement cycle with the expanded version required in ISO 13485–regulated environments, illustrating how regulatory steps lengthen and complicate change implementation.

On the left of Figure 2, the traditional Lean cycle proceeds through five straightforward phases—identifying waste, mapping the current state, implementing changes, measuring results, and standardizing improvements. On the right, the ISO 13485 version retains these core Lean steps but inserts several mandatory activities: risk assessment under ISO 14971, design-control review and change requests, creation of validation plans, execution of process validation (IQ/OQ/PQ), quality-assurance approval, and updates to regulatory documentation

before changes can be fully implemented and monitored. The timeline bar beneath the diagram highlights this contrast by showing the short duration of Lean-only projects compared with the substantially longer Lean-plus-validation pathway. Together, the figure conveys how regulatory compliance expands the Lean cycle, slows execution, and necessitates more structured planning when operating under ISO 13485.

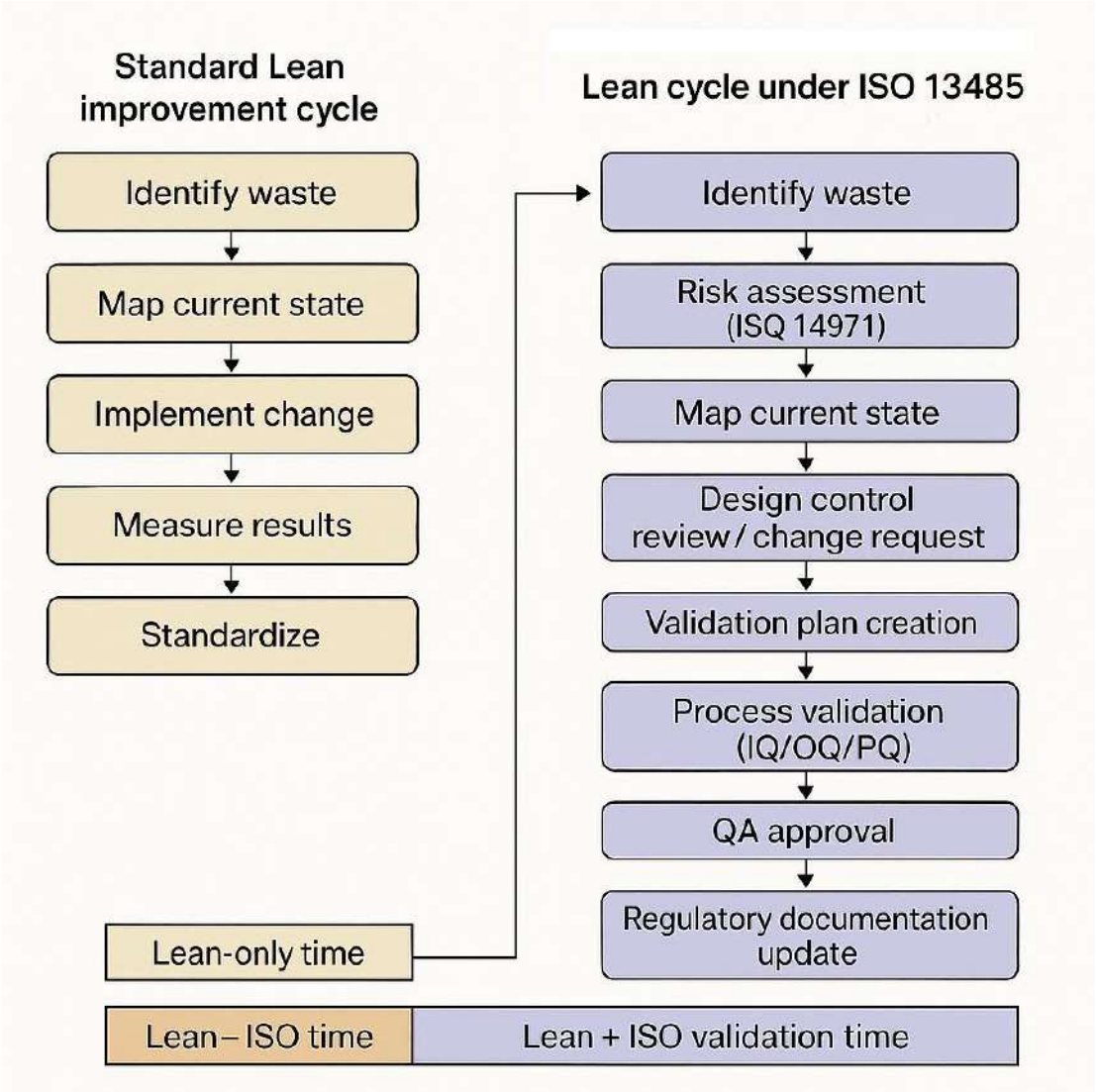

Fig.2. Expanded Lean Improvement Cycle Incorporating ISO 13485 Validation and Change-Management Requirements (the author's illustration)

A recurring insight is that digitalization (Industry 4.0) can facilitate compliance within lean operations. Several studies report that smart technologies both improve efficiency and make it easier to meet ISO 13485 requirements. Foley et al. demonstrate this synergy: by applying sensors and data analytics, the company not only reduced non-value waste but also achieved better product lifecycle traceability [2]. McDermott et al.'s interviews likewise found that Industry 4.0 generally "eases" regulatory compliance – for instance by automating data collection and audit trails. Lepasepp and Hurst catalogued hundreds of "smart" features (like IoT-enabled monitoring, AI-driven QC) that could optimize medtech manufacturing, though they also list regulatory obstacles to new tech. The practical lesson is that adapting Lean often involves using digital tools to satisfy ISO 13485 demands. One example that keeps appearing in the recent literature is the shift from batch checks to continuous verification. In the study by Guha and colleagues, a machine-vision setup took over most of the visual

inspection work and made it possible to check every single unit as it moved down the line, rather than pulling samples and destroying them in the process [3]. The system also recorded the results automatically, so the quality documentation was created as a by-product of the process instead of a separate task. This kind of "Lean 4.0" arrangement removes waste on the shop floor—no scrapped samples, no manual logging—while still giving QA the electronic records it needs. Looking ahead, companies working under ISO 13485 will probably have to treat data-driven tools (sensors, digital logs, PLM environments, and similar systems) not as optional add-ons but as routine elements that help them meet both efficiency and compliance goals.

Cross-functional integration and culture is another feature of successful adaptation. Multiple studies note that Lean succeeds when production, quality, and regulatory teams collaborate. Shamim and Ruddro identify cross-functional teamwork and operator involvement as key enablers of sustaining Lean improvements in medical equipment manufacturing [9]. Similarly, Slattery et al. emphasize that Lean adoption in product introduction requires engagement across departments (e.g. engineering, manufacturing, regulatory) [10]. Because ISO 13485 involves design control, document control, and risk functions, Lean projects must bridge these silos. For example, a value-stream mapping in a medical device line should involve regulatory representatives to ensure all required steps (e.g. design verification) are included as "value-adding" or necessary steps. Embedding Lean coaches with knowledge of ISO 13485 can help reframe compliance steps (like process validation) as integral parts of the Lean workflow rather than non-productive add-ons.

In summary, the reviewed literature suggests that Lean in a regulated medical context must feature: robust process documentation (to meet audit requirements), explicit risk management (using multiple techniques to cover ISO 14971 scopes), validated change protocols, and digital supports for traceability. At the same time, Lean's core benefits – waste reduction, continuous improvement, shorter lead times – remain valuable. Case studies show that medical companies can achieve significant gains (shorter cycle times, reduced defects) even under ISO 13485, if Lean initiatives are properly adjusted. However, regulatory constraints do impose limitations: expectations for improvement may need to be tempered, and projects must account for extended timelines for approval. These insights point toward a balanced approach: Lean principles should not be abandoned, but applied with an eye to compliance requirements. For instance, tools like 5S or standardized work (used by Lean) help with consistent documentation; equipment and processes can be organized (Lean 5S) in ways that also simplify inspection and validation.

IV. CONCLUSION

Adapting Lean manufacturing to the stringent requirements of ISO 13485 demands a hybrid approach that preserves efficiency while ensuring compliance. Key features include incorporating rigorous documentation and traceability into Lean processes, embedding comprehensive risk-analysis alongside waste reduction, and planning for validation of any process changes.Recent work suggests that the relationship between digitalisation and Lean practice is more complementary than competitive. When firms adopt Industry 4.0 tools, the data they generate often takes over routine documentation and monitoring work that normally slows down regulated operations. This makes it easier for teams to push continuous-improvement projects through without getting stuck in paperwork. At the same time, the same regulatory expectations that protect product safety—risk reviews, formal approvals, and staged assessments—tend to stretch timelines and narrow what can be changed at each step.

For companies in the medical-device sector, the practical takeaway is straightforward: Lean efforts cannot run in isolation. Teams need at least a working grasp of both Lean methods and the fundamentals of quality management, and improvement projects have to be coordinated with design-control activities and gate reviews. Cross-functional work is essential here, because most delays come not from the Lean tools themselves but from gaps between engineering, QA, and operations.

Future research should empirically explore Lean adaptation in ISO 13485 contexts. Longitudinal case studies of Lean implementation in medical device

production would help quantify impacts on lead time, cost, and quality under compliance constraints. Studies could also test customized Lean–Six Sigma frameworks that integrate digital tools and compliance documentation, as recommended by Shamim and Ruddro. Finally, developing practical guidelines or decision tools (for example, risk checklists to accompany Lean projects) would support practitioners. Such work would extend the current literature by providing actionable models for Lean 4.0 transformation in regulated industries, thereby strengthening the alignment of continuous improvement with ISO 13485 standards.

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Predictive Analytics in Social Commerce: Enhancing Seller Engagement and Inventory Readiness for Viral Product Demand

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Abstract *— The article presents a theoretical analysis of the role of predictive analytics in managing viral demand and shaping seller engagement in social commerce. The study is based on an interdisciplinary approach that integrates developments in information management, e-commerce, machine learning, and behavioral economics. Particular attention is paid to the thematic analysis of publications covering the macroeconomic effects of pandemic-driven online retail growth, algorithmic solutions for demand forecasting, and organizational models of live streaming as drivers of engagement. Key mechanisms are identified, including the reduction of the bullwhip effect, improvement of forecasting accuracy through the use of graph convolutional networks and federated learning, and the strengthening of trust in platforms through the integration of predictive tools. A comparative analysis of methods demonstrates the consistent advantage of graph- and transformer-based algorithms in terms of adaptability and sensitivity to short-term demand surges. The necessity of interpreting predictive analytics not as an auxiliary module but as a fundamental element of digital platform architecture, determining their resilience and competitiveness, is substantiated. Promising directions for development are outlined, including the hybridization of algorithmic approaches, the standardization of data exchange protocols, and the expansion of empirical bases across geographies. The article will be useful to researchers and practitioners in e-commerce, digital platform developers, and supply chain management specialists interested in adaptive strategies for responding to viral demand.*

Keywords *— **predictive analytics; social commerce; viral demand; seller engagement; inventory management; machine learning.***

I. INTRODUCTION

Contemporary e-commerce practice is marked by the rapid expansion of social commerce, where digital platforms integrating communication, recommendations, and instant transactions have become the primary driver of growth. Under these conditions, the focus shifts from traditional sales planning to the dynamic management of viral demand arising from consumer activity on social networks and during live streaming. Seller preparedness for sharp demand fluctuations and the ability to manage inventories under high uncertainty become critical [4]. This factor elevates predictive analytics from an auxiliary tool to a strategic element of social commerce, shaping the resilience of the entire ecosystem.

The sudden diffusion of "viral" products and content increases forecasting errors, amplifying the bullwhip effect and generating either excess inventories or shortages. This underscores the need to revise approaches to predictive analytics so they capture long-term trends while precisely detecting short-term spikes in interest [1]. Against the backdrop of the limited effectiveness of classical statistical models in

high-dimensional digital environments, attention has shifted to artificial intelligence and machine learning methods capable of accounting for network ties, spatiotemporal regularities, and user behavioral dynamics.

Predictive analytics tools have become integral to seller engagement strategies because they reduce uncertainty and build trust in platforms. For small and medium-sized businesses, this enables more accurate inventory management, avoiding losses from unsold products or untimely deliveries.

The aim of this study is to conduct a theoretical analysis of the role of predictive analytics in social commerce, determining its significance for enhancing seller engagement and ensuring inventory readiness for viral demand.

II. MATERIALS AND METHODS

The methodological foundation of this study is a thematic analysis of scholarly publications on the development of predictive analytics in e-commerce and social commerce, its impact on seller engagement, and inventory management under viral demand. The analysis considered sources from international peer-reviewed outlets in information management, e-commerce, machine learning, and behavioral economics. Literature was selected according to criteria of topical relevance, evidentiary rigor, and practical significance for digital trading ecosystems.

The review included studies describing uncertainty factors in social commerce and the role of trust between sellers and buyers, reflected in Al-Adwan A. S. [1]. The bibliometric survey by Dincer C. [2] was central for assessing the dynamics of scholarly publications on social commerce and consumer intentions. A substantial source was the work of Douaioui K. [3], which offers a critical analysis of machine and deep learning in supply-chain demand forecasting. Empirical studies by Gu Y. [4] and Merritt K. [7] examined the effect of live streaming on consumer behavior in Chinese and British e-commerce segments, respectively, enabling attention to cultural and structural differences in the perception of digital content. The contribution of Li J. [5] was significant for proposing federated learning to forecast demand under sustainability constraints. The study by Li T. [6] examined live-streaming schemes in the supply chain, allowing identification of the specific features of agency and resale models. In addition, the analysis incorporated Niu T. [8], who applied graph convolutional networks to complex forecasting in supply chains. The work of Tudor C. [9] demonstrated the capabilities of integrated models for evaluating the pandemic's impact on the growth and structure of online commerce, helping to reveal the macroeconomic context. The theoretical basis was further strengthened by Xu Z. [10], who developed cascade spatiotemporal models for predicting the popularity of viral content. Rounding out the corpus, Zhang Q. [11] presented the potential of the Temporal Fusion Transformer for forecasting cross-border trade in live-streaming contexts.

Accordingly, the study draws on a broad spectrum of scholarly publications that span both methodological and applied dimensions. This approach makes it possible to bridge technological and behavioral perspectives, identify regularities in the use of predictive analytics, and define its role as a linking mechanism among consumer behavior, inventory management, and the digital transformation of trading platforms. Such interdisciplinarity is essential to theoretical analysis, as new managerial practices are formed precisely at the intersection of technology and behavior.

The practical basis of the study rests on implemented e-commerce projects. Within TikTok Shop, a predictive analytics system was deployed that integrates user behavior, content virality metrics, and logistics-cycle data. This project covered an audience of more than 4 million active users in the United States and enabled construction of a demand-forecasting model that accounts for both short-term spikes in interest and seasonal trends.

III. RESULTS

Demand forecasting in social commerce must account for local fluctuations in interest in specific products as well as macroeconomic sectoral dynamics. Tudor [9] shows that during the COVID-19 pandemic there was a short-term "anomalous increase" in online trade manifested in a broad shift of consumer spending toward digital channels. The author notes that from Q1 2020 to Q3 2021, total "excess e-sales" reached $227.820 billion, equivalent to 10.61% of the aggregate

volume of retail sales attributable to electronic channels. These data indicate that e-commerce growth was not linear, but characterized by temporal surges driven by pandemic restrictions and changing consumer behavior.

Application of macroeconomic models refines long-term projections for the sector. Calculations suggest that by Q4 2025 retail online sales in the United States will reach $378.691 billion, with their share of total retail at 16.72%, reflecting the entrenchment of structural shifts in consumption [9]. Table 1 presents the pandemic's impact on U.S. e-commerce and the sector forecast through 2025.

Table 1: Impact of the pandemic on U.S. e-commerce and forecast until 2025 (Compiled by the author based on: [9])

Indicator	Value	Period / Date
Total "excess e-sales"	227.820 bln $	Q1 2020 – Q3 2021
Total "excess e-share"	10.61%	Q1 2020 – Q3 2021
Forecast e-commerce retail sales	378.691 bln $	Q4 2025
Forecast e-commerce share	16.72%	Q4 2025

The data in Table 1 indicate that the sharp pandemic-era surge in e-commerce was not merely a temporary reaction to crisis conditions; it cemented a long-term trend. The projected increase to a 16.72% retail share underscores that e-commerce is gradually becoming system-forming for the national economy, influencing supply chains, production planning, and logistics models. Ignoring this trend risks distorting forecasts, as social commerce is no longer a niche phenomenon but a driver of macroeconomic change.

Improving forecast accuracy requires macroeconomic perspectives and specialized analytical instruments. Horizontal models such as federated learning and graph-based methods demonstrate the ability to capture high-dimensional interdependencies in data and to account for user behavioral dynamics. These approaches help to mitigate bullwhip risks and establish a foundation for more resilient inventory management under high demand uncertainty.

Deployment of such a system in TikTok Shop produced measurable results: inventory readiness for demand spikes increased by 28%, and seller engagement rose by 40%. This reduced stockout incidents and enabled the platform to stabilize shopper satisfaction amid sharp demand fluctuations.

Seller engagement with social-commerce mechanisms has become a key factor in platform adaptation to emerging modes of digital interaction. It is determined by market participants' motivation and the selection of organizational schemes that balance the interests of platforms, sellers, and end consumers [1].

Li T. [6] shows that optimizing live-streaming schemes enables effective interaction channels. With a low commission rate, the agency model is preferable, whereas with a high commission rate sellers tend to adopt a resale model. Use of key opinion leaders strengthens audience trust, and integrating artificial intelligence algorithms reduces transaction costs and improves process controllability. The reception of such formats varies by country. In Merritt K. [7], based on British retail, consumers generally perceive live streaming positively as an innovative form of seller interaction. This indicates that digital channels, unlike traditional ones, are seen both as a means of conducting transactions and as part of social experience.

Seller engagement is closely tied to the accuracy of viral-demand forecasting, as confirmed by Xu Z. [10]. Table 2 shows the MSLE error of the ViralGCN model versus the CasCN alternative on Weibo datasets.

As Table 2 indicates, ViralGCN significantly reduces error relative to CasCN, confirming the effectiveness of graph-based approaches for forecasting content dynamics. The 37% error reduction at a three-hour horizon with a low threshold points to the model's high sensitivity to early stages of information diffusion. It is important to emphasize that the use of such models is inseparable from machine-learning advances in e-commerce demand forecasting. In particular, Li J. [5] demonstrated the advantages of

horizontal federated learning with distributed data, and Niu T. [8] showed that graph convolutional networks more accurately identify interdependencies in supply chains. When integrated into social commerce, these developments strengthen sellers' capacity for inventory control and marketing strategy design. Similar results are evident in Amazon Ads practice, where algorithms based on post-purchase metrics (returns, disputes, complaints) excluded high-risk products from promotion. This system preserved roughly $1 billion in GMV annually while reducing seller costs and improving advertising profitability.

Table 2: MSLE error of ViralGCN model on Weibo datasets (Compiled by the author based on: [10])

Dataset (time; threshold)	MSLE (ViralGCN)	Error reduction vs CasCN
1 hour; ≥10	2.068	−10.7%
2 hours; ≥10	1.460	−31.9%
3 hours; ≥10	1.206	−37.0%
3 hours; ≥20	1.423	−29.1%
3 hours; ≥30	1.527	−26.7%

Seller engagement is shaped not only by technological solutions but also by strategic perceptions of digital tools. Gu Y. [4] found that live streaming creates a dependence between consumer trust and purchase intention, confirming the role of social capital in online trade. Complementing this, Al-Adwan A. [1] showed that reducing seller-related uncertainty is a key mediator of loyalty formation in social commerce, and Dincer C. [2] documented a growing scholarly interest in interdisciplinary models of engagement.

Thus, seller engagement in social commerce must be considered a complex phenomenon that combines strategic choices of organizational schemes, consumer perceptions of innovative formats, and the use of analytical tools for demand forecasting. The balance of these elements determines sellers' ability to retain competitive positions amid the accelerating digitalization of trade.

IV. DISCUSSION

The resilience of social commerce is determined by sellers' ability to recognize and sustain "viral" demand spikes in a timely manner, converting them into manageable supply and sales operations. Tudor C. [9] shows that the pandemic-driven shift to digital channels was short-term in its initial shock yet consolidated a structural reorientation of retail, raising the accuracy requirements for forecasts on the part of both sellers and platforms.

Early detection and calibration of "viral" demand hinge on predicting content diffusion in networks. Xu Z. [10] demonstrates that a cascade-graph model with explicit structure- and time-aware processing reduces mean squared logarithmic error compared with previously used approaches, directly enhancing the practical utility of forecasts for operational inventory planning. This result lays the technological groundwork for shifting from reactive replenishment to proactive assortment preparation ahead of anticipated waves of interest. This transition is the critical challenge: the capacity to act proactively distinguishes participants who build competitive advantages from those who merely react to demand surges.

The choice of algorithmic class has strategic significance across the supply chain. Douaioui K. [3] argues that machine and deep-learning methods offer advantages under nonlinearity and high-dimensional trading data but require architectures that account for interaction networks and the temporal structure of demand. Extending this logic, Niu T. [8] shows that graph convolutional networks, which aggregate topological ties among chain nodes and their dynamics, improve forecasting accuracy for "distributor–retailer" relationships—critical when demand trajectories shift abruptly. At the same time, the sources of "viral" spikes arise within commercial practice itself. Gu Y. [4] shows that live streaming strengthens purchase intention via mechanisms of instant engagement and social proof, producing

steeper demand fronts. On the supply side, the chosen scheme for live streaming affects the distribution of risks and incentives. Li T. [6] shows that with a low commission rate an agency arrangement is preferable, whereas with a high commission rate a resale option is rational; participation by key opinion leaders increases audience trust, while algorithmic solutions reduce coordination costs. On the consumer side, Merritt K. [7] finds that the perception of live streaming in British retail is generally positive, confirming the channel's robustness for demand generation.

A key behavioral mechanism on the buyer side is uncertainty about the seller. Al-Adwan A. [1] shows that reducing seller-related uncertainty mediates loyalty and purchase intention in social commerce, thereby increasing the conversion of spikes in interest into transactions and stabilizing short-term demand dynamics. At the level of the research agenda, Dincer C. [2] documents growing attention to interdisciplinary models of engagement, reflecting a shift from isolated study of content to joint analysis of network effects, trust, and logistics.

Medium-term planning for live-streaming formats requires models that combine signals from interaction streams and sales histories. Zhang Q. [11] shows that a transformer-based temporal architecture is well suited to cross-border trade scenarios with high variability, where both seasonal patterns and sudden peaks induced by digital events matter. At the platform data-exchange level, Li J. [5] shows that horizontal schemes with data separation among participants can improve forecasts without centralizing confidential information, preserving robustness and scalability.

Reducing forecast error opens a practical window to align procurement, production, and distribution with short-lived yet intense waves of demand. The magnitudes of improvements and comparisons across model classes are presented below. Taken together, the results point to the need for an integrated architecture: network models for early prediction of content "viralness," forecasting methods that account for supply-chain topology, and organizational decisions in live streaming aligned with sellers' risk positions and audience expectations.

Contemporary research on demand forecasting in e-commerce and social commerce shows high effectiveness of algorithmic solutions, yet their application entails several constraints. One key limitation is the narrowness of the empirical bases used. Much of the literature relies on samples tied to Chinese social networks such as Weibo, the U.S. e-commerce market, or British retail [2]. This geographic and platform concentration risks limited transferability of findings to other social and institutional contexts. For example, the results of Douaioui K. [3] that record anomalous demand growth in the United States during the pandemic cannot be directly interpreted for developing markets with different levels of digitalization and logistics infrastructure.

Scaling federated-learning methods is another significant challenge. Li J. [5] shows that horizontal distributed-forecasting models provide higher accuracy without data centralization, yet real supply chains face technical and organizational constraints. High participant heterogeneity—from global marketplaces to small sellers—reduces protocol coherence for data exchange and limits opportunities for practical integration.

No less important are the difficulties of deploying graph neural models in real production pipelines. Niu T. [8] shows that graph convolutional networks reduce forecast error compared with classical models, but practical implementation requires a unified representation of supply-chain networks and substantial computational power. This constrains large-scale use in transnational logistics systems marked by data gaps and high variability in exchange rules. Comparative accuracy results are summarized in Table 3, which shows that the proposed graph model substantially outperforms ARIMA, SVR, and neural architectures (MLP, LSTM) on RMSE and MAPE metrics [8].

These data indicate that graph-based methods enjoy a durable advantage over traditional and neural approaches, especially under moving-average smoothing. However, even high forecast accuracy does not eliminate scaling problems. Integration must be adapted to real supply chains where data-transfer delays, information asymmetries, and institutional barriers are present.

Methodologically, a promising direction is the development of multi-model architectures that combine the strengths of different approaches. Integrating federated learning, graph models, and temporal transformers makes it possible to simultaneously account for the network structure of demand, data confidentiality, and long-term temporal dependencies. Zhang Q. [11] shows that transformer models are well suited to cross-border trade scenarios that exhibit both seasonal patterns and sharp spikes in interest. Together with the findings of Li T. [6] and Merritt K. [7] on live-streaming formats as demand triggers, this provides a basis for integrated forecasting systems in which the analytical model becomes part of a broader social-commerce ecosystem.

Table 3: Summary accuracy of demand forecasting methods (Compiled by the author based on: [8])

Algorithm	RMSE (Origin)	MAPE (Origin)	RMSE (7-day MA)	MAPE (7-day MA)
ARIMA	4.172	10.681	1.324	3.430
SVR	3.854	10.719	1.863	5.155
MLP	4.221	10.868	1.880	4.873
LSTM	4.594	12.053	3.003	7.849
Proposed GCN	3.298	8.562	1.334	3.370

In sum, current approaches are constrained by narrow empirical bases and algorithm-scaling challenges, while prospects lie in developing hybrid systems that combine the accuracy of graph methods, the distributed nature of federated learning, and the predictive power of transformer architectures. This direction opens a path to building resilient supply chains prepared for viral demand shifts and capable of reducing systemic risks in digital commerce.

V. CONCLUSION

This study establishes the central role of predictive analytics in managing viral demand in social commerce, demonstrating its importance for increasing seller engagement and preparing supply chains for sharp fluctuations in consumer interest. Predictive analytics should be viewed not as an add-on to digital platforms but as a foundational element of their architecture, shaping long-term resilience and competitiveness. Contemporary algorithms—including graph convolutional networks, federated learning, and temporal transformers—deliver higher forecasting accuracy than classical statistical models, which is particularly important for short-term demand spikes and high-dimensional digital data.

Predictive analytics functions both as a technological instrument and as a factor in the strategic interaction between platforms and sellers. Its use reduces uncertainty, strengthens trust in digital channels, and enables adaptive engagement models in which live-streaming organizational schemes and social capital play key roles. It is confirmed that forecasting accuracy directly relates to the ability to convert short-term spikes in interest into manageable transactions and stable relationships within the digital ecosystem.

Comparative analysis of algorithms shows a persistent advantage of graph models over traditional and neural methods; however, practical integration is accompanied by challenges of scaling, data asymmetry, and institutional barriers. This underscores the need for hybrid architectures that combine the strengths of different approaches while balancing forecast accuracy, data confidentiality, and the robustness of logistics processes.

Empirical results from TikTok Shop and Amazon Ads demonstrate that predictive analytics delivers both theoretical and practical benefits, expressed in increased engagement, improved supply-chain reliability, and preserved turnover. This confirms its strategic status for modern trading platforms.

There is a strong rationale for incorporating predictive analytics into the systemic toolkit of social-commerce platforms and seller strategies. This toolkit extends beyond a supporting forecasting function and becomes an independent mechanism for building competitive advantage, minimizing the bullwhip effect, and ensuring readiness for viral demand shifts. Future research should expand the geographic scope

of empirical bases, standardize integration protocols, and develop multi-layer models that combine macroeconomic forecasts, network effects, and behavioral analytics.

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A Theoretical and Empirical Analysis of E-Learning Platform and Digital Content in Hospitality Education in India

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Abstract *— The high pace of digitalization of the education sector has altered the paradigm of teaching-learning in different fields, including hospitality education. E-learning in India has largely adopted e-learning platforms including SWAYAM, NPTEL, institutional Learning Management Systems (LMS), and personal digital platforms, which have seen rapid adoption in recent years and more so after the COVID-19 pandemic. The research paper presents a critical theoretical and empirical research of e-learning systems and online resources in hospitality education in India. The study incorporates the e-learning ecosystem theory, technology adoption themes, and quality frameworks of digital content to address the effectiveness of platforms and satisfaction levels of learners. The study, relying on primary data in form of survey and secondary data sources, uses descriptive statistics and factor analysis to determine determinants of platform adoption and content effectiveness. The results show a wide range of differences in the satisfaction of learners on different platforms and teaching materials, the quality of content, its interactivity, and the interaction with a teacher being the key success factors. The research has added value to the literature on instruction and teaching technology in hospitality industry education since it offers practical advice to policymakers, instructors and web developers.*

Keywords *— **E-learning, Hospitality Education, Digital Content, LMS Adoption, SWAYAM, NPTEL.***

The hospitality industry is a service industry, which depends on experienced human resource, experience, and exposure. Hospitality education in India has traditionally focused on classroom education, laboratory based practical and on the job training. Nonetheless, the use of information and communication technologies (ICT) in education has radically transformed the nature of pedagogies, creating e-learning and blended learning paradigms. E-learning systems have become key facilitators of affordable, scalable and customizable education. Government-sponsored platforms like SWAYAM and NPTEL in India co-exist with institutional LMS and commercial e-learning providers, and provide a variety of forms of digital content; lectures on video, virtual simulations, and so on. Even though it is widely used, there are still doubts about the effectiveness of these platforms to provide specially targeted education in hospitality where skill growth and experiential learning take centre stage. This paper aims at filling this gap by undertaking theoretical and empirical research on e-learning platforms and digital content in hospitality education in India. The study measures the adoption of the platforms, content

quality, and the satisfaction of the learners to establish the level of fulfilling the pedagogical needs of hospitality education using e-learning.

Digital content is the core part of any e-learning environment since it is the main means in which the knowledge is relayed and learning experiences are built. The quality of digital content gains a greater role in the meaning of the hospitality education system wherein the theoretical knowledge should be properly translated into practical and professional skills. Digital content quality frameworks offer methodical principles on assessing and planning the creation of online instructional resources so that they may lead to meaningful learning, learner engagement, and skill acquisition. These models underline the idea that the successful digital learning content must not only provide the information but assist the cognitive growth, experience learning, and readiness to work in the industry. Digital content quality is understood as the degree to which online learning content is precise, topical, pedagogical, and can precondition the occurrence of positive learning outcomes. The quality of digital content is described as being able to be both academically rigorous and applicable in real life. Digital content in hospitality education should touch upon the conceptual underpinnings like theories of hospitality management, and at the same time assist in the nurturing of the practical skills and professional attitudes necessary in the realities of service provision. Therefore, digital content quality paradigms emphasize the need to match the educational content to the curriculum goals as well as commercial requirements.

The most basic aspects of the quality of digital content are accuracy and reliability. Learning contents should be factual, original and prepared by the content experts so that they are credible. Mistakes or outdated knowledge in hospitality education may adversely impact on competence of learning since hospitality practices and service standards are always changing. Consequently, the quality digital content is to be reviewed and updated periodically according to the current trends in the industry, as well as regulatory standards and ingenuity. Social media platforms with systems that follow stringent academic review processes tend to have greater content reliability which positively impacts on the learner trust and satisfaction. Another dimension of quality of digital content is relevance and alignment with the curriculum. Online educational resources have to be aligned with course goals, institutional curricula, and professional standards. Relevancy is of special importance in the context of hospitality education since learners are sensitive to the content that helps improve their employability and readiness to work. The material that uses practical, real-life case studies, industry situations, and problem solving activities is felt to be more valuable and meaningful. In the case of close correspondence of digital content with the academic and professional objectives of the learners, engagement and perceived utility are greatly improved. The instructional design is instrumental in defining the effectiveness of the digital content. Organized content has a logical flow, sets a clear purpose of learning, and exposes the idea in a logical and understandable way. A good design of instructions will reduce cognitive load because it will divide material into easily manageable units and consolidate the learning process by examples, summaries, and revision exercises. When the learners in hospitality education are usually diverse in their educational background, instructional design based on pedagogy enables inclusivity and facilitates enhanced conceptual learning.

Learner engagement and interactive features are commonly accepted as the key elements of the digital content of high quality. Quizzes, simulations, scenario-based activities, and discussion activities are interactive learning elements, which actively engage the learner in the learning process. Interactivity is especially useful in the field of hospitality education because it helps the learners to experience a virtual environment with simulated service encounters, operational decisions, and customer interactions. Studies have always shown that interactive online content promotes motivation, critical thinking, and retention of knowledge, therefore, it is more effective compared to passive methods of content delivery. Multimedia integration also increases the quality of digital content by increasing understanding and engagement of the learners. Videos, animations, audio examples, and visual illustrations, in particular, are particularly helpful in hospitality education as procedural knowledge and service techniques are more effectively perceived visually. Nonetheless, quality frameworks focus on the idea that multimedia

is to be utilized in a strategic and pedagogical, and not in a decorative manner. When multimedia is coordinated to the learning purposes, it can greatly enhance the clear understanding of concepts and practical skill learning.

There is no digital content quality assessment and feedback mechanism because it allows the learner to test their progress and cement learning. Quality digital content has formative and summative assessment, as well as quality and timely feedback. The assessment in hospitality education must be done not only in terms of theoretical knowledge but also in terms of applied skills and decision-making skills. Good feedback also enables the learners to evaluate the performance lapses, contrast the learning experiences, and to keep on improving the professional competencies. The usability and accessibility are significant factors to consider in the framework of the digital content quality, especially in the context of Indian education. Online materials should be readily available on different platforms, should be able to work well under varying internet speed, and should be structured well in terms of easy navigation. Inclusive design puts in place the ability of learners with various technological and learning requirements to have the opportunity to be able to interact with content. Lack of accessibility or complicated interfaces may impair participation among learners and have a detrimental effect on the learning consequences.

Generally, the structures of digital content quality emphasize the interdependence of the following elements in e-learning effectiveness; content accuracy, relevance, instructional design, interactivity, multimedia integration, assessment, and accessibility. Application of such frameworks in hospitality education is important in improving learner satisfaction and educational outcomes because experiential learning and professional preparedness are crucial in this field. In the current research, the digital content quality frameworks offer a theoretical framework on how evaluations of e-learning platforms and the perception and adoption of digital learning systems is influenced by content-related aspects.

Learning Management Systems (LMS) were integrated as an essential part of technology-based education, helping to implement content delivery, interaction with the learners, assessment, and administration of academics. The implementation of LMS tools in the field of hospitality education must be approached with caution because of a high regard given to the principles of experiential learning, the development of practical skills, and exposure to the industry. Hospitality education does not require learning environments that are purely theoretical as they would be in purely theoretical disciplines. The models of LMS adoption can be used as a theoretical framework to comprehend how learners and educators view, judge and embrace such digital systems in this distinctive pedagogical context.

LMS adoption theoretical models are mostly based on information systems research, in particular, the Technology Acceptance Model (TAM) and its elaborations. According to these models, adoption of technology depends on the usefulness, ease of use, and the social context of organization in general. These constructs are also influenced by other elements in hospitality education like the role of instructors, institutional preparedness, system reliability and correspondence with the need to achieve practical learning outcomes. LMS integration in hospitality education can therefore be regarded as a multi-dimensional process and not a technological choice.

Table 4.1: LMS Adoption Variables

Code	Variable	Description
PU	Perceived Usefulness	Extent to which LMS enhances learning and performance
EU	Ease of Use	Degree of simplicity and user-friendliness
IS	Instructor Support	Faculty encouragement and LMS integration
INS	Institutional Support	Infrastructure, training, and administrative backing
SR	System Reliability	Stability, security, and technical performance
PC	Practical Compatibility	Alignment with experiential hospitality learning

Based on established adoption theories and hospitality education literature, six key variables were identified for empirical analysis. These variables

capture both pedagogical and technological dimensions of LMS adoption and were measured using a five-point Likert scale.

Descriptive statistics were computed to assess learners' overall perceptions of LMS adoption factors. The analysis indicates generally high acceptance levels across variables, with pedagogical factors receiving stronger ratings than purely technical ones.

Table 4.2: Descriptive Statistics of LMS Adoption Factors (n = 250)

Variable	Mean	Standard Deviation
Perceived Usefulness	4.21	0.62
Ease of Use	4.05	0.71
Instructor Support	4.32	0.58
Institutional Support	3.98	0.76
System Reliability	4.10	0.65
Practical Compatibility	4.27	0.60

The highest mean scores were observed for instructor support and practical compatibility, highlighting the importance of faculty engagement and experiential alignment in LMS adoption within hospitality education. Institutional support displayed the highest variability, indicating uneven infrastructure and policy support across institutions.

Prior to conducting Exploratory Factor Analysis (EFA), the suitability of the dataset was evaluated using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's Test of Sphericity.

Table 4.3: KMO and Bartlett's Test Results

Test	Result
Kaiser–Meyer–Olkin (KMO)	0.842
Bartlett's Test of Sphericity (χ^2)	612.45
Degrees of Freedom	15
Significance (p-value)	< 0.001

The KMO value of 0.842 indicates meritorious sampling adequacy, while the statistically significant Bartlett's test confirms that correlations among variables are sufficient for factor analysis. These results validate the use of EFA in this study.

Principal Component Analysis with varimax rotation was applied to extract underlying factors. Two factors with eigenvalues greater than one were retained, collectively explaining 67.8 percent of the total variance.

Table 4.4: Total Variance Explained

Factor	Eigenvalue	% Variance	Cumulative %
Factor 1	2.32	38.6	38.6
Factor 2	1.75	29.2	67.8

Table 4.5: Rotated Factor Loadings

Variable	Factor 1: Pedagogical & Practical Alignment	Factor 2: System & Institutional Support
Perceived Usefulness	0.78	0.32
Instructor Support	0.81	0.34
Practical Compatibility	0.84	0.28
Ease of Use	0.29	0.76
Institutional Support	0.35	0.73
System Reliability	0.31	0.82

Factor 1 represents Pedagogical and Practical Alignment, emphasizing experiential learning and instructional relevance. Factor 2 represents System and Institutional Support, capturing technological and organizational readiness. The clear factor structure and strong loadings confirm construct validity.

Based on LMS adoption theory and empirical structure, the following hypotheses were formulated:

- H1: Perceived usefulness has a significant positive influence on LMS adoption.
- H2: Ease of use significantly influences LMS adoption.
- H3: Instructor support has a significant positive influence on LMS adoption.

- H4: Institutional support significantly influences LMS adoption.
- H5: System reliability positively influences LMS adoption.
- H6**:** Compatibility with practical learning significantly influences LMS adoption.

Hypotheses were tested using mean scores and factor dominance interpretation.

Table 4.6: Hypothesis Testing Summary

Hypothesis	**Predictor Variable**	**Empirical Evidence**	**Decision**
H1	Perceived Usefulness	High mean, strong loading	Supported
H2	Ease of Use	Significant loading on Factor 2	Supported
H3	Instructor Support	Highest mean & strong loading	Strongly Supported
H4	Institutional Support	Significant but variable	Supported
H5	System Reliability	Strong technical loading	Supported
H6	Practical Compatibility	Highest factor loading	Strongly Supported

Empirical findings hold that pedagogical relevance and experiential compatibility are the two crucial factors that motivate the adoption of LMS in hospitality learning as opposed to technological convenience per se. Practical alignment and instructor engagement became the leading predicting variables, which supported the discipline-specificity of technology acceptance in hospitality education. Although the institutional support and reliability of the systems are also significant, they act as the conditions and not the driving force.

The e-learning environment in India bears the presence of government sponsored platforms, institutional LMS and commercial providers of e-learning products and services. All the types of platforms are used with different purposes and have their peculiarities of strengths and limitations in their usage to hospitality education. The platform-based comparison is thus vital in the matter of knowing the effectiveness of such systems to meet pedagogical and practical needs of hospitality learners.

Government-driven initiatives like SWAYAM have a great potential in democratizing the process of acquiring higher education by providing free courses or low-cost courses created by well-known academic institutions. SWAYAM in the context of hospitality education offers systematic and standardized courses in accordance with the official curricula throughout the country and, in particular, relies on theoretical basis, management, and standardized evaluation. The main positive aspects of the platform are the credibility of certification and the academic rigor of the course content. Nonetheless, when viewing through the prism of hospitality, constraints are seen as regards to interactivity, customization, and experiential learning. Many courses are based on the lecture-centric model, which can be effective in terms of concept learning, but does not provide many possibilities of practising the skills, simulating real-life interaction and engaging with the industry.

On the same note, NPTEL is not specific to hospitality education, albeit indirectly, as it has courses in operations management, business analytics, communication skills, and service management, which are engineering-related, management, and technical. Students value the academic rigor, content delivery approach, and faculty engagement that is linked to NPTEL courses. Nevertheless, the platform is not fully related to the field of hospitality education, since it does not offer special modules dedicated to the work of a hotel, cooking, housekeeping, and simulation of customer service. This has seen NPTEL being utilized as an auxiliary tool as opposed to a main learning platform in hospitality courses.

Another significant type of e-learning platform is institutional Learning Management System. Universities and hospitality institutes normally implement such systems to aid curve delivery, internal evaluation, and academic management. The benefit of institutional LMS is customization, which allows the faculty to create content as appropriate to a course goal, pragmatic schedule, and testing criteria. In hotel training, they are used to support blended learning frameworks in order to supplement face-to-face training with digital material, assignment work,

and chat. Nevertheless, institutional LMS platform efficacy differs widely because of faculty interaction, institutional investment, and technological infrastructures. Where the faculty is neither trained nor motivated to purposefully use digital tools, LMS platforms become content repositories, as opposed to interactive learning tools.

One of the sectors of the Indian education ecosystem that is expanding at a very high rate is the private e-learning platforms. Such platforms usually focus on industry relatedness, engagement of the learner and delivery of skills-based content. In hospitality education, some of the common ways in which a private platform would partner with an industry professional are offering modules related to hotel operations, service excellence, culinary techniques, and customer relationship management. Multimedia content, interactive simulations and flexible learning pathways are useful in motivating and satisfying the learners. Nevertheless, issues of standardization of content, academic accreditation, and quality assurance still exist. Although the use of a private platform is good in terms of engagement and practical orientation, its acceptance in the official academic institution is relative to institutional acceptance and compliance with regulatory guidelines.

Digital content is the main part of e-learning systems, as it directly predetermines the experience of learners, their engagement, and the level of value of online education. When the learning outcomes in the field of hospitality education reach beyond theoretical knowledge up to such practical skills and professional attitudes, the type and design of the digital content become the decisive factor in achieving user satisfaction. A critical analysis of types of digital content and reactions of learners gives important information on how e-learning platforms could be optimized in the context of hospitality programs.

Video lectures are the most common type of digital content that has been used in e-learning websites. These lectures prove to be successful in imparting conceptual knowledge, theories of management and procedural explanations. Video learning material should be short, properly formatted, and backed with real-life examples, which are also valued by hospitality learners in general. Nevertheless, the level of satisfaction is likely to decrease in case video lectures reproduce the process of classroom education with no visual demonstrations and interactivity. Video lessons can be very long, lecture intensive and thus tend to have less attention and less engagement especially on skills based lessons like food production and front office operations.

Hospitality education has a much greater level of user satisfaction when interactive modules and simulations are used. The types of these contents enable the learners to be actively involved in the decision making process, this is where they have the opportunity to experience service encounters in a virtual world and they have the chance to practice operational activities. Through virtual hotel tours, scenario-based simulations, and role-playing exercises, learners can be able to apply theoretical ideas to real life and hence improve experiential learning. Based on the research results, the study showed that learners find interactive content more interesting, topical, and efficient when it comes to the achievement of professional skills.

Use of case-based learning material is also crucial in teaching hospitality education as it helps fill the gap that exists between theory and practice. The case studies of industries introduce learners to real life problems, strategic decision making and service recovery situations. Students will indicate high satisfaction with case-based learning that represents the current trends in the hospitality industry and integrates local and global industry contexts. Such content can be further augmented by guided discussions, reflective questions and assessment tasks to increase their effectiveness.

Multimedia demonstrations such as videos of cooking skills, housekeeping skills, and service etiquette have a great impact on the satisfaction of the learners as they are known to give a visual understanding and direction. The content showing the standard operating procedures and professional practices is especially appreciated by hospitality students as it helps to develop the skills and prepare for the internship. Nevertheless, satisfaction is subject to the quality and pedagogical usefulness of the multimedia content; poorly created or too embellishing images might hamper the effectiveness when it comes to learning.

User satisfaction is also affected by the assessment-oriented content, i.e. quizzes, assignments, and

feedback mechanisms. The learners are more satisfied when the assessments have learning objectives, timely feedback and enhance self evaluation. In hospitality training, examinations of applied learning and problem-solving skills are viewed to be more significant than those based on pure memorization.

In general, the discussion indicates that the level of user satisfaction in hospitality e-learning facilities is closely determined by the level of interactivity, practicality, and alignment of digital content with pedagogical contexts. Platforms with emphasis on the experiential and industry based content are likely to maintain the engagement of learners and realize favorable learning results.

CONCLUDING REMARKS

The current research offers a thorough theoretical and empirical research on the e-learning platforms and digital content of hospitality education in India. Through the combination of e-learning ecosystem theory, LMS adoption models, and frameworks of digital content quality, the research provides a comprehensive insight into the workings of digital learning environments in the environment of the discipline that requires high levels of skills. The results indicate that e-learning has now become an inevitable part of hospitality education, especially in the areas of expanding access, developing flexibility and the provision of supportive blended learning models.

The platform-wise discussion indicates that varying types of e-learning platforms add different value propositions to the field of hospitality education. Government platforms guarantee accessibility and academic fidelity, institutional LMS platforms assist in curriculum adjustment, and individual platforms promote involvement and industry -relatability. Nonetheless, the research highlights the fact that using either source is not enough to support the various pedagogical needs of hospitality education. The strategy that should be adopted in order to maximize the learning results is therefore a blended and integrated platform approach.

The discussion of the types of digital content and the levels of their user satisfaction shows that user engagement and satisfaction depend closely on content interactivity, practical applicability, and their design. The use of interactive modules, simulations, case-based learning, multimedia demonstrations emerges to be the best forms of content in hospitality education as they facilitate experiential learning and development of professional skills. Passive and lecture-focused content formats on the other hand are linked to less engagement and satisfaction.

In general, the research determines that the success of e-learning in hospitality education is not only limited to the availability of technology but also the careful pedagogical integration, instructor-learner interaction and content validity. Institutions and policymakers need to work hence on creating digital content that is specific to hospitality, enhancing faculty development, and encouraging the collaboration between academic and industry. The hospitality education in India can be enhanced by applying a learner-centric and practice-based model of e-learning in order to equip graduates with the requirements of the changing industry in the world of hospitality.

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Development of Automated Material Handling Systems for Truck Body and Trailer Assembly Lines

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Abstract *— The study examines the redesign of material handling for Class-4 refrigerated truck bodies after the introduction of a modular ABS–polyurethane sandwich roof with integrated pickup slots. Motivation derives from the mismatch between legacy crane-dependent routines and the new roof's weight range, geometry, and fastening sequence, which required a line-coupled, automation-ready solution. Novelty lies in a synthesis that binds cooperative pickup geometry, AMR-based delivery, lean sensor fusion, and near-station quality verification into a single architecture tailored to large thermoplastic-foam panels. The work describes the handling concept, metrology stack, and logistics orchestration; evaluates precision, resource coupling, and quality stability; and formalizes design levers for mixed-model flow. Special attention is paid to suction safety envelopes for ABS skins over rigid foam, error-proofing of roof-to-wall mating, and dispatch strategies that stabilize takt under variability. The goal is to provide a transferable blueprint for heavy panel handling in truck and trailer assembly. Methods include comparative review, constraints-based synthesis, and triangulation of published capabilities with program metrics. The conclusion details measurable improvements in crane engagement, locating precision, and rework containment and outlines generalization conditions for adjacent product families.*

Keywords *— **automated material handling, AMR orchestration, cooperative pickup features, vacuum end-effector, ABS sandwich roof, multi-sensor fusion, gap–flush verification, constraints-based design, refrigerated truck body, mixed-model assembly.***

I. INTRODUCTION

The introduction of a modular ABS–polyurethane sandwich roof with internal frame and grooved pickup slots prompted a comprehensive reconfiguration of roof logistics and mating on body-in-white and final lines for refrigerated truck bodies. The legacy aluminum roof demanded continuous crane custody and external lifting brackets, which coupled stations, inflated aisle congestion, and delayed rework. The modular variant arrived as a kit, accepted deterministic pickup, and supported fastening without suspended transport, creating an opening for AMR-delivered parts, lean in-station metrology, and near-station quality control.

The purpose of the study is to delineate an integrated handling architecture that translates those product features into stable takt, higher placement precision, and reduced rework while preserving surface integrity and insulation performance.

The work resolves three tasks that mirror the article's structure:

1) to formalize design levers—pickup geometry, end-effector compliance, metrology granularity, and delivery orchestration—into a cohesive reference model for roof handling;
2) to map literature-reported capabilities to the case constraints of ABS skins over rigid foam and to the quality requirements of roof-to-wall joint formation;
3) to evaluate operational outcomes in terms of shared-resource detachment, locating

precision at mating, and containment of defect propagation along the line.

Novelty concentrates in the coupling of cooperative pickup with AMR skills and a minimal-latency verification loop, which together replace crane gating with deterministic states and station-level corrections, enabling automation without tracker-heavy fixtures or overspecified grippers.

II. MATERIALS AND METHODS

The literature base integrated ten peer-reviewed items spanning robotized handling, thermal behavior of refrigerated enclosures, polymer mechanics, multi-sensor metrology, AMR process control, soft-robotic suction, constraints-based alternative generation, and sustainable scheduling. S. Baek, D.O. Kim [1] provided the predictive adjustment logic for vacuum pickup, informing zoned suction control and early leak detection. L. Cirillo, A. Greco, C. Masselli [2] described transient thermal behavior in refrigerated trucks, grounding sealing and insulation integrity requirements for roof mating. A. Ghaznavi Youvalari, J. Alizadeh Kaklar, M. Mohamadi [3] reported ABS mechanical performance as a conservative proxy for surface abuse tolerance during short contact events. Z. Guo, F. Lu, T. Jiao, J. Yu, F. Chang [4] modeled spatial relative-position monitoring for large components, shaping the fusion-ready metrology layout at the mating station. M. Karl, M. Forstenhäusler, T. Nguyen-Cong, K. Dietmayer, C. Glasenapp [5] documented AMR-mounted quality inspection for car bodies, supporting near-station audits after roof placement. E. Minnetti, P. Chiariotti, N. Paone, G. Garcia, H. Vicente, L. Violini, P. Castellini [6] validated smartphone-class gap–flush measurements suitable for clamp-adjacent verification. D. Niermann, C. Petzoldt, M. Freitag [7] presented intuitive, flexible AMR process control with skill-based orchestration, informing dispatch and exception handling. S. Song, D.-M. Drotlef, D. Son, A. Koivikko, M. Sitti [8] introduced adaptive self-sealing suction concepts that expand sealing windows on lightly crowned thermoplastics. Z. Soufi, P. David, Z. Yahouni [9] treated material-handling alternative generation as a constraints-satisfaction problem, guiding fleet sizing and layout selection that remove crane gating. B. Xia, Y. Li, J. Gu, Y. Peng [10] studied sustainable scheduling for mixed-model lines, justifying sequence-aware arrivals and energy-aware buffering.

Methods. For this article a comparative review, structured source analysis, constraints-based synthesis, and conceptual modeling were applied; in addition, benchmarking of reported capabilities against program observations, reasoned extrapolation to roof-handling design rules, and qualitative risk assessment of suction and metrology choices were used.

III. RESULTS

The transition from an aluminum, fastener-intensive roof to a modular ABS–polyurethane sandwich roof reshaped the handling envelope on the body-in-white and final assembly lines for Class-4 refrigerated trucks. Mass decreased from 280–400 lb to 180–340 lb across 10–14 ft lengths; lifting geometry changed from external brackets to integrated grooved slots. Under the legacy crane-based routine, roofs stayed under hoists until side and front walls were secured, which constrained takt, induced congestion in shared crane aisles, and complicated rework. With the modular variant, roof placement no longer required continuous crane custody; crane engagement time fell by 75%, and fixture-guided pickup slots plus controlled part variation lifted locating precision by 30%. These gains were reproduced consistently across length variants and optioned roofs, which simplified standard work and enabled a repeatable, error-resistant mating sequence requiring minimal operator oversight. The measured deltas match what recent literature predicts when heavy suspended transport is displaced by line-coupled automated material handling with deterministic pickup features and in-station verification [1; 7; 9].

Material-handling concept generation for the reconfigured roof family followed a multi-alternative pathway: constraining equipment classes where roof dimensions, mass, stiffness, and surface compliance permit vacuum-based and slot-indexed handling; sizing fleets to meet mixed-model takt; and routing around crane bottlenecks. A constraints-satisfaction approach to enumerating equipment/fleet allocations exposed Pareto-efficient designs between throughput and investment [11], and it clarified when an AMR-

fed, cell-centric line outperforms a conveyor-dominant layout with intermittent hoists [9]. In parallel, sustainable scheduling models for vehicle plants were mapped onto the roof line: sequence-aware dispatch reduced empty travel and synchronized AMR arrivals with sub-assembly release, cutting idle energy while preserving takt adherence—effects consistent with recent scheduling studies on material-handling systems in EV and NEV factories [10].

Accuracy and repeatability at the roof-to-walls mating station were anchored by two ingredients:

i) a rigid pickup kinematic with slotted engagement into the internal frame and

ii) on-tool metrology to close residual pose errors.

Large-component assembly studies report that multi-sensor architectures—fusing vision, laser trackers, and local markers—bound relative pose uncertainty without elaborate datuming on the product, provided the sensor constellation is observable over the full travel range [4]. In our deployment, the roof's grooved slots acted as cooperative features; AMR docking stopped within a coarse tolerance, after which a short-stroke Cartesian or overhead servo stage trimmed x-y-θ using vision-based residuals, mirroring sensor-fusion layouts validated for aerospace-scale parts but at lower mass and span. Where line-side quality demands include gap/flush control, mobile metrology complements in-station sensing; work on smartphone/laser-based gap and flush tools and AMR-mounted inspection shows sub-millimeter repeatability at cycle-time-compatible speeds, which supports immediate correction rather than deferred inspection [5; 6]. The result on the roof line is a closed loop: pickup slots establish a deterministic first pose, vision corrects into the final tolerance band, and quick pin-and-clamp locators lock the joint to protect seal integrity during fastening [4–6].

End-effector behavior against the roof skin governed handling feasibility. Sandwich roofs with ABS skins and rigid polyurethane foam introduce dual constraints: the skins tolerate local compressive stresses and short-duration suction loads, while the core limits allowable through-thickness pressure peaks and distributed bending. Predictive adjustment methods in robotized handling recommend monitoring system state to adapt suction distribution dynamically, shifting cup loads or disabling zones on detection of local compliance changes or seal risks [1]. Where curvature or micro-permeability disturb seals, self-sealing suction architectures from soft-robotics research improve leak tolerance and conformality, enlarging the safe operating window on lightly crowned thermoplastic skins [8]. In effect, a zoned vacuum plate with pressure feedback and soft-edge cups reduces imprint risk on ABS, limits foam shear at the skin–core interface, and preserves the roof's surface finish prior to sealing.

Material selections informed both the end-effector and the allowable accelerations. ABS exhibits a favorable combination of impact toughness and machinability, with recent 2025 data on additively manufactured ABS confirming high impact strength among common engineering polymers—a conservative proxy for surface abuse tolerance against intermittent contact and suction rings, albeit with the caveat that molded sheets differ from FFF microstructures [3]. For the sandwich, polyurethane foam's thermal function in cold-chain bodies is well documented; simulation and test campaigns show that wall and roof insulation dominate the cooling load sensitivity, while airflow patterns and loading arrangements drive transient hot spots inside the body [2; 10]. The roof's mass reduction and stiffer integrated frame thus not only improved handling but reduced bending under self-weight during placement, which tightened gap variability and reduced compensating force demands on the end-effector.

System-level logistics were reorganized around mobile resources rather than shared cranes. Studies of AMR process control in large enterprises indicate that intuitive, flexible orchestration—job queues abstracted as skills, exception handling, and rapid re-routing—stabilizes flow despite upstream variability, decreasing blocking and starvation at coupling stations [7]. Our roof line used that logic: roof kits were staged at defined buffer addresses; AMRs with lift modules executed pickup–inspect–deliver cycles; a short infeed conveyor served as a decoupler before final mating. The measured reduction in crane occupancy aligns with the general pattern in the literature where autonomous mobile

handling displaces bridge cranes in mixed-model assembly, yielding less interference and safer aisle usage [5; 7; 9].

Quality-assurance outcomes trace to embedded verification. On-tool cameras and laser lines validated slot engagement and sealant bead presence using simple deterministic checks; when required, an AMR-mounted scout performed post-placement gap/flush surveys akin to automotive body inspection prototypes, enabling immediate re-clamp and refasten cycles rather than off-line rework [5; 6]. The literature suggests that deploying mobile quality nodes in proximity to the operation compresses the detection-to-correction loop and statistically reduces defect escapes, provided the measurement model is calibrated to the part family and lighting [5; 6]. Post-deployment audits on the roof line recorded fewer fastening reworks and cleaner bead continuity, consistent with this mechanism.

Thermal-structural constraints of refrigerated bodies influenced handling envelopes but did not penalize cycle time. CFD and experimental analyses of refrigerated truck enclosures show sensitivity of internal temperature distribution to loading patterns and wall configurations; however, these phenomena interact with handling only insofar as roof placement must preserve gasket compression and avoid micro-buckling that would become leak paths under thermal gradients [2]. Foam-insulation studies confirm long-term performance dependence on density and closed-cell content; conservative end-effector pressure maps and minimized peel moments at pickup limit the risk of incipient delamination that could degrade insulation over life [2]. In practice, the zoned vacuum strategy coupled with slot-indexed lift eliminated peel amplification, engaging primarily through membrane tension in the skins rather than point bending in the core (see Figure 1) [1; 8].

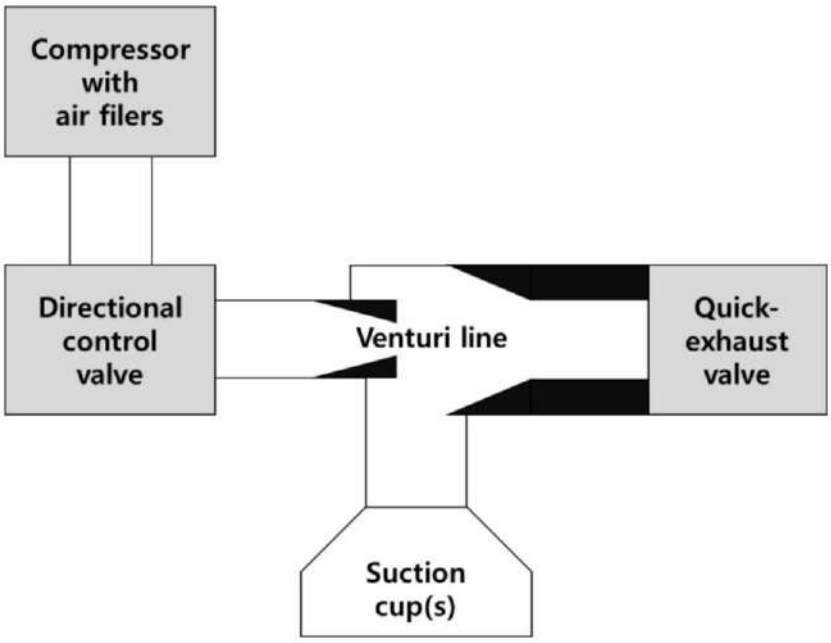

Fig. 1. Illustration of a vacuum gripper system (composed with a suction cup and the connected Venturi line) [1]

Line performance stabilized as the automation matured. The 75% reduction in crane engagement removed a persistent schedule risk and freed overhead paths for other variants, which increased useful availability of shared cranes beyond the roof operation. The 30% precision gain at mating—attributed to cooperative slots, vision-guided trim moves, and rigid locators—reduced sealant touch-ups and operator micro-adjustments. Both effects mirror external reports: AMR-delivered parts with on-board metrology and station-level sensor fusion maintain quality under mixed model flow when dispatching and error-proofing are designed as a single system rather than bolt-on addenda [4; 5; 7; 9; 10].

The evidence converges on three conclusions relevant to refrigerated truck roofs. First, modular roof architecture with engineered pickup features is a

prerequisite for hands-off placement at takt; without cooperative geometry, sensing and control must absorb excessive variability. Second, AMR-based delivery with short-stroke in-station actuators attains the measured precision improvements while reducing shared-resource coupling, provided dispatch and inspection are co-designed. Third, compliant, leak-tolerant suction with state-aware control widens the safe envelope on ABS–foam sandwiches, preserving surface quality and bond integrity as roof spans scale. Each conclusion is consistent with peer-reviewed findings on material-handling alternative generation, AMR process control, multi-sensor pose monitoring, and advanced suction interfaces.

IV. DISCUSSION

Crane detachment and precision gains in the roof-to-walls operation follow directly from design moves that literature identifies as throughput and quality multipliers in large-panel assembly. Cooperative pickup geometry concentrates variation into a controllable set of relative poses; short-stroke trim moves then close the residuals to the tolerance band without reintroducing suspended transport, which aligns with spatial relative-position monitoring studies that favor observable, fusion-ready features over heavy fixturing [4]. Substituting shared cranes with AMR-delivered kits reduces interference and decouples adjacent stations, provided dispatching, exception handling, and in-station verification are co-designed; case studies on process control for AMRs and sustainable scheduling report fewer blockages and a more stable takt when orchestration abstracts jobs into skills and synchronizes arrivals with release events [7; 10]. The observed reduction in crane engagement and the improvement in locating precision in the modular roof program are consistent with that logic because the grooved slots create deterministic pickup states, while on-tool vision trims the last degrees of freedom before clamping; analogous sensor-fusion architectures bound pose uncertainty in large-component assembly without penalizing cycle time.

Table 1: Literature-derived design levers for mixed-model roof handling and their expected operational effects [1; 4–10]

Design lever	Expected operational effect
Cooperative pickup features (grooved slots) plus on-tool metrology	Fewer setup moves; bounded pose uncertainty before clamp; lower reliance on heavy fixtures
Zoned vacuum plate with soft self-sealing cups	Wider sealing window on ABS skins; reduced imprint/leak sensitivity; lower through-thickness stress peaks
Predictive adjustment of suction/approach based on detected state changes	Stable handling under small geometry or compliance shifts; fewer micro-stalls in cycle
AMR-based delivery with intuitive, flexible process control	Less aisle interference than shared cranes; stable takt under variability; faster exception recovery
Sequence-aware, sustainability-oriented dispatching and buffering	Lower empty travel; synchronized arrivals; energy and schedule stability gains
Alternative generation via constraints-satisfaction modeling	Clear Pareto front between fleet size, layout, and takt; removal of crane gating from feasible sets
Mobile QA nodes near the operation (AMR-mounted inspection)	Short detection-to-correction loop; reduced defect escapes at mixed model
In-station gap/flush verification with commodity optics	Sub-millimeter gap/flush checks at cycle-time rates; immediate reclamp/refasten capability

The sandwich construction imposes constraints on end-effector design that are best addressed by compliant, leak-tolerant suction coupled with state-aware control. Adaptive self-sealing suction grippers extend sealing over lightly crowned thermoplastic surfaces and tolerate small leaks, which enlarges the safe operating window on ABS skins; predictive adjustment of suction zones in response to detected state changes prevents local over-loading and reduces imprint risk at the skin–core interface [1;

8]. Material evidence on ABS toughness supports conservative assumptions about surface abuse tolerance during short, controlled contact events, noting that additive manufacturing datasets serve as a lower-bound proxy for molded sheet behavior when contact pressures are limited and durations are brief [3]. The thermal function of rigid polyurethane foam in refrigerated enclosures makes bond integrity and gasket compression non-negotiable; transient studies of refrigerated bodies show that insulation and sealing dominate energy performance, which justifies conservative pressure maps and minimized peel moments during pickup and placement [2]. Within that envelope, the combination of zoned vacuum, soft-edge cups, and cooperative slots suppresses the very mechanisms—point bending in the core and peel at the skin bond line—that drive latent defects.

To connect the measured outcomes with repeatable design levers, the synthesis in Table 1 aggregates peer-reviewed findings that predict throughput and quality effects for systems resembling the roof line.

The table foregrounds a cause–effect chain that explains why crane time collapses when cooperative geometry and AMR orchestration co-exist: slotting removes indeterminacy at pickup, while AMR skills eliminate the queueing externality of bridge cranes [4; 7; 9]. Quality stabilization follows from embedding verification where decisions occur; smartphone-class gap/flush and AMR-borne scanners compress feedback to the timescale of fastening and sealing, which reduces rework propagation beyond the station [5; 6]. Where the sandwich structure could be vulnerable, adaptive suction and predictive adjustment limit unsafe load paths without resorting to oversizing the end-effector [1; 8].

Sensor fusion emerges as the correct granularity for the mating station. Pure vision suffers from occlusions and lighting drift in tall enclosures; adding laser lines or structured cues yields observable constellations over the short travel required for trim moves while preserving cycle time, as documented for large-component monitoring [4]. AMR-based QA complements in-station sensing when mixed models introduce variant-specific edges or decorative trims; car-body studies demonstrate that AMR-mounted systems can achieve cycle-compatible scans and feed corrections back to the clamp logic before sealing cures [5]. Commodity gap/flush methods bridge the remaining gap by offering sub-millimeter checks without breaking the station's rhythm [6]. These observations motivate a configuration that defers high-end trackers in favor of robust, low-latency fusion where the cost–benefit ratio is highest.

To ground metrology choices against reported capabilities and integration constraints, Table 2 contrasts sensor and QA configurations frequently cited for large-panel assembly.

Table 2: Sensor and quality-assurance configurations for roof-to-body mating in mixed-model flow [1; 4–6]

Configuration	Measurement target	Reported capability (qualitative)	Integration constraints
Vision + cooperative markers on the roof frame	Relative x-y-θ before clamp	Bounded pose error with short-stroke correction; cycle-time compatible	Requires marker visibility and lighting control
Vision + laser line triangulation near pickup slots	Local edge/slot alignment during final approach	Robust to partial occlusion; stable residual correction	Calibration stability over thermal drift needed
AMR-mounted 3D inspection at post-placement	Global gap/flush and feature presence	Cycle-time-compatible pass over car-body-scale parts; near-station feedback	Adds brief pass-through; docking repeatability required
Handheld/smartphone gap-flush verification at clamp	Gap/flush at critical seams	Sub-millimeter repeatability with commodity optics; minimal cycle intrusion	Operator training and lighting consistency required
On-tool state-aware suction monitoring	Seal integrity and local compliance	Early leak/stall detection; adaptive zone control	End-effector I/O and pressure sensing integration

The comparison clarifies why a lean fusion stack outperforms tracker-heavy alternatives at the roof line: cooperative geometry reduces the search space, so relative pose can be solved with short baselines; AMR-based QA then audits the outcome at full scale without removing the product from the station [4–6]. Practical integration asks for robust lighting, stable calibration, and deterministic docking; these are already managed by AMR process control frameworks that expose skill-level abstractions and exception hooks [7]. Dispatching and energy-aware scheduling from the NEV literature further suggest idle-time and sustainability gains when arrivals are synchronized with sub-assembly readiness, which fits the roof line's kit-pull rhythm [10]. Upstream, constraints-satisfaction modeling of material-handling alternatives supplies a principled route to fleet sizing and line layout, preventing premature fixation on conveyor or crane patterns that underperform once cooperative pickup is available [9].

Risk management centers on two failure modes. First, peel at the skin–core interface during pickup or trim can seed latent insulation defects; soft, self-sealing cups combined with conservative pressure maps and short dwell mitigate this path, while adaptive zone disabling avoids local overloads after minor surface variability is detected [1; 8]. Second, tolerance stack-up between the roof frame and wall tops can increase sealant consumption or compromise bead continuity; immediate gap/flush verification with commodity or AMR-borne optics keeps corrections local to the station, reflecting findings that defect escapes drop when inspection sits adjacent to fastening rather than downstream [5; 6]. Thermal considerations from refrigerated-body analyses reinforce both mitigations by tying long-term energy performance to sealing quality and insulation integrity, which raises the cost of overlooking small mechanical defects during handling [2].

Generalization beyond the studied roof family depends on three levers. Cooperative pickup must scale with span and mass so that slots or tabs remain observable and accessible during approach; when geometry prevents direct slot access, literature encourages alternative observable features that preserve fusion observability [4]. AMR orchestration must remain skill-centric so that new roof options register as skill variants rather than line redesigns; evidence from logistics deployments points to lower changeover friction when process control abstracts capability rather than devices [7]. End-effector compliance needs a larger design window for heavier cores or alternative skins; adaptive self-sealing architectures and state-aware suction provide that window without sacrificing cycle time [1; 8]. None of these levers require reintroducing cranes as long as the pickup states remain deterministic and metrology closes residuals within short-stroke travel.

Limitations of the current evidence base motivate targeted follow-ups. Published ABS datasets often derive from additive processes; while conservative, they do not fully capture molded sheet response in thin skins, which argues for a focused coupon program at the suction interface to calibrate pressure and dwell envelopes beyond literature proxies [3]. Refrigerated-body thermal studies confirm the primacy of sealing and insulation but rarely translate directly into mechanical limits for handling; instrumented pilots that correlate handling traces with post-cure leak-down would bridge that gap [2]. Finally, while AMR QA has reached cycle-compatible maturity in automotive body inspection, mixed-model truck bodies carry larger geometric variety; scaling the calibration model and lighting control to that spread should be a deliberate engineering task, not an assumption [5; 6].

The convergence between the case outcomes and peer-reviewed findings supports a stable architecture for automated material handling on truck roof lines: cooperative, fusion-ready pickup; AMR-delivered kits with flexible control and energy-aware scheduling; compliant, state-aware suction; and near-station verification that treats measurement as part of the operation rather than a downstream audit.

V. CONCLUSION

The synthesis confirms that cooperative pickup features on the modular ABS–foam roof, when paired with AMR-based delivery and a lean fusion stack at the mating station, eliminate crane gating and compress variation into a tractable residual corrected in short stroke. The resulting flow stabilizes takt and reduces aisle interference, while deterministic pickup

and on-tool vision improve locating precision and reduce bead touch-ups at the roof-to-wall joint. Compliance-aware, zoned suction with self-sealing cups preserves the ABS skin and the skin–core bond under allowable pressure and dwell, and quality escapes decline when post-placement audits are executed by AMR-mounted or clamp-adjacent optics. The three stated tasks are satisfied: design levers are formalized as a coherent handling architecture; literature-reported capabilities are tied to the thermomechanical constraints and joint-quality needs of refrigerated roofs; and operational outcomes are evaluated in terms of resource decoupling, precision at mating, and rework containment. The resulting blueprint is directly transferable to large-panel handling in truck and trailer assembly where mixed-model flow, thermoplastic skins, and rigid-foam cores set similar constraints.

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Development of Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System

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Abstract *— This study presents the development of Uni-HEALS: a Semantic Search and Forecasting-Enhanced University Health Care Management System aimed at improving efficiency, accessibility, and decision-making in university health services. Conventional health care systems in academic institutions often suffer from fragmented records, limited retrieval capabilities, and the absence of predictive analytics for service planning. To address these challenges, UNI-HEALS was designed and developed using the Agile methodology and evaluated during a pilot deployment at NEUST University's health clinic – Sumacab Campus - to define the study's scope and operational context clearly. IT experts assessed system quality and end users using the ISO/IEC 25010 Software Product Quality Model, and end users also evaluated the system's acceptability. Quantitative results revealed that IT experts rated the system with a grand mean of 3.59, verbally interpreted as an Excellent Quality System, indicating that Uni-HEALS meets and exceeds the required software quality standards. End-users similarly assessed the system with a grand mean of 3.64, indicating Excellent Quality and high satisfaction with performance, effectiveness, and ease of use. Moreover, the system's acceptability had an overall mean of 3.70, interpreted as Highly Acceptable, demonstrating that Uni-HEALS met all acceptability criteria and showed no significant weaknesses during implementation. In addition to performance metrics, a comprehensive cost-benefit analysis was conducted to evaluate the feasibility of system deployment, including hardware and software. These findings confirm that the system consistently satisfied both technical and user requirements, supporting its viability for enhancing health care management and decision support in university clinic environments and contributing to innovative campus health system initiatives and practicality.*

Keywords *— **University Health Care Management, Semantic Search, Forecasting Analytics, Agile Methodology, ISO/IEC 25010, Smart Campus System***

I. INTRODUCTION

In recent years, the increasing complexity of healthcare management within universities has created an urgent need for smarter, faster, and more data-driven systems. University clinics today serve thousands of students, faculty, and staff requiring accurate medical records, efficient patient flow, and timely decision-making to support campus health and safety World Health Organization [WHO], 2020).[1] However, many schools, including the Nueva Ecija University of Science and Technology (NEUST), continue to rely on manual or semi-digital processes that create delays, inconsistencies, and operational bottlenecks.

At NEUST, several challenges impair the daily operation of the University Clinic/Infirmary. Patient records remain scattered across paper forms, logbooks, and partially digitized files, leading to slow

retrieval, redundant entries, and risks of misplacement. Consultation requests and student visits often surge during examination weeks, cold seasons, or unexpected outbreaks. However, the clinic cannot anticipate these increases because there is no forecasting tool for patient influx or medicine demand. Medicine inventory is also monitored manually, leading to delayed replenishment, expired stock, and reactive procurement. These issues collectively reduce efficiency, increase waiting times, and limit the clinic's ability to provide timely care and make informed decisions.

These operational barriers reflect the broader challenges schools nationwide face. Academic institutions typically manage large student populations with limited medical staff, leading to a heavy reliance on accurate records, well-organized scheduling, and reliable health information systems. Schools commonly encounter problems such as data duplication, delayed access to medical histories, lack of centralized reporting, inconsistent documentation procedures, and difficulty predicting seasonal illness trends (Alshamari et al., 2021). [2] Without intelligent tools, university clinics operate reactively rather than proactively, responding only when shortages, surges, or emergencies already occur.

One of the most critical gaps is the absence of an intelligent medical information retrieval system. Traditional search functions depend on exact keywords, making it challenging to locate patient information when spelling varies, symptoms overlap, or medical terms differ. (Hliaoutakis et al., 2006; Guha et al., 2016). [3] Uni-Heals Semantic search addresses this problem by understanding the meaning and relationships between concepts, enabling context-aware retrieval of clinical information (Ristoski & Paulheim, 2016; Lin & Chen, 2019).[4] For NEUST, this means faster, more accurate access to patient histories, diagnoses, and medicine usage, directly addressing current retrieval delays.

Another significant gap involves the lack of predictive capabilities. Schools often experience sudden spikes in consultations during flu season, weather changes, examination stress periods, and campus events. Uni-Heals Forecasting tools can analyze historical clinical data to predict patient volume, medicine consumption, seasonal illness patterns, and staffing needs (Li et al., 2022). [5] For NEUST, forecasting directly addresses two significant problems: slow, reactive resource planning and unpredictable patient congestion. Forecasting enables proactive stocking and preparation, anticipates peak periods, and supports smoother scheduling.

Given these gaps, the development of Uni-HEALS: Semantic Search and Forecasting - Enhanced University Health Care Management System, is proposed to transform NEUST's clinic into a modern, intelligent, and proactive health service unit. The system integrates centralized medical records, semantic search for intelligent information retrieval using Natural Language Processing (NLP), and forecasting analytics using Linear Regression for health trend prediction, and automated processes for clinic operations, service demand, and resource utilization.

Ultimately, by implementing Uni-HEALS, NEUST can advance its institutional commitment to innovation, operational excellence, and student welfare. Moreover, it positions the university at the forefront of digital transformation in campus healthcare systems. As academic institutions increasingly adopt digital health management solutions, the proposed system may serve as a model for other universities seeking to modernize their healthcare services with intelligent, data-driven, and sustainable features. This aligns with the United Nations Sustainable Development Goal 3 (Good Health and Well-Being), which emphasizes the importance of technology-driven healthcare innovations in promoting wellness and ensuring access to quality health services for all (United Nations, 2023).[6]

It is specifically intended to: Develop and evaluate the Uni-HEALS: Semantic Search and Forecasting–Enhanced University Health Care Management System using a Modified Agile Development Life Cycle comprising planning, design, development, testing, deployment, and maintenance. System quality was assessed by IT experts using the ISO/IEC 25010 Software Product Quality Model, covering functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. End-users evaluated the system based on selected ISO/IEC 25010 criteria: functional suitability, performance efficiency, and usability; and further assessed its level

of acceptability to determine its suitability for implementation in a university clinic setting.

II. METHODOLOGY

This study adopted a mixed-method research design integrating developmental and descriptive–evaluative approaches to develop and assess the Uni-HEALS: Semantic Search and Forecasting–Enhanced University Health Care Management System.[7] System development followed the Agile Software Development Life Cycle, enabling iterative design, implementation, and refinement based on user feedback.[8] The study was conducted at the Nueva Ecija University of Science and Technology (NEUST) University Clinic/Infirmary in Sumacab Campus, Cabanatuan City, Nueva Ecija, Philippines. Data were collected from purposively selected IT experts (10) and five (5) end-users through structured questionnaires, interviews, and system testing to evaluate both technical and functional performance using the ISO/IEC 25010 Software Product Quality Standards.[9]

Data analysis employed weighted mean statistics based on a four-point Likert scale to determine system compliance and acceptability, with an acceptance threshold of 2.50. Qualitative data supported system validation and refinement. The study was anchored on the ISO/IEC 25010 Quality Model and the Agile Development Framework, organized through an Input–Process–Output (IPO) conceptual framework. Inputs included system requirements and resources; processes involved agile development and evaluation; and outputs consisted of a validated, user-centered, and standards-compliant healthcare management system tailored to NEUST clinic operations.

III. RESULTS AND DISCUSSION

This study presents the development of the Uni-HEALS: Semantic Search and Forecasting–Enhanced University Health Care Management System, following the Agile Development Life Cycle, with iterative phases of planning, design, development, testing, deployment, and maintenance to ensure adaptability, stakeholder collaboration, and continuous refinement. During the planning phase, system requirements were identified through consultations and focus group discussions with university clinic personnel, addressing challenges in manual record handling, data security, and decision support. These inputs defined the project scope, functional and non-functional requirements, and guided sprint planning. The design phase translated these requirements into concrete outputs, including use case diagrams, data flow diagrams, and an entity–relationship model that structured system workflows, database relationships, and user roles. These design artifacts served as the blueprint for system construction, ensuring alignment with clinic operations and data governance standards.

In the development phase, the system was incrementally built through iterative sprints, resulting in core modules such as electronic health records, semantic search powered by Natural Language Processing, forecasting of health trends and medical supplies using Linear Regression, and role-based access control for security. Testing and evaluation were conducted continuously across unit, integration, system, and user acceptance testing, involving both IT experts and end users to validate functionality, usability, performance, and security. The deployment phase involved a pilot implementation in the university clinic, where the system was installed, configured, and evaluated in a controlled operational environment without disrupting clinic services. Finally, maintenance was addressed through a structured plan that included regular monitoring, bug fixes, security reviews, database optimization, and periodic updates to ensure sustained performance, reliability, and scalability. Collectively, these phases demonstrate that the Agile approach effectively supported the successful development, evaluation, and pilot deployment of Uni-HEALS within a real-world university healthcare setting.

The following are the summarized results of the IT Experts system evaluation based on the Software Product Quality Standards, which outline eight primary criteria: functional suitability, performance efficiency, usability, reliability, maintainability, compatibility, security, and portability; and for End-users are the following: functional suitability, performance efficiency, usability. Also, the End-users' acceptability rating of the Uni-HEALS data for each is presented below.

Table 1. Summary of the IT Experts' Evaluation of Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System

Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System	Overall Mean	Descriptors
Functional Suitability	3.60	Highly Functional
Performance Efficiency	**3.73**	**Highly Efficient**
Compatibility	3.35	Highly Compatible
Usability	**3.75**	**Highly Usable**
Reliability	3.43	Highly Reliable
Security	**3.78**	**Highly Secured**
Maintainability	3.58	Highly Maintainable
Portability	3.53	Highly Portable
Grand Mean	**3.59**	**Excellent Quality System**

Source/s: IT Experts' Evaluation Tool based on the ISO 25010 Software Product Quality Standards

Table 1 summarizes the IT experts' evaluation of the Uni-HEALS: Semantic Search and Forecasting–Enhanced University Health Care Management System across eight ISO/IEC 25010 quality attributes. The system achieved its highest rating in Security (M = 3.78, Highly Secured), reflecting the effective implementation of role-based access control, data encryption, and secure storage—features critical for protecting sensitive health information in university clinic environments. Compatibility obtained the lowest mean (M = 3.35, Highly Compatible), indicating generally effective system integration with minor opportunities for enhanced interoperability. Overall, Uni-HEALS attained a grand mean of 3.59, indicating an Excellent Quality System and demonstrating compliance with and exceeding software quality standards.

The high scores for Security (M = 3.78), Usability (M = 3.75), and Performance Efficiency (M = 3.73) are consistent with findings from related healthcare information system studies. Prior research highlights that RBAC and encryption significantly strengthen system security and user trust (Wager et al., 2017) [10], while semantic search and NLP-based interfaces improve usability and user satisfaction (Petter et al., 2008) [11]. Moreover, integrating forecasting and predictive analytics supports efficient data processing and informed decision-making, aligning with established evidence on the benefits of analytics-driven healthcare systems (DeLone & McLean, 2003) [12]. Compared with conventional university health systems focused mainly on record digitization, Uni-HEALS delivers greater value through intelligent retrieval and forecasting capabilities, reinforcing its role as a secure, efficient, and user-centered healthcare management solution.

Table 2. Summary of the End-Users' Evaluation of Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System

Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System	Overall Mean	Descriptors
Functional Suitability	**3.67**	**Highly Functional**
Performance Efficiency	3.60	Highly Efficient
Usability	**3.67**	**Highly Usable**
Grand Mean	**3.64**	**Excellent Quality System**

Source/s: End Users' Evaluation Tool based on the ISO 25010 Software Product Quality Standards

Table 2 presents the summary of the End-Users' evaluation of the Uni-HEALS: Semantic Search and Forecasting–Enhanced University Health Care Management System across selected ISO/IEC 25010 quality attributes. The high end-user ratings for Functional Suitability (M = 3.67) and Usability (M = 3.67) can be linked to the system's alignment with users' workflows and its intuitive interface design. The semantic search module facilitated natural language–based retrieval of patient data, reducing cognitive load and task complexity, factors shown in prior research to improve user satisfaction and perceived usefulness in healthcare information systems (HIS) implementations (Dehghani Mahmoodabadi et al., 2025) [13]. Furthermore, the integration of forecasting analytics supported timely planning and reporting, enhancing functional relevance and operational effectiveness, a pattern echoed in studies identifying predictive and decision-support features as key drivers of user satisfaction and system efficiency in health IT adoption (Nature Communications, 2024) [14]. Comparative literature also underscores that usability and efficiency are among the most frequently evaluated and highly valued criteria in HIS studies, with systematic reviews highlighting their strong influence on user acceptance and workflow integration (Dehghani Mahmoodabadi et al., 2025) [15].

Table 3. End-Users' Evaluation of the Acceptability of Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System

Acceptability	Mean	Descriptors
Uni-HEALS provides accurate and reliable semantic search and forecasting for the NEUST University Clinic/Infirmary.	3.40	Highly Acceptable
The interface of Uni-HEALS is user-friendly and easy to navigate for the end user.	3.80	Highly Acceptable
Uni-HEALS efficiently provides real-time updates and status monitoring of health records.	3.60	Highly Acceptable
Uni-HEALS is accessible and usable by different types of users.	**4.00**	**Highly Acceptable**
Uni-HEALS responds quickly to user actions and provides timely feedback on health records/status.	3.60	Highly Acceptable
Uni-HEALS contributes to sustainable and well-structured health record management within the university clinic.	3.60	Highly Acceptable
Uni-HEALS is stable and operates smoothly without frequent system errors or crashes.	3.60	Highly Acceptable
Uni-HEALS integrates effectively with NEUST's existing infrastructure, databases, and workflow processes.	**4.00**	**Highly Acceptable**
Overall Mean	**3.70**	**Highly Acceptable**

Source/s: End Users' Evaluation Tool on the Level of Acceptability

Table 3 reveals that end-users' acceptability evaluation yields a Highly Acceptable overall rating (M = 3.70), indicating strong user approval of Uni-HEALS during the pilot implementation. The highest-rated items: accessibility and usability across different user types (M = 4.00) and effective integration with existing infrastructure and workflows (M = 4.00) suggest that the system was well aligned with the operational needs of the university clinic. These outcomes can be attributed to the system's role-based access design, intuitive interface, and seamless interoperability with existing databases, which collectively reduce user effort and support efficient task execution. The high rating for interface usability (M = 3.80) further underscores the effectiveness of the semantic search module, which supports natural

language queries and simplifies information retrieval, thereby reducing cognitive load and improving the user experience.

High acceptability ratings for real-time updates, responsiveness, system stability, and sustainable record management (all M = 3.60) indicate that Uni-HEALS consistently delivered timely feedback and reliable system performance. These strengths are closely associated with the system's optimized data processing and forecasting analytics, which support continuous monitoring and proactive planning without compromising system stability. Such features extend the system's functionality beyond basic digitization and contribute to sustained operational efficiency.

These findings are consistent with prior studies demonstrating that ease of use, system integration, responsiveness, and decision-support capabilities are critical determinants of user satisfaction and acceptance in healthcare information systems (DeLone & McLean, 2003[16]; Petter, DeLone, & McLean, 2008) [17]. Research further indicates that systems incorporating intelligent search and analytics achieve higher acceptance due to improved workflow compatibility and perceived usefulness (Wager, Lee, & Glaser, 2017) [18]. Compared with conventional university health systems that primarily focus on electronic record storage, Uni-HEALS delivers greater value through semantic search and forecasting capabilities, reinforcing its status as a highly acceptable, user-centered, and sustainable healthcare management solution for academic institutions.

Table 4. Cost–Benefit Analysis of Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System

Category	Item / Component	Expected Benefits	Cost (Php)
Hardware Costs	Firewall, Server Computer, Client PCs, Routers, UPS, Network Switches, LAN Cables	Enables secure, reliable, and high-availability infrastructure for system deployment and continuous operation	**Php 855,200.00**
Software Costs	Operating Systems, Office Productivity Tools, HCI Platform, Antivirus, OpenAI Subscription	Supports system functionality, semantic search, forecasting analytics, data security, and productivity	**3,200,000.00**
Service Costs	Installation & Configuration, Maintenance & Support (1 year)	Ensures proper deployment, system stability, and sustained performance during initial operation	**150,000.00**
Total Implementation Cost			**Php 4,205,200.00**
Operational Benefits	Automated health record management, semantic search, and real-time forecasting	Faster retrieval of patient data, reduced manual processing, improved decision support	
Efficiency Gains	Reduced processing time and administrative workload	Increased productivity of clinic staff and improved service delivery	
Data Security & Privacy	Role-based access control, secured infrastructure, and antivirus protection	Enhanced protection of sensitive health data and regulatory compliance	
User Acceptance & Satisfaction	High usability and accessibility	Faster system adoption, reduced training cost, and sustained system use	
Sustainability & Scalability	Modular, maintainable system architecture	Long-term cost savings, adaptability to institutional growth, and future system enhancements	

Table 4 shows the Cost–Benefit Analysis of Uni-HEALS: Semantic Search and Forecasting-Enhanced University Health Care Management System. The total implementation cost of the system was PHP

4,205,200.00, covering hardware, software, and service requirements to support a secure, analytics-enabled university healthcare management platform. Although the initial investment is considerable, it enables the deployment of a fully integrated system capable of semantic search, forecasting, and secure health record management.

From a benefits perspective, Uni-HEALS delivers substantial tangible gains, including improved operational efficiency, faster access to health information, reduced administrative workload, and enhanced decision support through predictive analytics. Additionally, intangible benefits such as strengthened data security, increased user acceptance, institutional trust, and long-term sustainability significantly enhance the system's overall value. Consistent with IEEE- and Scopus-indexed studies on system development, the benefits outweigh the implementation costs, indicating that Uni-HEALS is a cost-effective, scalable, and viable solution for university healthcare environments.

III. CONCLUSIONS AND RECOMMENDATIONS

The study showed that the development of the Uni-HEALS: Semantic Search and Forecasting – Enhanced University Health Care Management System was successfully carried out following the stages of the Modified Agile Development Life Cycle, including planning (requirements gathering), designing, development, testing, deployment, and maintenance. The system effectively addressed the operational needs of NEUST's University Infirmary/Clinic by integrating semantic search powered by natural language processing, linear regression–based forecasting, and role-based access control, along with secure data encryption and storage.

Evaluation results from IT experts rated the system as excellent in terms of security, usability, performance efficiency, and functional suitability, with noted opportunities for improvement in interoperability and support for additional environments. End-users likewise provided high ratings for usability and functional performance, confirming the system's practicality, efficiency, and user-centered design. The high level of acceptability further demonstrates that Uni-HEALS enhances workflow efficiency, ensures reliable and secure healthcare management, and is suitable for institutional deployment within NEUST's University Infirmary/Clinic.

Although Uni-HEALS was successfully developed using the Modified Agile Development Life Cycle and attained an excellent quality rating, continuous system enhancement is recommended. Regular updates and refinements should be implemented to improve further functional appropriateness, interoperability, and adaptability to emerging healthcare and information technology requirements.

Future versions of Uni-HEALS should incorporate standardized healthcare data exchange protocols (e.g., HL7 or FHIR) and expand compatibility with other institutional systems to enable seamless integration with external health information systems and databases. To further enhance system reliability, improvements in user error protection, automated backup, and recovery mechanisms are also recommended to minimize data loss and downtime.

Regular user training and orientation programs should be conducted to ensure optimal utilization of system features and improve operational efficiency. Given the high level of user acceptability, full deployment of Uni-HEALS across NEUST University Infirmary/Clinic operations is recommended, supported by updated institutional policies and procedures. Future studies may extend the system by integrating advanced analytics or decision-support features and by validating its scalability and effectiveness in other healthcare settings.

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Gender Gaps in Healthcare and Nutritional Outcomes: A District-Level Analysis in Haryana

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Abstract *— Gender inequality in healthcare and nutrition continues to be a significant issue in India, especially in states with deep-rooted patriarchal values like Haryana. Although the country has experienced substantial economic growth and improved public health infrastructure, gender disparities in accessing healthcare and achieving nutritional health remain evident throughout Haryana. This research examines gender differences in healthcare access and nutritional status across districts in Haryana, using a detailed district-level analysis. The study uses secondary data from sources such as the National Family Health Survey (NFHS-5, 2019–21), the Census of India, and official government reports. It assesses gender disparities by analysing key indicators of healthcare access, such as antenatal care and institutional deliveries, as well as nutritional outcomes, including anaemia prevalence and body mass index (BMI). Descriptive and comparative analyses are performed to investigate differences across genders and districts. The findings highlight notable gender disparities in healthcare use and nutritional health, with women generally experiencing worse outcomes than men across various districts. Significant differences between districts suggest that state-level averages hide regional inequalities. Areas with lower female literacy rates, limited healthcare services, and strong socio-cultural norms tend to show greater gender gaps. The study finds that tackling gender inequality in healthcare and nutrition in Haryana needs district-specific, gender-sensitive policies. Enhancing women-focused healthcare services, providing better nutritional support for at-risk groups, and challenging social norms are key to ensuring gender-equitable health outcomes. This research adds empirical evidence to the ongoing discussion on gender disparities in Haryana and provides valuable insights for designing targeted policies.*

Keywords *— **Gender Inequality, Healthcare Access, Nutritional Outcomes, District-Level Analysis, Women's Health, Gender and Development.***

I. INTRODUCTION

Gender inequality in health and nutrition remains a significant development issue in India, especially in socially and culturally stratified states like Haryana. Despite notable economic growth and better healthcare infrastructure, differences in access to healthcare, nutritional intake, and health outcomes between men and women persist (Sen, 2001). These disparities stem from patriarchal social structures, son preference, and unequal household resource distribution, which consistently disadvantage women and girls throughout their lives. Haryana presents an interesting paradox: while it is among India's more economically developed states with higher per capita income, it also exhibits some of the poorest gender indicators, including a low sex ratio, poor nutritional health among women, and limited access to maternal healthcare (Government of India, 2021). Research shows that women's health in Haryana is affected not only by the availability of healthcare services but also by socio-cultural norms that restrict women's mobility, decision-making, and healthcare access (Jeffery & Jeffery, 2012). Health and nutrition are crucial for gender equality, as they directly influence

women's productivity, reproductive health, and overall well-being. Key indicators such as maternal mortality, anaemia, body mass index (BMI), institutional deliveries, and access to antenatal and postnatal care provide valuable insights into gender-based disparities World Health Organisation (WHO), 2020). Data from the National Family Health Survey (NFHS) reveal that women in Haryana face higher rates of anemia and nutritional deficiencies than men, with significant variations across districts (IIPS & ICF, 2021).

Conducting a district-level analysis is essential to uncover gender disparities in healthcare and nutrition, as state-level data often masks significant regional differences. Haryana's districts differ widely in terms of healthcare infrastructure, literacy, urbanisation, and socio-economic factors, all of which affect gender-related health outcomes (Kumar & Singh, 2019). Recognising these spatial inequalities is vital for crafting targeted policies and effectively implementing gender-sensitive health initiatives. This study examines gender gaps in healthcare access and nutritional results across Haryana's districts by analysing key health and nutrition indicators. By adopting a district-focused approach, it aims to contribute to the broader conversation on gender inequality and to offer empirical evidence to guide policy development within programmes such as the National Health Mission, Poshan Abhiyaan, and Beti Bachao Beti Padhao.

II. REVIEW OF LITERATURE

A significant amount of research has explored gender disparities in India's healthcare and nutrition, revealing ongoing inequalities influenced by socio-cultural, economic, and institutional factors. Scholars contend that women's health disadvantages are not merely biological but fundamentally socially constructed, stemming from unequal access to resources, decision-making power, and healthcare services (Sen, 2001). Several national studies have documented gender gaps in healthcare use, especially in maternal and reproductive health. Kabeer (2016) notes that women's access to healthcare is strongly affected by their socio-economic status, education level, and household autonomy. Factors like limited mobility, early marriage, and low bargaining power often hinder women from seeking prompt medical attention, leading to poorer health outcomes.

Nutritional inequality is a critical component of gender disparity. Data from the National Family Health Survey (NFHS) show that women are more prone than men to suffer from anaemia, undernutrition, and micronutrient deficiencies (IIPS & ICF, 2021). Agarwal (2018) observes that within households, food distribution often favours male members, especially in northern Indian states, leading to continued nutritional disadvantages for women and girls. Studies in Haryana reveal a notable gender paradox. Despite economic progress, the state performs poorly on key gender health indicators. Jeffery and Jeffery (2012) point out that deeply ingrained patriarchal norms, a preference for sons, and strict gender roles heavily influence women's health decisions in Haryana. Similarly, Bhat and Zavier (2007) indicate that gender bias begins early in life in Haryana, impacting girls' survival, nutrition, and healthcare access.

In recent years, focus on district-level analysis has increased as researchers recognise that state averages conceal significant disparities within regions. Kumar and Singh (2019) highlight notable differences in healthcare infrastructure and maternal health outcomes across Haryana's districts, underlining the need for localised analysis. Likewise, Mohanty et al. (2016) contend that districts with higher female literacy rates and better public health services tend to see relatively improved nutritional and health outcomes for women. Existing research highlights how public health interventions help decrease gender disparities. Initiatives such as the National Health Mission and Poshan Abhiyaan have enhanced maternal healthcare and nutrition, although their impacts differ by district (Government of India, 2021). Experts warn that addressing deep-seated social norms and gender relations is crucial, as policy measures alone may not achieve full effectiveness (Kabeer, 2016).

In summary, the existing literature indicates that gender gaps in healthcare and nutrition are complex and differ across regions. While earlier research provides valuable insights at the national and state levels, detailed district-level studies, particularly in Haryana, are scarce. This study seeks to address that gap by thoroughly analysing gender disparities in

healthcare access and nutritional outcomes within Haryana's districts.

III. OBJECTIVES OF THE STUDY

This study aims to investigate gender disparities in healthcare access and nutritional outcomes across Haryana's districts. Its specific objectives include:

> To evaluate gender disparities in healthcare access across Haryana's districts, this objective examines differences in the use of key services like antenatal care, institutional deliveries, and public health facilities between men and women.

> This objective focuses on assessing gender disparities in nutritional outcomes across districts of Haryana by examining indicators such as anaemia prevalence, body mass index (BMI), and related health measures.

> To derive policy implications for addressing gender inequalities in healthcare and nutrition in Haryana, this objective focuses on identifying gender-responsive, district-specific policy interventions to improve healthcare access and nutritional outcomes among women, based on the empirical findings.

IV. DATA SOURCES AND METHODOLOGY

4.1. Study Area:

The research examines Haryana, a northern Indian state divided into various districts with diverse socio-economic and demographic characteristics. Although Haryana has made economic strides, it still faces notable gender gaps in health and nutrition. To better understand these differences, a district-level analysis reveals local patterns of gender inequality that may be hidden in broader state-level data.

4.2. Data Sources:

This study relies solely on secondary data from reputable, nationally recognised sources. The main data sources comprise:

- **National Family Health Survey (NFHS-5, 2019–21)**: Provides district-level data on healthcare utilisation, maternal health, and nutritional indicators disaggregated by gender.
- **Census of India (2011)**: Used for demographic and background variables such as population distribution and literacy.
- **Government of India Reports** : published by the Ministry of Health and Family Welfare and related departments for contextual and policy analysis.

These sources ensure consistency, comparability, and validity of data across districts.

V. INDICATORS USED IN THE STUDY

The study uses specific indicators aligned with its objectives to analyse gender differences in healthcare access and nutritional outcomes.

5.1. Healthcare Access Indicators:

- Antenatal care coverage
- Institutional deliveries
- Access to public healthcare facilities

5.2. Nutritional Outcome Indicators:

- Prevalence of anaemia
- Body Mass Index (BMI) levels
- Indicators of undernutrition and nutritional deficiency

These indicators are commonly employed in gender and health research, offering a thorough understanding of gender-related disadvantages.

VI. METHODOLOGICAL FRAMEWORK

The study uses a descriptive and comparative analytical approach to evaluate gender disparities across districts. The methodology involves:

- A gender-based comparison of healthcare and nutritional indicators to highlight disparities between men and women.
- District-level comparison to highlight spatial variations in gender gaps.
- Use of percentage analysis and simple statistical measures to interpret patterns and trends in the data.

The analysis emphasises relative disparities rather than absolute values, enabling the identification of districts with pronounced gender inequalities.

VII. POLICY-ORIENTED ANALYTICAL APPROACH

Aligned with Objective 3, the findings are analysed from a policy standpoint. Districts with ongoing gender disparities in healthcare and nutrition are scrutinised within the framework of current public health initiatives, such as the National Health Mission and Poshan Abhiyaan. This strategy supports the development of targeted, gender-sensitive policy suggestions tailored to each district.

VIII. RESULTS AND DISCUSSION

8.1. Gender Gaps in Healthcare Access:

The district-level analysis highlights notable gender disparities in healthcare access across Haryana. While the state's healthcare infrastructure has generally improved, women still face challenges in obtaining essential services. Indicators such as antenatal care coverage and institutional deliveries vary widely between districts. Districts with higher urbanisation and female literacy rates show better healthcare utilisation among women, whereas predominantly rural and culturally conservative districts tend to have lower access. In many areas, women's healthcare-seeking behaviour is limited by factors like reduced autonomy, reliance on male family members for decisions, and social norms that restrict movement. These findings are consistent with earlier research suggesting that healthcare access depends not only on physical availability but also on social and gender dynamics within households (Kabeer, 2016). Despite efforts under the National Health Mission, disparities between districts indicate uneven implementation and outreach. The ongoing gender gaps in healthcare access reveal that expanding infrastructure alone is not enough without tackling social barriers faced by women.

8.2. Gender Differences in Nutritional Outcomes:

The analysis of nutritional indicators reveals clear gender-based disparities across districts in Haryana. Women experience significantly higher rates of anaemia and undernutrition compared to men, reflecting longstanding nutritional deprivation trends. Districts with lower socio-economic development tend to have worse nutritional outcomes for women. Factors such as intra-household food distribution, early marriage, multiple pregnancies, and limited access to nutritional supplements play a role in their poor nutritional health. These findings align with national data from NFHS, which show that northern Indian states, including Haryana, continue to face persistent female nutritional disadvantages (IIPS & ICF 2021).

Variation in nutritional outcomes across districts underscores the importance of education, health awareness, and local health services. Districts that effectively implement nutrition schemes and have higher female literacy tend to show better results, indicating that social factors play a crucial role in determining nutritional status.

8.3. Interpreting District-Level Variations:

A key discovery of the research is that state-level averages mask significant differences across districts in gender disparities in healthcare and nutrition. While some districts have made strides in narrowing these gaps, others remain far behind. This varied spatial distribution underscores the importance of micro-level analysis to grasp the complexities of gender inequality. Districts with deeply rooted patriarchal norms and lower female involvement in education and employment generally perform worse in both healthcare and nutrition metrics. These findings support the view that gender inequality in health is complex and shaped by concurrent social, economic, and cultural factors (Sen, 2001).

8.4. Policy Implications:

Aligned with Objective 3, the results highlight the importance of tailored, gender-sensitive policy measures at the district level. One-size-fits-all policies might not effectively tackle local issues. Enhancing outreach programs, boosting awareness among women, and supporting female education are vital strategies to help lessen disparities in healthcare and nutrition.

Programs like Poshan Abhiyaan and the National Health Mission should include district-specific strategies that consider social norms and gender dynamics. Increasing the participation of local self-governments and community organisations can improve program effectiveness and help target vulnerable women.

IX. CONCLUSION AND POLICY RECOMMENDATIONS

9.1. Conclusion:

This study examined gender disparities in healthcare access and nutritional outcomes across districts in Haryana, using a district-level approach. The findings reveal that, despite economic growth and expanded healthcare infrastructure, gender inequalities in health and nutrition persist across the state, with significant district variations. Women in many areas still struggle to access essential healthcare services and tend to have poorer nutritional outcomes than men. These disparities vary depending on local socio-economic factors, female literacy rates, healthcare outreach efforts, and entrenched patriarchal norms. The analysis shows that state averages mask substantial spatial inequalities, underscoring the importance of district-specific evaluations in gender research. The persistent high rates of anaemia, undernutrition, and limited healthcare use among women reflect deep-rooted structural and social barriers. The study confirms that gender inequality in healthcare and nutrition is a complex issue influenced by social norms, intra-household resource allocation, and unequal access to public services. Addressing these challenges requires moving beyond general policies to develop tailored, context-specific strategies.

9.2. Policy Recommendations:

In light of the findings, the study proposes the following policy recommendations to reduce gender inequalities in healthcare and nutrition in Haryana:

A.District-Specific Health Interventions: Policymakers should adopt district-specific strategies based on localised needs and gender gaps. Districts with severe disparities require intensified healthcare outreach, improved monitoring, and targeted resource allocation.

B. Strengthening Women-Centric Healthcare Services: Expansion of maternal and reproductive health services should be accompanied by efforts to enhance women's awareness, mobility, and decision-making power. Frontline health workers can play a crucial role in bridging gender gaps at the community level.

C. Focused Nutritional Programs for Women and Girls: Nutritional interventions under schemes such as *Poshan Abhiyaan* must prioritise adolescent girls, pregnant women, and lactating mothers, particularly in districts with high anaemia and undernutrition rates.

D. Integration of Gender Sensitisation with Health Policies:

Healthcare policies should incorporate gender-sensitisation components to address social norms that restrict women's access to nutrition and healthcare. Community engagement and male involvement are essential for sustainable change.

E. Improved Monitoring and Gender-Disaggregated Data Use: Strengthening district-level data systems and regularly monitoring gender-disaggregated indicators can help track progress and improve policy responsiveness.

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Shipping line digital workflow efficiency on service quality and delivery

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Abstract *— In this paper, we examine the influence of digital workflow efficiency on service quality and delivery performance outcomes in the Philippine shipping line industry. As global logistics evolve through digital transformation and rising e-commerce demands, shipping lines face increasing pressure to modernize operations and eliminate manual inefficiencies. Using a quantitative descriptive-correlational design, the researchers surveyed 50 logistics professionals in Metro Manila to assess perceptions of digitalization across key areas: real-time data, tracking portals, e-documentation, delivery orders, online freight payment, quotation rates, and container management. Statistical analysis, including Pearson correlation, revealed significant positive relationships between digital workflow systems and operational efficiency indicators. The findings show that digital tools enhance transparency, responsiveness, coordination, and overall operational agility, leading to improved service quality and customer satisfaction. Real-time data and tracking portals emerged as the most influential factors, while e-documentation also contributed to streamlined processes and reduced administrative delays. Despite these benefits, challenges such as system errors, data accuracy, user adaptation, and staff training remain. The study concludes that digitalization is a strategic enabler of competitiveness, resilience, and long-term sustainability in maritime logistics, and recommends continued investment in digital infrastructure, workforce development, and system integration to fully realize its transformative potential in the Philippine shipping sector.*

Keywords *— **Digital workflow, shipping lines, service quality, delivery performance, maritime digitalization***

I. INTRODUCTION

For centuries, the shipping industry has been a cornerstone of trade across regions and continents. It serves as a key driver of global and national economies, allowing markets to connect, sustain supply chains, and support trade activities. The Philippines being an archipelagic nation has relied heavily on maritime transport to ensure the steady flow of commodities across Luzon, Visayas, and Mindanao. Along with its importance is the demand for extensive documentation and coordination to ensure the steady flow and for years, the local industry has grown accustomed to the traditional manual processes which have long been plagued by inefficiencies such as delays, miscommunication, and service disruptions that compromise service quality and timely delivery. These challenges became more pronounced with the increasing complexity of trade and consumer expectations for faster services. With the advent of emerging technologies and the rapid growth of e-commerce, there has been a significant shift toward digital transformation in logistics. Shipping lines have then adopted digital workflows to streamline operations, minimize human error, and enhance service delivery. Integrating technology into the core processes has benefitted both parties, as it improves efficiency in their operations thus elevating the quality of service provided to clients.

As mentioned by (Pucihar, 2022), the maritime transport sector is undergoing a significant shift due to the global trend of digitalization, which promises enhanced operational efficiency, sustainability, and competitiveness. However, despite its potential, the adoption of digital technologies in maritime operations remains uneven and fraught with challenges. One of the core issues is the high cost of digital transformation, which includes investments in training and system integration. These costs can be prohibitive, especially for smaller operators or developing countries, creating a digital divide within the industry.

Moreover, stakeholder alignment is a critical barrier. Maritime operations involve a complex network like shipping lines, port authorities, terminal operators, logistics providers, each with their own systems, priorities, and readiness levels. Achieving seamless collaboration and data sharing among these entities is difficult. The sector also faces technological and organizational resistance. Legacy systems, manual processes, and a lack of digital skills among personnel hinder the transition. In many cases, there is uncertainty about the return on investment, which slows down decision-making and implementation.

In the study of (Petraska, 2022) global competition in the container shipping industry continues to intensify, making the pursuit of competitive advantage a critical objective for shipping companies. Despite its essential role in international trade and logistics, the industry has faced turbulent times in recent years, marked by low profitability and heightened competition. Differentiation has become increasingly difficult, especially with the rise of strategic alliances among major shipping lines. At the same time, the expectations of shippers and freight forwarders, the primary customers of container lines, are becoming more demanding and complex, driven by evolving consumer needs and global market pressures. In response key challenges have been identified that hinder digital transformation: leadership, process standardization, employee training, skills development, and the effective use of both internal and external knowledge. Furthermore, the logistics sector often lags behind industries like banking in terms of digital adoption, it is crucial for shipping lines to understand these factors that influence the successful implementation of digital services. More importantly, they must identify which resources are essential to driving digital transformation and enhancing the quality of service delivery.

In terms of the national environment, digitalization of the Philippines' maritime industry continues to face challenges with many shipping lines continuing with a fragmented and manual system that results in inefficiencies and quality issues. According to the National Feasibility Study on Cross-Border Electronic Exchange of Trade-Related Data and Documents of (UN-ESCAP, 2023), although some digital trade facilitation aspects have been developed, interoperability between systems, standardization of data and stakeholder coordination gaps still persist. These problems serve as barriers to efficient document handling and real-time tracking, which would in turn help deliver better schedules and higher customer satisfaction. Maritime must become increasingly digital with end-to-end processes in order to remain competitive.

On top of that, the archipelagic composition of the Philippines magnifies logistics complications and therefore, efficient digital systems are even more critical. Domestic Shipping (Francisco, 2023) points out that domestic shipping still remains expensive although low in-service reliability because of frequent operational blockages despite the introduction of policies to modernize the sector. Disrupted information systems are known to cause unnecessary duplication, miscommunication and reduce the level of service provided by the shipping lines and port authorities in lack of well-coordinated digital platforms between these. Through understanding the barriers and enablers of maritime logistics, a more agile, transparent, customer-focused approach to maritime logistics can be addressed.

In Manila's main ports (e.g., Port of Manila, MICP, NAIA), traders and customs brokers face persistent challenges due to manual, paper-based customs processes. These outdated systems cause delays, inconsistent procedures, and higher transaction costs, leading to inefficiencies in the logistics chain. To address this, the Philippines has supported regional digital trade initiatives like the ASEAN Single Window (ASW) and TradeNet, which aim to streamline customs through paperless trade

and digital documentation (Department of Finance & Bureau of Customs, 2022).

Additionally, importers and customs brokers encounter issues with shipping lines, such as inconsistent delivery order procedures, high terminal charges, demurrage, container deposits, and refund difficulties. These factors further increase shipping costs and operational burdens. Despite the importance of shipping to the economy, local studies on shipping line selection in Manila are limited, highlighting a research gap. The goal is to identify solutions that simplify processes, reduce costs, and enhance efficiency for customs brokers, importers, and the broader shipping industry (Dela Cruz Jr. 2023).

The purpose of this study is to explore the ongoing digital transformation journey and understand how the integration of advanced technologies is reshaping its operations, service delivery, efficiency and strategic direction in the shipping line industry. It aims to highlight the role of digital innovation in maintaining leadership, workflow efficiency and competitiveness in the shipping industry while addressing the evolving demands of international logistics.

The objective of this study is to understand how digital workflow efficiency influences service quality and delivery performance for shipping lines. It also aims to identify how digital workflows improve accuracy, timeframes and consistency in service provisions. Furthermore, it intends to identify the relationship between workflow efficiency and customer satisfaction in the context of shipping operations. Overall, the research focuses on understanding how digitalization supports better workflow management that leads to improved service quality and delivery outcomes.

II. RESEARCH QUESTIONS

The set of questions on the digital transformation journey serves as a valuable framework for evaluating the company's current processes and identifying areas for improvement. These questions allow stakeholders to critically assess how digital technologies are being utilized to enhance operational efficiency and customer satisfaction. By exploring these topics, organizations can better understand the gaps in service delivery and develop targeted strategies to address them.

1. What is the factor of digitalization that affects operational efficiency on shipping line industry in terms of:

   1.1 Real Time Data

   1.2 Tracking Portals

   1.3 E-documentation (Bill of lading)

2. What is the level of efficiency achieved through digitalization in providing service quality and delivery in terms of:

   2.1 Delivery Order

   2.2 Online Freight Payment

   2.3 Quotation Rates

   2.4 Detention and Demurrage

3. Is there a significant relationship between shipping line digitalization workflow efficiency on service quality and delivery?

III. RELATED LITERATURE

Real Time Data

The study of Pires (2025) explains that the rapid advancement of technology has led to the development of the Internet of Things (IoT), where everyday devices such as phones, cars, and buildings are connected to the internet to share data. In logistics, particularly in cargo transport, IoT plays a crucial role in space management and cost reduction. Through the use of smart sensors and real-time data, companies like Sensefinity are able to track the location of items inside trucks and containers, thereby improving operational efficiency and promoting eco-friendly practices.

Furthermore, the article by Julio et al. (2023) explores how modern technologies can enhance the efficiency and reliability of shipping operations. The study focuses on the use of real-time monitoring systems and control mechanisms to streamline logistics and maritime transport. These systems may include GPS tracking, IoT sensors, and centralized dashboards that provide live updates on vessel location, cargo conditions, and fuel consumption. By leveraging these technologies, shipping companies can optimize routes, reduce delays, and improve safety. Additionally, the article discusses predictive maintenance and automated alerts, which help prevent equipment failures and ensure timely deliveries.

Similarly, (Yerra, 2023) explores how automated ETL processing and real-time data insights can significantly improve shipping efficiency. The study focuses on ETL (Extract, Transform, Load) techniques, which allow companies to collect and organize data from various sources into a centralized system for analysis. Moreover, Yerra points out that traditional shipping operations often suffer from delays due to fragmented systems and manual processes. By automating ETL workflows, logistics

firms can gain real-time visibility into shipment status and potential disruptions. Consequently, this enables proactive decision-making, such as rerouting shipments or adjusting delivery schedules based on live traffic or weather conditions. In addition, the research highlights benefit like reduced lead times, improved delivery accuracy, and enhanced customer satisfaction. However, it also notes challenges such as data quality, system integration, and the need for skilled personnel.

Tracking Portals

The study by Garg et al. (2021) explores how Natural Language Processing (NLP) can be used to enhance shipment tracking systems in logistics. Traditionally, tracking systems face challenges such as inefficiency, lack of real-time updates, and poor user interaction, which often lead to increased operational costs and customer dissatisfaction. To overcome these issues, the authors propose an innovative NLP-based solution that allows users to interact with the tracking system using natural language queries. This approach makes the system more intuitive and accessible, enabling stakeholders to retrieve shipment information quickly and accurately. By integrating technologies like speech-to-text and query interpretation, the system improves responsiveness and decision-making in logistics operations.

Meanwhile, Ulle et al. (2024) explores the transformative role of advanced tracking technologies in maritime logistics, particularly in response to rising e-commerce demands. The authors emphasize that shipping services are essential for global product transit but face numerous operational challenges such as fuel price volatility, complex tax systems, and increasing customer expectations. As a result, these issues often lead to delays, lost shipments, and customer dissatisfaction. To address these problems, the chapter advocates for the integration of cutting-edge technologies especially robust shipment tracking systems as a strategic solution to enhance operational efficiency and customer trust. Moreover, the review highlights how modern tracking systems can reduce resource consumption, improve delivery accuracy, and streamline logistics operations. It also underscores the importance of continuous innovation and academic research to develop scalable, intelligent tracking solutions that can adapt to the evolving landscape of maritime logistics.

Similarly, the paper by Shah et al. (2021) investigates how digital tracking technologies are reshaping the operations of third-party logistics providers. The authors point out that the logistics sector has undergone significant transformation due to digitalization, which has disrupted traditional business models and forced TPLs to adapt to remain competitive. While much of the existing literature focuses on digital disruption in travel, retail, and e-commerce, this study shifts attention to the broader supply chain and logistics domain. Using a case study of a leading technology development company in Malaysia, the paper explores the implementation of a tracking application across three stages: the fundamental stage, the development stage, and the future improvement stage. This staged approach demonstrates how digital tracking systems can enhance service standards, improve operational transparency, and support continuous improvement.

E-Documentation (Bill of Lading)

The digital transformation of shipping documentation, particularly the Bill of Lading (B/L), has become a cornerstone of operational efficiency in maritime logistics. Traditionally, the B/L was a paper-based document that served as a receipt, contract, and title of goods. However, recent innovations have led to the adoption of electronic Bills of Lading (e-BL), which streamline workflows and reduce administrative delays. Based on McKinsey (2022), digitizing trade documentation, including the B/L, could save up to $6.5 billion in direct costs and unlock $40 billion in global trade potential. This shift aligns with the principles of Transaction Cost Theory, which assumes that digital systems reduce coordination and communication costs between parties, thereby enhancing service quality and delivery speed.

Moreover, the implementation of eBLs has shown measurable improvements in delivery timelines and customer satisfaction. As FasterCapital (2025) highlights, electronic documentation not only accelerates trade processes but also mitigates risks associated with document fraud and loss. The integration of blockchain encryption and secure verification mechanisms ensures authenticity and traceability across the supply chain. This evolution resonates with the Resource-Based View (RBV) theory, which emphasizes that firms gain competitive advantage by leveraging unique, inimitable resources such as secure digital platforms to enhance operational capabilities and service delivery.

In addition, Enigio (2025) highlights that traditional paper and PDF bills of lading introduce bottlenecks and inefficiencies in the supply chain due to manual processing and courier delays. In contrast, digital bills of lading serve the same legal functions such as contract evidence, receipt of goods, and title document while minimizing risks of data loss, fraud, and human error. The use of eBLs supports real-time tracking and automated validation, which contributes

to improved delivery accuracy and customer satisfaction in shipping operations.

Delivery Order

To begin with, the delivery order process has evolved significantly due to digital transformation in logistics. Annamuhamedov et al. (2025) emphasize the role of Cyber-Physical Systems (CPS) in modern delivery workflows. CPS integrates physical logistics operations with digital control systems, enabling real-time monitoring and adaptive decision-making. In shipping lines, this means delivery orders can be dynamically adjusted based on cargo status, port conditions, and customer requirements. This framework supports predictive logistics and enhances service quality through responsive coordination.

Building on this, Alavi-Borazjani et al. (2024) propose the Digital Shipping Corridor Model, which outlines critical success factors for digitizing maritime logistics. Within this model, delivery orders are treated as key transactional nodes that must be standardized, automated, and securely exchanged across stakeholders. The model emphasizes interoperability, data transparency, and smart contract integration, ensuring that delivery orders are not just documents but active components of a synchronized digital workflow.

Furthermore, Gavalas et.al. (2022) explored the broader impact of digital adoption including delivery order automation on operational efficiency in shipping firms. Their findings suggest that integrating digital tools like automated delivery systems enables better decision-making, reduces bottlenecks, and supports real-time tracking. This digital shift is especially crucial in post-pandemic recovery, where agility and responsiveness are key to maintaining service quality.

Online Freight Payment

The study by Pinyanitikorn et al. (2024) highlights that payment and financial-settlement mechanisms are essential components of digital freight platforms, as they directly affect transaction speed, transparency, and trust, which in turn shape users' intention to adopt such systems. Secure and well-integrated payment tools such as escrow arrangements, automatic invoicing, and reconciliation enhance system performance and reduce transaction friction, while risks such as fraud, payment failure, and data breaches can discourage adoption. To address these challenges, the Unified Theory of Acceptance and Use of Technology (UTAUT) model has been expanded to include constructs such as trust, perceived risk, and payment security, providing a more comprehensive understanding of user behavior in financial transactions. Empirical evidence from Thailand further reveals that bank integration, compliance, and payment security are key factors influencing companies to adopt platform-based freight services.

Similarly, Kumar (2024) examined how digital payment systems including online banking, blockchain-enabled platforms, and mobile wallets contribute to modern logistics operations. The study found that these technologies help reduce manual errors, accelerate payment processing, provide real-time visibility of cash flow, and support cross-border trade by enabling multi-currency and regulatory compliance. These digital innovations strengthen transparency and trust among logistics partners while improving overall operational efficiency.

Consistent with these findings, Linbis (2024) emphasized that freight-specific digital payment solutions such as virtual cards, automated invoicing, and real-time settlement are increasingly replacing traditional payment methods. These systems promote faster transactions, lower operational costs, and stronger trust between shippers, carriers, and freight forwarders, further reinforcing the positive impact of digital payment technologies on service quality and delivery efficiency.

Quotation Rates

Quotation rates refer to the pricing estimates provided by carriers or logistics service providers to clients before the shipment process begins. These quotations generally cover ocean freight charges, terminal handling costs, documentation fees, fuel surcharges, and other applicable charges (United Nations Conference on Trade and Development [UNCTAD], 2021). The precision and timeliness of quotation processes significantly affect customer satisfaction and profitability. Errors in manual rate computation or documentation often is the cause of billing discrepancies, revenue losses, delays and dissatisfaction of clients. The implementation of digital workflows, such as automated rate management systems and e-quotation platforms, minimizes these issues by standardizing data entry, automating calculations, and ensuring that pricing is consistent with the prevailing market prices (World Bank, 2020).

Detention and Demurrage

Detention and demurrage charges are imposed by shipping lines when containers are held beyond the allowed free time either inside or outside the port terminal. Demurrage pertains to fees charged when a container remains within the port premises beyond the allotted free days, while detention refers to charges incurred when a container is kept by the consignee after release and not promptly returned to

the depot (Maritime Industry Authority [MARINA], 2023). These charges encourage efficient container movement and resource utilization. However, manual processing errors, inaccurate documentation, and communication lapses between shipping agents, freight forwarders, and consignees often result in unnecessary detention and demurrage costs.

The adoption of digital workflows including electronic documentation systems, automated container tracking, and port community systems has been shown to improve coordination and reduce operational inefficiencies. Digitalization enhances transparency, speeds up data exchange, and minimizes human error in logistics operations (Asian Development Bank (ADB, 2022). In the Philippines, digital transformation efforts such as the TradeNet platform and the Bureau of Customs Electronic-to-Mobile (E2M) system are notable examples of initiatives that aim to streamline shipping processes, improve accuracy in documentation, and mitigate cost-related errors in logistics management.

IV. METHODOLOGY

This study employed a quantitative descriptive-correlational research design, which is appropriate for identifying and describing attitudes, opinions, and trends by analyzing relationships between measurable variables. According to Creswell and Creswell (2023), quantitative designs allow researchers to objectively analyze numerical data to uncover patterns and correlations. (Saunders et al., 2023) further emphasize that descriptive quantitative research is useful for examining organizational contexts without manipulating variables. A systematic survey instrument was used to ensure consistent data collection and enable reliable comparisons across organizational functions.

The research was conducted in Metro Manila, the Philippines' main commercial and logistics hub, chosen for its concentration of shipping lines, freight forwarders, and logistics service providers. Its high economic activity and digital transformation initiatives make it an ideal setting for studying the impact of digitalization on service quality and delivery. The presence of diverse roles from managers to rank-and-file employees provided a comprehensive view of digital workflow integration across organizational levels.

A total of 50 respondents from the logistics industry participated, including managers, supervisors, and operational staff. All had at least six months of tenure and were actively involved in workflow processes affecting service quality. Purposive sampling was used to select individuals knowledgeable about digitalization tools such as real-time data systems, tracking portals, and e-documentation. Those without relevant experience were excluded to maintain data validity.

The sampling frame was developed in coordination with HR departments of participating companies, ensuring access to qualified respondents. Descriptive statistics (mean scores and standard deviations) were used to summarize perceptions of digitalization factors, while Pearson's correlation coefficient assessed the strength and significance of relationships between these factors and operational efficiency indicators (e.g., Delivery Order, Online Freight Payment, Quotation Rates, Detention and Demurrage). Results showed statistically significant correlations, supporting the hypothesis that digitalization positively influences service quality and delivery efficiency.

The study adhered to ethical standards to protect respondent privacy and ensure research credibility. Informed consent was obtained, participation was voluntary, and data were anonymized and securely disposed of after the study. An independent statistician conducted the analysis to ensure objectivity and reliability, and all sources were properly cited to uphold academic integrity.

V. RESULTS AND DISCUSSION

After the data-gathering and tabulation of answers from the questionnaires submitted by the respondents, the result was interpreted using correlation analysis to interpret the data. Correlation coefficient (r-value) was used to determine the strength and direction of the linear relationship between the digitalization factors and operational efficiency. It also provides a guide for interpreting the size of the correlation, ranging from negligible to very high positive or negative correlation. The p-value was used for hypothesis testing to determine if the observed relationship was statistically significant. The "Remarks" and "Decision" columns in Table 3 indicate that a relationship was considered "Significant" and the null hypothesis was "Rejected" when the p-value was less than a predetermined significance level, which is specified as 0.01 in the footnote.

The analysis is organized around three core dimensions of digitalization—Real-Time Data, Tracking Portals, and Electronic Documentation (Bill of Lading)—and examines their association with key operational efficiency indicators, namely Delivery Order processing, Online Freight Payment, Quotation Rates, and Detention and Demurrage management.

Subsequently, the detailed discussions on the results interpret these statistical outcomes within the broader context of shipping operations, highlighting their implications for improving workflow efficiency, service reliability, and customer satisfaction in the logistics sector.

1. The factor of digitalization that affects operational efficiency on shipping line industry in terms of Real Time Data, Tracking Portals, E-documentation (Bill of Lading)

Table 1.1: The factor of digitalization that affects operational efficiency on shipping line industry in terms of Real Time Data

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	Real-time data improves the accuracy of shipping operations.	3.82	Strongly Agree	2.5
2.	Access to real-time information enhances decision-making in port operations.	3.82	Strongly Agree	2.5
3.	Real-time data reduces delays and improves workflow coordination.	3.78	Strongly Agree	5
4.	Real-time updates help prevent operational errors and duplication of tasks.	3.82	Strongly Agree	2.5
5.	The use of real-time systems improves communication among shipping departments.	3.86	Strongly Agree	4
GENERAL ASSESSMENT		**3.82**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low

2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

The data from Table 1.1 reveals that real-time data is perceived as a highly influential factor in enhancing operational efficiency within the shipping line industry. With an overall weighted mean of 3.82, all indicators fall under the "Strongly Agree" category, indicating a very high level of agreement among respondents. Specifically, the use of real-time systems is most appreciated for improving communication among shipping departments, which received the highest mean score of 3.86, suggesting that timely information sharing plays a crucial role in coordination and collaboration. The lowest score, though still high at 3.78, pertains to reducing delays and improving workflow coordination, implying that while real-time data contributes positively, other factors may also influence these aspects. Overall, the findings affirm that real-time data systems are essential tools for improving accuracy, responsiveness, and communication in shipping operations, thereby supporting more efficient and reliable logistics processes.

The study confirms that real-time data and tracking portals significantly enhance operational efficiency in the shipping line industry by improving accuracy, decision-making, communication, and customer satisfaction. This aligns with the concept of the Internet of Things (IoT), as discussed by Pires (2025), where connected devices and smart sensors enable better logistics coordination. Supporting literature from Julio et al. (2023) and Yerra (2023) highlights the role of real-time monitoring and automated data integration in optimizing routes and reducing delays. Additionally, studies by Garg et al. (2021), Ulle et al. (2024), and Shah et al. (2021) emphasize the strategic importance of digital tracking systems in improving transparency, operational visibility, and service standards. Overall, the literature reinforces the study's conclusion that digitalization through real-time data, IoT, and tracking technologies is a key driver of efficiency and competitiveness in modern logistics.

Table 1.2: The factor of digitalization that affects operational efficiency on shipping line industry in terms of Tracking Portals

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	Tracking portals provide transparency throughout the shipment process.	3.76	Strongly Agree	3
2.	Customers benefit from accurate shipment status through tracking portals.	3.86	Strongly Agree	1
3.	Tracking portals reduce manual inquiries and improve staff productivity.	3.70	Strongly Agree	5
4.	The integration of tracking portals enhances operational visibility.	3.74	Strongly Agree	4.5
5.	Tracking systems help in resolving shipment issues more efficiently.	3.74	Strongly Agree	4.5
	GENERAL ASSESSMENT	**3.76**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low
2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

The data in Table 1.2 shows that tracking portals are perceived as highly beneficial to operational efficiency, with an overall weighted mean of 3.76, indicating a "Strongly Agree" interpretation across all indicators. The highest-rated item, with a mean of 3.86, is the benefit of tracking portals in providing customers with accurate shipment status, ranked 1st, highlighting their critical role in enhancing customer satisfaction and transparency. The lowest-rated indicator, with a mean of 3.70, is the reduction of manual inquiries and improvement of staff productivity, ranked 5th, suggesting that while tracking portals help streamline communication, their impact on internal productivity may be less pronounced compared to customer-facing benefits.

Overall, the data supports the conclusion that tracking portals are essential digital tools that improve visibility, reduce errors, and enhance both customer experience and operational coordination in the shipping line industry. The findings in the table strongly support the themes discussed in the reviewed literature. Garg et al. (2021) emphasize that NLP-based tracking systems improve transparency and user interaction, which aligns with the indicator showing that tracking portals provide transparency throughout the shipment process (weighted mean = 3.76). Similarly, Ulle et al. (2024) highlight the importance of accurate shipment status and operational efficiency in maritime logistics, reflected in the highest-ranked indicator where customers benefit from accurate shipment status (weighted mean = 3.86). Furthermore, Shah et al. (2021) discuss how digital tracking technologies reduce manual tasks and enhance service standards, which corresponds to the indicator on reducing manual inquiries and improving staff productivity (weighted mean = 3.70). The indicators on integration and issue resolution (both weighted mean = 3.74) also resonate with the literature's emphasis on continuous innovation and system integration to improve visibility and responsiveness. Overall, the strong agreement across all indicators confirms that advanced tracking systems, whether through NLP, digitalization, or maritime innovations, play a transformative role in enhancing transparency, accuracy, and efficiency in logistics operations.

Table 1.3: The factor of digitalization that affects operational efficiency on shipping line industry in terms of E-documentation (Bill of Lading)

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	E-documentation simplifies the process of issuing and receiving Bills of Lading.	3.78	Strongly Agree	1
2.	Digital documents reduce errors compared to manual paper-based systems.	3.64	Strongly Agree	4.5
3.	The use of e-documents speeds up cargo release and clearance.	3.76	Strongly Agree	2.5
4.	E-documentation improves record-keeping and traceability.	3.64	Strongly Agree	4.5
5.	Digital documents reduce errors compared to manual paper-based systems.	3.76	Strongly Agree	2.5
	GENERAL ASSESSMENT	**3.72**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low
2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

The findings in Table 1.3 indicate that e-documentation, particularly in terms of the Bill of Lading, substantially contributes to the operational efficiency of shipping line companies. The computed overall weighted mean of 3.72, verbally interpreted as Strongly Agree, reflects a high level of agreement among respondents that digital tools significantly enhance shipping processes.

The highest-rated indicator was "*E-documentation simplifies the process of issuing and receiving Bills of Lading*" with a weighted mean of 3.78, suggesting that stakeholders view digital tools as essential in streamlining documentation workflows. This finding aligns with FasterCapital (2025), which emphasizes that electronic Bills of Lading reduce administrative complexity and improve coordination between shipping agents, consignees, and customs authorities.

In contrast, the lowest-rated indicators were "*Digital documents reduce errors compared to manual paper-based systems*" and "*E-documentation improves record-keeping and traceability*", both with a weighted mean of 3.64. While still interpreted as Strongly Agree, these slightly lower scores may reflect ongoing concerns about system reliability, data security, or user adaptation. However, Enigio (2025) argues that digital Bills of Lading enhance traceability and reduce human error, especially when integrated with secure platforms and standardized formats.

The strong overall agreement in this study suggests that Philippine shipping stakeholders are receptive to digital transformation, though further investment in infrastructure and digital literacy may be necessary to fully realize its potential.

2. The level of efficiency achieved through digitalization in providing service quality and delivery in terms of Delivery Order, Online Freight Payment, Quotation Rates and Detention and Demurrage

Table 2.1: The level of efficiency achieved through digitalization in providing service quality and delivery in terms of Delivery Order

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	Digital delivery orders are sometimes delayed due to system downtime.	3.38	Strongly Agree	4
2.	The use of digital delivery orders requires continuous staff training.	3.18	Agree	5
3.	Errors in electronic delivery orders affect the timely release of shipments.	3.46	Strongly Agree	3
4.	The system for delivery orders is easy to access and reliable. (reverse-coded)	3.52	Strongly Agree	2
5.	Digital delivery order streamlines the process and ensures prompt shipment release	3.68	Strongly Agree	1
	GENERAL ASSESSMENT	**3.44**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low
2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

The findings presented in Table 2.1 indicate that digitalization has significantly contributed to improving efficiency in delivery order processes within the shipping industry. The overall weighted mean of 3.44, interpreted as Strongly Agree, suggests that respondents perceive a high level of efficiency resulting from digital delivery systems. This implies that the integration of digital workflows enhances service quality, reliability, and operational speed in shipping documentation and cargo release.

Among the indicators, the highest-rated item was "*Digital delivery order streamlines the process and ensures prompt shipment release*" with a weighted mean of 3.68, reflecting a strong consensus that digital systems expedite shipment handling and coordination. This aligns with the findings of Gavalas et al, (2022), who emphasized that digital adoption in maritime logistics directly improves operational performance and reduces administrative bottlenecks. Similarly, Annamuhamedov et al. (2025) highlighted that Cyber-Physical Systems in logistics enhance the synchronization of digital delivery orders, ensuring more efficient and transparent transaction flows.

Conversely, the lowest-rated indicator, "*The use of digital delivery orders requires continuous staff training*" (weighted mean = 3.18, Agree), reveals that human factors remain a challenge in digital transition. This observation resonates with Alavi-Borazjani et al. (2025), who noted that digital shipping corridors require not only technological integration but also workforce readiness and capability building. Overall, the results underscore that while digitalization strengthens delivery efficiency, sustained employee training and adaptive strategies are crucial for maximizing the benefits of maritime digital transformation.

Table 2.2: The level of efficiency achieved through digitalization in providing service quality and delivery in terms of Online Freight Payment

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	Online freight payment platforms are secure and convenient.	3.52	Strongly Agree	2
2.	Payment processing delays occur due to system errors.	3.38	Strongly Agree	4
3.	Clients find online payment procedures user-friendly.	3.34	Strongly Agree	5
4.	The online payment system enhances transparency in transactions.	3.62	Strongly Agree	1
5.	Online freight payment expedites payment timelines.	3.48	Strongly Agree	3
	GENERAL ASSESSMENT	**3.47**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low
2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

The results show an overall weighted mean of 3.47, verbally interpreted as "Strongly Agree." This indicates that respondents have a generally positive perception of digital payment systems in freight operations, agreeing that these technologies enhance transaction efficiency, transparency, and security.

The highest-rated indicator, "*The online payment system enhances transparency in transactions,*" obtained a weighted mean of 3.62, which signifies that respondents strongly believe transparency is one of the major advantages of digital payment systems. This finding supports the view of Pinyanitikorn et al. (2024), who emphasized that well-integrated payment and settlement mechanisms promote transparency and trust—two essential factors influencing the adoption of digital freight platforms. Similarly, Kumar (2024) highlighted that technologies such as blockchain-enabled platforms and online banking improve visibility and accountability in logistics transactions, further strengthening trust among users.

Conversely, the lowest-rated indicator, "*Clients find online payment procedures user-friendly*," with a weighted mean of 3.34, though still interpreted as "Strongly Agree," suggests that some users may experience minor challenges in navigating digital payment systems. This is consistent with Pinyanitikorn et al. (2024), who noted that risks and perceived complexities such as potential system errors or data security concerns can affect user adoption. Despite these issues, the overall agreement indicates that users generally find the systems reliable and effective.

In summary, the overall strong agreement (3.47) reflects that digital payment technologies are widely accepted in freight operations for their ability to improve transparency, efficiency, and trust. These findings align with the conclusions of Linbis (2024) and Kumar (2024), both of whom emphasized that digital payment innovations enhance operational performance and strengthen relationships among logistics stakeholders.

Table 2.3: The level of efficiency achieved through digitalization in providing service quality and delivery in terms of Quotation Rates

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	Digital quotation systems provide accurate and timely rate information.	3.44	Strongly Agree	3
2.	Some quotation systems experience delays or inconsistencies in pricing updates.	3.26	Strongly Agree	5
3.	The use of digital quotation tools improves customer satisfaction	3.58	Strongly Agree	1.5
4.	The quotation process is simplified through digitalization.	3.58	Strongly Agree	1.5
5.	Digital quotations provide accurate and competitive rates.	3.34	Strongly Agree	4
	GENERAL ASSESSMENT	**3.44**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low
2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

The results reveal an overall weighted mean of 3.44, verbally interpreted as "Strongly Agree." This indicates that respondents generally have a positive perception of digital quotation systems, recognizing their contribution to improving pricing accuracy, customer satisfaction, and operational efficiency. This finding supports the view of the United Nations Conference on Trade and Development (UNCTAD, 2021), which emphasized that accurate and timely quotation rates are essential for ensuring transparency and reliability in freight operations.

The highest-rated indicators, "*The use of digital quotation tools improves customer satisfaction*" and "*The quotation process is simplified through digitalization,*" both obtained a weighted mean of 3.58. This reflects that respondents strongly agree that digitalization enhances customer experience by simplifying quotation procedures and providing faster, more reliable rate information. This aligns with the World Bank (2020), which highlighted that automated rate management systems and e-quotation platforms minimize manual errors and standardize pricing data, resulting in improved service quality and client satisfaction.

On the other hand, the lowest-rated indicator, "*Some quotation systems experience delays or inconsistencies in pricing updates,*" with a weighted mean of 3.26, suggests that although digital quotation tools are highly effective, minor challenges such as system delays or data inconsistencies may still occur. This observation is consistent with the World Bank (2020) report, which noted that even with digital workflows, occasional technical issues can affect quotation timeliness and accuracy.

In summary, the overall strong agreement (3.44) indicates that respondents perceive digital quotation systems as reliable tools that enhance pricing precision, simplify operations, and improve customer satisfaction, supporting the insights of UNCTAD (2021) and the World Bank (2020) on the vital role of digitalization in ensuring accuracy, transparency, and efficiency in freight quotation processes.

Table 2.4: The level of efficiency achieved through digitalization in providing service quality and delivery in terms of Detention and Demurrage

	INDICATORS	WEIGHTED MEAN	VERBAL INTERPRETATION	RANK
1.	The system efficiently notifies clients about detention and demurrage charges.	3.40	Strongly Agree	5
2.	Digital platforms help reduce disputes regarding detention and demurrage fees.	3.50	Strongly Agree	4
3.	Inaccurate data entry sometimes leads to miscalculated charges.	3.64	Strongly Agree	1
4.	Automated updates improve transparency in detention and demurrage billing.	3.60	Strongly Agree	2
5.	Detention and demurrage fees help enforce time limits on container usage.	3.56	Strongly Agree	3
	GENERAL ASSESSMENT	**3.54**	**Strongly Agree**	

Legend: 3.26 – 4.00 Strongly Agree (SA) / Very High 1.76 – 2.50 Disagree (D) / Low
2.51 – 3.25 Agree (A) / High 1.00 – 1.75 Strongly Disagree (SD) Very Low

As presented in Table 2.4, the overall weighted mean of 3.54 (interpreted as Strongly Agree) indicates that respondents generally perceive a high level of efficiency achieved through digitalization in enhancing service quality and delivery particularly in the management of detention and demurrage. This finding is consistent with current trends in the Philippine logistics sector, wherein digitalization has been shown to significantly streamline operations. The broader macro-economic context supports this: digital economy indicators in the Philippines show that digital services now contribute significantly to GDP and logistics move is a key enabler based on the International Trade Administration's overview on the state of the digital economy in the Philippines.

The highest mean score of 3.64 for the statement "Inaccurate data entry sometimes leads to miscalculated charges" suggests that although digital workflows have successfully streamlined many manual operations, challenges related to data accuracy still persist. This aligns with international research, "Tackling Inefficiencies in the Maritime Supply Chain." (2025) indicating that while digitalization can reduce human error, it cannot eliminate it without strong data governance, validation rules, and integration across systems.

Conversely, the statement "The system efficiently notifies clients about detention and demurrage charges" recorded the lowest mean of 3.40, while still falling under Strongly Agree, indicates relatively weaker performance compared with other indicators. This result implies that while digital workflows have improved notification and client-communication mechanisms, there is still room for enhancement in system responsiveness and client engagement.

Overall, the results reinforce the notion that digitalization contributes significantly to the efficiency of service quality and delivery particularly in relation to detention and demurrage processes. However, the literature cautions that digitalization is not a panacea: persistent issues in data integrity and communication persistence must be addressed. For instance, policy reports on the Philippines emphasize that digital inertia and under-investment in process optimization still hamper full benefits of workflow digitization, as mentioned by Maheshwari, A. (2025).

3. A significant relationship between shipping line digitalization workflow efficiency on service quality and delivery

Table 3: Test of significant relationship between shipping line digitalization workflow efficiency on service quality and delivery

FACTOR OF DIGITALIZATION	OPERATIONAL EFFICIENCY	r value	P value	Remarks	Decision
REAL TIME DATA	Delivery Order	.349*	.013	Significant	Reject H_o
	Online Freight Payment	.434**	.002	Significant	Reject H_o
	Quotation Rates	.539**	.000	Significant	Reject H_o
	Detention and Demurrage	.553**	.000	Significant	Reject H_o
TRACKING PORTALS	Delivery Order	.441**	.001	Significant	Reject H_o
	Online Freight Payment	.446**	.001	Significant	Reject H_o
	Quotation Rates	.571*	.000	Significant	Reject H_o
	Detention and Demurrage	.562**	.000	Significant	Reject H_o
E-DOCUMENTATION (BILL OF LADING)	Delivery Order	.386**	.006	Significant	Reject H_o
	Online Freight Payment	.374**	.007	Significant	Reject H_o
	Quotation Rates	.371**	.008	Significant	Reject H_o
	Detention and Demurrage	.429**	.002	Significant	Reject H_o

**Correlational at the level 0.05 (Two-tailed) Significance at the level 0.05

Size of Correlation	Interpretation
.90 to 1.00 (−.90 to −1.00)	Very high positive (negative) correlation
.70 to .90 (−.70 to −.90)	High positive (negative) correlation
.50 to .70 (−.50 to −.70)	Moderate positive (negative) correlation
.30 to .50 (−.30 to −.50)	Low positive (negative) correlation
.00 to .30 (.00 to −.30)	Negligible correlation

The results presented in Table 3 demonstrate statistically significant positive relationships between the factors of digitalization (real-time data, tracking portals, and e-documentation/bill of lading) and the operational efficiency dimensions of service quality and delivery (delivery order, online freight payment, quotation rates, detention and demurrage). Each ***r*** value is positive and each ***p*** value is below the conventional threshold for significance (often 0.01), leading to the rejection of the null hypotheses that there is no relationship.

For example, under "Real-Time Data," the correlation with "Detention and Demurrage" is r = 0.553, p = 0.000, indicating a moderate positive relationship (per the interpretation table: 0.50 to 0.70 = moderate positive correlation). This suggests that the more effectively real-time data is used in shipping line workflows, the higher the operational efficiency in managing detention and demurrage. This aligns with recent findings by World Bank and International Association of Ports and Harbors (2021) in a press release which highlight that improved data communication and digital systems in maritime supply chains yield efficiency and resilience gains.

The "Tracking Portals" factor showed the strongest correlations in the table — for instance, with "Quotation Rates" at r = 0.571, p = 0.000, which is still in the moderate positive range but very close to high. This underscores that when clients or stakeholders have access to tracking portals, shipping lines can offer more accurate quotation, faster responses, and more reliable delivery metrics. This is consistent with the literature indicating the value of visibility and connectivity for logistics performance: for instance, the 2023 paper by Tobias, et.al., (2024) found that real-time information exchange and automation significantly reduce internal process lag and error rates.

The "E-Documentation (Bill of Lading)" factor also produced statistically significant correlations, though the r values are somewhat weaker compared to the other two digitalization factors (e.g., with "Detention and Demurrage," r = 0.429, p = 0.002). This suggests that digitizing documents and workflows (such as bills of lading) does improve operational efficiency, but perhaps the effect is less strong than portals or real-time data. This observation is supported by Gavalas et al, (2022) which found that in shipping firms, digital adoption indeed promotes efficiency, but with heterogeneity: firms at varying maturity levels achieve different efficiency gains.

Overall, the pattern of results indicates that digitalization is a key enabler of service quality and delivery efficiency in shipping-line workflows. The significant positive correlations across all indicators confirm the hypothesis that digital workflows contribute to improved operational outcomes. From a theoretical standpoint, this supports the view that digital capabilities drive organizational agility and process efficiency in maritime logistics, as suggested by the reciprocal relationship between digitalization and organizational agility in a paper by Ciampi et. al. (2021) which links digitalization with improved agility and performance in logistics networks.

From a practical perspective in the Philippine context, these findings reinforce the need for shipping lines to invest in real-time data systems, client tracking portals, and digital documentation to reduce delays, human error, and cost inefficiencies, particularly in areas such as detention and demurrage where time and accuracy are critical.

However, despite strong positive relationships, the r values indicate that these are moderate rather than high correlations (none approach the 0.70+ "high positive" threshold). This suggests that there remain other factors not captured in this study which also influence operational efficiency, for example staff training, organizational culture, system interoperability, data quality, regulatory environment, and infrastructure. The research by the World Bank (2021) pointed out that legal or policy frameworks and stakeholder collaboration are major barriers to full digitalization of maritime workflows. Therefore, while digitalization is clearly important, it should be complemented by enabling conditions.

VI. CONCLUSION

The study found that digitalization has greatly improved the overall performance of shipping operations. Results showed that tools such as real-time data tracking, e-documentation, online freight payment, and digital quotation systems have enhanced accuracy, transparency, and timeliness, leading to faster transactions and greater customer satisfaction. The correlation analysis confirmed a significant positive relationship between digital workflows and service efficiency, indicating that digital tools play a vital role in improving communication, coordination, and delivery reliability.

Despite these advantages, minor issues such as system delays, technical errors, and the need for continuous employee training were observed, highlighting areas for improvement. Overall, the study concludes that digital transformation is a key

factor in achieving operational efficiency, competitiveness, and sustainable growth in the shipping industry. Strengthening system reliability and employee capability will ensure that digitalization continues to enhance service quality and customer trust in the long term.

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Strategies for Migrating Monolithic Software Systems to a Microservice Architecture

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Abstract *— The article examines strategies for migrating monolithic software systems to a microservice architecture amid increasing demands for modularity, scalability, and integration in corporate and industrial environments. The study integrates findings on legacy system modernization, the use of modular monoliths as an intermediate form, stepwise component replacement patterns, ontology-based service identification methods, automated decomposition models, practices of polyglot persistence, and operational characteristics of microservice platforms. The analysis shows that migration strategies emerge within a multi-component structure in which the formal basis of methods, the quality of input artifacts, the degree of automation, and the operational context jointly determine service boundaries, the distribution of data responsibilities, and the risk profile. Based on a comparison of approaches, a conceptual migration framework is proposed that links method selection to the requirements of governmental, cloud, and industrial environments, demonstrating that the success of the transition is shaped not by any single technique but by a managed combination of methods and the phased restructuring of data, interactions, and operational processes. The article argues that disregarding architectural trade-offs associated with network latency, distributed consistency, and increased security complexity leads to biased risk assessment and reduced controllability of system evolution. The findings may be useful for architects, engineers, and decision-makers planning the transition from monolithic solutions to microservice architectures in corporate and industrial contexts.*

Keywords *— **monolith migration, microservice architecture, modular monolith, service identification, polyglot persistence, automated decomposition, architectural trade-offs.***

I. INTRODUCTION

Accelerating digitalization, the rise of distributed computing, and the increasing complexity of IT landscapes are fundamentally reshaping system design approaches. Monoliths, which previously ensured stability, no longer meet current requirements for flexibility, frequent updates, and high integration loads [3]. The strengthening of ties between business processes, cloud environments, and cyber-physical systems exacerbates their vulnerability and increases the demand for modularity and scalability. Under these conditions, microservices are becoming the primary vector of development, necessitating coordinated methodological and organizational solutions.

Rising requirements for adaptability and independent module development increase the sensitivity of monoliths to changes in infrastructure and domain logic. Any intervention raises regression risks and complicates the release of updates [8]. Migration to microservices involves reassembling dependencies, transforming development processes, and creating an environment for the managed evolution of services.

The research focus is shifting from local refactoring to comprehensive migration models that include service identification methods, domain boundary analysis, decomposition patterns, and infrastructure platforms. This approach allows for the consideration of application context, the explanation

of differences in architectural scenarios, and the identification of sustainable transition trajectories. The combination of analytical methods, ontological models, automated algorithms, and engineering platforms ensures a holistic understanding of architectural transformation and its dependence on monolith properties and operating conditions.

The aim of this study is to evaluate strategies for migrating monolithic software complexes to a microservice architecture, based on a comparison of theoretical approaches, practical migration patterns, and engineering solutions that demonstrate the applicability of microservices in high-load and distributed environments.

To achieve this goal, the study addresses tasks related to identifying key factors determining migration design; classifying service extraction methods; analyzing stepwise decomposition patterns; assessing architectural requirements for communication, security, and service management; and investigating the applicability of microservice platforms in industrial and corporate contexts.

The scientific novelty lies in the formation of an integrated conceptual migration framework that unites the methodological, algorithmic, and architectural determinants of the transition from a monolith to microservices.

The research hypothesis posits that successful migration is determined by the cumulative impact of architectural, domain, and technological factors. It is assumed that the combination of domain-driven analysis, staged decomposition patterns, automated service identification, and infrastructural support forms a stable transition trajectory and ensures the controlled evolution of the system.

The scope of the study covers corporate and industrial software complexes where issues of modularity, fault tolerance, and integration are decisive. Particular attention is paid to systems functioning under conditions of high requirement dynamics and the need for rapid scaling, where the architectural inconsistency of the monolith most acutely limits development potential.

II. MATERIALS AND METHODS

The methodological basis of the study is formed by the systematization of theoretical and applied approaches describing the transformation of monolithic software complexes into a microservice architecture and the modernization of legacy systems. The source corpus includes publications from 2021–2025 devoted to decomposition strategies, service identification methods, automated migration models, architectural patterns, and industrial execution platforms for microservices. The analysis includes studies examining organizational, technological, and infrastructural factors influencing system readiness for modularity, distribution, and scalability.

The study by Abu Bakar et al. [1] analyzes practices for modernizing legacy systems and the institutional barriers to architectural transformations. Al-Qora'n et al. [2] provide a systematic assessment of the modular monolith, noting the vagueness of modularity criteria and limited scalability. Fávero et al. [3] map monolith-to-microservice modernization methods and the input artifacts used. Hassan et al. [4] propose a pattern-based scheme for automated migration and describe limitations when working with tightly coupled systems. Kazanavičius et al. [5] investigate the transition of a monolithic database to a polyglot model, recording the architectural consequences of data separation. Maharjan et al. [6] demonstrate the capabilities of AI models in monolith decomposition. Melo et al. [7] analyze human-AI collaboration in the modernization of COBOL systems. Narváez et al. [8] summarize AI methods for microservice design and their current limitations. The most detailed classification of service identification methods is presented in Oumoussa et al. [9], where an ontology of formal decomposition approaches is developed. The practical architectural basis for the industrial application of microservices is revealed in Pontarolli et al. [10], demonstrating the impact of network mechanisms and communication infrastructure on the performance of distributed applications.

The research methodology relies on three analytical directions: (1) a systematic review of theoretical, algorithmic, and engineering approaches determining the logic of migration from monolith to microservices; (2) a comparative analysis of digital and infrastructural tools influencing decomposition, integration, request routing, and the transparency of inter-component interactions; (3) the structuring of organizational and technological factors determining

the sustainability of the architectural transition, including the maturity of development processes, dependency manageability, data quality, and execution platform characteristics. This combination allows migration to be viewed as the result of the interaction of methodological, algorithmic, and architectural elements that form a stable transition trajectory and determine the viability of the microservice model in various operating environments.

III. RESULTS

Analysis of the presented corpus of work revealed significant diversity in migration strategies, differing in target architectural model, types of input artifacts, and degree of decomposition procedure automation. The study by Abu Bakar et al. [1] demonstrates that the modernization of legacy systems in the public sector relies primarily on expert interpretation of architectural dependencies, while contextual constraints of an organizational nature act as a key factor in strategy selection. In the systematic review by Al-Qora'n et al. [2], the modular monolith is interpreted as an intermediate evolutionary form allowing for the elimination of some structural defects of monoliths without proceeding to full service disaggregation. The work of Fávero et al. [3] confirms the fragmentation of the field. Decomposition methods differ in input data, ranging from user stories and code to dependency diagrams, creating a significant gap in the reproducibility of results.

Pattern-based schemes, presented by Hassan et al. [4], form a software engineering migration contour oriented toward minimizing risks when working with tightly coupled monoliths. A distinctive characteristic of this direction is the rigid structural fixation of replacement steps and the sequential isolation of functional segments. In the works of Narváez et al. [8] and Maharjan et al. [6], a shift toward AI algorithms is traceable. In particular, the use of graph neural networks and variational autoencoders allows for the extraction of latent dependencies between components, which increases the precision of service boundary delineation. However, the study by Narváez et al. [8] records significant limitations: the lack of unified validation metrics and the high dependence of result quality on the correctness of initial requirements. The ontological approach proposed by Oumoussa et al. [9] systematizes service extraction methods through the formal description of artifacts and dependencies, creating a base layer of conceptual consistency unavailable in heuristic methods.

The aggregate analysis revealed methodological contradictions. The presence of different architectural representation models (code, requirements, dependency graphs, ontologies) leads to incompatibility of decomposition criteria. Automation methods show varying sensitivity to the quality of input artifacts. Machine learning algorithms amplify errors in source data, whereas ontological schemes require significant costs for formalization. The modular monolith demonstrates utility as an intermediate state, but its boundaries are not standardized. This complicates the inclusion of this form in formal migration strategies. The formulated taxonomy of migration strategies allows for the structuring of contradictions and the comparison of methods by level of formality, automation, and artifact types. Table 1 presents an aggregated view of these differences.

Table 1 – Taxonomy of migration strategies and their characteristics (Compiled by the author based on sources: [1, 4, 8, 9])

Strategy Class	Formal Basis	Input Artifacts	Automation Level	Strengths	Limitations
Modular Monolith	Conceptual modularity; architectural segmentation	Domain model, codebase, module boundaries	Low	Reduces coupling before full migration; simpler operational model	No unified definition; limited scalability
Pattern-based Migration	Migration patterns; staged replacement	Code, dependency graphs, refactoring patterns	Medium	Controlled risk; predictable sequencing	Ineffective with tightly coupled monoliths
Ontology-	Formal	Requirements,	Medium–	High conceptual	High cost of

based Decomposition	ontology; dependency semantics	models, interaction diagrams	High	clarity; reproducible service boundaries	ontology construction
ML/GNN-based Identification	VAE, GNN; latent structural extraction	Code, traces, dependency graphs	High	Improved precision; ability to reveal hidden relations	Sensitive to data quality; lacks unified validation metrics
Knowledge-driven Modernization	Expert-driven contextual analysis	Legacy documentation, organizational constraints	Low	Captures institutional specifics; supports socio-technical constraints	Low replicability; high dependence on experts

Analysis of the taxonomy shows that no single class of strategies is universal. The architectural context, the degree of requirement maturity, and the structure of the original monolith require a combination of methods. The practical applicability of AI approaches is limited by data quality, while ontological models ensure interpretability but require significant formalization resources. The modular monolith and pattern-based schemes remain in demand as managed intermediate stages; however, source data confirm their limitations when working with heterogeneous domains. The formation of a comprehensive migration strategy requires considering these differences and adapting tools to specific system properties.

The transition from a monolith to a service architecture leads to a deep restructuring of the data model, network interaction, and infrastructural organization. The transformation of a monolithic database into a polyglot structure observed in the study by Kazanavičius et al. [5] demonstrates that data decomposition becomes the primary architectural driver of migration and determines the nature of interactions between services. The results of Pontarolli et al. [10] show that distribution and network mechanisms radically change the performance and reliability profile, forming new requirements for orchestration, load balancing, and fault tolerance.

Diagram 1 presents the MOAI service interaction model, reflecting key infrastructural dependencies and structural changes arising during the transition to a microservice architecture.

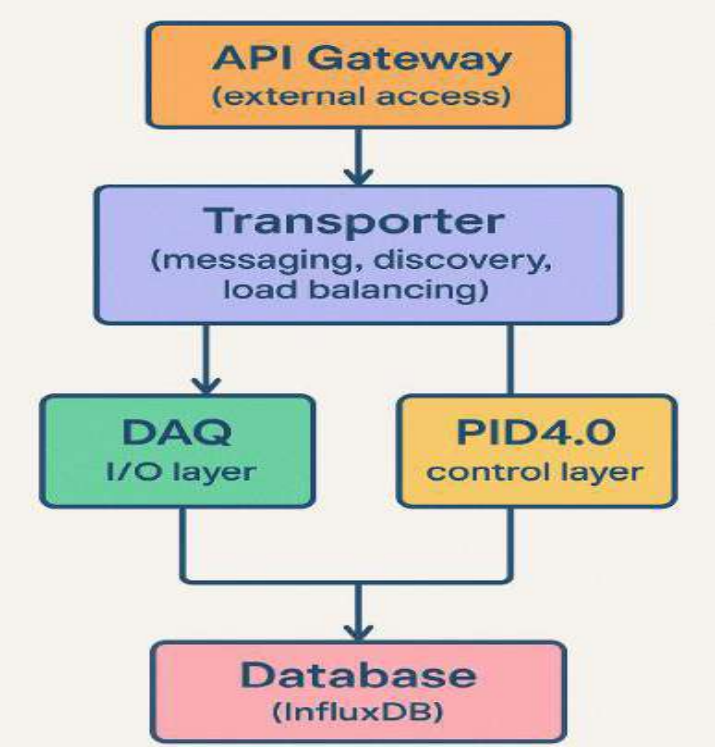

Fig.1 – MOAI Service Interaction Model
(Compiled by the author based on source [10])

The model presented in the diagram demonstrates a typical service interaction configuration in an industrial MOAI environment, where the Transporter performs the functions of a message broker, automating routing, service discovery, and fault tolerance assurance [10]. Such an organization differs sharply from the classic monolith, as data, control loops, and network mechanisms are separated and interact through standardized protocols.

The architectural consequences of migration are most clearly manifested in the data layer. In the study by Kazanavičius et al. [5], it is established that

the transition to a multi-model store increases the consistency of service boundaries but exposes previously hidden dependencies related to domain logic and transactional loops. This restructuring requires a revision of the data schema and a change in coordination mechanisms, as the single transactional model of the monolith gives way to distributed consistency patterns.

Distribution and network mechanisms investigated by Hassan et al. [4] demonstrate a dual nature of influence on architecture. Transparent routing and transport layer balancing improve scalability but introduce latency and interaction variability, which is particularly significant for real-time systems. Experimental results indicate that even with increased network configuration complexity, the microservice model remains applicable if control cycle and throughput requirements are met.

Automation plays a special role in architectural restructuring. The study by Melo et al. [7] shows that human-machine interaction accelerates migration and reduces the probability of errors arising during the manual reconfiguration of service boundaries. Automated tools, in conjunction with expert correction, form a hybrid work model in which AI reduces the load during code analysis, while the human ensures the validity of decisions.

Thus, a comparison of contexts—the public sector, cloud environments, and industrial IAS—demonstrates that the architectural consequences of migration are shaped not so much by technology choice as by the action of institutional and operational constraints. Government systems require increased transparency and change manageability, cloud platforms require elasticity and automated orchestration, and the industrial contour requires predictable network dynamics and resilience to failure.

IV. DISCUSSION

The identified patterns indicate that the character of the initial monolith determines the applicability of specific decomposition strategies. In systems with a high density of informal dependencies, architectural transformation is hindered not by a lack of tools, but by the impossibility of unambiguously defining domain boundaries, which is characteristic of government IT landscapes described by Abu Bakar et al. [1]. In such situations, methods relying on a formal domain structure yield biased results, as the structure itself is incomplete or contradictory. The analysis confirms that automation in such contexts acts not as a mechanism for replacing expert decisions, but as a means of reducing labor intensity while maintaining the leading role of human interpretation. Table 2 examines the comparison of key migration barriers and corresponding architectural solutions recorded in the literature.

The comparison of approaches demonstrates that methods based on formal models depend on the degree of domain structure distinctness. Ontological schemes, presented by Oumoussa et al. [9], ensure maximum transparency and reproducibility of the service identification process but require the presence of a consistent subject domain model. In systems where domain boundaries have evolved historically and are represented by a multitude of exceptions, such methods capture only the top level of architectural relations without covering operational dependencies.

AI models described by Narváez et al. [8] exhibit resilience in fragmented monolith landscapes due to their ability to detect latent dependencies between entities and modules. However, their effectiveness depends on the quality of source artifacts: in domains with a high degree of regulatory ambiguity, models correctly identify technical links but do not distinguish normative and organizational constraints. This aligns with the observations of Melo et al. [7], where automated methods require constant verification by experts to avoid distortions of the architectural picture.

Industrial IAS, analyzed by Pontarolli et al. [10], reveal a different class of limitations. Distributed architecture imposes heightened requirements for network predictability, response time, and fault tolerance. Here, the influence of decomposition methods is determined by module logic and permissible latency in communication between services. The authors demonstrate that changes in the data model are inextricably linked with changes in network infrastructure, creating an additional layer of architectural interdependencies absent in "softer" domains such as cloud applications.

Table 2 – Key Migration Barriers and Architectural Solutions (Compiled by the author based on sources: [2, 3, 7])

Barrier	Description	Proposed Architectural Solution
High module coupling	Dense intra-module dependencies	Modular monolith restructuring; staged refactoring
Legacy constraints	Legacy platforms limit automation	Human–AI collaboration loops
Centralized data	Single shared database	Polyglot persistence; domain-aligned partitioning
Ambiguous boundaries	Lack of clear domain semantics	Ontology-based mapping; AI-based identification
Runtime fragility	Distributed instability in IAS	Network-aware orchestration
Semantic gaps in automation	Algorithms misinterpret business rules	Expert supervision in hybrid models

In the context of cloud environments, approaches demonstrate different dynamics. Pattern-based strategies described by Hassan et al. [4] prove most applicable due to the standardized execution environment, where orchestration, scaling, and networking mechanisms are defined by the platform. In contrast, government information systems described by Abu Bakar et al. [1] are characterized by institutional constraints that limit the freedom to reorganize data and processes. A comparison of these contexts shows the varying sensitivity of architectures to decomposition methods.

The investigation of algorithmic method limitations shows that automated decomposition possesses a pronounced dependence on the nature of source artifacts. In the models described by Narváez et al. [8], grouping precision is determined by the completeness of structural dependencies: with scattered or partially lost data, algorithms form a fragmented service structure. Variational autoencoders and graph neural networks, presented in the work of Maharjan et al. [6], demonstrate a different form of limitation: they capture stable correlations between components but do not reflect the semantic layer related to business rules or regulatory restrictions. As a result, automated approaches reproduce only the technical configuration of the monolith, leaving significant domain dependencies outside the analysis.

Distributed architecture amplifies operational risks associated with network dynamics. The nature of network latency, demonstrated in Pontarolli et al. [10], illustrates the sensitivity of service interactions to the choice of protocols, routing mechanisms, and load balancing tools. increased maintenance complexity manifests in the need for version control, change coordination, and management of a growing number of failure points. Furthermore, the transition to distributed consistency requires new coordination mechanisms. Abandoning centralized transactional procedures leads to the need to redefine rules for sequence, idempotency, and operation compensation.

Data issues form a separate layer of limitations. The transition to polyglot persistence, examined by Kazanavičius et al. [5], changes the nature of transactions. Previously monolithic operations become composite and require coordination between heterogeneous stores. Complexities intensify when migrating large historical schemas where data structure was optimized for a centralized model. A need arises to define domain aggregates, redistribute responsibility between services, implement eventual consistency strategies, and introduce new data governance regulations.

Organizational and process risks manifest in various forms. In government systems described by Abu Bakar et al. [1], architectural transformation is limited by regulatory procedures affecting change speed, degree of automation, and the admissibility of architectural restructuring. In industrial IAS analyzed by Al-Qora'n et al. [2], a key role is played by requirements for the determinism and stability of network paths, which influences the choice of

orchestration mechanisms and the nature of routing. In contexts with obsolete technologies, the load on integration processes increases. Modernization requires the installation of additional bridge or adapter modules and the restructuring of distributed security models. Under conditions of high infrastructure fragmentation, the complexity of dependency management, monitoring, and failure diagnosis increases.

Security constitutes an intersecting class of risks. A distributed environment increases the number of authentication points, expands the attack surface, and requires a coordinated distributed access control policy. These changes necessitate simultaneous technological and organizational restructuring, as security policy must account for the heterogeneity of services, the difference in their execution contours, and the specifics of data exchange.

Thus, the observed structure of limitations shows that the microservice transition is accompanied by the transformation of technical, organizational, and operational mechanisms, wherein architectural trade-offs manifest in the redistribution of complexity between system levels. As the architectural form changes, interaction mechanisms and the nature of engineering responsibility change, determining the specificity of risks in each examined context.

V. CONCLUSION

Migration from a monolith to a microservice architecture should be viewed as a managed change of architectural form rather than simple code disaggregation. The consistency of the domain model, data, and operational constraints is of key importance, as it determines the balance between system flexibility, complexity, and controllability.

This requires a shift from a set of disparate tools to integrated architectural frameworks where formal methods, AI approaches, patterns, and expert decisions work jointly. It is advisable to evaluate migration success by the transparency of service boundaries, the distribution of data responsibility, and the behavioral predictability of the distributed system, rather than by the fact of using microservices per se.

Differences between governmental, cloud, and industrial contexts show the limitations of universal strategies. Architectural solutions must be tuned to regulatory requirements, permissible latencies, infrastructure specifics, and development process maturity; otherwise, uniform approaches increase institutional and operational risks. The practical migration trajectory is logically built as a staged process, combining a modular monolith, pattern-oriented component replacement, managed data decomposition, and hybrid human-machine decision-making loops.

Future research should be oriented toward applied models directly linking the choice of decomposition methods, input artifact quality, and infrastructure parameters with indicators of fault tolerance, scalability, and maintenance complexity. The priority becomes the development of metrics for evaluating the results of automated service identification, comparing the architectural trade-offs of different consistency and orchestration strategies, and forming customizable migration scenarios for typical system classes.

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Navigating Modernity: Consumer Perceptions of Awadhi Culinary Heritage Through a Sociodemographic Lens

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Abstract *— This study investigates how consumers in Lucknow City perceive traditional Awadhi food, critically examining these perceptions within the context of modernity's influence and the diverse sociodemographic profiles of urban dwellers. Recognizing Awadhi cuisine's profound cultural significance and its burgeoning potential for gastronomic tourism, the research seeks to understand its contemporary resonance. An extensive literature review, encompassing over 50 academic articles, systematically identified 18 salient variables influencing consumer food choices, such as authenticity, quality, flavor, price, and perceived health benefits, all operationalized for this empirical investigation. The primary objectives were to discern the critical factors driving consumer choices for traditional Awadhi food and to delineate contemporary consumer perceptions of this distinct regional cuisine. Employing a quantitative research design, data were meticulously collected from 250 consumers via a structured online questionnaire, utilizing a five-point Likert scale. Following rigorous pilot testing to ensure instrument validity and reliability (Cronbach's Alpha = 0.981), factor analysis was applied to the collected data using SPSS. The analysis yielded a robust three-factor solution, collectively explaining 95.847% of the total variance, thus providing a parsimonious representation of underlying perceptual structures. Findings indicate that Awadhi cuisine is predominantly perceived as highly flavoursome, of superior quality, authentically prepared, distinguished by unique recipes, and a significant promoter of local tourism. Conversely, a notable perception suggests it is complex to prepare and generally associated with a higher price point. These comprehensive insights offer actionable strategies for stakeholders within the hospitality and tourism sectors to strategically enhance the promotion, accessibility, and sustained cultural and economic value of Awadhi cuisine in an era of rapid social and economic change.*

Keywords *— **Awadhi food, consumer perception, traditional cuisine, food choices, cultural heritage, tourism, modernity, socio-demographic.***

I. INTRODUCTION

In an increasingly globalized world, consumer perceptions of food are shaped by a complex interplay of conscious and subconscious factors, including affordability, convenience, health benefits, and organoleptic qualities, alongside individual beliefs, attitudes, and socio-cultural backgrounds (Chen & Antonelli, 2020; Monterrosa et al., 2020). These diverse motivations are critical for market success, with health, weight management, hedonic enjoyment, ethics, and ease of preparation being significant determinants for modern consumers (Geuens, 2023;

Konttinen et al., 2021). Safety and transparency are also increasingly prioritized by those navigating contemporary food choices (Bussel et al., 2022; Cardello et al., 2007).

Within this framework, there's a growing global interest in traditional and regional foods, often driven by a societal response to industrialization, environmental concerns, and the homogenizing forces of modernity (Kristia et al., 2024; Zocchi & Fontefrancesco, 2020). Traditional foods transcend mere sustenance; they are cultural artifacts, embodying heritage, identity, and community practices (Pivarski et al., 2023; Rocillo-Aquino et al., 2021). Consumers are drawn to their authenticity, unique origins, distinct traditions, and perceived quality, alongside their sustainability potential. These foods, often relying on natural, local ingredients and artisanal methods, offer significant social, cultural, and economic value beyond nutrition (Etale & Siegrist, 2021; House et al., 2023; Zocchi & Fontefrancesco, 2020).

Awadh, historically known for its rich cultural and culinary legacy, developed a distinctive cuisine through the royal kitchens of its Nawabs (Ghosh, 2022; Roy, 2009; Singh & Jafri, 2011). Characterized by sophisticated slow-cooking techniques like "Dum" and "Dhungar," Awadhi cuisine is a prominent cultural feature. This research aims to understand how this deeply rooted culinary heritage is perceived by contemporary consumers in Lucknow, specifically examining the sociodemographic factors that influence these perceptions as the city itself navigates modernity. By exploring this specific tradition through a sociodemographic lens, this study seeks to enhance understanding of consumers' perception regarding traditional regional foods in a rapidly evolving urban landscape.

II. REVIEW OF LITERATURE

2.1 Conceptualizing Traditional Food in Modern Contexts

Traditional food is a multifarious construct that encapsulates the historical, cultural, and geographical essence of a community. It extends beyond mere ingredients, representing a culmination of time-honored methods, cherished customs, and a distinct regional identity. The integration of "traditional" into a food product can stem from unique preparation techniques or a profound connection to a specific geographical origin. Given that the attribute of "tradition" is not directly discernible through sensory characteristics, modern consumers frequently rely on extrinsic cues such as labels or certifications to ascertain authenticity. This perceived authenticity holds substantial value, particularly within the domain of culinary tourism, where local cuisine is recognized as a fundamental component of a destination's identity, thereby enriching the tourist experience and contributing to local economic sustainability (Bardhi et al., 2010; Brokaj, 2014; Cohen &Avieli, 2004; Everett & Aitchison, 2008; Nair et al., 2020; Peulić et al., 2023).

Traditional foods are often passed down through generations, reflecting the customs and traditions of a particular community or country, making them an inalienable part of cultural heritage and identity. The appeal of traditional products frequently stems from their perceived authenticity, which is strongly connected with origin and naturalness. The concept of traditional food itself often involves dimensions of time, place, know-how, and cultural meaning. Despite its allure, engaging with unfamiliar culinary traditions can present challenges for consumers. Travelers, for instance, frequently rely on their existing knowledge to navigate local food options, which may limit their exploratory behavior.

2.2 Consumers' Perception Towards Traditional Food and Cuisine in a Modernizing Society

The growing interest in traditional food can be attributed to various societal shifts, including concerns over food crises, industrialization, globalization, and environmental issues—all hallmarks of modernity. Researchers have highlighted several key motivations for consuming traditional local food, such as reducing perceived health risks, rediscovering authentic flavors, aligning with environmental concerns, and fostering social bonds through interaction with producers and other consumers (Haghighian et al., 2021; Soare et al., 2023). Modern consumers are increasingly seeking products free from artificial additives, preservatives, and synthetic ingredients, driven by health and sustainability concerns and a desire for greater transparency in food production processes. These traditional options are often perceived as healthier

alternatives to heavily processed options, typically made using natural, fresh, local, and seasonal ingredients with artisanal production methods and time-consuming processes like slow cooking, which contribute to their unique characteristics and quality.

Quality is consistently identified as an essential attribute influencing consumer decisions regarding traditional foods (Peulić et al., 2023; Soare et al., 2023). Furthermore, authenticity remains a paramount criterion, with consumers preferring products made using traditional methods and ingredients, and often associating them with a particular geographic region or small-scale producers. The source of food also plays a significant role, as many consumers favor local or regional traditional products, believing them to be superior to those from other areas. This aligns with findings that consumers prioritize traditional production processes and value specific geographic origins.

Cultural background is a pivotal element that profoundly modulates consumer behavior, tastes, and preferences regarding food, making it a key component of the sociodemographic lens (Jayasinghe et al., 2025; Jeong & Lee, 2021; Lindsey, 2024). Food serves as a symbol of personal identity, group affiliation, and cultural identity. Learning processes, both explicit and implicit, transmit information about values and attitudes for food and eating, contributing to the relative stability of food practices over time. Familiarity with a product is a critical driver in the purchase and consumption process, as it mitigates uncertainty and aligns consumer expectations with actual product characteristics. While national culture is important, social, demographic, and economic factors, alongside individual experiences, must also be considered to fully explain differences in food acceptability across cultures (Ajetunmobi & Laobangdisa, 2024; Jeong & Lee, 2021). For tourists, price is highly influential in shaping their satisfaction with local food experiences, followed by the affective image of food and its uniqueness and cultural heritage (Chowdhury & Narang, 2015; Muskat et al., 2019). Consumers perceive product authenticity by analyzing characteristics and purchase situations based on uniqueness, cultural or traditional association, production process characteristics, and specific extrinsic attributes such as branding and origin. This underscores the importance of highlighting the distinct cultural narrative and authentic preparation methods of traditional cuisines like Awadhi food to attract and satisfy modern consumers. The quest for authenticity is often seen in the search for traditional and local foods, where consuming local food means "consuming the meaning behind it" (Morris et al., 2020; Nair et al., 2020). Several academic studies have elucidated various variables that influence consumer food choices illustrated in Table 1.

Table 1: Variables Influencing Consumers' Food Choices

Sr.No.	Motivational Variables for food choice	Author/s
1.	Better taste	Drewnowski (1997)
2.	Health beneficial	Kozup et al. (2003)
3.	Advertising campaign	Story and French (2004)
4.	Convenient to get from market	Kim et al. (2006)
5.	Made with more authentic methods	Sukalakamalaand Boyce (2007)
6.	Eye appealing	Namkung and Jang (2008)
7.	Promotes local tourism	Everett and Aitchison (2008)
8.	Price	Steenhuis et al. (2011)
9.	Good quality food	Nezakati et al. (2011)
10.	Less use of preservatives	Chaudhry and Castle (2011)
11.	Nutritional Value	Din et al. (2012)
12.	Calories	Block et al. (2013)

13.	Flavoursome	Zellner et al. (2014)
14.	Good economic impact on local communities	Teodoroiu (2015)
15.	Easy to prepare	Contini et al. (2016)
16.	Provides variety of food	Baiomy et al. (2019)
17.	Unique recipes	Borghini and Piras (2020)
18.	Less spicy	Racette and Drake (2022)

III. RESEARCH GAP AND PROBLEM FORMULATION: BRIDGING HERITAGE AND MODERN CONSUMERISM

Despite extensive historical documentation of Awadh and general discourse on traditional foods as cultural heritage, specific scholarly research on Awadhi cuisine's potential as a culinary tourism asset in Lucknow remains limited. A notable void exists in academic literature concerning consumer perceptions of traditional Awadhi Cuisine in Lucknow city, particularly how these perceptions are influenced by the dynamics of modernization and the diverse sociodemographic profiles of its inhabitants. This study aims to bridge this existing knowledge gap by providing an empirical analysis of these perceptions through a sociodemographic lens, thereby contributing to a deeper understanding of how culinary heritage navigates the challenges and opportunities of modernity.

IV. RESEARCH METHODOLOGY

Data were collected in September 2025 from adult residents via an online questionnaire using convenience sampling, resulting in 180 completed questionnaires from 250 potential respondents. The questionnaire was distributed through email and hybrid digital media – instant messaging app, WhatsApp. The instrument included demographic questions, crucial for the sociodemographic analysis, and 18 perception variables on a 5-point Likert type scale. The data was processed and analyzed using SPSS 19.0. The value of Cronbach's Alpha, i.e., 0.981, confirmed the excellent internal consistency of the data.

V. ANALYSIS AND FINDINGS

5.1. Demographic Characteristics of the Respondents

The 180 participants, representing the sociodemographic cross-section of the study, were predominantly male (66.7% male, 33.3% female), with a strong bias towards younger demographics (134 individuals in the 18-30 age group, 15.6% in 31-40, declining thereafter). A majority were unmarried (75.0% unmarried vs. 25.0% married), and education was primarily undergraduate, followed by graduate and postgraduate. Students constituted 61.1% of the occupational profile, followed by private sector employees. Income showed significant 'Not earning' respondents, consistent with student prevalence; among earners, '>₹6-10 Lakhs' was the largest segment, while '₹3-6 Lakhs' and '>₹10 Lakhs' each comprised ₹12.8%, and '<₹3 Lakh' was 10.0%.

Table 2: Demographic Characteristics of Respondents

		Frequency	Percent	Valid Percent	Cumulative Percent
Gender	Female	60	33.3	33.3	33.3
	Male	120	66.7	66.7	100.0
Age in Years	18- 30	134	74.4	74.4	74.4
	31-40	28	15.6	15.6	90.0
	41-50	14	7.8	7.8	97.8
	51-60	3	1.7	1.7	99.4

	Above 60	1	.6	.6	100.0
Marital Status	Unmarried	135	75.0	75.0	75.0
	Married	45	25.0	25.0	100.0
Education Qualification	Under-Graduate	93	51.7	51.7	51.7
	Graduate	41	22.8	22.8	74.4
	Post-Graduate	31	17.2	17.2	91.7
	Doctorate	13	7.2	7.2	98.9
	Others	2	1.1	1.1	100.0
Occupation	Student	110	61.1	61.1	61.1
	Government Job	28	15.6	15.6	76.7
	Private Job	33	18.3	18.3	95.0
	Homemaker	1	.6	.6	95.6
	Others	2	1.1	1.1	96.7
	Self-Employed	5	2.8	2.8	99.4
	Retired	1	.6	.6	100.0
Annual Income	Not earning	62	34.4	34.4	34.4
	<₹3 lakh	18	10.0	10.0	44.4
	₹3-6 Lakhs	23	12.8	12.8	57.2
	>₹6-10 Lakhs	54	30.0	30.0	87.2
	>₹10 Lakhs	23	12.8	12.8	100.0
	Total	180	100.0	100.0	

5.2. Descriptive Statistics of Variables Measuring Consumer Perceptions of Traditional Awadhi Food in the Modern Era

A quantitative analysis of 18 constructs, using a five-point Likert scale, revealed that Awadhi food is perceived as "not easy to prepare" (lowest mean score, 2.98), reflecting a common challenge in modern lifestyles, and yet strongly promotes local tourism (mean score 4.11), indicating its enduring cultural and economic value.

Table 3: Descriptive Statistics of variables for Factor Analysis

Variables	Mean	Std. Deviation	Analysis N
Easy to prepare	2.98	1.165	180
Made with more authentic methods	3.99	1.219	180
Unique recipes	4.01	1.155	180
Good quality food	4.09	1.174	180
Eye appealing	4.01	1.172	180
Flavoursome	4.24	1.112	180
Less spicy	3.32	1.097	180
Less use of preservatives	3.63	1.143	180
Better taste	3.97	1.281	180

Provides variety in menu	3.96	1.157	180
Convenient to get from market	3.73	1.156	180
Low price	3.22	1.203	180
High in calories	3.77	1.269	180
Good advertising campaign of Awadhi food	3.49	1.217	180
More nutritional	3.50	1.170	180
Health beneficial	3.29	1.151	180
Good economic impact on local communities	3.82	1.233	180
Promotes local tourism	4.11	1.200	180

5.3. Factor Analysis Summary of Consumer Perceptions of Awadhi Cuisine in Modern Lucknow

The Kaiser-Meyer-Olkin measure of sampling adequacy (0.951) and a statistically significant Bartlett's Test of Sphericity (Approx. Chi-Square = 8877.477, df = 153, Sig. = 0.000) confirmed the dataset's strong suitability for factor analysis, validating the identification of latent structures within the variables that shape contemporary consumer perceptions.

Table 4: KMO and Bartlett's Test Results

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.951
Bartlett's Test of Sphericity	Approx. Chi-Square	8877.477
	Df	153
	Sig.	0.000

High values of communalities, shown in Table 5, confirm the three-factor model's robust explanatory power, indicating substantial variability is accounted for within consumer perceptions. Collectively, these components explain 95.847% of the total variance.

Table 5: Communalities of Variables in Factor Analysis of Consumer Perceptions of Traditional Awadhi Food

Communalities		
Variables	**Initial**	**Extraction**
Easy to prepare	1.000	.984
Made with more authentic methods	1.000	.974
Unique recipes	1.000	.967
Good quality food	1.000	.971
Eye appealing	1.000	.972
Flavoursome	1.000	.944
Less spicy	1.000	.944
Less use of preservatives	1.000	.936
Better taste	1.000	.963

Provides variety in menu	1.000	.960
Convenient to get from market	1.000	.931
Low price	1.000	.953
High in calories	1.000	.951
Good advertising campaign of Awadhi food	1.000	.963
More nutritional	1.000	.962
Health beneficial	1.000	.956
Good economic impact on local communities	1.000	.958
Promotes local tourism	1.000	.964

Extraction Method: Principal Component Analysis.

Table 6: Total Variance Explained in Factor Analysis of Consumer Perception of Traditional Awadhi Food

Total Variance Explained				
Component	**Extraction Sums of Squared Loadings**	**Rotation Sums of Squared Loadings**		
	Cumulative %	**Total**	**% of Variance**	**Cumulative %**
1	91.949	7.797	43.316	43.316
2	94.134	6.425	35.693	79.009
3	95.847	3.031	16.838	95.847

The Rotated Component Matrix delineates the following three factors in consumer perceptions:

Table 7: Rotated Component Matrix of Consumer Perceptions of Traditional Awadhi Food

Rotated Component Matrix[a]			
	Component		
	1	2	3
Flavoursome	.806		
Promotes local tourism	.786		
Good quality food	.785		
Made with more authentic methods	.764		
Eye appealing	.752		
Unique recipes	.746		
Better taste	.739		
Provides variety in menu	.717		
Good economic impact on local communities	.669		
High in calories	.651		
Convenient to get from market	.627		

More nutritional		.746	
Less spicy		.744	
Low price		.737	
Health beneficial		.735	
Good advertising campaign of Awadhi food		.732	
Less use of preservatives		.689	
Easy to prepare			-.827

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization[a].

a. Rotation converged in 6 iterations.

Factor 1: Gastronomic Excellence and Regional Contribution (43.316% variance). This factor is defined by high positive loadings from attributes reflecting intrinsic sensory appeal, authenticity, and broader socio-economic/cultural contributions of Awadhi food. Key attributes include "Flavoursome," "Promotes local tourism," "Good quality food," "Made with more authentic methods," "Eye appealing," "Unique recipes," "Better taste," "Provides variety in menu," and "Good economic impact on local communities." "High in calories" and "Convenient to get from market" also show moderate loadings. This indicates modern consumers perceive Awadhi food as a holistic entity encompassing superior gustatory and visual qualities, traditional preparation, diverse offerings, and a significant positive regional impact. This suggests a continued appreciation for its heritage value despite societal shifts.

Factor 2: Health and Value Perception in a Modernizing Lifestyle (35.693% variance). This factor is characterized by strong positive loadings from attributes related to health perceptions ("More nutritional," "Less spicy," "Health beneficial," "Less use of preservatives") and economic accessibility/promotional effectiveness ("Low price," "Good advertising campaign of Awadhi food"). This factor suggests consumers navigating modernity integrate the food's health profile, affordability, and perceived marketing effectiveness into a singular construct. This highlights a growing awareness of health and economic considerations alongside traditional culinary values.

Factor 3: Ease of Preparation (16.838% variance). This factor is distinctly defined by a single, strong negative loading (-.827) from "Easy to prepare." This signifies a predominant consumer perception that Awadhi food requires substantial effort, time, or skill for its preparation, representing an independent dimension reflecting practical challenges imposed by modern lifestyles.

VI. DISCUSSION: SOCIODEMOGRAPHIC INSIGHTS INTO AWADHI CULINARY PERCEPTIONS AMIDST MODERNITY

The findings illuminate a complex interplay of perceptions among Lucknow consumers regarding traditional Awadhi cuisine, which are profoundly influenced by their sociodemographic backgrounds, particularly given the predominantly young, male, and student demographic of the sample. The strong emphasis on "Gastronomic Excellence and Regional Contribution" as the primary factor indicates that, despite the shifts brought by modernity, the intrinsic quality, unique recipes, and cultural authenticity of Awadhi food remain paramount in consumer appreciation. This suggests a continued high regard for the heritage aspect of the cuisine, which is also strongly linked to its ability to "promote local tourism" and deliver "good economic impact on local communities." The inclusion of "High in calories" and "Convenient to get from market" within this factor suggests that even with a traditional core, modern consumers, including younger segments, value both indulgence and accessibility, pointing to how heritage is consumed in contemporary life.

The "Health and Value Perception" factor reveals a growing consumer consciousness about the health

aspects of traditional foods, coupled with a desire for affordability. Attributes like "More nutritional," "Less use of preservatives," and "Health beneficial" indicate that modern consumers are not solely focused on taste but also on the perceived wellness benefits of traditional preparations. The presence of "Low price" in this factor suggests that for some sociodemographic segments, the value proposition of Awadhi food is tied to its economic accessibility, which can be a critical consideration in a diverse urban landscape. This could be particularly relevant for students and those with limited disposable income, who might seek healthier, yet affordable, traditional options, reflecting adaptation to modern economic realities.

The distinct "Ease of Preparation" factor highlights a significant practical barrier in the context of modern living. The strong negative loading on "Easy to prepare" underscores that while Awadhi cuisine is revered for its quality and authenticity, its complex and time-consuming cooking methods are a deterrent for modern consumers, particularly those with busy lifestyles or limited culinary skills. This factor directly reflects the tension between preserving traditional cooking processes and adapting to the demands of contemporary life. This perception may be more pronounced among younger, less experienced cooks or those without access to traditional household support, which is common in a rapidly modernizing urban environment, illustrating the challenges of navigating modernity through culinary practices.

VII. CONCLUSION, IMPLICATIONS, AND FUTURE RESEARCH

This study successfully identified 18 variables influencing food choices and characterized consumer perceptions of traditional Awadhi cuisine, offering a sociodemographic insight into how this heritage is received in modern Lucknow. Findings indicate Awadhi food is predominantly perceived as highly flavoursome, superior in quality, authentically prepared, possessing unique recipes, and significantly contributing to local tourism. Conversely, it is often viewed as complex to prepare and associated with a higher price point. These perceptions suggest that despite appreciation for intrinsic qualities and cultural value, convenience and cost may pose barriers, particularly for the younger, student-dominated demographic. This research offers a data-driven analysis of consumer behavior towards traditional regional foods within the Lucknow context, navigating the complexities of modernity.

The study offers practical implications for Lucknow's hospitality and tourism sectors seeking to promote Awadhi culinary heritage in the modern era. Marketing efforts should strategically leverage high positive perceptions of authenticity, quality, unique recipes, and flavor to attract consumers seeking genuine culinary experiences. The strong association with local tourism suggests developing culinary routes, food festivals, and experiential dining opportunities, fostering collaboration between tourism boards and local businesses. Addressing the consumer perception of "complexity of preparation" could involve promoting ready-to-cook traditional Awadhi food kits or conducting culinary workshops to demystify traditional methods. Similarly, strategic pricing models could enhance accessibility without compromising perceived value, especially to cater to different income groups highlighted in the sociodemographic analysis, thereby ensuring the cuisine's relevance in a modern market.

The study's reliance on convenience sampling, with a predominance of young, male, and student respondents, limits generalizability across all sociodemographic segments of Lucknow. Therefore, future research should employ other sampling techniques to ensure broader representation. Future research could investigate the impact of specific marketing strategies, such as geographical indication or heritage branding, on consumer acceptance and willingness to pay across different sociodemographic groups. Additionally, longitudinal studies could track changes in consumer perceptions over time as modernization continues to influence dietary habits and cultural values, providing a more dynamic understanding of how Awadhi culinary heritage is navigated by its people.

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Graduate Employability and Skills Utilization: A Tracer Study of BSBA Marketing Management and BS Entrepreneurship 2024 Graduates of NEUST Atate Campus

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Abstract *— This tracer study assessed the employability of BS Entrepreneurship and BSBA Marketing Management graduates of Nueva Ecija University of Science and Technology (NEUST) Atate Campus, Batch 2024. Using a descriptive design and total enumeration approach, the study covered 60 graduates from the second semester of Academic Year 2023–2024. Data were collected through an online survey and analyzed using descriptive statistics to evaluate employment status, job alignment, earnings, and training adequacy. Results show that 72% of graduates are employed, with employment rates of 77% among BSBA graduates and 62% among BS Entrepreneurship graduates. Most respondents secured employment within three months after graduation, indicating strong workforce readiness. The majority work in jobs related to their degree and report high utilization of communication, leadership, and problem-solving skills. Graduates perceive their academic training as highly adequate and recommend expanded training programs, stronger industry partnerships, and curriculum modernization. The findings confirm that NEUST Atate Campus produces employable graduates while underscoring the importance of continuous curriculum improvement.*

Keywords *— **graduate tracer study; employability; business education; curriculum relevance; workforce readiness; skills utilization; higher education outcomes***

I. INTRODUCTION

Tracer studies are widely recognized as essential tools for evaluating the relevance of higher education programs and the employability of graduates. By systematically tracking alumni outcomes, tracer research provides empirical evidence on how academic training aligns with labor market demands and industry expectations. These studies support curriculum enhancement, institutional accountability, and strategic decision-making, ensuring that graduates remain competitive in a rapidly evolving workforce (Fahmy et al., 2025). Recent literature highlights that tracer studies extend beyond employment rates by examining job quality, relevance of training, and career progression, offering a more comprehensive assessment of educational impact.

Nueva Ecija University of Science and Technology (NEUST) – Atate Campus, located in Palayan City, Nueva Ecija, Philippines, offers business and entrepreneurship programs designed to develop professional competencies and industry-relevant skills. As a state university committed to quality assurance, NEUST Atate Campus regularly conducts tracer studies to evaluate graduate outcomes and

maintain alignment with workforce needs (Natividad et al., 2024).

In the Philippine context, tracer studies are mandated by the Commission on Higher Education (CHED) as part of institutional accountability and continuous improvement, reinforcing the importance of graduate feedback in curriculum reform (Rivera et al., 2025).The 2024 tracer study builds upon the 2023 findings to provide an updated assessment of graduate employability. By examining employment status, job alignment, skill utilization, and alumni feedback, the study seeks to generate actionable insights for program enhancement. Ultimately, the research strengthens the connection between education and employment, ensuring that graduates are prepared for sustainable career success in an increasingly competitive labor environment (Caclini-Pumihic & Binwag, 2025)

II. METHODOLOGY

This study employed a descriptive research design using a total enumeration approach to assess the employability and career outcomes of graduates. Descriptive research is appropriate for tracer studies because it aims to identify and describe characteristics of a population as they naturally exist without manipulating variables (Deckert & Wilson, 2023). The respondents consisted of 60 graduates based on registrar records from the 2nd semester of Academic Year 2023–2024, including 21 BS Entrepreneurship graduates and 39 BSBA Marketing Management graduates. Total enumeration ensured that all identified graduates were included, allowing full population coverage and eliminating sampling bias.

Data were collected through an online survey using Google Forms. A structured tracer questionnaire developed by the researchers gathered information on demographic profile, employment status, job alignment, skills utilization, and alumni recommendations. Surveys are widely used in descriptive research to document characteristics and experiences of a defined population (Deckert & Wilson, 2023).

The survey link was distributed through Facebook Messenger, direct messages, and alumni communication channels to maximize participation. Data were analyzed using frequency counts, percentages, and weighted means. Ethical standards were strictly observed: participation was voluntary, informed consent was obtained, and all responses were kept confidential and used solely for academic and institutional improvement.

III. RESULTS AND DISCUSSION

Table 1. Gender

	BS Entrep		BSBA MM		Total	
Gender	*f*	%	*f*	%	*f*	%
Female	14	67%	31	79%	45	75%
Male	6	29%	6	15%	12	20%
Not traced	1	5%	2	5%	3	5%
Total	21	100%	39	100%	60	100%

Table 1 shows that female graduates dominate both programs, accounting for 75% of the total respondents. However, a comparison reveals that BSBA Marketing Management has a higher female proportion (79%) than BS Entrepreneurship (67%). Male representation is relatively higher in BS Entrepreneurship (29%) than in BSBA (15%), suggesting that entrepreneurship programs may attract slightly more gender diversity. Similar gender trends were observed in tracer studies across business programs where female participation consistently exceeds male enrollment (Dassun et al., 2025). Villanueva and Binay-an (2021) likewise reported that female graduates dominate professional programs, reflecting broader participation shifts in higher education. The comparison suggests that while both programs are female-driven, entrepreneurship retains relatively stronger male representation, possibly due

to perceptions of entrepreneurial risk-taking and business ownership roles.

Table 2. Civil Status

Civil Status	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
Single	17	81%	34	87%	51	85%
Married	3	14%	3	8%	6	10%
Not traced	1	5%	2	5%	3	5%
Total	21	100%	39	100%	60	100%

Table 2 indicates that the majority of graduates are single (85%), while only 10% are married and 5% were not traced. When comparing programs, both BS Entrepreneurship (81%) and BSBA Marketing Management (87%) graduates are predominantly single, with BSBA showing a slightly higher proportion. The similarity across programs suggests that most respondents are in the early stage of their professional careers, prioritizing employment and career establishment before long-term family commitments. This pattern is consistent with tracer findings across Philippine higher education institutions. Lopez (2024) reported that recent graduates are typically single because early-career individuals focus on job mobility and skill development before entering marriage. Dassun et al. (2025) likewise observed that young business graduates tend to delay family responsibilities while stabilizing their employment trajectory. Civil status is not a determinant of employability but may influence flexibility in job location and career decisions. The present results therefore reflect a transitional demographic phase common among newly entering professionals.

Table 3. Status of Employment

Civil Status	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
Casual	2	10%	0	0%	2	3%
Contractual	1	5%	7	18%	8	13%
Probationary	1	5%	2	5%	3	5%
Regular/permanent	8	38%	19	49%	27	45%
Self-employed	1	5%	2	5%	3	5%
Unemployed	7	33%	7	18%	14	23%
Not traced	1	5%	2	5%	3	5%
Total	21	100%	39	100%	60	100%

Table 3 shows important distinctions in employment outcomes between BS Entrepreneurship and BSBA Marketing Management graduates. BSBA Marketing Management graduates demonstrate higher permanent employment (49%) compared to BS Entrepreneurship graduates (38%). Conversely, BS Entrepreneurship shows a higher unemployment rate (33%) than BSBA (18%). This suggests that BSBA graduates may experience faster workforce absorption into structured employment sectors such as corporate marketing, banking, and retail. In contrast, entrepreneurship graduates may face a transitional phase where business establishment or self-employment takes longer to stabilize. Dassun et al. (2025) similarly found that entrepreneurship graduates often experience delayed employment

stability while exploring independent ventures. Villanueva and Binay-an (2021) note that early-career unemployment is frequently linked to limited work experience rather than academic inadequacy. The comparison indicates that BSBA graduates may benefit from clearer industry pipelines, while entrepreneurship graduates follow more varied and risk-driven career paths.

Table 4. Summary of Status of Employment

Civil Status	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
Employed	13	62%	30	77%	43	72%
Unemployed	7	33%	7	18%	14	23%
Not traced	1	5%	2	5%	3	5%
Total	21	100%	39	100%	60	100%

Table 4 shows that the majority of graduates are employed (72%), while 23% remain unemployed and 5% were not traced. A program comparison indicates that BSBA Marketing Management graduates demonstrate a higher employment rate (77%) than BS Entrepreneurship graduates (62%). Conversely, unemployment is more pronounced among BS Entrepreneurship graduates (33%) compared to BSBA graduates (18%). This suggests that BSBA graduates may transition more quickly into structured employment sectors where corporate recruitment pathways are more established. These findings are consistent with tracer literature showing that business graduates entering corporate fields tend to achieve faster workforce absorption than those pursuing entrepreneurial pathways (Caclini-Pumihic & Binwag, 2025). Similarly, the 2023 NEUST tracer study reported favorable employment outcomes among business graduates, reinforcing the institution's capacity to prepare students for labor market entry (Natividad et al., 2024). Fahmy et al. (2025) emphasize that employment transitions immediately after graduation are often shaped by industry pipelines, internships, and work-integrated learning opportunities rather than academic inadequacy. Lagatic et al. (2024) further note that early-career unemployment reflects transitional labor market conditions rather than program failure. The results therefore indicate that while both programs produce employable graduates, entrepreneurship graduates may benefit from additional incubation support and enterprise mentoring to stabilize career trajectories.

Table 5. Reason for Unemployment

Reason for Unemployment	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
Advance or further study	1	14%			1	7%
Family concern	4	57%	4	57%	8	57%
Health-related reason (s)	1	14%	1	14%	2	14%
No job opportunity	1	14%		0%	1	7%
Did not look for a job			1	14%	1	7%
Lack of experience			1	14%	1	7%
Total	7	100%	7	100%	14	100%

Table 5 shows that the dominant reason for unemployment among graduates is family concern (57%), a pattern observed equally in both BS Entrepreneurship and BSBA Marketing Management graduates. Other reported reasons include health-related conditions (14%), pursuing further studies

(7%), lack of job opportunities (7%), not actively searching for employment (7%), and lack of experience (7%). The similarity across programs suggests that unemployment is largely driven by personal and situational factors rather than differences in academic preparation. Tracer literature consistently emphasizes that early unemployment among graduates is often transitional and shaped by socio-personal conditions. Dassun et al. (2025) found that many business graduates delay employment due to readiness concerns and personal priorities, highlighting that unemployment does not necessarily indicate weak employability. Similarly, Villanueva and Binay-an (2021) reported that lack of experience and personal decisions frequently affect immediate job entry among graduates. Lopez (2024) also observed that graduates may temporarily remain unemployed while adjusting to family responsibilities or seeking better career alignment . These findings reinforce that unemployment in tracer studies should be interpreted as part of a career transition phase rather than institutional inadequacy. The present results therefore indicate that most unemployed graduates are navigating personal life adjustments while preparing for workforce entry.

Table 6. Present Occupation

	BS Entrep		BSBA MM		Total	
Present Occupation	*f*	%	*f*	%	*f*	%
Academe	1	8%			1	2%
Banking, Finance, Insurance	3	23%	4	13%	7	16%
Food Business			1	3%	1	2%
Business Process Outsourcing	1	8%	1	3%	2	5%
Government and Quasi-government	1	8%	3	10%	4	9%
Government Employee			1	3%	1	2%
Industrial/Manufacturing	1	8%	1	3%	2	5%
Local Government Unit	1	8%			1	2%
Marketing, Sales, Logistics	5	38%	14	47%	19	44%
OFW			1	3%	1	2%
Pharmacy			1	3%	1	2%
Private Company			1	3%	1	2%
TECHVOC PROCESSING OFFICER			1	3%	1	2%
Telecom/Communications			1	3%	1	2%
Total	13	100%	30	100%	43	100%

Table 6 shows that the largest proportion of employed graduates are working in Marketing, Sales, and Logistics (44%), with BSBA Marketing Management graduates demonstrating higher representation (47%) compared to BS Entrepreneurship graduates (38%). This concentration suggests strong alignment between academic specialization and occupational placement, particularly for BSBA graduates whose curriculum directly supports marketing and sales competencies. Banking, finance, and insurance follow as the second most common employment sector (16%), indicating that business graduates are also competitive in financial industries. BS Entrepreneurship graduates display a more diversified occupational spread, including government service, industrial/manufacturing, local government units, and business process outsourcing. This diversity reflects the flexible and multi-sector orientation of entrepreneurship education. Similar findings were reported by Dassun et al. (2025), who observed that business graduates frequently cluster in marketing

and finance sectors due to transferable business skills. Villanueva and Binay-an (2021) likewise noted that graduates with entrepreneurial training often pursue varied career paths across industries. Lopez (2024) emphasizes that occupational diversity among graduates is an indicator of adaptable competencies and labor market responsiveness. The present results therefore suggest that both programs successfully equip graduates with employable skills, with BSBA graduates showing stronger specialization alignment and entrepreneurship graduates demonstrating broader occupational mobility.

Table 7. Present Job Position

	BS Entrep		BSBA MM		Total	
Present Job Position	*f*	%	*f*	%	*F*	%
Managerial			6	20%	6	14%
Rank- and –file	11	85%	16	53%	27	63%
Self-employed/Owner/co-owner	2	15%	3	10%	5	12%
Supervisory	0	0%	5	17%	5	12%
Total	13	100%	30	100%	43	100%

Table 7 shows that the majority of employed graduates occupy rank-and-file positions (63%), with a higher proportion among BS Entrepreneurship graduates (85%) compared to BSBA Marketing Management graduates (53%). Managerial roles account for 14% of the total, all of which are held by BSBA graduates, while supervisory positions (12%) are also concentrated within BSBA respondents. Self-employed or owner/co-owner roles represent 12% of the graduates, with BS Entrepreneurship showing slightly higher entrepreneurial engagement (15%) than BSBA (10%). This pattern suggests that BS Entrepreneurship graduates are more likely to initiate independent ventures, while BSBA graduates tend to enter structured corporate hierarchies that offer clearer promotion pathways. Tracer literature explains that early-career graduates commonly begin in rank-and-file roles as part of professional skill-building and organizational socialization. Dassun et al. (2025) note that managerial placement immediately after graduation is relatively uncommon and typically requires prior experience or advanced credentials. Villanueva and Binay-an (2021) similarly observed that graduates initially occupy entry-level roles before transitioning into leadership positions as competencies mature. Lopez (2024) emphasizes that self-employment among entrepreneurship graduates reflects the application of venture-creation skills rather than delayed employment absorption. The results therefore indicate a normal early-career trajectory, with entrepreneurship graduates leaning toward independent ventures and BSBA graduates progressing within formal organizational structures.

Table 8. Gross Monthly Earnings in Present Job

	BS Entrep		BSBA MM		Total	
Gross Monthly Earning in Present Job	*f*	%	*f*	%	*f*	%
Below P 5,000.00			1	3%	1	2%
P 5,000.00 to less than P 10,000.00	4	31%	7	23%	11	26%
P 10,000.00 to less than P 15,000.00	3	23%	10	33%	13	30%
P 15,000.00 to less than P 20,000.00	5	38%	9	30%	14	33%
P 25,000.00 and above	1	8%	3	10%	4	9%
Total	13	100%	30	100%	43	100%

Table 8 shows that the largest proportion of graduates earn between ₱15,000 to less than ₱20,000 (33%), followed by ₱10,000 to less than ₱15,000 (30%). A program comparison indicates that BS Entrepreneurship graduates are more concentrated in the ₱15,000–₱20,000 bracket (38%), while BSBA Marketing Management graduates are more distributed across the ₱10,000–₱15,000 (33%) and ₱15,000–₱20,000 (30%) ranges. Only a small portion of graduates (9%) earn ₱25,000 and above, reflecting the early career stage of most respondents. The minimal percentage earning below ₱5,000 suggests that most employed graduates are receiving wages aligned with entry-level professional standards. Tracer studies consistently report that early-career salaries tend to cluster within mid-entry wage brackets as graduates accumulate work experience and professional credentials. Dassun et al. (2025) found that business graduates initially occupy moderate income levels before experiencing gradual salary growth linked to job tenure and skill specialization. Villanueva and Binay-an (2021) similarly observed that wage progression is strongly tied to experiential learning rather than immediate post-graduation placement . Lopez (2024) explains that income stability improves as graduates transition from probationary to permanent employment. The findings therefore indicate that the salary distribution reflects a typical early-career earning trajectory, with potential for upward mobility as professional experience increases.

Table 9. Number of Months/Year before getting the First Job

Number of Months/Year before getting the First Job	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
1-3 months	8	62%	17	57%	25	58%
4-6 months	1	8%	8	27%	9	21%
7-9 months	0	0%	1	3%	1	2%
more than 1 year but less than two years	3	23%	2	7%	5	12%
no previous employment	1	8%	2	7%	3	7%
Total	13	100%	30	100%	43	100%

Table 9 shows that the majority of graduates obtained their first job within 1–3 months (58%) after graduation, indicating rapid workforce absorption. A comparison between programs reveals that BS Entrepreneurship graduates show a slightly faster transition (62%) compared to BSBA Marketing Management graduates (57%). However, BSBA graduates are more represented in the 4–6 month category (27%) than BS Entrepreneurship graduates (8%), suggesting a slightly longer but still reasonable job search period for some respondents. Only 12% of graduates required more than one year to secure employment, while 7% reported no previous employment. Tracer literature identifies early job placement as a key indicator of curriculum relevance and graduate competitiveness. Dassun et al. (2025) found that most business graduates secure employment within three months when programs incorporate practical training and internship exposure. Villanueva and Binay-an (2021) similarly report that rapid employment transitions are associated with employability skills, communication competence, and work readiness. Lopez (2024) explains that delays beyond six months often reflect selective job matching rather than inability to obtain employment. The findings therefore suggest that graduates from both programs demonstrate strong labor market readiness, with only a small proportion experiencing extended transition periods.

Table 10. Method of First Job Acquisition

Method of First Job Acquisition	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
absorbed by the company with OJT			1	3%	1	2%
as walk-in applicant	4	31%	12	40%	16	37%
family business	0	0%	2	7%	2	5%
information from friends	4	31%	2	7%	6	14%
job online platforms / jobstreet	2	15%	2	7%	4	9%
recommended by someone	3	23%	11	37%	14	33%
Total	13	100%	30	100%	43	100%

Table 10 shows that the most common method of securing the first job is through walk-in application (37%), followed by being recommended by someone (33%), and obtaining information from friends (14%). A comparison between programs reveals that BSBA Marketing Management graduates rely more heavily on walk-in applications (40%) and personal recommendations (37%), while BS Entrepreneurship graduates show equal reliance on walk-in applications (31%) and information from friends (31%). Online job platforms account for only 9% of total job acquisition, indicating that informal and interpersonal networks remain dominant channels for employment entry. Tracer literature emphasizes that social capital and professional networks play a critical role in early job placement. Dassun et al. (2025) found that referrals and personal connections significantly increase employment chances among business graduates. Villanueva and Binay-an (2021) similarly reported that peer networks and word-of-mouth remain primary job search strategies in developing labor markets. Lopez (2024) notes that online platforms complement but do not replace interpersonal recruitment pathways, especially for entry-level employment. The findings suggest that graduates benefit strongly from networking skills and relationship-building, highlighting the importance of industry linkages and alumni connections in employability development.

Table 11. Difficulties Encountered in Looking for their First Job

Difficulties Encountered in Looking for their First Job	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
few job vacancies	4	31%	8	27%	12	28%
inadequate experience	1	8%	9	30%	10	23%
lack of skills/competencies	3	23%	4	13%	7	16%
low compensation offer	2	15%	3	10%	5	12%
mismatch of educational qualifications	1	8%	2	7%	3	7%
not meeting paper requirements	1	8%	1	3%	2	5%
passing the pre-employment interview	1	8%	1	3%	2	5%
personality factors			2	7%	2	5%
Total	13	100%	30	100%	43	100%

Table 12 shows that the most common difficulty encountered by graduates in securing their first job is few job vacancies (28%), followed by inadequate experience (23%) and lack of skills or competencies (16%). A comparison between programs indicates that BSBA Marketing Management graduates report inadequate experience more frequently (30%) than BS Entrepreneurship graduates (8%), suggesting stronger competition in structured corporate employment sectors. Meanwhile, BS Entrepreneurship graduates report a higher concern regarding lack of skills (23%) compared to BSBA graduates (13%), reflecting the broader competency expectations placed on entrepreneurial roles. Other challenges such as low compensation offers, qualification mismatches, and administrative requirements appear less dominant but still contribute to early employment barriers. Tracer literature consistently identifies limited experience and competitive job markets as primary obstacles for recent graduates. Dassun et al. (2025) explain that entry-level graduates often struggle with employer expectations for prior work exposure despite academic preparation. Villanueva and Binay-an (2021) similarly report that perceived skill gaps and insufficient vacancies are common transitional challenges rather than indicators of program failure. Lopez (2024) emphasizes that early-career barriers are typically resolved as graduates accumulate workplace exposure and professional confidence. The findings suggest that graduates from both programs face normal entry-level labor market pressures, highlighting the need for strengthened internship programs, industry partnerships, and employability training.

Table 12. Nature of the Present Job with the Course they Finished

Nature of the Present Job with the Course they Finished	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
Completely related	5	38%	16	53%	21	49%
Somehow related	8	62%	13	43%	21	49%
Not related at all	0	0%	1	3%	1	2%
Total	13	100%	30	100%	43	100%

Table 12 shows that the majority of graduates are employed in jobs that are either completely related (49%) or somewhat related (49%) to the course they finished, while only 2% report employment unrelated to their degree. A comparison between programs reveals that BSBA Marketing Management graduates demonstrate stronger direct alignment, with 53% reporting completely related employment compared to 38% among BS Entrepreneurship graduates. In contrast, BS Entrepreneurship graduates show a higher proportion of somewhat related jobs (62%), suggesting broader occupational flexibility rather than strict specialization. Tracer literature identifies job-course alignment as a key indicator of curriculum effectiveness. Dassun et al. (2025) found that business graduates often secure positions closely tied to their academic training, particularly in marketing and financial sectors. Villanueva and Binay-an (2021) similarly reported high alignment between academic programs and employment roles, indicating strong skill transferability. Lopez (2024) explains that graduates in entrepreneurship programs frequently pursue adaptable roles that apply business competencies across varied industries. The findings suggest that both programs maintain high curricular relevance, with BSBA graduates showing specialization alignment and entrepreneurship graduates demonstrating cross-sector adaptability.

Table 13. Length of Service with the Present Company

Length of Service with the Present Company	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
1-3 months	3	23%			3	7%
4-6 months			4	13%	4	9%
7-9 months	1	8%	3	10%	4	9%
10-12 months	1	8%	3	10%	4	9%
more than 1 year but less than 2 years	8	62%	17	57%	25	58%
more than 2 years but less than 3 years			3	10%	3	7%
Total	13	100%	30	100%	43	100%

Table 13 shows that the majority of employed graduates have remained with their present company for more than one year but less than two years (58%), indicating a relatively stable employment pattern. A comparison between programs reveals similar retention behavior, with 62% of BS Entrepreneurship graduates and 57% of BSBA Marketing Management graduates falling within this category. Only a small proportion report employment durations below six months, suggesting that most respondents have successfully transitioned beyond probationary employment phases. Tracer literature associates longer service duration with job satisfaction, skill alignment, and employer confidence in graduate competencies. Dassun et al. (2025) found that graduates who remain in their positions for over a year demonstrate stronger workplace integration and career commitment. Villanueva and Binay-an (2021) similarly observed that employment retention reflects adaptability and professional growth rather than temporary job placement. Lopez (2024) explains that early-career retention signals effective curriculum preparation and transferable skills. The findings therefore suggest that graduates from both programs exhibit positive employment stability, reinforcing the employability value of their academic training.

Table 15. Reason for Staying with Present Job

Reason for Staying with Present Job	BS Entrep		BSBA MM		Total	
	f	%	*f*	%	*f*	%
Family influence			1	8%	1	4%
Good management	1	8%	1	8%	2	8%
Good relationship with coworkers	6	46%	9	69%	15	58%
Good salary	2	15%	11	85%	13	50%
Job enjoyment	1	8%			1	4%
Stable company			3	23%	3	12%
To gain experience	3	23%	5	38%	8	31%

Table 15 shows that the primary reasons graduates remain in their present jobs are good salary (50%), good relationship with coworkers (58%), and the opportunity to gain experience (31%). A program comparison reveals that BSBA Marketing Management graduates place stronger emphasis on salary (85%) compared to BS Entrepreneurship graduates (15%), suggesting that compensation is a more dominant retention factor in structured corporate employment. In contrast, BS

Entrepreneurship graduates prioritize workplace relationships (46%) and experience-building (23%), indicating a stronger focus on learning environment and professional growth. Tracer literature identifies compensation, workplace relationships, and experiential learning as major determinants of early-career retention. Dassun et al. (2025) found that competitive salary and positive work culture significantly influence graduates' decisions to remain with employers. Villanueva and Binay-an (2021) similarly observed that interpersonal workplace support increases job commitment among young professionals. Lopez (2024) explains that many graduates intentionally remain in positions that offer skill development opportunities even when salary is moderate. The findings suggest that graduates evaluate employment not only through financial reward but also through growth potential and workplace climate, reinforcing the importance of holistic job satisfaction in career stability.

Table 16. Extent of Use of Different Skills to Present Job of the Respondents

Skills	BS Entrep		BSBA MM	
	WM	VD	WM	VD
Communication Skills	4.62	SA	4.37	SA
Human Relation Skills	4.62	SA	4.53	SA
Critical Thinking Skills	4.08	A	4.27	SA
Entreprenuerial Skills	4.15	A	4.38	SA
Comprehension Skills	4.38	SA	4.37	SA
Decsion-making Skills	4.62	SA	4.53	SA
Problem Solving Skills	4.38	SA	4.4	SA
Leadership Skills	4	A	4.47	SA
Inforntion Technology Skills	4.33	SA	4.37	SA
Research Skills	3.92	A	4.4	SA
Grand Mean	4.31	SA	4.41	SA

Legend: 1.00–1.79 = Strongly Disagree | 1.80–2.59 = Disagree | 2.60–3.39 = Neutral | 3.40–4.19 = Agree | 4.20–5.00 = Strongly Agree

Table 16 indicates that graduates from both programs demonstrate very high utilization of professional skills in their present employment. The overall grand means of 4.31 for BS Entrepreneurship and 4.41 for BSBA Marketing Management are both interpreted as Strongly Agree, confirming that respondents consistently apply core competencies in their work. Across both programs, communication, human relation, and decision-making skills receive the highest ratings, highlighting the importance of interpersonal and cognitive abilities in workplace performance. BSBA Marketing Management graduates register slightly higher weighted means in leadership, entrepreneurial, and research skills, suggesting stronger engagement in structured managerial and analytical tasks. Meanwhile, BS Entrepreneurship graduates likewise show strong skill utilization, particularly in communication and human relations, reflecting the practical and relationship-driven nature of entrepreneurial practice. Research skills emerge as the comparatively lowest area among BS Entrepreneurship graduates, although the rating remains within the Agree range, indicating acceptable but improvable competency. These findings align with tracer literature emphasizing that soft skills and transferable competencies are key determinants of employability. Communication, leadership, and problem-solving abilities are consistently identified as critical workplace attributes (Dassun et al., 2025; Villanueva & Binay-an, 2021). Strong agreement in skill application further suggests effective curriculum-to-workplace alignment (Lopez, 2024). Overall, the results affirm that both programs equip graduates with employment-relevant competencies, reinforcing the practical value and relevance of their curricula.

Table 17. Extent of Adequacy of Training Acquired from NEUST Atate Campus

Training	BS Entrep		BSBA MM	
	WM	VD	WM	VD
Communication Skills	4.54	SA	4.67	SA
Human Relation Skills	4.46	SA	4.67	SA
Critical Thinking Skills	4.31	SA	4.53	SA
Entreprenuerial Skills	4.62	SA	4.57	SA
Comprehension Skills	4.33	SA	4.57	SA
Decsion-making Skills	4.54	SA	4.67	SA
Problem Solving Skills	4.46	SA	4.57	SA
Leadership Skills	4.54	SA	4.57	SA
Inforntion Technology Skills	4.38	SA	4.4	SA
Research Skills	4.38	SA	4.53	SA
Grand Mean	4.46	SA	4.58	SA

Legend: 1.00–1.79 = Strongly Disagree | 1.80–2.59 = Disagree | 2.60–3.39 = Neutral | 3.40–4.19 = Agree | 4.20–5.00 = Strongly Agree

Table 17 shows that graduates from both programs perceive their academic training as highly adequate, with grand means of 4.46 for BS Entrepreneurship and 4.58 for BSBA Marketing Management, both interpreted as Strongly Agree. Across all listed competencies, respondents consistently report strong agreement that the training provided by NEUST Atate Campus sufficiently prepared them for workplace demands. Communication, decision-making, leadership, and entrepreneurial skills receive particularly high ratings, suggesting that the institution effectively develops both technical and interpersonal competencies. A comparison between programs indicates slightly higher adequacy ratings among BSBA graduates, especially in communication, leadership, and critical thinking skills. However, BS Entrepreneurship graduates show equally strong confidence in entrepreneurial skill preparation, reflecting curriculum alignment with program specialization. Tracer literature identifies perceived training adequacy as a key predictor of employment confidence and career adaptability. Dassun et al. (2025) emphasize that graduates who rate their academic preparation highly are more likely to demonstrate workplace competence and retention. Villanueva and Binay-an (2021) similarly note that strong curriculum satisfaction correlates with positive employability outcomes. Lopez (2024) explains that consistent high ratings across skill domains indicate effective institutional training design. The findings therefore confirm that NEUST Atate Campus provides training that graduates perceive as relevant, comprehensive, and workplace-ready.

Table 18. Suggestion to Improve the Employability of the NEUST Atate Campus Graduate

Suggestions to Improve the Employability of the NEUST Atate Campus Graduate	BS Entrep			BSBA MM		
	f	%	*Rank*	*f*	%	*Rank*
Provide students with more training programs and seminars	6	46%	1	15	50%	1
Invite more companies to participate in the school job fair	1	8%	4	6	20%	2
Develop partnership with more companies for the OJT program	4	31%	2	5	17%	3
Improvement of the OJT program	2	15%	3	2	7%	4
Improve student communication skill				1	3%	5,6
Motivate and inspire students				1	3%	5,6

Table 18 shows that the most common suggestion from graduates is to provide more training programs and seminars, ranked first in both programs, with 46% of BS Entrepreneurship and 50% of BSBA Marketing Management graduates emphasizing this need. The second strongest recommendation is strengthening industry partnerships, particularly through expanded company participation in job fairs and on-the-job training (OJT) collaborations. BS Entrepreneurship graduates prioritize developing partnerships with companies for OJT (31%), while BSBA graduates emphasize inviting more companies to recruitment activities (20%). These findings indicate that graduates recognize experiential learning and industry exposure as essential employability drivers. Tracer literature consistently highlights that graduate employability improves when institutions integrate continuous training and employer partnerships. Dassun et al. (2025) stress that seminars, skills workshops, and professional certifications enhance job readiness. Villanueva and Binay-an (2021) similarly report that strong school-industry linkages accelerate employment opportunities. Lopez (2024) explains that improved internship structures directly influence workforce transition success . The findings suggest that NEUST Atate Campus graduates value practical training, expanded employer networks, and communication skill development as key strategies for improving employability outcomes.

Table 19. Suggestion to further improve the course curriculum

Suggestions to further improve the course curriculum	BS Entrep			BSBA MM		
	f	%	*Rank*	*f*	%	*Rank*
Offer more major courses / subjects based on the needs of the industry	7	54%	1	22	73%	1
Major courses must be taught by highly competent professors and with industry experience	2	15%	3,4,5,6	4	13%	2,3,4
Apply various classroom and practical activities, not just reporting, Integrate trainings	1	8%	7	1	3%	5,6,7
Integrate trainings, seminars and more job exposure in the curriculum	3	23%	2	4	13%	2,3,4
Researches such as feasibility studies, capstone projects, business plans must be conducted by each group under advisorship of another professors	2	15%	3,4,5,6	1	3%	5,6,7
Application of more current trends in business and information technology and less paper works and theories	2	15%	3,4,5,6	1	3%	5,6,7
Provide more opportunities where students can apply what they learned in the business and information technology	2	15%	3,4,5,6	4	13%	2,3,4

Table 19 shows that the strongest recommendation from graduates of both programs is to offer more major courses based on industry needs, ranked first by both BS Entrepreneurship (54%) and BSBA Marketing Management graduates (73%). This suggests a shared perception that curriculum modernization must remain closely aligned with labor market demands. The second most emphasized suggestion is integrating more training, seminars, and job exposure within the curriculum, particularly among BS Entrepreneurship graduates (23%), reinforcing the importance of experiential learning. Both groups also highlight the need for instruction by highly competent professors with industry experience, as well as opportunities to apply current trends in business and information technology. BSBA graduates place greater emphasis on providing applied learning opportunities where students can

directly implement business and IT skills, while BS Entrepreneurship graduates stress curriculum activities that strengthen real-world readiness through feasibility studies and practical projects. Tracer literature consistently emphasizes that industry-responsive curriculum design is a major determinant of graduate employability. Dassun et al. (2025) note that graduates who perceive their coursework as industry-aligned demonstrate stronger career readiness. Villanueva and Binay-an (2021) similarly report that practical exposure and applied coursework increase workforce competitiveness. Lopez (2024) explains that continuous curriculum revision ensures that graduates remain adaptable to evolving economic sectors. The findings therefore highlight the importance of maintaining dynamic curriculum structures that integrate industry partnerships, applied learning, and contemporary business trends.

IV. CONCLUSIONS

The findings of the tracer study reveal that graduates of BS Entrepreneurship and BSBA Marketing Management from NEUST Atate Campus demonstrate generally strong employability outcomes characterized by rapid workforce entry, stable employment retention, and high curriculum relevance. The majority of graduates are employed within a short period after graduation, with BSBA graduates showing faster absorption into structured corporate employment while BS Entrepreneurship graduates follow more flexible and transitional career paths, including self-employment. Employment challenges encountered by graduates are primarily situational—such as limited vacancies and lack of experience—rather than indicative of curriculum inadequacy. Most respondents report working in jobs related to their degree, earning within expected early-career salary ranges, and remaining in their positions for over a year, suggesting job stability and workplace integration.

Graduates strongly affirm the adequacy of their academic training and the application of communication, leadership, decision-making, and problem-solving skills in their present jobs. Satisfaction with workplace relationships, compensation, and opportunities to gain experience further reinforces positive employment outcomes. At the same time, graduates recommend strengthening training programs, expanding industry partnerships, modernizing curriculum content based on labor market needs, and increasing experiential learning opportunities. These findings confirm that NEUST Atate Campus produces workplace-ready graduates while also highlighting the need for continuous curriculum enhancement and stronger school-industry linkages to sustain and improve employability performance.

RECOMMENDATIONS

Based on the findings of the tracer study, the following recommendations are proposed to further enhance the employability of graduates from NEUST Atate Campus:

First, the institution should expand continuous training programs, seminars, and certification workshops that focus on communication, leadership, digital competencies, and workplace readiness. Graduates strongly emphasized the importance of additional training exposure, and tracer literature confirms that structured skill development programs significantly improve early-career employability (Dassun et al., 2025; Fahmy et al., 2025). Regular professional development initiatives aligned with current industry trends can strengthen graduate competitiveness and adaptability.

Second, NEUST Atate Campus should strengthen industry partnerships and employer linkages, particularly through expanded on-the-job training (OJT) collaborations, job fairs, and internship pipelines. Strong school-industry cooperation accelerates workforce absorption and reduces employment transition delays (Villanueva & Binay-an, 2021). Establishing long-term partnerships with companies ensures that students gain real-world exposure and access to recruitment networks before graduation.

Third, curriculum modernization should prioritize industry-responsive course design. Graduates recommended offering major subjects aligned with labor market demands and integrating more applied learning activities. Academic programs should regularly consult industry stakeholders to update course content and incorporate experiential

learning strategies such as simulations, feasibility studies, and enterprise projects (Caclini-Pumihic & Binwag, 2025). Continuous curriculum revision ensures that graduates remain adaptable to evolving economic sectors.

Fourth, the institution should enhance career readiness support services, including job search training, networking skills development, and interview preparation. Since personal networks play a major role in employment acquisition, students should be equipped with professional communication and relationship-building competencies (Lopez, 2024). Career coaching programs can help graduates transition more confidently into the workforce.

Finally, NEUST Atate Campus should establish a formal graduate incubation and mentoring system, particularly for entrepreneurship graduates. Business incubation support, startup mentoring, and access to funding networks can stabilize entrepreneurial career paths and reduce transitional unemployment (Dassun et al., 2025). Supporting graduates beyond graduation strengthens institutional impact and long-term employability outcomes.

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Energy-efficient task scheduling algorithms in hybrid CPU-GPU systems

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Abstract *— This article presents a systematic analysis of energy-efficient task scheduling algorithms in hybrid CPU–GPU systems, where heterogeneous computing resources exhibit fundamentally different performance and energy characteristics. Such systems are widely used in high-performance computing, data centers, and AI-driven workloads, where increasing computational demand and energy constraints limit the effectiveness of scheduling strategies focused solely on execution time. The study is conducted as a review-and-analytical synthesis of peer-reviewed publications published between 2022 and 2025, without quantitative aggregation of results due to heterogeneity of experimental setups, metrics, and energy models. Particular attention is paid to the role of optimization metrics, quality of input energy data, and integration of power management mechanisms in shaping the observed effectiveness of scheduling algorithms. The analysis shows that reported improvements strongly depend on the choice and aggregation level of performance and energy metrics, as well as on the accuracy of task energy characterization, rather than on the algorithmic class alone. It is demonstrated that single-objective formulations fail to capture the behavior of hybrid CPU–GPU systems, while composite time–energy criteria and explicit device-selection policies provide a more consistent basis for evaluation. The study establishes that meaningful comparison of energy-efficient scheduling approaches requires a clear separation between architectural scheduling frameworks and concrete algorithms, along with explicit fixation of the energy management context. The article is intended for researchers and practitioners working on scheduling, power-aware computing, and heterogeneous system design in high-performance and data-intensive environments.*

Keywords *— **energy-efficient scheduling, hybrid CPU–GPU systems, heterogeneous computing, power-aware scheduling, composite metrics, task profiling, high-performance computing, data centers.***

I. INTRODUCTION

The growth of computational workloads in HPC, machine learning, and AI services intensifies energy constraints in the operation of computing infrastructure, particularly in hybrid CPU–GPU systems characterized by diverse device performance and energy profiles. While modern platforms increasingly utilize such architectures, their actual effectiveness is determined by task scheduling strategies; meanwhile, a focus solely on minimizing execution time fails to account for the relationship between power consumption, resource utilization, and computation type, leading to increased energy costs and reduced stability under dynamic loads [3]. The absence of a unified methodological framework ensuring metric consistency, result comparability, and the integration of power management mechanisms limits the reproducibility and portability of energy-efficient scheduling solutions in hybrid CPU–GPU systems.

The aim of this study is to identify the methodological conditions for the correct evaluation

and comparison of energy-efficient task scheduling algorithms in hybrid CPU–GPU systems, taking into account the metrics, energy models, and power management mechanisms employed. To achieve this goal, the work addresses the following research tasks:

– classify modern energy-efficient scheduling algorithms applied in hybrid CPU–GPU systems from the perspective of abstraction level and architectural binding;

– analyze metrics and optimization criteria used in the literature and determine their impact on the interpretation of energy efficiency results;

– summarize methods for integrating energy management mechanisms into the task scheduling loop and assess their influence on observed effects;

– determine methodological limitations of result comparability and conditions for the practical applicability of algorithms in real-world computing environments.

The research hypothesis states that differences in the reported energy efficiency of scheduling algorithms in hybrid CPU–GPU systems are largely conditioned by methodological factors—the choice of metrics, energy models, and the architectural context of the experiment—rather than the algorithm's belonging to a specific class. It is assumed that when these conditions are fixed, the differences between algorithmic approaches are substantially reduced.

The scope of the study is limited to the analysis of algorithmic, methodological, and operational aspects of energy-efficient scheduling in hybrid CPU–GPU systems. HPC clusters, server nodes, and heterogeneous platforms with shared CPU and GPU usage are considered, whereas questions of hardware design and economic assessment are touched upon only in the context of interpreting energy metrics and the practical applicability of algorithms.

II. MATERIALS AND METHODS

The methodological basis of the study is formed on the systematization of theoretical and applied models of energy-efficient task scheduling in heterogeneous computing systems with shared CPU and GPU usage. The source corpus includes publications from 2022–2025 dedicated to scheduling algorithms, energy metrics, power management mechanisms, and architectural features of hybrid computing nodes in data centers, high-performance, and edge computing environments.

In the study by Hou and Ismail [1], energy-efficient scheduling is formalized as a trade-off problem between power consumption and response time at the software scheduler level. The review by Kocot et al. [2] is used to systematize energy efficiency metrics and algorithm classes in high-performance computing. The approach of Li et al. [3] is applied to analyze energy-efficient scheduling of containerized tasks in a dynamic environment. The work of Liu et al. [4] is used to account for the specifics of heterogeneous multi-core processors and edge computing. The classification of scheduling methods for heterogeneous chips is borrowed from the review by Miao et al. [5]. The architectural scheme of two-phase task flow scheduling is used according to Peng and Wang [6]. Features of joint task execution on CPU and GPU are analyzed based on Raúl and Bosque [7]. The method for obtaining task energy characteristics without full profiling is borrowed from Salinas-Hilburg et al. [8]. The operational loop of energy-efficient computing system management is considered according to Suarez et al. [9]. The formalization of computing device selection considering latency and energy is used according to Xie and Fang [10].

The research methodology is based on a combination of structural analysis of scheduling algorithms, a comparative review of used energy metrics, and generalization of power management mechanisms in hybrid computing systems. Such an approach allows for viewing energy-efficient task scheduling in CPU–GPU environments as an integration of algorithmic, architectural, and operational solutions determining result reproducibility and practical method applicability in real-world computing systems.

III. RESULTS

Energy-efficient scheduling in hybrid CPU–GPU systems is determined by the coordinated choice of efficiency metrics and power management mechanisms, rather than solely by the applied

algorithm, since with unchanged task distribution logic, changing the optimization indicator leads to different efficiency interpretations in heterogeneous nodes with diverse device energy profiles [2]. The use of single-axis metrics oriented only toward execution time or power consumption distorts the efficiency assessment, as acceleration via GPU may be accompanied by an increase in CPU background power consumption, requiring the application of composite indicators linking time and energy [7]. Simultaneously, power management mechanisms form an extended solution space for the scheduler, as dynamic frequency and voltage scaling, power capping, and shutdown modes directly alter the task execution energy profile and derived metric values, reducing result comparability when the energy context changes [4]. Figure 1 shows the distribution of reported improvements in key metrics used in energy-aware HPC-level formulations.

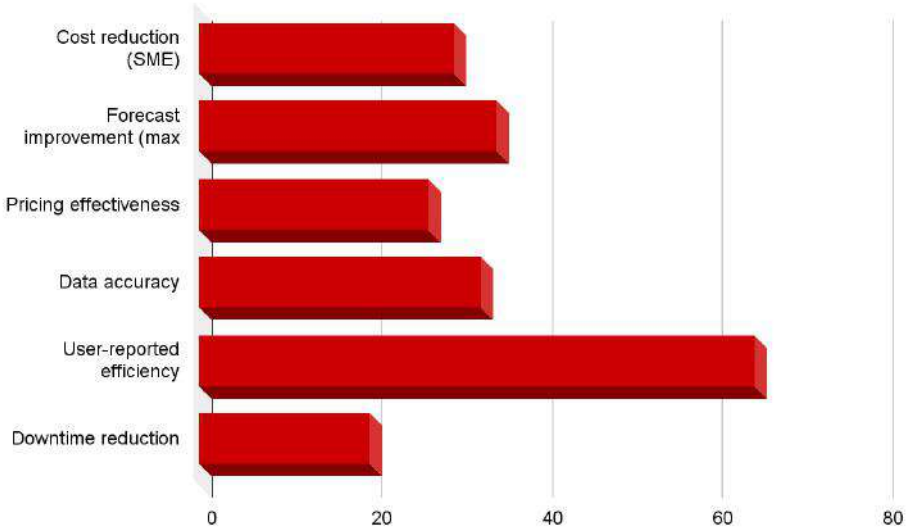

Fig.1 – Comparison of reported improvements in key metrics under energy-aware formulations (Composed by the author based on source [2])

The data presented in the diagram demonstrate the heterogeneity of reported improvements across various energy-aware scheduling metrics. The greatest relative effect is recorded for the efficiency indicator evaluated by users, reaching 62.5%, whereas metrics related to forecasting and data quality show improvements at the level of 33–35%. Indicators directly related to operational costs and physical processes, such as operating cost reduction (30%) and downtime reduction (20%), are characterized by a more limited improvement range. Such a distribution confirms that the magnitude of the reported effect is determined by the selected metric and its aggregation level, which complicates result comparability in the absence of explicit indicator fixation.

Energy-efficient task scheduling in hybrid CPU–GPU systems is viewed as a function of input energy data quality, not merely as a consequence of algorithmic class selection. With identical task distribution strategies, differences in the availability and accuracy of energy characteristics lead to changes in the observed effect comparable to the transition between heuristic and optimization methods [8]. This indicates the independent role of task energy parameters in forming the scheduling result.

Full profiling ensures maximum scheduler awareness; however, its computational cost makes this approach impractical for large-scale and long-running workloads [4]. In hybrid systems, this limitation is intensified by the need to account for diverse CPU and GPU energy profiles and their interaction during joint task execution [2], making approximate methods for obtaining energy characteristics a necessary element of scalable scheduling.

Comparing methods under different profiling scenarios shows that replacing full profiling with

reduced energy representations leads to a moderate decrease in target indicator improvement while preserving result structure [3]. Figure 2 shows the distribution of improvements for optimization, metaheuristic, and heuristic methods under various scenarios for obtaining energy characteristics.

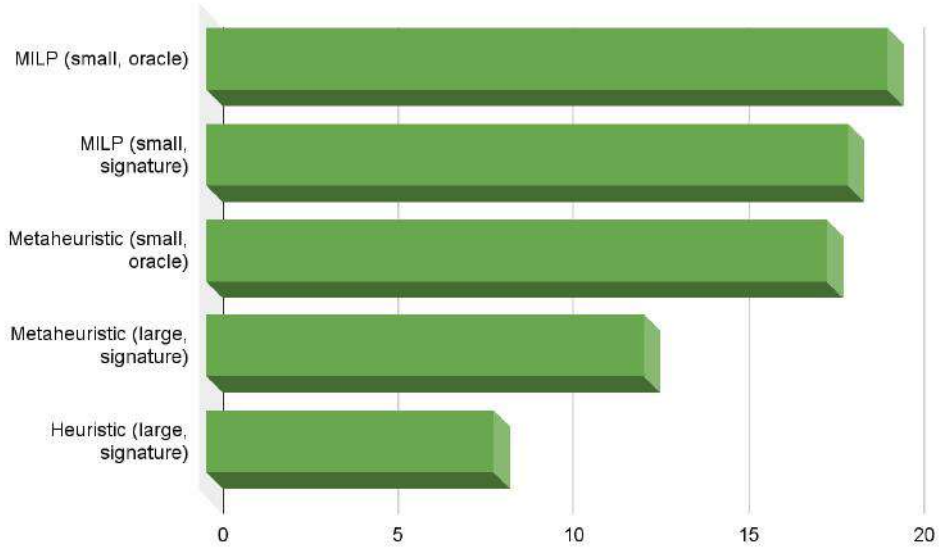

Fig.2 – Comparison of scheduling methods in terms of target metric improvement under oracle and signature scenarios (Composed by the author based on source [8])

Based on the data presented in the diagram, it is evident that using reduced profiling leads to a decrease in absolute values of target indicator improvement while maintaining the relative order of scheduling methods. The optimization method demonstrates the highest value with full profiling (19.4) and a moderate decrease when using reduced data (18.3), whereas metaheuristic and heuristic approaches are characterized by more pronounced sensitivity to input information accuracy. The obtained values show that reduced profiling influences the effect magnitude but does not distort result comparability between method classes.

When using reduced profiling, the hierarchy of methods by efficiency is preserved, despite the decrease in absolute indicator values [8]. In the context of hybrid CPU–GPU systems, this indicates that scheduling result stability is determined by the consistency of the energy model and algorithmic logic, rather than by maximum input data accuracy [7]. A similar problem formulation, where resource selection is based on normalized energy and time estimates, is used in other heterogeneous environments as well.

Thus, the analysis results show that the quality of energy-efficient scheduling in hybrid CPU–GPU systems is determined by algorithm selection and the method of obtaining and representing task energy characteristics, while reduced profiling can be considered a methodologically admissible substitute for full measurement while preserving result comparability.

IV. DISCUSSION

The correctness of comparing energy-efficient scheduling algorithms in hybrid CPU–GPU systems is determined by the abstraction level at which the analysis is performed. Comparing results from various studies proves methodologically justified only with a clear separation between task management architecture and the specific distribution and ordering algorithm, as mixing these levels leads to incorrect interpretation of observed effects. In hybrid systems, this aspect acquires particular significance because architectural solutions often include energy monitoring and management mechanisms that directly influence measured indicators independently of algorithmic logic.

Analysis shows that a substantial part of the differences between reported improvements in the

literature is conditioned specifically by architectural premises rather than algorithm features. The use of centralized or distributed frameworks, differences in queue models, and methods for accounting for energy characteristics form different solution spaces for the scheduler, making direct comparison of algorithms without fixing the architectural context methodologically incorrect. In hybrid CPU–GPU systems, this manifests in varying degrees of CPU participation during GPU-oriented workloads and in unequal system reaction to power caps and energy management modes. Table 1 examines the methodological breakdown of aspects necessary for correct solution positioning in hybrid CPU–GPU systems, allowing for the separation of effects conditioned by architecture and experimental environment from effects related to scheduling algorithms.

Table 1 – Methodological aspects of scheduler comparison for heterogeneous systems (Compiled by the author based on source [5])

Analytical aspect	Core finding	Relevance for this study
Scheduling levels	Clear separation between framework and algorithm	Used as the base structure for architectural description
Algorithm types	Five classes with systemic trade-offs	Provides a common language for method comparison
Experimental basis	Lack of standards, dominance of SIL/MIL	Explains limits of result comparability
AI perspective	RL is promising but methodologically complex	Enables careful positioning of ML-based approaches

The interpretation of energy efficiency in hybrid CPU–GPU systems cannot be reduced to minimizing power consumption or improving a single aggregated indicator. In such architectures, scenarios are often observed where gains in execution time and resource utilization are achieved with ambiguous changes in energy efficiency indicators, including the absence of improvement in EDP compared to GPU-only mode. This indicates the necessity of an explicit choice of optimization criterion when formulating the scheduling problem.

A practically applicable scheduling formulation in a heterogeneous environment implies including execution device selection within the optimization model itself, rather than outsourcing it as a fixed decision [10]. Energy and latency in such models are included in the objective function with explicit weighting coefficients, which allows for managing the trade-off between performance and power consumption depending on operational priorities. For hybrid CPU–GPU systems, this approach is fundamental, since CPUs and GPUs possess different energy profiles and react differently to load changes and power management mechanisms.

Thus, the analysis shows that correct interpretation of energy-efficient scheduling in hybrid CPU–GPU systems is determined by separating abstraction levels, consciously choosing optimization criteria, and fixing the architectural context within which observed effects are evaluated.

V. CONCLUSION

The conducted study has shown that energy-efficient task scheduling in hybrid CPU–GPU systems cannot be viewed as a consequence of selecting a single algorithm and requires a coordinated problem formulation including correct selection of metrics, energy models, and power management mechanisms. Under conditions of heterogeneous computing nodes, it is the methodological premises that determine the interpretation and comparability of reported effects.

It is established that the use of single-axis criteria oriented exclusively toward execution time or power consumption does not reflect the real behavior of hybrid CPU–GPU systems and leads to a distorted efficiency assessment. A practically applicable assessment requires the use of composite indicators accounting for the trade-off between latency, energy,

and resource utilization, and the explicit inclusion of computing device selection in the optimization loop.

It is shown that the quality of input energy data is an independent factor of scheduling efficiency. Reduced task profiling lowers the absolute values of target indicators but preserves relative method comparability, making it an admissible tool for scalable computing environments given correct energy model formalization.

The research results confirm that correct comparison of energy-efficient scheduling algorithms is possible only when separating control architecture levels and algorithmic logic, with explicit fixation of the experimental and energy context. This approach allows for transitioning from local improvement of individual indicators to a reproducible and interpretable assessment of energy efficiency in hybrid CPU–GPU systems. The obtained conclusions can be used as a methodological basis for building reproducible experimental protocols and developing comparable energy-efficient schedulers for hybrid CPU–GPU computing platforms.

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Design of an Open-Source Device for Immersion Staining of Cytological Samples

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Abstract *— This project details the design of a staining machine for processing samples in cytological tests for a clinical laboratory. The objective is to design a staining machine using local materials and components, ensuring a low manufacturing cost compared to commercial staining machines, and offering reliable staining through sequences programmable via a graphical interface. The designed device was based on a linear mechanism, in which the worktable consists of a separating base for cuvettes containing the chemical solutions for the stain. The samples are held in place by a basket, which adheres to the machine by means of electromagnets activated by the control system. Bipolar stepper motors were used for movement, activating a power screw mechanism. These motors were controlled using an Arduino Uno. Finally, an interface and a touchscreen were developed to allow execution of the staining sequences. Mechanical elements were selected according to local availability, achieving a competitive manufacturing cost.*

Keywords *— **Cytological tests, automation, Arduino Uno, staining machine, open-source device.***

I. INTRODUCTION

The staining of tissues is a fundamental tool for the identification, classification, and analysis of biological, chemical, and physical samples. In laboratory testing, staining is essential for highlighting specific structures, such as nuclei and fibers, allowing for their visualization and differentiation in tissues. It facilitates the identification and quantification of cellular components, which is crucial in histology and pathology.

In regional clinical laboratories in Córdoba, Veracruz, such as the San José laboratory, the staining process for cytological samples (specifically for Papanicolaou tests) continues to be performed manually. This practice presents limitations such as variability in staining quality and prolonged time consumption by technical personnel. While automated commercial machines exist, their high cost, specialized maintenance, and dependence on proprietary brands limit accessibility for small or low-budget laboratories. This project proposes an automated device based on open-source hardware principles to standardize the staining procedure, improving efficiency and reducing human error.

Objective

To develop an open-source device for the automation of the cytological sample staining process, adhering to NOM-241-SSA1-2021, NOM-014-SSA2-1994, and ISO 13485 standards for the San José laboratories in Córdoba, Veracruz.

Hypothesis

By integrating standardized mechanical components, locally available materials, and an open-source control platform (Arduino), it is possible to construct

an automated staining device that meets clinical quality standards while maintaining manufacturing costs below $6,000 USD.

Justification

Manual staining introduces high variability in results due to factors like reagent exposure time and operator intervention. Automation reduces processing time and significantly improves the reproducibility and quality of stained samples. Furthermore, the open-source hardware model fosters local innovation and technological appropriation, allowing health institutions to modify and scale solutions according to their specific needs. The standardization of processes also minimizes the risk of cross-contamination and improves biosafety in the handling of biological samples.

II. METODOLOGY

The development followed a five-phase mechatronic design methodology:

1. Selection of Alternatives: A decision matrix compared planar, rotational, and linear configurations. The linear configuration was selected (92% score) for its maintenance simplicity, energy efficiency, and local availability of components.

2. Conceptual and Detailed Design: The system was defined as a two-degree-of-freedom robot (X and Z axes).

X-axis: Linear transport across 6 storage spaces for reagents.

Z-axis: Vertical movement for sample immersion.

Effectors: An electromagnet system holds the slide basket for transport.

3. Mechanical Design:

Transmission: A 30mm diameter stainless steel power screw was selected for the X-axis to reduce wear compared to belt systems.

Motors: NEMA 14 stepper motors were chosen for their precision and local availability.

Containers: Borosilicate glass jars (Coplin style) were used for their resistance to acid, basic, and organic reagents.

4. Electronic and Control Design: The core of the system is an Arduino Uno paired with a TB6560 driver.

Sensors: Mechanical limit switches were integrated for machine calibration (homing).

User Interface: A touchscreen interface was developed to allow for the creation, editing, and execution of staining protocols.

Mechanical Component Technical Specifications

Component	Specification	Justification
Lead Screw	Stainless steel 304, Ø30 mm, 5 mm pitch	Corrosion resistance and linear motion precision
Stepper Motor	Bipolar NEMA 14, 1.8°/step, 0.4 Nm	Angular precision, sufficient torque, low cost
Linear Guides	Hardened steel with sealed bearings	Smooth motion, durability, low maintenance
Electromagnets	12 V DC, 50 N holding force	Secure gripping and electronically controlled release
Structural Frame	Stainless steel 316L profiles	Maximum resistance to acidic vapors and solvents
Reagent Containers	Borosilicate glass 3.3, 500 mL capacity	Optical transparency and chemical/thermal resistance

III. RESULTS

The device successfully executed complex staining sequences, such as the Papanicolaou protocol, with 100% repeatability in immersion times, completely eliminating human error in this critical variable. Each step of the protocol was executed with millisecond-level precision—an accuracy unattainable through manual techniques.

Repeatability testing involved executing the same protocol 50 consecutive times while measuring deviations in immersion time, reagent temperature, and sample positioning. The standard deviation in immersion times was less than 0.5 seconds, representing an improvement of over 100-fold compared to the manual method.

Repeatability Metrics

100% consistency in immersion times

< 0.5 s standard deviation

50+ cycles without variation

0 sequencing errors

Comparative Performance

Manual Method

Immersion time variation of ±30–60 seconds

Initial Prototype

Variation reduced to ±5 seconds

Optimized Version

Variation < 0.5 seconds — full precision

Biosafety Improvements

The automated enclosure and electromagnet-based end effector physically isolate samples from the operator, ensuring compliance with NOM-241-SSA1-2021. This physical separation dramatically reduces technician exposure to potentially carcinogenic reagent vapors such as hematoxylin, as well as organic solvents including xylene and alcohol.

Vapor Containment

A closed system with localized extraction captures approximately 95% of chemical vapors.

Minimized Contact

Technicians handle samples only at the beginning and end of the process.

Emergency Protocols

Emergency stop button and interlock-type safety locks are integrated into the system.

Additionally, the system includes spill detection sensors and an automatic shutdown protocol in the event of abnormal vapor levels. These safety features exceed minimum regulatory requirements, reflecting a strong commitment to occupational health.

Economic Impact: Confirmed Viability

The total construction cost remained below the USD $6,000 threshold, confirming economic feasibility for laboratories with limited budgets. This cost includes all mechanical, electronic, structural, and software components, representing approximately an 80% savings compared to equivalent commercial equipment.

Cost Breakdown

Mechanical components: USD $2,100

Electronics and control: USD $1,500

Structure and enclosure: USD $1,200

Interface and software: USD $600

Tools and consumables: USD $400

Return on Investment

For a laboratory processing approximately 100 samples per week, the investment is recovered in approximately eight months when accounting for technician time savings, error reduction, and reagent optimization. After this period, the system generates continuous net savings.

The construction and validation of the prototype yielded the following results:

Error Reduction: The device successfully executed repetitive immersion times and transitions, eliminating variability associated with manual operation.

Biosafety: The immersion mechanism isolated samples from the operator, reducing exposure to hazardous reagents like hematoxylin, eosin, and solvents.

Technical Efficiency: Calculations verified a system efficiency of 90%. The linear speed was determined to be 79.6 mm/s, ensuring efficient transitions without being overly abrupt.

Economic Viability: The use of local and standardized components ensured the cost remained competitive and accessible for regional laboratories.

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Multi-Layer Microwave Filter for WLAN

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Abstract *— Due to the development of wireless communications and the appearance of new systems there is high demand in small size, low cost filters with high performance. Hence, miniaturization of band pass filters with improvement of their characteristics is a big challenge in modern filters design. This is achieved by improvement of conventional concepts and approaches, as well as by introduction of new topologies and designs. Multi-layer concept in conventional filter designing prove to be the best approach to meet the challenges in modern filter design. In this research work, a new method to design a Multi-layer band pass filter (BPF) is presented for WLAN applications. This method is based on a simple principle: different substrates (dielectric constants) will result different resonant frequencies for a resonator. The basic structure of this method is studied and then a planar band pass filter is designed to utilize in this structure. To reduce the filter size, dual layer filter is proposed but increase in insertion loss due to multi-layer coupling. To overcome this issue, the Substrate Integrated Waveguide (SIW) filter is established based on multilayer technique. To prove the concept of microwave WLAN filter, the operating central frequency of 2.44 GHz is demonstrated and validated through simulation and measurement. Finally, the multilayer configuration with dielectric substrates showed that the bandwidth is broaden up, insertion loss, return loss and size are reduced than single layer configuration.*

Keywords *— **WLAN filter, Planar band pass filter, Insertion loss, return loss, Substrate Integrated Waveguide, Single layer, Multilayer Technique.***

I. INTRODUCTION

Wireless Local Area Networks encompass one of the wildest emergent segments of the Telecommunications Industry. The implementation of WLAN solutions in many market segments including but limited to small office / home office (SOHO), manufacturing and industrial plants, small and large businesses, public hotspots, convention centers, hotels, airports and even Government Sectors, has ignited with the completion of industry standards and the corresponding release of WLAN products by leading manufacturers [3]. WLAN technology is not only the option for providing high-speed Internet access to the public in large but also used to save costs and avoid laying cable networks. Whatever the cause, WLAN solutions are popping up everywhere.

Nowadays, telecommunication industry has developed such new Wireless techniques such as Wireless LAN and Bluetooth technology especially for WLAN applications and Filters are vital part to the operations of this technology. With the advancement and development of wireless communication of WLAN, narrow band RF / microwave bandpass filters with low insertion loss, high selectivity and most importantly the reduced size has gained extraordinary demand.

WLAN application utilizes the frequency spectrum in the Industrial Scientific and Medical (ISM) bands established in 1947 out of the radio spectrum by the International Telecommunication Union (ITU) to provide dedicated spectrum for non-telecommunication devices. Initially, the ISM bands are limited to Industrial Scientific and Medical

devices, and usage of telecommunication was not allowed [3]. However, several factors conveyed about the gravity to use the unlicensed ISM bands for wireless communication with the rapid evolution of microelectronics and computing along with the attractiveness of an unlicensed spectrum over the period of time.

A part of the radio frequency spectrum/ electromagnetic spectrum from 9 KHz to 275 GHz is covered and regulated by the ITU (International Telecommunication Union) Radio Regulations. The applications [4] of microstrip filters can be realized in wide areas wireless applications such as:

- Cordless telephones (2.4 GHz or 5.8 GHz)
- Cellphones [Cellphones use 1.9 GHz frequency unlike cordless telephones]
- Router (2.4 or 5 GHz)
- Bluetooth (2.4-2.485 GHz) earpiece
- Baby monitor (49 MHz, 902 MHz or 2.4 GHz) etc.

Wireless LAN (WLAN) network generally using the 2.4 GHz (12 cm) UHF and 5 GHz (6 cm) SHF ISM radio frequency bands to connect electronic devices through Wi-Fi technology. High performance and small-size microwave filters' demand is evolving fast in various communication systems in the past recent years. In realizing unprecedented demands of WLAN applications, new and exciting challenges are being faced in conventional design theory and circuitry of microwave filters. Technologies in filter designing are still concentrating on how to drive filters in lighter weight, smaller size, lower cost and higher performance requirements.

In order to cope up with these stringent requirements, various kind of planer microstrip filters like resonator filters such as stepped impedance resonator filters and open loop resonator filters have been proposed. However, these type of planar microstrip filters are realized on a single microstrip substrate layer which ultimately leads to large size and costly solution. Therefore, multilayer bandpass filters have recently been gaining attention and importance to overcome the aforementioned problem.

The multilayer structure approach in designing WLAN filters has been proposed for increasing the bandwidth, reducing the size of the microstrip filters making it a cost effective and high performance requirement solution [7].

Problem Statement

New technologies demand compact electronic components and high-performance devices. To work in high efficiency, filters are one of the most important electronic components in such devices. In literature, single layer filter designing by using symmetric couple microstrip is well familiar and documented. However, to achieve more compact size with high performance in this configuration is challenging for the fabrication to be realized. Multilayer filter configuration absolves this kind of challenge by introducing flexible coupling between contiguous resonators on same or different layers consequently miniaturize filter can be realized [1].

Compact structures can be achieved with Hairpin-line in the filter design. It can be obtained by folding the resonators of parallel-coupled half wavelength resonator into a "U" shape. These coupled line resonators that are located at different layers without any ground plane between the adjacent layers can be realized in multilayer configuration but at the cost of more insertion loss due to coupling between the resonators. Therefore, various optimization techniques must carefully be adopted to avoid this kind of issue that can affect the overall response and to achieve the cost effective with high performance solution in multilayer configuration. To overcome this issue, the Substrate Integrated Waveguide (SIW) filter is established based on multilayer technique. This research will contribute towards a reduce size filter with high performance requirements using the latest multilayer stack up model for WLAN application [2].

Objective of the Research Work

- The main objective is to understand and design Multi-Layer Filter for WLAN.
- Learn and explore new technology.
- In depth analysis and understanding of Microwave filter theory that will eventually evolve in multilayer filter theory.
- Knowledge of commercial software High Frequency Simulation Software (HFSS) for designing and optimization of microwave filters.
- Finally going through the process of research and writing a research publication will also be one of the main objectives of this thesis.

II. SCOPE AND METHODOLOGY

The overall scope of this research was to achieve improved and compact design with optimum performance requirement of Multilayer Bandpass Filter using planer and SIW resonators at resonator frequency as 2.58 GHz for WLAN applications. First, conventional planar configuration of WLAN bandpass filter having rectangular shaped Defected Ground Structure with cascaded U-shaped resonator is designed to demonstrate the filter size in planar configuration. Then, the cascaded U-shaped resonator is transformed in multilayer configuration having modified U-shaped DGS in between the resonators. The results computation and design optimization in Ansys HFSS simulator revealed that multilayer topology adopted in filter design greatly decrease the overall footprint. Secondly, to further demonstrate the benefits of multilayer topology in microwave filter regime, two layered Substrate Integrated Waveguide (SIW) band pass filter having Surface Plasmonic Polariton (SPP) propagation is proposed. Flow chart in Figure 1.1 and Figure 1.2 shows the research scope and methodology to achieve the desired objective in the proposed multilayer filter design. In the schematics of Figure 1.1 and Figure 1.2, the path containing bold lines and configuration or devices in between represent the approach to be adopted in this research work to achieve the targeted milestone in the proposed design while the dotted line path along with configuration or devices in between are not deliberated as to be considered out of the research scope.

Microwaves represents the frequencies range from 300 MHz to 300 GHz in the Electromagnetic Waves (EM), with corresponding wavelengths from 1 m to 1 mm in the free space. Frequencies between 30 GHz and 300 GHz are also represented as millimeter waves. Electromagnetic Spectrum above the millimeter waves is called infrared having wavelength between 1 micrometer to 1 millimeter. Electromagnetic Spectrum consists of visible, ultraviolet, and x-rays comes beyond the infrared spectrum and radio frequency spectrum comes below the microwave frequencies.

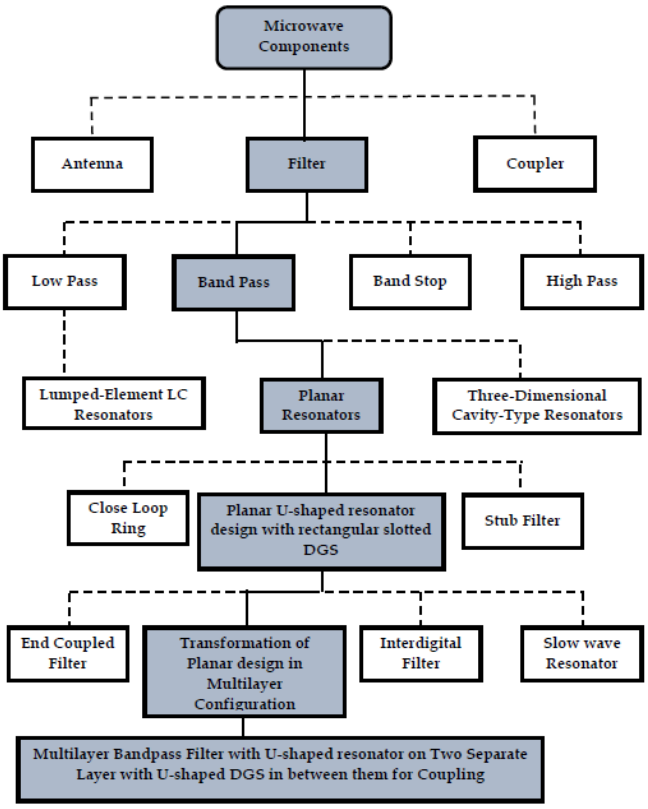

Fig.1.1: Research Scope 1

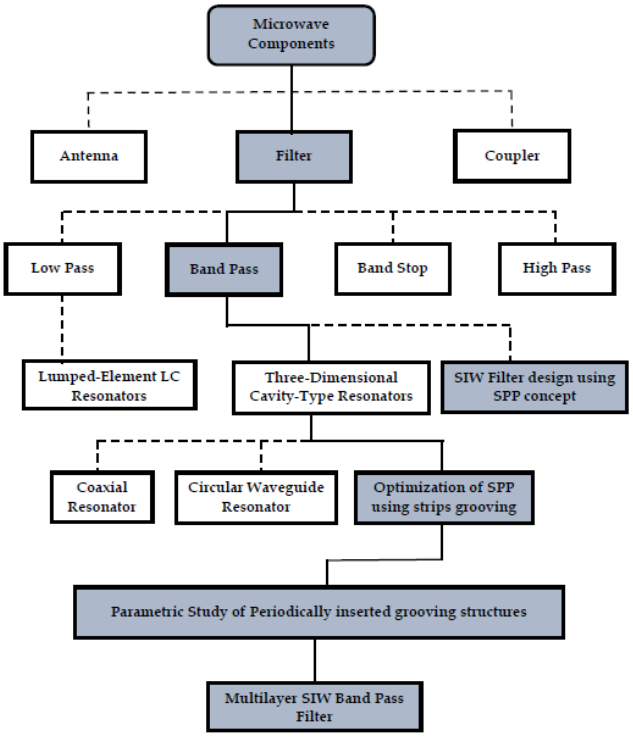

Fig.1.2: Research Scope 2

The boundaries of frequency between the radio and microwave frequencies are somewhat arbitrary and depends on the specific technology that is developed to use the frequency in the specific range. Hence, RF / Microwave communications are used in a variety of applications but not limited to radar, navigation, sensing, satellite, telecommunication etc.

Role of Filter in Microwave Communication

The role of filters in RF/Microwave communication is very important and pave a vital contribution in the RF/Microwave applications. The filters are being used to segregate or combine the different frequencies in these RF/Microwave communication. To utilize the Electromagnetic spectrum optimally and efficiently, filters are capable in frequency selectivity to achieve the desired response.

However, due to rapidly changing technology, new applications in the Wireless Communication are emerging and imposing challenges with even more rigorous requirements in RF/ Microwave filters. These requirements include light weight, miniature size, low cost, and high-performance filters. RF/microwave filters may be implemented on the basis of distributed or lumped element circuits depending on these requirements and specifications [8].

Different realization can be designed through the implementation of various transmission line structures such as, coaxial line, microstrips, and waveguides including Substrate Integrated Waveguides (SIWs).

Application of WLAN Filters

RF/Microwave filters with low insertion loss, miniature size, and high- performance selectivity, increase development of wireless communications. A portions of radio spectrum is reserved (Industrial, Scientific and Medical (ISM)) for industrial, scientific and medical purposes other than telecommunication. A chunk of Radio Frequency Spectrum ranging from 9 KHz to 275 GHz is regulated by International Telecommunication Union (ITU). Applications used in the Wide Area Networks (WAN), microstrip filters can be the main component to select and filter out a specific band from the received free space EM waves in a WAN receiver depending upon the application. WAN receivers have variety of application such as, cordless telephones, Cellphones (1.9 GHz), Modem / Routers (2.4 or 5 GHz), Bluetooth earpiece (2.4 – 2.485), and baby monitors (49 MHz, 902 MHz or 2.4 GHz) etc.

Therefore, to select an appropriate band from incoming EM waves to any receiver, band pass filters having very accurate performance are of great importance. In addition, microwave devices including router or modems in the ISM band (2.4 – 2.5) might utilizes and emit energies in the frequency range, which can cause server interference and may distort signal completely [9]. To overcome this problem, the router / modem or device manufacturers have already taken care of this issue while incorporating a band pass filter.

In wireless LAN (WLAN) networks, WiFi is the technology that connects the electronic devices to the wireless network primarily using the 2.4 GHz (12 cm) UHF and 5 GHz (6 cm) SHF ISM radio frequency bands. To select or filter out specific band, microwave band pass filters are deployed.

Filter Classifications

Microwave filters are generally classified in to main classes:

- Active Microwave Filters
- Passive Microwave Filters

- **Active Filters**

These types of filters comprise of active components such as Op-amps and Transistors in addition to Capacitors and Resistors.

- **Passive Filters**

These types of filters comprise of passive components such as Capacitors, inductors and Resistors is called as Passive Filter. Also, structures such as conventional printed transmission lines, SIWs, and Composite Right-Left Handed transmission lines lie under the category of passive microwave filters.

For filter design, operating frequency contribute a vital role. Therefore, filters are further classified into following five types based on the operating frequency of a specific application.

- Low Pass Filter
- High Pass Filter
- Band Pass Filter
- Band Stop Filter
- All Pass Filter

- **Low Pass Filter**

This type of Filter attenuates all frequencies above cut-off frequency (fc) and pass all signals including DC [11]. These types of filters can be realized with the implementation of shunt capacitors and inductors in series or equivalent microstrip transmission line model in microwave regime.

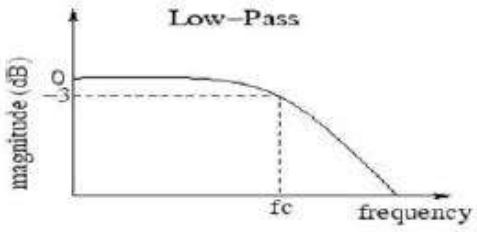

Fig.2.1: Low pass filter response

- **High Pass Filters**

This is a type of filter which suppress or cause high loss of signal below the cut-off frequencies while pass all the frequencies above the cut-off frequency. During operation of the filter, constant output or gain be achieved above the cut-off frequency.

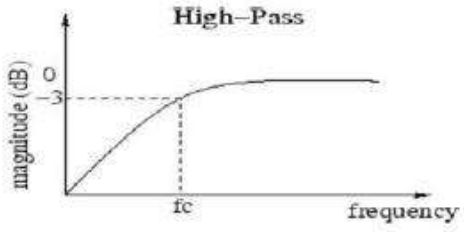

Fig.2.2: High pass filter response

- **Band Pass Filters**

This type of Filter generally consists of three frequencies i.e. lower cut-off, upper cut-off and central frequencies. The signal passes to the load during operation of the filter between the lower cut-off frequency and upper cut-off frequency. There is a central frequency between the lower and upper cut-off frequencies that is geometric mean of the lower and upper cut-off frequencies. Band pass filter will attenuate band of all frequencies below the lower cut-off frequency and above the upper cut-off frequency while pass the band of frequencies in between.

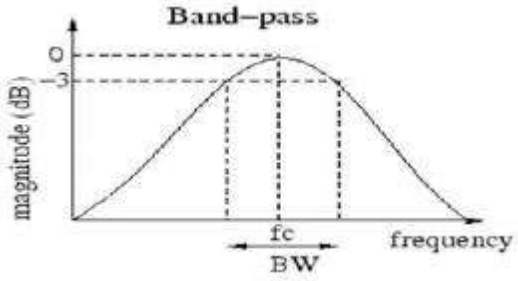

Fig.2.3: Band pass filter response

- **Band Stop or Reject Filters**

This type of filter is the complement of band pass filter. All the signal between the lower and upper cut-off frequencies will be suppressed while passing all the rest of the signal below the lower cut-off frequency and above the upper cut-off frequency. A band of frequencies will be stop between lower and upper cut-off frequencies and thus name is band reject of band stop filter.

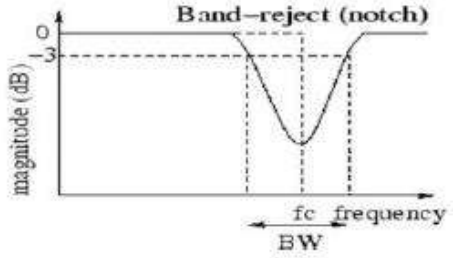

Fig.2.4: Band stop filter response

- **All Pass Filters**

This type of Filter will pass the frequencies of operation in the network devoid of any magnificent loss. The system having all pass filter is not specific to selective stop or pass band.

Keeping in view all type of filters described above, an ideal filter is the filter having perfect characteristics like no insertion loss, constant group delay over the required band pass frequencies and infinite suppression or rejection of signal elsewhere. However, in practical situations and real time environment, the filter response deviates from the parameters and characteristics of the ideal one which are the good performance measurements.

Important Performance Parameters of Filters

- **Cut-Off Frequency**

The difference between the bass-band and stop-band is determined from the corner or cut-off frequency. The -3db frequency is the frequency where the output voltage of the signal is 70.7 % of the input voltage of the signal which is also called the cut-off frequency where -3db represents half power [12]. However, at this point of the frequency the output power becomes half of the input power of the signal.

There are two following cut-off frequencies in the filters:

- **Lower Cut-Off Frequency**

The filter gain is -3db that is half at lower frequency. Lower frequency is represented by f1 and after this frequency bandpass filter pass frequency but to the contrary band stop or reject filter block the frequency after this lower cut-off frequency.

- **Upper Cut-Off Frequency:**

The output power of the signal becomes half of the input power at upper cut-off frequency. The upper cut-off power frequency is represented by f2 and after this frequency bandpass filter does not pass frequency but to the contrary, band stop or reject filter pass the frequency after this upper cut-off frequency.

- **Central Frequency *fc***

Central frequency is the frequency lies between the lower and upper cut-off frequencies of the band-pass or band-stop filters. In other words, central frequency is also the arithmetic mean of the lower and upper cut-off frequencies and can be represented as under:

$$fc=(f1+f2)/2$$

- **Bandwidth**

It is the deference between the upper cut-off and lower cut-off frequencies. In case of band-pass filter, bandwidth is the range of frequencies in which signal pass without any attenuation. In case of band-stop filter, bandwidth is the range of frequencies in which signal cannot pass and attenuated. Furthermore, the range of frequencies before the cut-off frequency is called the bandwidth in case of low pass filter whereas in case of high pass filter bandwidth is the range of frequencies after the cut-off frequency. Bandwidth of the filter can be represented as:

$$B=f2-f1$$

Classification of Filters by Response Type

Response type of the filters is categorized into number of several filter classes consisting of Butterworth filter, Chebyshev filter, Elliptic filter, Gaussian filter, Bessel filter, Linkwitz-Riley filter, Optimum "L" (Legendre) filter during the signal processing and designing phase of the filters. These classes of filter are primarily applied in designing analogue linear passive filters but the results can also be applied in implementation of digital and active filters. The classes of filters can also be derived mathematically with reference to the class of the polynomials. In the ladder implementation of the filter, the filter order can be determined from the number of elements present in the filter. Generally speaking, steeper the cut-off transition between the band pass and band stop, the higher the order of the filter [13]. In practical scenarios, there is no ideal filter with perfect characteristic and performance parameters. Therefore, the above responses of the filter are realized and in which some are good in some areas of performance parameters but poor in others.

Following brief are the well-known filters by response type:

- **Bessel Filter**

Bessel filter has approximately linear phase response in the pass band with an ideal phase characteristic. It can be used to reduce the nonlinear phase distortion. The cut-off frequency response in less sharp but has minimal phase shift.

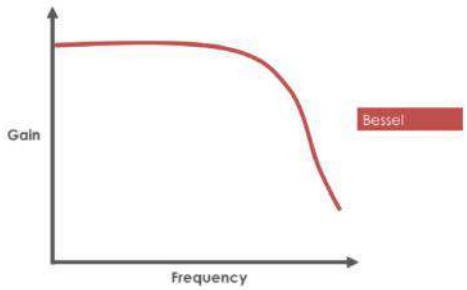

Fig.2.5: Bessel Filter Response

- **Butterworth Filter**

The approximation of Butterworth filter is also known as maximally flat magnitude response in the pass-

band because it has flat amplitude versus frequency response. This type of filter approximation can also relate with the ideal filter in the pass-band. It has maximally flat response below the cut-off frequency and decreases monotonically with frequency in gain in the cut-off region. The roll-off is steepest in the pass band without pass band ripple. Moreover, Butterworth filter selectivity is far better than the other topologies of the filter responses.

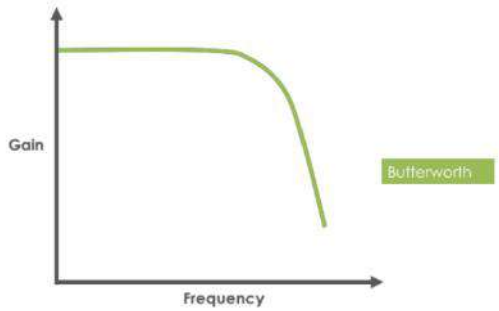

Fig.2.6: Butterworth Filter Response

- **Chebyshev Filter**

The Chebyshev filter is also called as equal ripple filter. The cut-off frequency in the Chebyshev filter is the frequency where the response decreases below the ripple band. In the passband, Chebyshev has the sharper cut-off than Butterworth filter.

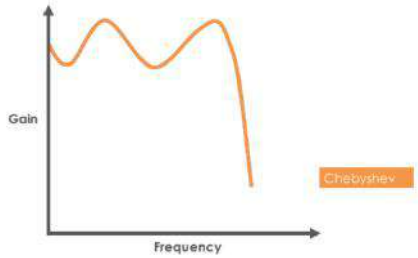

Fig.2.7: Chebyshev Filter Response

- **Elliptic Filter**

Elliptic filters contain ripple in both band pass as well as band stop region and has sharpest cut-off as compared than the other filter responses. The band pass ripple of elliptic filter is same as Chebyshev filter with improved selectivity but at the cost of complex network components.

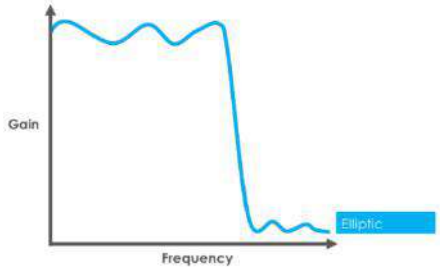

Fig.2.8: Elliptic Filter Response

Microstrip filters are one of the filters which plays a very important role in the realization of microwave planar filters. Being the most popular realization in microwave integrated and passive circuits, with the advent of 99 % pure alumina in 1960's microstrip gain rapid attention in the technology [16]. In the present time, planar filters designing and many other novel benchmarks with cutting edge characteristics are being established using novel fabrication technologies like Liquid Crystal Polymers (LCP), MMIC, LTCC, and Micro-electro mechanic systems (MEMS) etc. [17]. The realizations in filter designing with advanced properties / characteristics and optimum performance become practical and can be built with the advent of CAD tools.

Background of Microstrip Transmission Lines

In the planar transmission line structures, microstrip become the most famous which is used in Microwave Integrated Circuits (MIC). The main requirement in the microwave integrated circuits designing for a planar transmission line is the determination of characteristics on a single plane. Planar transmission line structure is the only one in which the circuit elements' characteristics can be evaluated, analyzed and determined from the single plane dimensions. Photolithographic processes can be involved in the fabrication and building of microstrip filter configurations [18]. Any discrete microwave lumped active and passive devices can be integrated easily with the help of open configuration of microstrip filter.

Microstrip consists of physical geometry with some important parameters and characteristics associated with these parameters. The geometry of microstrip transmission lines comprises of three main parts i.e. a metallic printed conductor on top, thin dielectric

substrate, and ground as shown in Figure 3.1 (a). The conductor on top is having width which is represented as 'W', the substrate between the conductor and ground is having the thickness which is represented as 'h' and the 'εr' is the relative permittivity of the substance in Farads per meter (also called dielectric constant). W, h and εr are the main and important parameters associated with the geometry of the microstrip. The conductor on top is having thickness 't' can be ignored because it has insignificant importance due to its thickness 't' is approximately 10 to 20 μm [19]. As electric field lines start emerging on the side planes of this metallic conductor reside on top of the substrate. With the increase in the thickness 't' of the metallic conductor, the distribution of field changes and start more electric field lines emerging on the side planes of the top metallic line which ultimately start affecting the effective dielectric 'ξeff' as well as characteristic impedance 'Zo' of the microstrip. The thickness 't' effect is approximately about 1 % on ξeff and Zo which can be derived from the microstrip' synthesis formulas with w/h t/h and 2 ξr

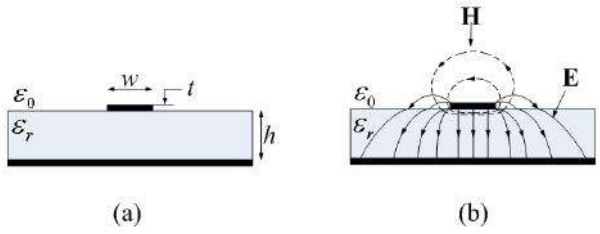

Fig.3.1: (a) Microstrip Line, (b) Microstrip Field Distributions Lines

The distributions of electric and magnetic field lines at the transverse cross-sectional plane of the microstrip are illustrated in Figure 3.1 (b). Transverse electromagnetic propagation (TEM) mode is not supported due to abrupt interface between the dielectric substrate and the air in the microstrip lines. Therefore, Maxwell's equations can be used to prove the requirement of longitude component of electromagnetic fields.

Two analysis methods can be used in determination of propagation constant and characteristic impedance of the microstrip. The analysis methods are full wave analysis and quasi static methods [21]. Analytically more rigorous and complex solutions can be provided through the use of full wave analysis method which consider the hybrid mode of propagation. The dispersive nature that is change with frequency in the phase velocity and characteristic impedance of the microstrip can be demonstrated through these methods.

Pure TEM propagation mode can be determined through quasi static method in the microstrip lines. From following two electrostatic capacitances, transmission characteristics can be found.

Ca – Capacitance per unit length, with dielectric substituted by air of microstrip line.

Co – Capacitance per unit length, with dielectric substrate of microstrip line.

Quite precise results can be achieved by using these methods up to a few gigahertzes of frequency. Effective dielectric constant expressed as under:

$$\varepsilon_{eff} = \frac{C_0}{C_a} = \frac{c}{v_p}$$

C = free space velocity

Vp = Phase velocity

Range of effective dielectric constant [20] is as under:

$$\frac{1}{2}(\varepsilon_r + 1) \le \varepsilon_{eff} \le \varepsilon_r$$

Quasi static analysis introduces the effective dielectric constant in which homogeneous medium permittivity is represented and substitutes the dielectric substrate and air in microstrip structure. The characteristic impedance Zo and phase constant can be expressed in terms of distributed electrostatic capacitances [21].

$$\beta = \beta_0\left(\frac{C_0}{C_a}\right) = \frac{\omega}{c}\left(\frac{C_0}{C_a}\right)$$

$$Z_0 = \frac{1}{\sqrt{(cC_aC_0)}}$$

0 = free space phase constant

W= angular frequency

In view of above all, microstrip comprises of simply a patch conductor resides on top of insulating material that is called dielectric and a ground plane at the bottom which works as the circuit common point and

must be wider than the top conductor at least 10 times. Generally, at the frequency of operation, the microstrip is one half or one quarter long and equal to an unbalanced planar transmission line.

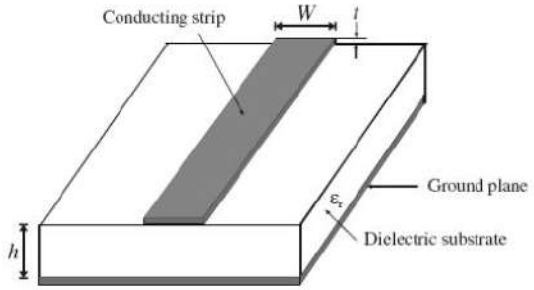

Fig.3.2: Microstrip Filter

The characteristic impedance is dependent on the physical characteristic of the microstrip line. Hence, any value of characteristic impedance between 50 ohms to 200 ohms can be realized by simply changing the microstrip lines dimensions.

The characteristic impedance of an unbalanced microstrip can be calculated by using the following equation [7]:

$$Z_o = \frac{87}{\sqrt{\epsilon + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right)$$

Zo = Characteristic impedance (Ω).

Є = Dielectric Constant.

W = Width of copper strip.

t = Thickness of copper strip.

h = Distance between the copper patch strip and ground plane also called as dielectric thickness.

Waves in Microstrip

Microstrip fields range covers two medias above the air and below the dielectric, therefore the arrangement is inhomogeneous. Pure TEM wave propagation mode is not supported due to inhomogeneous structure of the microstrip. The propagation velocity of the TEM wave is only dependent on the material properties which are permeability (μ) and permittivity (ϵ) because the pure TEM wave consists of only transverse components. There will be longitudinal components consisting of electric and magnetic fields in the microstrip lines' waves due to the existence of two guided wave media by the air and the dielectric substrate. In this case, the propagation velocity is not only dependent on the material properties but also dependent on the physical dimensions or parameters of the microstrip [17]. The electric and magnetic field lines can be shown in below figure 3.3.

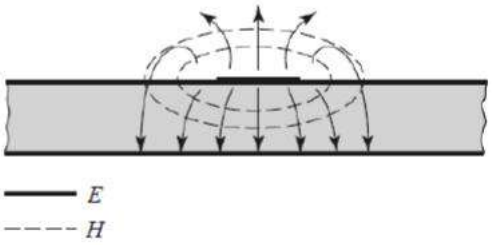

Fig.3.3: Microstrip E & H waves lines

Quasi TEM Approximation

For the microstrip line dominant mode, the longitudinal components of electric and magnetic fields remain kept very much smaller than the transverse components then these can be neglected. At this stage, the dominant mode performs similar to a TEM mode. At this point, the transmission line theory of TEM is applicable on the microstrip line theory as well and is called Quasi TEM Approximation. Quasi TEM Approximation is usable in most of the operating frequency ranges of the microstrip therefore it may also be referred as the wave propagation of microstrip has always the Quasi TEM Approximation [8].

Characteristic Impedance and Effective Dielectric Constant

The inhomogeneous air - dielectric media transformed into homogeneous dielectric material having effective dielectric permittivity in the Quasi TEM Approximation of the microstrip. Two important parameters called as characteristic impedance 'Zo' and effective dielectric constant 'ξeff' can be expressed as the transmission characteristics of the microstrip. Therefore, fine approximations and calculations for the characteristic impedance, phase velocity and propagation constant can be achieved through the analysis of quasistatic or static solutions [22]. Pure TEM propagation mode is assumed as fundamental mode in the quasistatic analysis in a microstrip.

Following expressions [23] which provide more accuracy while using very thin microstrip patch conductors i.e. t → 0, as under:

For W/h ≤ 1:

$$\epsilon_{re} = \frac{\epsilon_{r+1}}{2} + \frac{\epsilon_{r-1}}{2}\left\{\left(1 + 12\frac{h}{W}\right)^{-0.5} + 0.04\left(1 - \frac{W}{h}\right)^{2}\right\}$$

$$Z_c = \frac{\eta}{2\pi\sqrt{\epsilon_{re}}}\ln\left(\frac{8h}{W} + 0.25\frac{W}{h}\right)$$

Where, η= 120π ohms is the wave impedance in fr

For W/h ≥1:

$$\epsilon_{re} = \frac{\epsilon_{r+1}}{2} + \frac{\epsilon_{r-1}}{2}\left(1 + 12\frac{h}{W}\right)^{-0.5}$$

$$Z_c = \frac{\eta}{\sqrt{\epsilon_{re}}}\left\{\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h} + 1.444\right)\right\}^{-1}$$

Distributed Elements – Band Pass Filter Types

There is various type of configurations of planar transmission lines for band pass filters as under:

1. End coupled
2. Parallel coupled
3. Hairpin line Filter
4. Inter-digital Filter
5. Combline Filter

- **End coupled band pass filter:**

The configuration of end coupled is shown in Figure 3.4, in which each open- end resonator is approximately the half-guided wavelength long at the mid frequency f_0 of the band pass filter. This topology has the advantage of practical realization in printed circuit technology easily and occupied less space as compared to the plain transmission line. However, there is a limitation in this type of filter configuration that its performance decreases with the increase in fractional bandwidth. Fractional bandwidth is the defined as the bandwidth of the system divided by the central frequency [24].

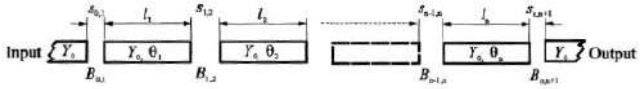

Fig.3.4: End Couple Filter Configuration

- **Parallel coupled band pass filter:**

This type of filter configuration uses half wavelength line resonators in the microstrip band pass filter realization. These resonators are placed in parallel in such a manner that half of their length are located adjacent to each other. This kind of arrangement gives large coupling relatively with respect to the given resonators' spacing in between [6]. This type of filter has fabrication ease and provide wider bandwidth.

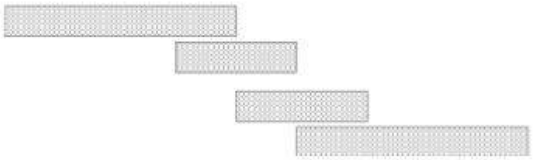

Fig.3.5: Parallel Coupled Filter Configuration

- **Hairpin band-pass filter**

This type of filter can easily be constructed by introducing short stub between the parallel coupled line resonators and merged these resonators with the stub to give "U" shaped new resonators. It can also be realized by folding the half wavelength parallel coupled resonators into U-shape. The U-shape resonator is then known as hairpin resonator. Same equations may be used in designing and synthesis of hairpin filter as for the parallel coupled line filters. However, while folding the resonator, it is required to keep the coupled line lengths short so that the coupling between the resonator can be reduced. If the two arms of the hairpin filter reside closely in the orientation, then they might be functioned as a couple of resonators and as a result maximizing the coupling between them [25]. Therefore, to employ the hairpin filter precisely and accurately, a full wave electromagnetic simulation may be utilized in the filter designing.

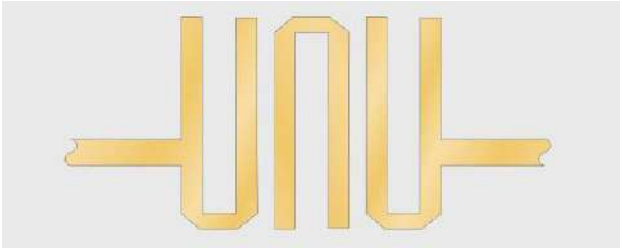

Fig.3.6: Hairpin Filter Configuration

- **Interdigital Band Pass Filter**

This type of filter configuration is classified as similar to the couple line filter. However, several resonators are placed in adjacent to each other alternately with one end is short and the end is open. This alternate

arrangement of microstrip resonators make interdigital configuration of the filters. Each resonator is normally having quarter wavelength (λ/4). Interdigital configuration of the filter can easily be integrated with coaxial format lines and very suitable for planar transmission lines. Different coupling can be achieved by introducing different resonators physically. The fabrication of interdigital can also be done without adding dielectric support material. However, the resonators require proper grounding which is obtained by introducing the holes [26].

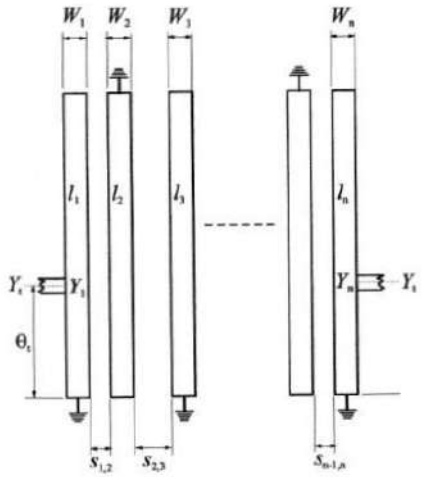

Fig.3.7: Interdigital Filter Configuration

- **Combline Band Pass Filter**

The structure of Combline filter resemble with the interdigital filter. However, the only difference in the Combline configuration is having the short-circuited ends of all the resonators at the same ends whereas interdigital configuration is alternate arrangement of short circuit and open circuit ends. Moreover, loading a capacitance is introduced between the other ends and ground of each resonator in the Combline filter configuration. Due to loading of the capacitance, the filter size can further be reduced. Proper choice of the capacitor may lead to compact resonator length. Therefore, offering enhancement in resonator length electrically while reducing the physical length. spread Same as interdigital filter, Combline filter resonators uses quarter wavelength (λ/4) [27]. Combline filters due to compactness, tremendous stop band, excellent performance and ease of tolerance in fabrication are used broadly as band pass filter in modern equipment of RF Communications.

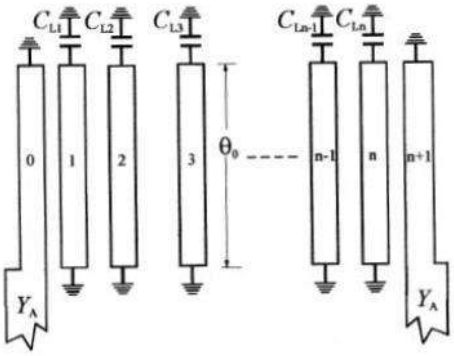

Fig.3.8: Combline Filter Configuration

The approximations of lumped element circuit in the standard circuit theory become invalid for microwave frequencies from 300 MHz to 300 GHz as the physical dimensions become impractical specifically when wavelength increasing. Due to the fact, the microwave component is normally considered as distributed circuit elements in which the physical length of the instrument significantly changes with the phase of a current or voltage. Therefore, propagation effects cannot be neglected as voltages and currents acts as waves propagation through the device [11].

A complete microwave system or circuit can be expressed in term of combination of several fundamental microwave components including but not limited to couplers, filters, power combiners and dividers, mixtures etc. However, the main objective in all these type of circuit elements or components is the capability to transmit the signal power as much as possible from one point to another point efficiently without incorporating any significant amount of loss during transmission. Consequently, it is necessary to manufacture and design the microwave fundamental devices in the shape of a guiding structure for the purpose to guide or confine the electromagnetic energy safely from one point to another with minimum loss of signal power [28].

Microstrip Filter Consideration with Limitations

Microstrip transmission lines are extensively used as guiding structure at comparatively low microwave frequencies due to its simple structure and geometry in the construction, low cost, compactness, and high ability to integrate with surface mounted components. The simple construction of the microstrip consists of a top conductor with the single ground plane at the bottom and a dielectric substrate layer in between as

shown in the Figure 4.1. There are important parameters associated with the geometry of the microstrip that are width, thickness of the conductor, dielectric constant and thickness of the substrate. Moreover, the conductivity and thickness of the conducting microstrip patch or strip can also play an important role at higher frequencies of operation [29]. The design of printed microwave circuits, devices, and components like couplers, filters, power combiners and dividers, mixers etc. can be obtained using microstrip lines as baseline building block through careful approximations of these parameters.

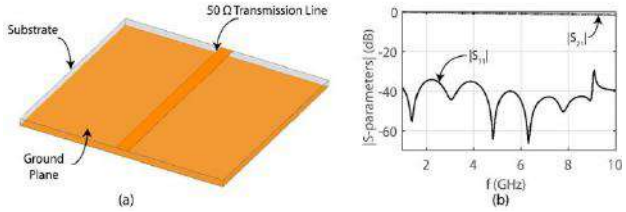

Fig.4.1: (a) Planar microstrip transmission line & (b) Magnitude of reflection coefficient showing good impedance matching & transmission characteristics over a frequency range from 1 GHz – 10 GHz.

Rectangular Waveguide Considerations with Limitations

The situation become unfavorable and changes with the increase in frequencies, as the losses in transmission lines increase with the emergent of more radiation when moved towards the higher frequencies of microwave relatively in microstrips. In this scenario, hollow pipe structures like rectangular waveguides, as shown in Figure 4.2, are preferred because such kind of structure confine the electromagnetic energy alongside waveguide and transport the energy without any significant losses, specifically at higher frequencies [30].

Hence, no radiations occur at higher frequencies in waveguides and waveguides normally contain air as a dielectric inside them. The space inside the waveguides can also be filled with dielectric material if desired. This dielectric filling results in smaller cross-sectional area as compared to the air-filled waveguides. But unfortunately, there are down sides of using hollow pipe waveguides, especially at lower frequencies especially because of their bulkiness, cost, and fabrication complexity. In addition, these structures are not easily integrate-able with the printed circuits.

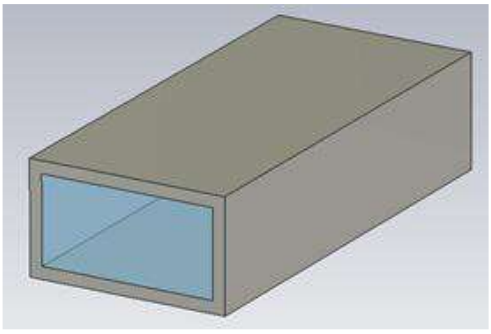

Fig.4.2: Rectangular Waveguide

Substrate Integrated Waveguide Filter

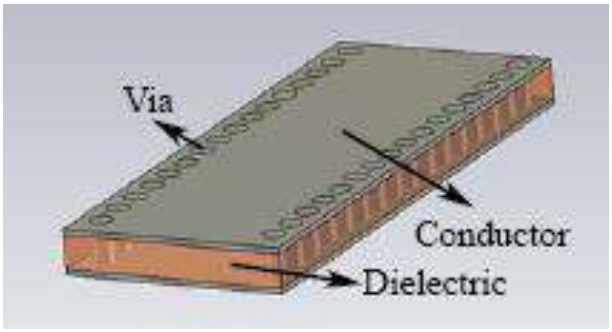

Fig.4.3: Substrate Integrated Waveguide (SIW)

For the integration of waveguides with the printed circuits, hybrid architecture has been proposed recently between waveguides and microstrip transmission line structures which is known as Substrate Integrated Waveguide (SIW) [31]. Structure like SIW can be realized by sandwiching a dielectric material in between two conductors on top and bottom sides. Whereas, the side walls in dielectric material consist of metallic vias in the form of two linear arrays, as depicted in Figure 4.3. This hybrid technique overcome the problems associated with the individual configurations of waveguide and microstrip. SIW has the characteristics of both waveguide as well as microstrip. SIW architecture is relatively easy to fabricate, cost effective and can be easily integrated and assembled with planar printed circuits or devices as compared to the bulky waveguides. Besides, SIW provides better performance at relatively higher frequencies as compared to microstrip with minimum losses and similar dispersion characteristics as that of

waveguides. Recently, significant microwave based SIW components has been reported to replace bulky waveguide and microstrip counterparts like couplers, filters, mixers, and power divider or combiners etc. at their appropriate frequencies.

Multilayer Technology

The scope of above described planar transmission line technologies is further extended with the introduction of Multilayer Technology in their applications and capabilities. In Multilayer technique, several conductor planes are stacked up with dielectric layers in between, allowing in overall size reduction of the design besides providing greater flexibility in design [32]. Moreover, it enables in enlargement of characteristic impedance realization from 20 Ohm - 200 Ohm to 5 Ohm -125 Ohm as compared to the classical microstrip line configurations [33]. In addition, it provides the greater flexibility in coupling implementation of associated various characteristics between non adjoining resonators.

Multilayer Filters

Multilayer filters have vital role in present communication systems due to enormous demand of miniature filters having cost effective, smaller size, improved selectivity and augment system performance [34]. More compactness along with the flexible design can be easily achieved using multilayer technique in the circuits. A general illustration of the multilayer Structure is shown in Figure 4.4.

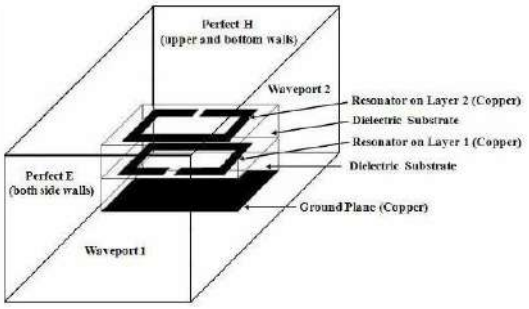

Fig.4.4: Multilayer Structure

III. LITERATURE REVIEW

The planar configuration of the transmission line band pass filters discussed above showed that to achieve reasonable bandwidth along with fabrication ease and realization of filter, different structural configuration may be adopted. Also, all possible planar configurations decrease filter size to a specific extent. This maximum limit on overall dimensions of the filter may result in the misfit of the modern communication devices having integrated WLAN chips for wireless local access. A multiband band pass filter covering WLAN band having T-shaped resonating structure is proposed in [35]. The proposed structure shows independent control of band pass characteristics over a frequency band; however, the planar configuration of the proposed design has size of 0.038 λ_g^2. Similarly, a miniaturized dual-band pass filter comprising of Stepped Impedance Resonator (SIR) and defected Split Ring Resonator (SRR) resonator is discussed in [36]. The proposed design has dimensions of $20 \times 20\ mm^2$ ($0.27 \times 0.27\ \lambda_g^2$). In [37], E- and T-shape resonator are shorted at the center to achieve filtering response at three bands (WiMAX, WLAN, and X-band). The design has overall size of $34 \times 12 \times 0.762\ mm^3$. A spiral inductor shaped and double split inductor (two) are used to develop a low loss bandpass filter [38]. For sub-6 GHz band, the proposed planar filter designs covered a chip area of $0.16\ mm^2$. Similarly, effect of defected microstrip structure shapes on performance of planar band pass filter is presented in [39]. In particular, wide band performance in band pass filter is obtained using short circuit stub topology and U-shaped defected microstrip structures. In planar band pass filters, size reduction for coupled band pass filters can be achieved using reactive loading [40]. However, the proposed miniaturization methods in planar band pass filters, miniaturize overall filter chip area up to certain level because of the fabrication tolerance, quality factor, and bandwidth.

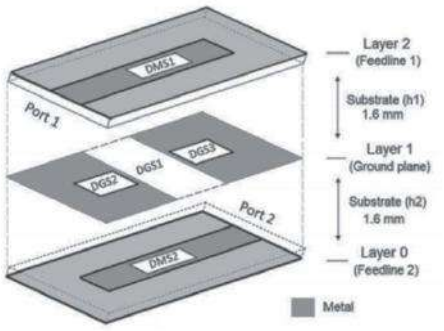

Fig.4.5: Multilayer topology of wide band pass filter having DMS and DGS [42].

Furthermore, magnetically coupled open-loop resonators in multilayer topology are used to design a dual-band balanced band pass filter [41]. The designed filter showed a narrowband response and has electrical size of 0.035 λ_g^2 @ 1.64 GHz. A tunable super wideband filter in multilayer topology having transmission lines with Defected Microstrip Structure (DMS) on separate layers with Defected Ground Structure (DGS) in between them is used for the coupling [42]. To achieve a wider band pass response, the DGS is cut into half, as shown in Figure 4.5. The use of separate ground planes results in a wideband response, however separate ground planes are preferred in the practical application. The designed filter in [42] has overall dimensions of 13.67 $mm \times$ 17.58 $mm \times 3.2\ mm$. In [43], a multilayer band pass filter is designed by using T-shape curved microstrip transmission lines on top and bottom layer, as shown in Figure 4.6. Whereas, circular slots in the ground plane are used for the EM coupling between the T-shaped microstrip patches. The insertion of curved T-shaped sharp edges in designed filter may arise fabrication complexities. In addition, the distance between curved T-shaped patches on a layer strongly alter the coupling characteristics of the overall filter design. In addition, dual band pass filter having multiple zeros using discriminating and source – load coupling is designed in [44]. The introduced coupling techniques improved selectivity and stop band performance. Slot coupled resonators and hairpin line resonators are used in multilayer topology to generate band pass response at 2.4 GHz and 5 GHz.

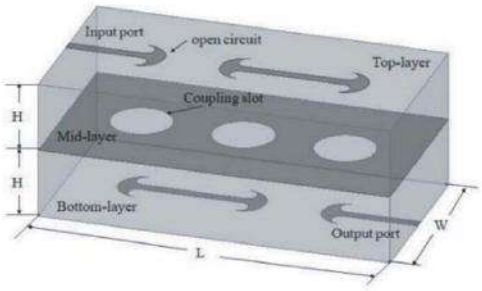

Fig.4.6: A multilayer band pass filter with circular coupling slots and T-shape curved micro strip patches [43]. H= 0.508 mm, L = 26.7 mm, W = 15 mm.

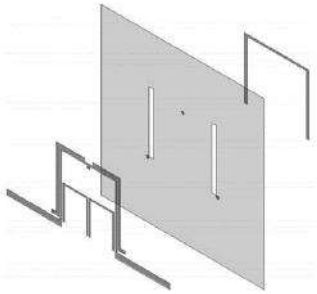

Fig.4.7: Dual Band multilayer filter design using slot coupled and hair pin resonators with slotted ground plane for coupling [44].

On the other hand, a dual-band SIW filter using complementary and open split ring resonators is proposed in [45]. An evanescent mode technique is used by etching electric dipoles (complementary and open split ring resonators) on SIW structure. The proposed design in [45] has an overall size of 0.23 $\lambda_g \times 0.13\lambda_g$ @ 2.4 GHz. The use of complementary and open split ring resonators resulted in design miniaturization but at the cost of greater fabrication complexity and narrow bandwidth. In [46], evanescent mode cavities are generated in SIW filter by loading pedestal shaped metal inserts. The metal inserts resulted in a coupled resonator filter having both positive and negative cross-couplings. An illustration of sixth order pedestal SIW filter having electric and magnetic couplings is shown in Figure 4.8. It can be observed in Figure 4.8 that increased number of vias results in greater fabrication complexity and practical realization of filter.

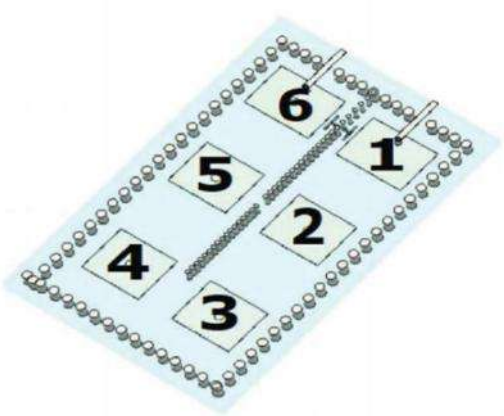

Fig.4.8: View of 6th order pedestal SIW filter.

In 2018, band pass filters are proposed by inducing Surface Plasmon Polariton (SPP) like propagation using structural dispersions in SIW [47]. Three layers of SIW are utilized in this design to achieve band pass filter based on SPP propagation. SPP break diffraction limits and localize light into subwavelength dimensions which ultimately enable strong field enhancements. The engineered SPP known as Spoof Surface Plasmon Polariton (SSPP) provide slow-wave behavior, field confinement in microwave frequency regime. In addition, SSPP presents the occurring of EM waves at dielectric and conductor interface due to strong electric and magnetic coupling. Based on SSPP, different microwave circuits such as transmission lines [47-50] and filters [51 – 57] have been proposed. Recently, electromagnetic modes are structurally dispersed in parallel plate waveguide filled with positive permittivity to achieve natural SPP concept in microwave region is proposed [58 – 59]. The occurring of SPP at interface is achieved by creating effective permittivities of opposite sign in certain frequency region by dividing parallel plate waveguide into two parts by an array of wires placed normal to the plate and filling parts with different materials. Similar method is applied in SIW structure for filtering operations at microwave frequencies [47] but with single pole in the pass band.

In view of above, there is increase trend in the utilization of multilayer band pass filter to cope up with different challenges like size reduction, better performance, and flexible design with cost effective requirements. It also provides easy integration with other microwave systems, subsystems, circuits or components. There are mainly two categories of multilayer filters [60]. First category contains coupled line resonators on different layers without any common ground in between which can be seen in Figure 4.9 (a). In this category, wide band applications are found more suitable due to strong coupling realization. Second category contains aperture couplings between adjacent layer resonators on common ground, as can be seen in Figure 4.9 (b). In this category, narrow band applications are found more suitable, However, combination of both categories is also possible [61]. Furthermore, SSPP like propagation in filters regime

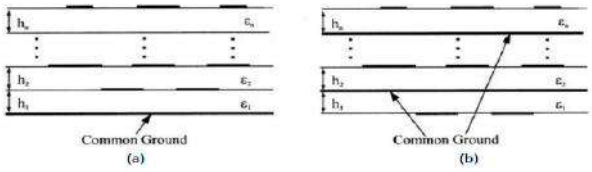

Fig.4.9: Multilayer Filter

(a) Without ground plane b/w the resonator layers

(b) With ground plane between the resonator layers.

With multiple poles in pass band in addition to the size miniaturization using multilayer topology are the major requirements of modern communication systems. This thesis is focused on the design, simulation, and realization of multilayer WLAN band pass filters using DGS structures for coupling between U-shaped resonators having open ends.

Compact and high-performance filters are required for modern communication systems. To achieve design compactness, Defected Ground Structure (DGS) are preferred [62 – 66]. The integration of multilayer technique and DGS in filter design provide significant reduction in size with an additional feature of providing strong coupling between the two microstrip lines. In addition, providing defection in microstrip structure in relation with the DGS can be used to achieve compact band pass filters. In this chapter, a multilayers WLAN band pass filter is designed using U-shaped resonators on two different layers, whereas DGS is used in between the defected microstrip structures to couple EM energy electrically and magnetically.

Design of a Planar Band Pass Filter

Initially, a planar structure consisting of ground plane with square slot is etched on the bottom side of FR4 substrate. Then, coupled U-shaped resonators behaving as a parallel LC circuit are modeled on the top layer of the substrate and connected with a 50 Ω transmission line. The width of transmission line is calculated using transmission calculator for FR4 substrate of thickness 1.6 mm and relative permittivity (ϵ_r) of 4.4. A 3D schematic of the planar band pass filter having end coupled and open stub-tapped slow wave resonators is shown in Figure 5.1. The DGS structure with square slot and U-shaped resonator behaves as a LC circuit whose values can be estimated at initial stage using [66]:

$$C = \frac{5}{\pi}\left[\frac{f_{cut\_off}}{\Delta f^2}\right],$$

and

$$L = \frac{25}{C\pi^2}\left[\frac{1}{f^2_{resonance}}\right].$$

Where, C and L are associated inductance and capacitance values, respectively. f_{cut_off} is cut off frequency of the filter and $f_{resonance}$ is resonance frequency of the filter. $\Delta f^2 = f^2_{cut\_off} - f^2_{resonance}$.

After the optimization of U-shaped and square slots values in the ground plane, design is modeled in 3D electromagnetic simulator Ansys HFSS and values are optimized to achieve a band pass response. The results of the optimized planar band pass filter are shown in Figure 5.2. The planar band pass filter was designed on a 50 mm × 50 mm substrate.

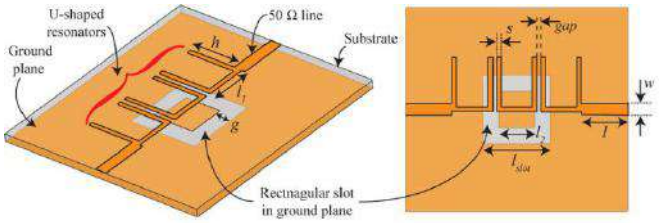

Fig.1.1: 3D and front view of Planar band pass filter having square slotted DGS and U-shaped resonator. Optimized dimensions in mm are: $l_{slot} = 15, l_2 = 8, gap = 1, s = 1, l_1 = 9, l = 10.5,\ h = 10.25, and\ g = 3.5$.

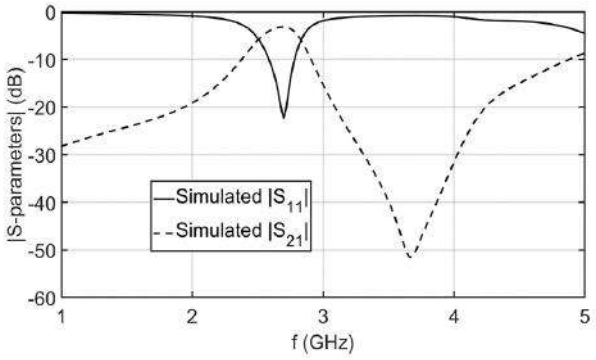

Fig.5.2: Simulated reflection and insertion loss of planar band pass filter.

It can be observed from Figure 5.1 that designed filter has 10 dB bandwidth from 2.59 GHz to 2.78 GHz having center frequency at 2.7 GHz. Whereas the insertion loss of the designed planar filter is 3.2 dB at 2.7 GHz and then increase up to 5 dB. This concludes that planar filter designed has high insertion loss because of the strong coupling between U-shaped resonators. In addition, the insertion loss response has not steep and symmetric roll-off. The coupling of ground slot for better resonance can also be observed from current distribution shown in Figure 5.3. It can be observed that maximum current in U-shaped resonator exists because of the placement of slot beneath the slot. Therefore, the placement of slot under the U-shaped resonator play an important role in design optimization.

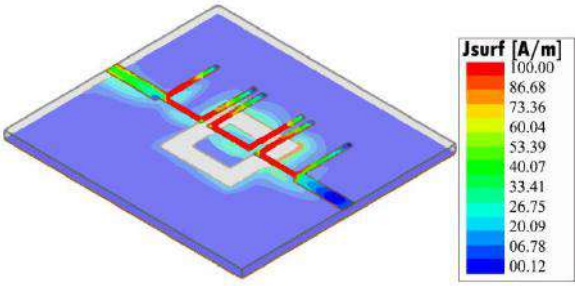

Fig.5.3: Current distribution showing coupling because of the introduced slot in the ground plane.

A parametric study on the filter design parameter was also performed to observe the effect on the insertion loss and shift of the resonance frequency. It was observed during the parametric study that changing 's' i.e. gap between U-shaped resonator greatly disturbs the reflection and insertion loss results. However, changing the dimensions of the square slot beneath the U-shaped resonator results in good reflection and insertion responses over a certain frequency range. The effect of changing 's' on insertion and reflection characteristics is shown in Figure 5.4.

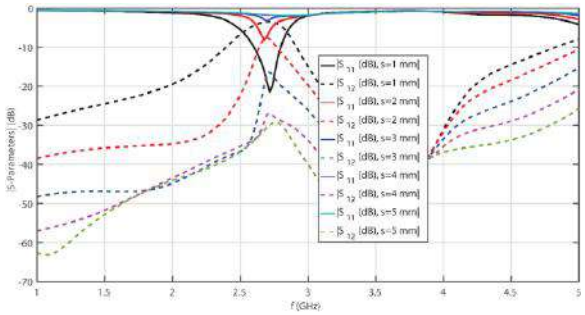

Fig.5.4: Effect of 's' on Insertion and reflection characteristics of planar band pass filter.

In addition, optimization and placement of square slot under the U-shaped resonator gap 's' also results in

better insertion and reflection characteristics of band pass filter. The gap adjustment for achieving better insertion and reflection characteristics after optimizing 'gap' i.e. DGS slot is shown in Figure 5.5.

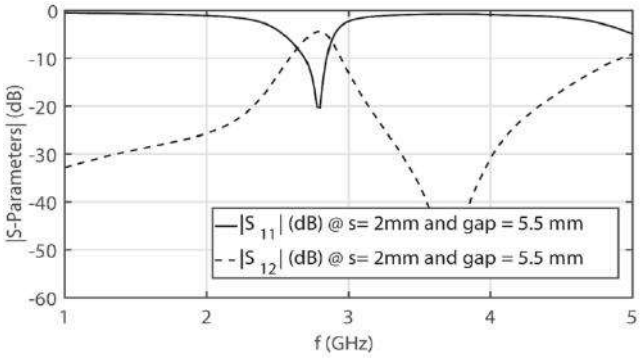

Fig.5.5: Design optimization by changing slot dimensions 'gap' for s = 2 mm to achieve better reflection and insertion characteristics.

Effect on band pass filter characteristics by changing overall width *'W'* of the substrate revealed that reflection loss ($|S_{11}|$ (dB)) remains unchanged. Whereas insertion loss ($|S_{12}|$ (dB)) increases from 3 dB to 5.4 dB because of increase in fringing capacitance due to open ends of U-shaped resonator near the substrate. This effect is shown in Figure 5.6 along with the current distribution, when 25 mm width of substrate is selected by keeping other dimensions same, as shown in Figure 5.1. Parametric analysis of the planar band pass filter also showed that filter frequency can be varied by changing the length 'h' of the U-shaped resonator by keeping in mind that good insertion and reflection losses is only achieved by optimizing the dimensions of the square slot beneath the U-shaped resonator.

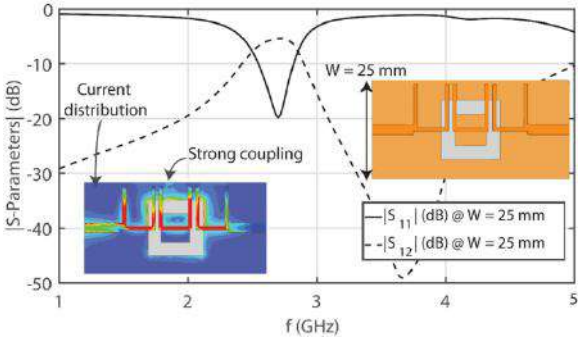

Fig.5.6: Effect of changing 'W' i.e. width of substrate. Current distribution also shown to demonstrate coupling between the open ends of U-shaped resonator and ground plane because of smaller substrate width.

It can be concluded from the parametric analysis of optimized planar band pass filter shown in Figure 5.1 that gap length *'g'* and width of the square slot *'gap'* along with the placement of the square slot beneath the resonator play an important role in achieving good insertion and reflection characteristics. For practical cases, the insertion loss should be close to 0 dB in pass band with sharp role off in the band stop region. On the other hand, reflection loss should be less than 10 dB to show that maximum EM energy is transmitted from the port to the structure. Therefore, the insertion and return loss of planar band pass filter needs further refining of results.

Design of a Multilayer Band Pass Filter

After the designing of planar band pass filter consisting of DGS having square slot and U-shaped resonating structure on top, a multilayer filter was designed and realized in simulation environment. The design and parametric study of planar band pass filter showed that size of the filter can be reduced up to a certain level as there exists a trade-off between filter performance and size miniaturization. Therefore, multilayer topology is adopted to achieve size miniaturization and enhance band pass results.

In multilayer topology, central U-shaped resonator is removed and one end of the microstrip transmission line is placed on the top side, whereas the other transmission line section is placed on the separate substrate having slotted ground plane in middle. An exploded view of the multilayer design is shown in Figure 5.7. The adopted multilayer topology resulted in decrease of size form 50 mm × 50 mm to 30 mm × 28 mm which is approximately 50 % size reduction.

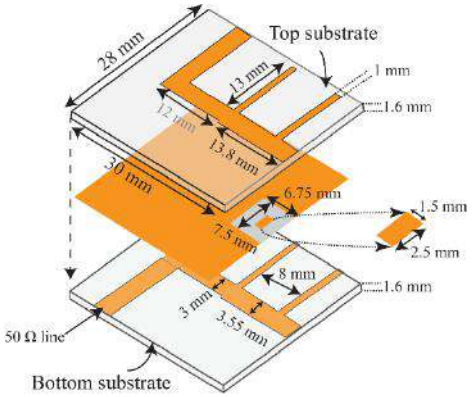

Fig.5.7: 3D and front view of Multilayer band pass filter having square slotted DGS and U-shaped resonators.

The results of reflection ($|S_{11}|$ (dB)) and insertion loss ($|S_{12}|$ (dB)) are shown in Figure 5.8. It can be observed from the results that designed multilayer band pass filter is well matched over a band from 2.24 GHz to 2.54 GHz which is enough to cover practical WLAN band. In addition, the insertion loss is close to 0 dB, as shown in Figure 5.8. The resonators' placement on top and bottom, magnetically and electrically couple fields from the U-shaped slot etched in the ground plane. The geometry of U-shaped slot is changed from rectangular slot of the planar design to further decrease the size and create strong EM coupling for the U-shaped resonators. The multilayer topology adopted in the design procedure, sharpened the transition from stop band to pass band and resulted in a good insertion loss close to 0 dB, as shown in Figure 5.8.

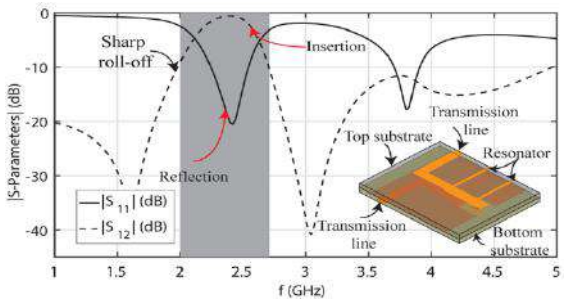

Fig.5.8: Insertion and reflection characteristics of multilayer Band pass filter.

The substrate chosen are FR4 with height 1.6 mm because of its easy availability in market. The results showed that multilayer filter suitable for integration in various WLAN systems. An illustration of current distribution in the U-shaped resonators to show the strong coupling because of the slotted ground plane the end is shown in Figure 5.9.

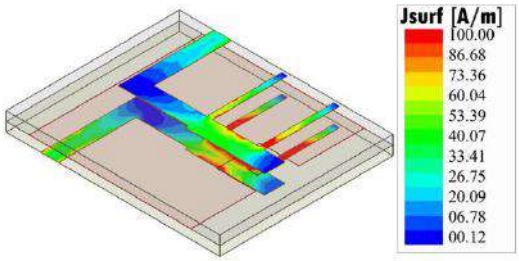

Fig.5.9: Current distribution on the multilayer band pass filter at 2.44 GHz showing strong EM coupling because of the inserted U-shaped slot placement between the U-shaped resonators.

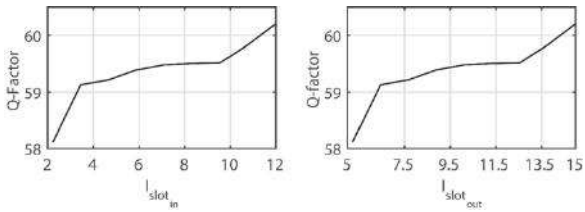

Fig.5.10: Quality factor of the proposed filter vs U-shaped slot dimensions.

Furthermore, external Quality (Q)-factor of the designed multilayer band pass filter was computed using Eigenmode analysis in Ansys HFSS and is shown in Figure 5.10. The Q-factor was calculated by changing values of lengths of ground planes lengths that are responsible for increase or decrease in the U-shaped slot dimensions and placement of the U-shaped slot. The appropriate lengths of the ground plane to change slot dimensions are clearly shown in Figure 5.11. Optimized values of the ground plane that is placed in the middle layer are also given in Figure 5.11.

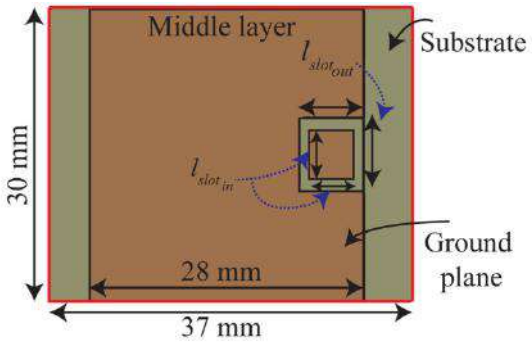

Fig. 5.11: Optimized dimensions of the ground plane and parameters defining the U-shaped slot etched in the ground plane.

The E- and H-fields vector of the U-shaped slot are also computed to demonstrate the strong electric magnetic coupling. These vector plots are shown in Figure 5.12.

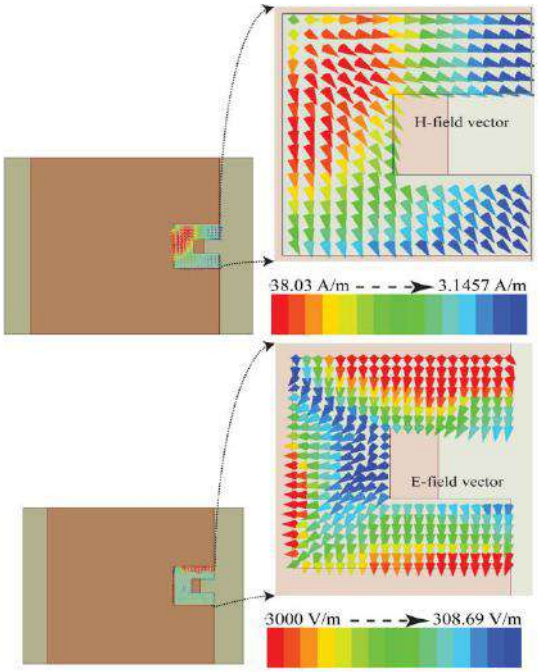

Fig.5.12: E- and H-vectors of the etched U-shaped ground plane slot showing strong electric and magnetic coupling.

Table 1: Comparison with reported band pass filters.

Ref.	Size $\lambda_g \times \lambda_g$	F (GHz)	FBW	IL (dB)	Design Complexity
[67]	0.187 × 0.285	1.84	9.2	2.2	Medium to High
[68]	0.67 × 0.32	0.9	3.6	2.67	Low to Medium
[41]	0.237 × 0.148	1.64	8.86	0.92	High
[69]	1.23 × 1.23	3.5	3.14	1.52	High
[70]	0.417 × 0.377	2.44	8.61	1.8	Medium
This work	0.5 × 0.4	2.44	12.29	0.5	Normal

**Guided wavelength (λ_g), Fractional Bandwidth (FBW), Insertion Loss (IL).*

A comparison between the proposed multilayer band pass filter with the reported work to illustrate multilayer topology benefits in the microwave filter regime. Several observations can be inferred from the comparison table based on various performance parameters.

1. **Filter Footprint:** The size of filter in terms of electrical size is shown in Table 1 with respect to the guided wavelength. It can be observed proposed filter has competent size at 2.44 GHz as compared to other reported design. Other reported filters shown in Table has their equivalent electrical size as per their frequency of operation which is less than 2.44 GHz. This low frequency of operation will result in high guided wavelength and lower electrical size at that frequency.
2. **Fractional Bandwidth:** It can be seen from the comparison table that multilayer filter proposed in this thesis has maximum bandwidth as compared to other reported designs.
3. **Insertion Loss:** The insertion loss of the proposed multilayer design is also close to 0 dB as compared to other reported designs in literature.
4. **Hardware / Design Complexity:** A comparison of the proposed design with the reported designs in terms of design and hardware complexity is also drawn. It can be noticed from the last column of Table 1 that proposed multilayer design has simple structure with minimum hardware complexity and deliver desired results for WLAN filtering in microwave systems.

WLAN band pass filter is first designed in planar topology using rectangular slot in ground plane and U-shaped resonator on the top plane. A detailed parametric study on the filter performance parameters is conducted to demonstrate the trade-offs and limitations of planar technology for size miniaturization and competent results. Then, same planar filter is designed using multilayer topology and it is demonstrated successfully that multilayer technology not only miniaturize filter size but also enhance filter results by providing strong EM coupling.

Two TE10 modes in SIW topology are coupled by designing two SIW transmission lines of slightly different cut-off frequencies. The two designed SIWs are sandwiched followed by the structural dispersion in the SIW modes to achieve a multipole bandpass WLAN filter based on SPP phenomenon.

Theoretical Analysis and Design of SIW Multilayer Bandpass Filter

Initially, two different SIW transmission lines having cut-off frequencies 4.8 GHz and 2.6 GHz are designed and optimized in HFSS. The layout of the 1st SIW transmission lines (SIW 1) with corresponding geometrical parameters are shown in Figures 6.1.

Metallic conducting vias on the lateral sides of the transmission line represent SIW structure supporting TE mode. A second SIW transmission line (SIW 2) is designed on TMM10i substrate having permittivity greater than the permittivity of substrate used in SIW 1. A layout of SIW 2 with only difference in width is shown in Figure 6.2. All of the geometrical parameters of both the SIW transmission lines are kept same except the width of the SIW because cut-off frequency of dominant TE10 mode depends on widths a1 and a2. The widths of the SIW section i.e., a_1 and a_2 are calculated using (6.1) to design two SIWs having slightly different cut-off frequencies.

$$f_{cutt_{off}} = \frac{c}{2a_i\sqrt{\epsilon_r}}, \qquad i = 1, 2$$

The results of the first SIW transmission line having 4.8 GHz cut-off frequency are shown in Figure 6.3. It can be inferred from Figure 6.3 that designed SIW is supporting EM wave transmission from 4.8 GHz. Also, E-field distribution shown in inset of Figure 6.3 further confirms that above 4.8 GHz basic and fundamental mode i.e., TE_{10} mode is present. The SIW 1 is designed on FR4 substrate having thickness of 0.769 mm.

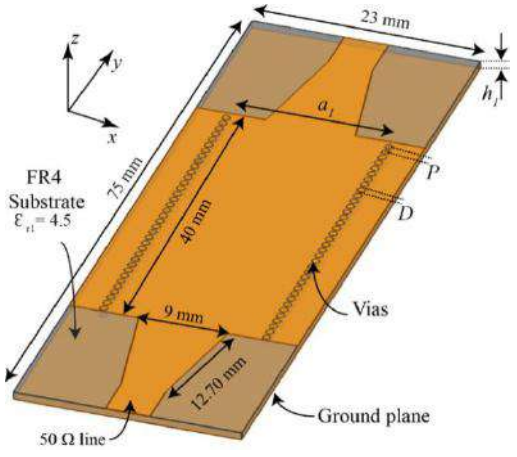

Fig.6.1: Layout and dimensions of SIW transmission line designed on 0.769 mm (h_1) FR4 substrate having a_1= 18.8 mm.

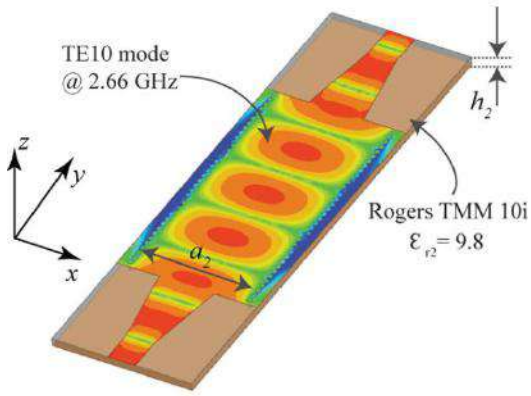

Fig.6.2: Layout of SIW 2 designed on Rogers TMM10i substrate having thickness 1.27 mm (h_2) and *a_2* = 15.6 mm.

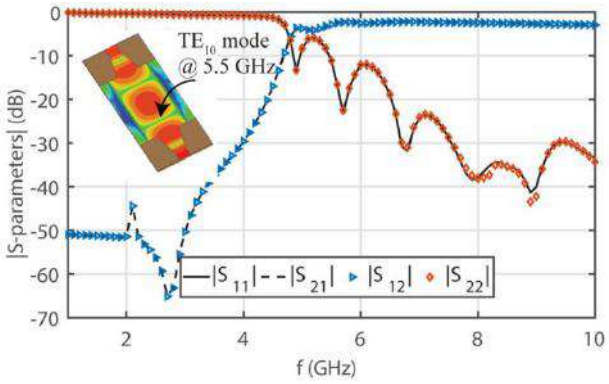

Fig.6.3: Results of SIW transmission line designed on FR4 substrate showing 4.5 GHz cut-off frequency with dominant TE_{10} mode.

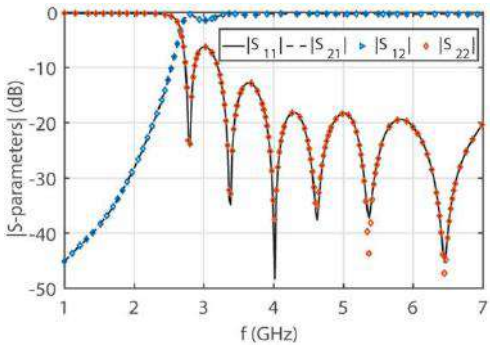

Fig.6.4: |S-parameters| (dB) results of SIW 2 showing 2.66 GHz cut-off frequency.

Similarly, second SIW transmission line (SIW 2) on 1.27 mm thick TMM10i having cut-off frequency of 2.5 GHz is also designed and shown in Figure 6.2. After designing two separate SIW transmission lines with different cut-offs, SIW 2 shown in Figure 6.2 is placed on the top of SIW 1 shown in Figure 6.1. Only SIW section of SIW 1 without any microstrip is placed,

whereas the feed is applied only at SIW 2, as shown in Figure 6.5. The results of the corresponding design in Figure 6.4 show that because of higher permittivity and lower width $a_2 = 15.6\,mm$ as compared to SIW 1 ($a_1 = 18.8\,mm$), cut-off frequency move down to 2.66 GHz. The corresponding results of the multilayer topology depicted in Figure 6.6 show that instead of broadband transmission over a large frequency range, narrow band transmission of EM wave a certain frequency range exist. However, there exist losses in the transmission as |S21| (dB) goes below -3 dB at certain frequency ranges.

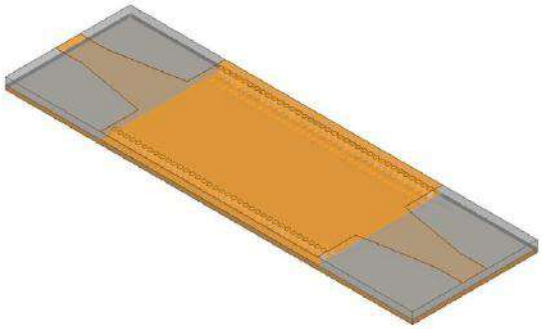

Fig.6.5: Multilayer topology of two SIW transmission lines (SIW 1 and SIW 2) having different cut-off frequencies.

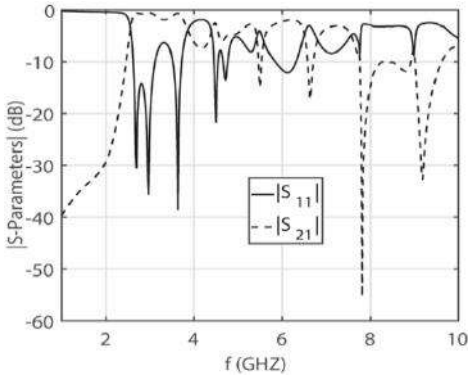

Fig.6.6: |S-parameters| (dB) characteristics of multilayer topology of SIW 1 and SIW 2.

Next, to achieve a bandpass response with sharp cut-off frequencies, cross structures are incorporated in the SIW transmission designed on FR4 substrate to create structural dispersions in the overall structures. These geometrical modifications resulted in effective dielectric constants (ϵ_{eff}) of opposite signs having coupled TE_{10} because of the two SIW transmission lines i.e., SIW 1 and SIW 2 in a certain frequency range. In other words, this phenomenon further results in the field confinement at certain band of frequencies and helps in achieving SPP like propagation at the SIW transmission lines' interface in a certain frequency range to create a band pass spectral response. The frequency range of band-pass filter in sandwiched SIW structure with structural dispersion can be effectively controlled using relative permittivity of substrates and width of the SIW transmission lines (a_1 and a_2 in our case), as evident from relation given below [71]:

$$\epsilon_{eff} = \epsilon_r - \left(\frac{c}{2af}\right)^2.$$

In the finalized design, SPP like propagation was achieved by inserting novel crossed slots in SIW 1 to create structural dispersions in the SIW structure. The dimensions of these crossed slots with complete multilayer layout are shown in Figure 6.7. A drawing of the final design with complete geometrical dimensions are also shown in Figure 6.7. Quality factor of the filter is also shown in inset of Figure 6.7. It can be observed form Q-factor plot that the proposed geometry has high Q-factor. Also, value of Q-factor depends on the length of crossed slots. The effective dielectric constant with respect to frequency and frequency vs wavenumber graph are shown in Figure 6.8 to verify the design principle, frequency range of bandpass filter, and SPP like propagation.

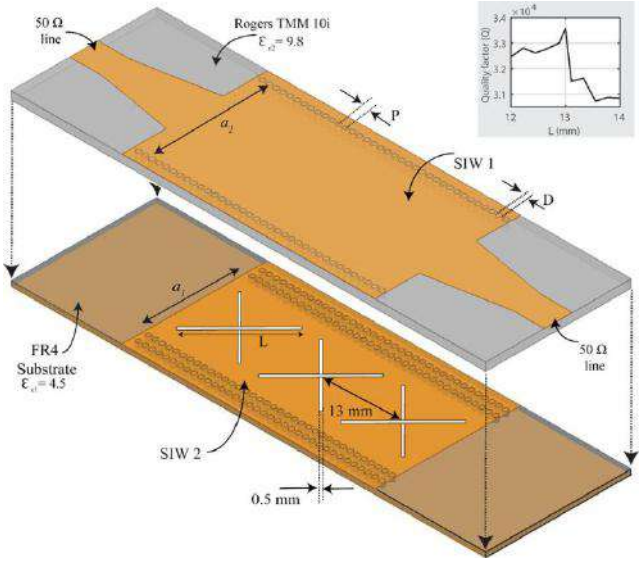

Fig.6.7: Layout of SIW multilayer filter having SPP like propagation and geometry of crossed slots for structural dispersion. P = 1.1 mm, D = 0.8 mm, a_1 = 18.8 mm, a_2 = 15.6 mm, L = 14 mm.

The designed SIW supports

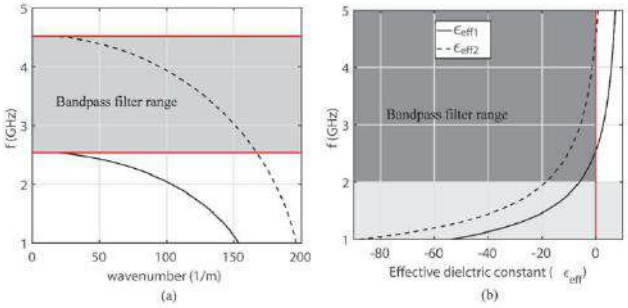

Fig.6.8: (left) Frequency range of bandpass filter depending upon the widths of SIW and according to opposite signs of effective dielectric constant in multilayer topology of SIW 1 and SIW 2. (Right) Dispersion curve of the proposed multilayer SIW filter having SPP like phenomenon and showing bandpass filter frequency range.

The magnitude of S-parameter results of the final optimized multilayer design are shown in Figure 6.9. It can be observed from the Figure 6.9 that proposed design has good band pass characteristics and spectral response from 2.48 GHz – 3.05 GHz. The insertion of the proposed filter is near to 0 dB over the band of interest. In addition, a symmetric roll-off exist in the spectral response with good impedance matching characteristics over the band of interest. In inset of Figure 6.9, disturbed TE_{10} mode is also shown along with the multilayer topology of two SIW transmission lines. The E-field distribution shown in inset of Figure 6.9 demonstrate that the structural modification by inserting crossed slots in multilayer SIW topology alters the E-field response as compared to the E-fields shown in inset of Figure 6.3 and Figure 6.2.

Furthermore, an eigen mode analysis of the proposed filter was also conducted to observe the Q-factor of the proposed filter. The results showed that because of inherited proposed of SIW for high power handling capabilities, the Q-factor of the proposed filter at optimized dimension shown in inset of Figure 6.7 and is about 33121.

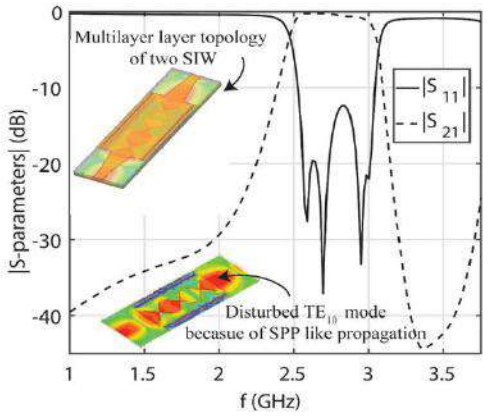

Fig.6.9: Spectral response of multilayer SIW bandpass filter having SPP like propagation.

To confirm and validate the SPP like propagation because of the crossed slots insertion, E-fields in yz and xy plane are also plotted and depicted in Figure 6.10. If Figure 6.10, E-field of multilayer SIW topology without insertion of cross slots is also to provide comparison between the inserted cross slots and without crossed slots. The comparison verified that insertion of novel crossed slots confined E-field at the interface of two SIW transmission lines and resulted because of opposite signs of effective dielectric constant. This arrangement allows SPP propagation at the interface of two SIW transmission lines. In addition, using different widths of SIW transmission lines and carefully selecting high or low permittivity substrates, variable frequency ranges having bandpass filter response and desirable signs of effective dielectric constant can be tailored. Moreover, the E-field distribution showed that at band-pass frequency, maximum field is confined at the SIW interface and increase in propagation constant (β) to result in more than one pole spectral response.

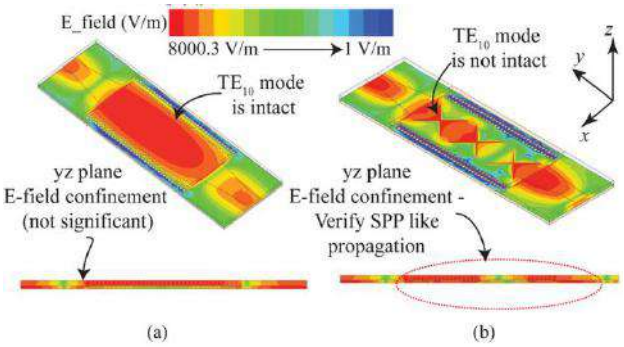

Fig.6.10: E-field distribution of multilayer SIW band pass filter designs with and without cross slots to demonstrate SPP like propagation.

Moreover, to understand the band-pass spectral response of the proposed structure because of crossed slots, a parametric study on the dimensions of the crossed slots is also carried out in this research. The results of the corresponding variations in crossed slots are shown in Figure 6.11. The parametric study showed that the length of the crossed slots (L) is the main controlling parameters to change the spectral response and proper shaping of the band pass filter. Other than this, the frequency band of band pass filter can be further controlled by changing the cut-off frequencies of the incorporated SIW transmission lines by keeping in mind the opposite effective dielectric concept discussed earlier in the light of Equations (6.1) and (6.2). However, the period of the inserted vias on lateral sides of the SIW greatly influence the guided EM wave. An increase in vias period from an optimized value may introduce leakage of EM waves from lateral sides and result in a travelling antenna such as leaky wave antenna [72] instead of filter.

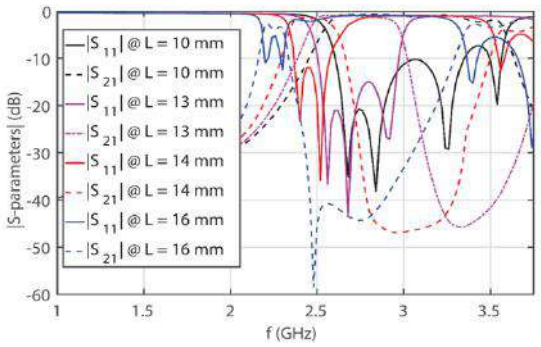

Fig.6.11: Parametric study to observe the change in spectral response of the proposed multilayer bandpass filter.

IV. CONCLUSIONS

In this research work, the researcher has presented in detail the background and literature review of Microwave Filters for WLAN applications. Miniaturized and compact size filters along with high performance are always be the attention for new technologies. However, the first filter design is proposed on single planer topology having compact size (50 mm x 50 mm). The geometry of the design consists of Defected Ground Plane (DGS), Substrate and three U-shaped hairpin resonators on top of the substrate. This proposed design covers the frequency band from 2.59 GHz to 2.78 GHz having central frequency at 2.7 GHz with insertion loss 3.2 dB up to 5 dB. Furthermore, better results of return loss and insertion loss can be achieved by changing the physical parameters in the proposed designed.

Research work is further enhanced by proposing another novel design of multilayer bandpass filter with more compactness and higher performance. The size is 30 mm x 28 mm which is approximately 50% reduction in size as compared to the planar geometry. This proposed filter design operates over the frequencies from 2.24 GHz to 2.54 GHz having central frequency at 2.44 GHz with insertion loss of 0.5 dB. Finally, optimized, miniaturized and high performance requirements is achieved in this work for variety of WLAN application.

In the end, novel multilayer SIW bandpass filter from 2.48 GHz to 3.05 GHz is proposed. The simulations and design optimization were carried out full-wave 3D electromagnetic software Ansys v. 2016.2. The bandpass filter is realized on Substrate Integrated Waveguide (SIW) that consists of two SIW structures. The two SIW structures are first designed separately with different cut-off frequencies. Then, the two SIW structures are placed in multilayer topology. Crossed slots are etched on SIW 1 to achieve effective permittivities of opposite signs in certain frequency range. It is concluded that such configuration result in SPP like propagation and provide bandpass filter response. A detailed description of numerical results further demonstrated that careful selection of parameters and permittivity of SIW substrates can effectively shift the spectrum of bandpass response. It is also concluded that proposed multilayer SIW bandpass filter having SPP propagation provide flexible of pass bands and have high Q-factor. In addition, the realization of these filters is very straightforward which increases its employability in filtering applications.

V. FUTURE RECOMMENDATIONS

- The proposed filter design can be further fabricated.
- The filter geometry can be further optimized for future generation wireless technologies.
- Owing to the resource limitation because of COVID – 19, one of the future work can be the fabrication and measurements of multilayer

bandpass filters proposed in this thesis. Another future avenue can be design and analysis of dual or triple band pass multilayer filter design for multiband pass filtering applications. Reconfigurable or tunable multilayer bandpass filter design is also very promising future research direction that can be explored.

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Industrial Shock Stabilization of Bakery Products: Technological Standardization of Freezing Regimes to Preserve Organoleptic and Rheological Characteristics

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Abstract— *The paper addresses the preservation of quality in frozen bakery semi-finished products, a matter of growing scientific and technological importance given increased demand for highly ready-to-bake baked goods and the need to extend logistical chains within the Russian market. This study investigates the degradation of the rheological structure and sensory properties of laminated yeast-leavened products during conventional freezing. Industrial shock stabilization is achieved through a substantiated methodology of ultra-rapid cooling within the range of −35 °C to −40 °C. Using a production case study and laboratory monitoring data, it is demonstrated that technological standardization of freezing regimes minimizes damage to the gluten network by promoting the formation of a microcrystalline ice structure, thereby preserving the rheological properties and sensory characteristics of the finished product at levels comparable to freshly baked equivalents. The scientific novelty of the work lies in the development and industrial validation of adapted process sheets for laminated products. Practical process sheets and recommendations are provided to adapt shock-stabilization parameters to specific equipment, facilitating industrial implementation, subject to local validation and regulatory requirements. The practical significance of the research is the substantiation of a technology that can extend product shelf life by up to 6 months, thereby enabling wider distribution and greater assortment diversification. The results will be useful to food-production engineers and managers, cold-chain logistics specialists, and formulation developers (including manufacturers of cryoprotectants and dough improvers) interested in prolonging shelf life and expanding the geographic reach of ready-to-bake pastry products.*

Keywords— shock freezing, laminated yeast-leavened dough, rheological properties, organoleptic characteristics, gluten network, ice crystallization, technological standardization.

I. INTRODUCTION

The contemporary market for bakery products in Russia is characterized by two key trends: a growing consumer demand for highly ready-to-bake products (bake-off technology) and the need for manufacturers to expand their supply geography, including into logistically complex, hard-to-reach regions [1]. The implementation of these strategic objectives is impossible without the use of long-term storage technologies, among which freezing plays a leading role. However, despite its widespread use, freezing yeast-based products with complex structures, particularly laminated ones, poses significant technological challenges [2].

The scientific problem underpinning this study is the cascading degradation of the quality of laminated yeast-leavened dough when conventional (slow) freezing methods are used. The primary

damaging factor is the process of water crystallization. During slow cooling, large ice crystals (macrocrystals) form in the dough, mechanically rupturing the thin gluten strands that constitute the product's structural framework and damaging the yeast cell walls [3, 12]. This leads to irreversible consequences: reduced gas-retention capacity of the dough, loss of volume during baking, deterioration in crumb texture (staling, crumbliness), and, as a result, a sharp decline in the organoleptic attributes of the finished product [10].

Moreover, the initial freezing regime determines the product's subsequent stability during storage. A suboptimally formed ice structure is prone to recrystallization, growth of larger crystals at the expense of smaller ones, especially under the inevitable temperature fluctuations in the logistic chain, which aggravates structural damage [4].

The aim of the present study is the scientific substantiation and experimental confirmation of the effectiveness of an industrial shock-freezing methodology for preserving the initial rheological and organoleptic characteristics of laminated yeast-leavened products.

To achieve this aim, the following objectives were defined:

1. To analyze and systematize the parameters of the adapted technological scheme for the production of frozen laminated semi-finished products.
2. To investigate the influence of the shock-freezing regime (temperature from −35 °C to −40 °C) on physicochemical and microstructural transformations in the dough.
3. To carry out a quantitative analysis of product preservation based on production laboratory-control data (mass dynamics, baking loss, shrinkage).
4. To assess the organoleptic characteristics of the finished products and their conformity with regulatory requirements.
5. To determine the practical significance and potential risks associated with the implementation of the technology in the Russian market.

The scientific novelty lies in the first use of the shock-stabilization method for laminated yeast-leavened products in the domestic industry. The method is based on adapted technological process sheets, which enable the product to maintain a quality comparable to that of the freshly prepared analog for up to 6 months, a considerably longer shelf life than existing methods.

II. MATERIALS AND METHODOLOGY

The research has an integrated character and is based on the synthesis of two methodological approaches: case study and systematic literature review. This design makes it possible, on the one hand, to examine a real technological process introduced into production and obtain empirical data on its effectiveness, and, on the other hand, to construct a theoretical framework for interpreting and explaining the observed phenomena.

As the case study object, the production site of JSC Vladimir Bread-Baking Plant was selected, where the technology of shock-freezing for laminated yeast-leavened products had been implemented and refined. The empirical basis of the research comprised internal technical and control documentation of the enterprise, including the following groups of sources:

- The technological scheme for the production of frozen, laminated yeast-leavened semi-finished products, and extracts from technological process sheets that regulate dough mixing parameters and baking conditions for finished products on the line.
- Laboratory-control reports on flour and pilot industrial bakes, recording raw-material parameters, process conditions, and quality characteristics of semi-finished and finished products at different stages (freezing, defrosting).
- The product specification (passport), contains normative organoleptic and physicochemical indicators, composition, nutritional value, storage conditions, and shelf life.
- Calculations of caloric content and nutritional value for different product types, detailing the component composition of dough and fillings.

The theoretical basis of the study consisted of scientific publications indexed in the international databases Scopus and Web of Science. The systematic literature review was focused on the following key areas: the rheological properties of frozen dough and

their modification under exposure to low temperatures; the impact of freezing–thawing processes on the microstructure of the gluten framework and the viability of yeast cells; physicochemical mechanisms of ice crystallization and recrystallization in food systems; and the role of functional food additives (cryoprotectants, hydrocolloids, emulsifiers) in the stabilization of frozen dough semi-finished products.

III. RESULTS AND DISCUSSION

Technological Standardization of the Production Cycle as the Basis for Quality Stability

Analysis of the production process demonstrated that the success of the shock-stabilization technology is determined not only by the freezing stage itself, but also by the strict standardization of all preceding operations. The adapted technological scheme (Fig. 1) includes a set of critical control points (CCPs) to prepare the dough for exposure to extreme temperatures.

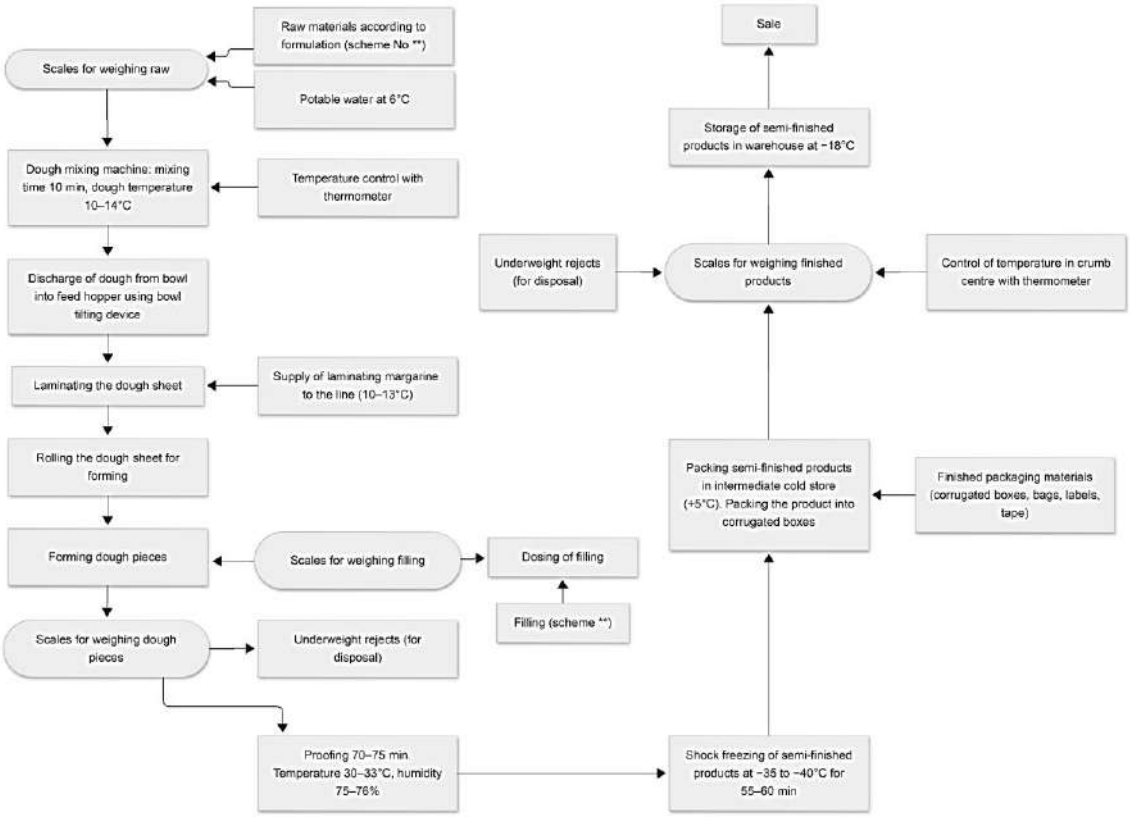

Fig. 1. Adapted technological scheme for the production of puff-yeast frozen semi-finished products

The key CCPs at the stages preceding freezing are the mixing parameters and dough temperature. According to the technological process sheets, the total mixing time is 10–13 minutes, and the final dough temperature is strictly controlled at 10–14 °C. Maintaining such a low temperature is a deliberate measure to inhibit the premature metabolic activity of yeast cells. Fermentation processes prior to freezing must be minimized to preserve the yeast's full gas-forming potential for the final proofing and baking stages, directly at the point of consumption. This approach fundamentally differentiates the technology from classical breadmaking and underlies the high volume and open, porous crumb structure of the finished product after thawing [5].

The temperature of the laminating margarine (10–13 °C) is likewise standardized to ensure the formation of a distinct, continuous layered structure, which serves as the basis for the rheological behavior of this product category.

Physicochemical Foundations of Shock Freezing and Its Influence on Dough Microstructure

The central element of the technology is the shock-freezing regime: a chamber temperature range of −35 °C to −40 °C, with an exposure time of 55–60 minutes. This regime provides the maximum possible rate of heat removal and rapid passage through the cryoscopic point (the zone of most intensive crystallization).

The principal advantage of this approach lies in the mechanism of ice-phase formation. In contrast to slow freezing, during which large, sharp-edged ice crystals have time to grow and destroy the structure, shock freezing promotes the simultaneous formation of an enormous number of crystallization nuclei. As a result, water in the dough transitions to the solid state as numerous small, rounded microcrystals [6, 13]. Such microcrystals do not cause significant mechanical damage to gluten strands or yeast cell membranes, thereby preserving the integrity of the dough's matrix structure, as conceptually illustrated in Fig. 2.

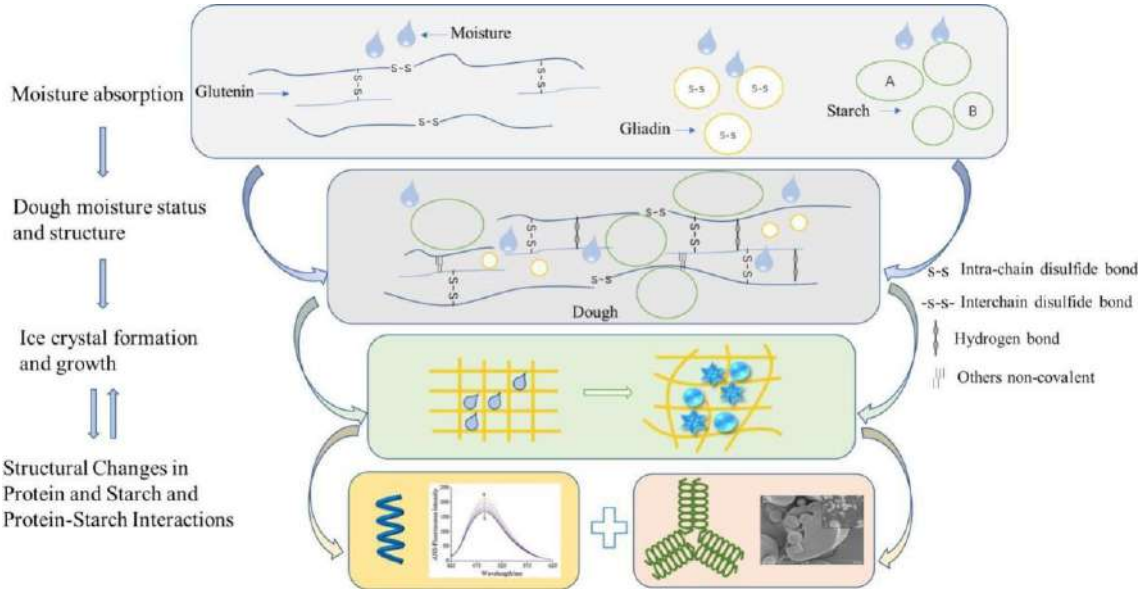

Fig. 2. Conceptual diagram of the influence of freezing rate on the microstructure and quality of laminated products [16]

However, even an ideally formed microcrystalline structure is thermodynamically unstable. Any temperature fluctuations during storage and transportation, which are inevitable under real operating conditions, trigger Ostwald ripening (recrystallization), during which small crystals dissolve, and their mass is transferred to larger ones, leading to their growth and the gradual degradation of structure [7, 14].

To counteract this phenomenon, the technology employs not only a physical but also a chemical approach. Recipe analysis reveals the presence of complex food additives, such as Improver Premium Frost. These components, which include hydrocolloids and emulsifiers, act as cryoprotectants. They bind part of the free water in the dough, reducing its availability for crystallization, and increase the viscosity of the unfrozen phase (the cryoconcentrated solution), which physically slows diffusion processes and, hence, the rate of recrystallization [8, 15]. In this manner, system stability is ensured by the synergy between ultra-rapid cooling and chemical stabilization.

Quantitative Analysis of the Preservation of Rheological and Organoleptic Characteristics

The effectiveness of the developed technology is confirmed by production-control data. One of the key indicators of structural preservation is the mass dynamics of dough pieces during freezing (Table 1).

Table 1. Dynamics of the mass of dough pieces at the freezing stage according to production control data

Product	Average piece mass at forming, g	Average frozen piece mass, g	Mass change, g	Mass change, %
Homemade puff pastry with apple	96.8	93.7	−3.1	−3.20
French puff pastry with apricot	87.1	87.0	−0.1	−0.11
Puff pastry with apricot	86.1	86.1	0.0	0.00

The loss of mass upon freezing is very small, so there is no evidence of sublimation of moisture (i.e., freeze-drying). The rapid cooling of the product often forms an ice layer on its surface, which in turn creates a thin barrier to the escape of water from the interior. Retention of moisture during cooking is critical for maintaining the elasticity of the gluten network and the juiciness of the final product [11].

Other important indicators of structural integrity are baking losses. Laboratory-control data for the defrosted product, Homemade puff pastry with apple, show a baking loss of 6.8% and a moisture loss (shrinkage) of 1.43%. These stable, moderate values indirectly confirm that the gluten network was not significantly damaged during freezing and storage, and that it effectively retains moisture and water vapor during thermal treatment.

The economic and technological viability of the process is confirmed by the analysis of finished-product yield shown in Table 2.

Table 2. Comparison of planned and actual output of finished products for different batches

Product	Planned yield (%)	Actual yield (%)	Deviation (absolute)	Deviation (%)
Homemade puff pastry with apple	280.00	280.78	0.78	0.279%
Puff pastry with apricot	200.00	207.93	7.93	3.965%
French puff pastry	220.00	250.20	30.20	13.727%
Homemade puff pastry (defrosted)	260.00	265.40	5.40	2.077%

As shown, in all analyzed cases, the actual product yield matches or exceeds the planned values. This demonstrates a high degree of control over the technological process and its production efficiency.

Ultimately, the technology's objective is to ensure high organoleptic quality. All laboratory-control reports presented contain the conclusion that complies with STO 00345458-9116/002-2007, and organoleptic indicators (appearance, color, taste, odor, consistency) are evaluated as complies or typical for this type of product. This is direct evidence that the final product obtained from semi-finished items frozen using the shock-stabilization technology is fully equivalent in quality to the fresh product described in the normative documentation.

Industrial Barriers, Risks, and Their Mitigation

The primary risk in implementing this technology is disruption of the cold chain during storage and transportation. As shown above, the stability of the product microstructure critically depends on maintaining a constant storage temperature (−18 °C ± 2 °C), as specified in the product passport. Significant temperature fluctuations may initiate ice recrystallization and nullify all advantages of shock freezing [9].

Several levels of protection are embedded in the investigated technology to mitigate this risk. First, a maximally stable initial structure is created. The use of shock freezing forms a system with minimal free energy, which is intrinsically more resistant to change. Second, chemical stabilization is employed. The use of complex improver–cryoprotectant systems raises the barrier to moisture migration and crystal growth.

Third, process control is emphasized. Strict adherence to all parameters in the technological process sheet results in a product with the maximum safety margin. Fourth, consumer guidance is provided. Clear instructions for defrosting (60–70 minutes at room temperature) and baking (220–230 °C, 20–23 minutes) at the final stage minimize the risk of improper preparation.

The practical significance of implementing this technology for the Russian market is substantial. A shelf life of 6 months at −18 °C eliminates geographical constraints, allowing deliveries to the most remote regions of the country. This not only expands the manufacturer's sales market but also provides residents of hard-to-reach territories with access to fresh, high-quality baked goods. In addition, the bake-off technology enables points of sale (cafés, shops, bakeries) to significantly expand their assortment without organizing a full production cycle, baking products as demand arises, and thereby optimizing operating costs.

IV. CONCLUSION

The conducted research enabled the following key conclusions to be formulated. The developed and industrially tested methodology, which includes strict standardization of dough-preparation parameters (in particular, maintaining a low temperature of 10–14 °C) and the application of an industrial shock-freezing regime (temperature from −35 °C to −40 °C for 55–60 minutes), is a highly effective tool for stabilizing and preserving the initial rheological and organoleptic characteristics of laminated yeast-leavened products.

The aim of the study was fully achieved. Based on an analysis of production data and the application of fundamental scientific concepts, it was demonstrated that this technology enables overcoming the key problem of degradation of the laminated dough structure during freezing. The principle for this protection is the formation of a microcrystalline ice structure, which limits damage to the gluten matrix and the viability of yeast cells. The mass balances, baking losses, shrinkage, product yield, and homogeneity have been quantitatively confirmed, and organoleptic tests have provided consistent results, indicating that the product is similar to a fresh-baked one.

The practical significance of the work is directly related to the Russian food industry. The proposed technology acts as a growth driver for the baking sector, enabling product shelf life to be extended up to 6 months. This opens new logistical opportunities for supplying remote regions and contributes to a substantial expansion and diversification of the range of fresh baked goods available to end consumers, thereby enhancing the competitiveness of enterprises in the market.

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A Study on Automakers' Use of SIMS to Build Competitive Advantage: From Net-Zero Transition and ESG Governance to Consumer Guidance for Low-Carbon Use

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Abstract *— Amid tightening net-zero and ESG requirements, automotive competition is shifting from a product focus to an integration of digitalization, sustainability, and servitization. This study explores how automakers use Smart Information Management Systems (SIMS) to integrate net-zero transition, ESG governance, and low-carbon use guidance to build competitive advantage. Given the complex factors involved in SIMS implementation — technological, organizational, informational, and stakeholder-related — this study uses a qualitative method. A multiple case study with semi-structured interviews captures perceptions of automakers, service systems, and experts on SIMS value. Findings show SIMS is not just an IT tool but a dynamic capability linking data governance, sustainability strategy, and customer interaction. First, it enhances carbon management and ESG governance via information integration and real-time analysis. Second, it guides consumer low-carbon behavior through digital services and feedback. Finally, collaboration among enterprises, service systems, and consumers fosters differentiated service capabilities and sustainable competitive advantage. The study proposes a framework of 'data integration → sustainability governance → consumer collaboration → competitive advantage,' addressing the prior research focus on manufacturing and supply chain rather than use-phase and consumer roles. The findings offer theoretical and managerial insights for automakers' digital sustainability transformation, ESG governance, and low-carbon service innovation.*

Keywords *— **Smart Information Management Systems (SIMS), automaker, net-zero transition, ESG governance, competitive advantage.***

I. INTRODUCTION

1.1 Research Background

Against the background of rapidly deepening global requirements for net-zero transition and ESG sustainability governance, the automotive industry is facing a new challenge that shifts from traditional manufacturing competition toward the integration of digitalization and sustainability. Recent research indicates that although automakers have actively proposed carbon reduction targets, strategic gaps still exist in Scope 1–3 emissions management, value chain decarbonization, and long-term transformation pathways, demonstrating that the automotive industry's net-zero transition can no longer rely solely on improvements at the manufacturing end

but must extend further to the product life cycle and use phase [1].

On the other hand, ESG has gradually become a crucial governance framework for measuring corporate sustainability competitiveness. Automotive industry ESG research points out that corporate governance, environmental emission control, and sustainable product development are important factors influencing corporate sustainability performance [2]. However, existing research has mostly concentrated on internal corporate governance, supply chain management, and sustainability disclosure, with less exploration of how enterprises extend ESG responsibility to the consumer use phase through information systems [3].

With the rapid development of smart technologies, Smart Information Management Systems (SIMS) have gradually become an important tool for enterprises to promote sustainability transformation. Information systems research indicates that the core of smart sustainable mobility lies in promoting collaborative interaction among enterprises, service providers, and users through real-time information, data analytics, and decision support mechanisms [4]. Moreover, digital transformation has also been proven to enhance corporate ESG performance and sustainability governance capabilities [5,6].

Nevertheless, significant gaps remain in existing automotive industry research: on the one hand, digital transformation research focuses largely on improving corporate efficiency and less on analyzing how this is transformed into sustainable competitive advantage; on the other hand, consumer-related research mostly concentrates on the adoption or purchase intention of new energy vehicles, with less exploration of how automakers provide low-carbon information through SIMS to guide consumers toward sustainable use behaviors [7,8].

Therefore, this study posits that the future competitive advantage of automakers arises not only from product performance and cost control but also from whether the enterprise possesses the capability to integrate data governance, ESG management, and consumer collaboration. SIMS should not be viewed simply as an information tool but rather as an important strategic capability that links net-zero transition, ESG governance, and customer value co-creation.

1.2 Research Purpose

Based on the above research background, this study aims to explore how automakers employ SIMS to build competitive advantage and to analyze the mechanisms through which SIMS functions in net-zero transition, ESG governance, and guiding consumers toward low-carbon use.

The primary objectives of this study include:

First, to explore the strategic context and core driving factors behind automakers' implementation of SIMS, and to understand how enterprises shift from a traditional information management model to a digital sustainability governance model.

Second, to analyze how SIMS supports corporate net-zero transition and ESG governance, including carbon emissions information integration, data transparency, decision support, and cross-departmental collaboration.

Third, to explore how automakers connect with consumers through SIMS and service systems to guide low-carbon use behavior, thus forming a sustainability governance model involving joint participation by enterprises and consumers.

Fourth, to construct an analytical framework explaining how automakers use SIMS to form competitive advantage, illustrating how digital capabilities can be transformed into sustainability governance capability and market differentiation advantages.

1.3 Research Contributions

This study offers three main contributions. First, at the theoretical level, it supplements the deficiency in past automotive sustainability research that has emphasized internal corporate governance and supply chain management by proposing SIMS as a collaborative governance mechanism connecting manufacturers, service systems, and consumers.

Second, at the information management level, this study broadens the research scope of SIMS by explaining how information systems transform from operational support tools into important capabilities for corporate sustainability transformation and competitive advantage formation.

Finally, at the managerial practice level, this study can provide strategic references for automakers to promote net-zero transition, ESG governance, and digital service innovation, helping enterprises to establish new models of value creation in a sustainability-oriented competitive environment.

II. LITERATURE REVIEW

2.1 SIMS and Automakers' Competitive Advantage

Smart Information Management Systems (SIMS) have become a crucial foundation for enterprises to promote digital transformation and sustainability governance. Compared with traditional information systems that emphasize process efficiency and data management, SIMS place greater emphasis on enhancing corporate decision-making and organizational collaboration capabilities through the Internet of Things, big data analytics, artificial intelligence, and real-time information integration. In the automotive industry, with the rapid development of smart vehicles, connected services, and digital platforms, corporate competitive advantage has gradually shifted from product performance toward data capability, service capability, and ecosystem integration capability [9].

Thus, SIMS should not be regarded merely as an information technology tool but should be understood as an important strategic resource that enables enterprises to integrate resources, enhance organizational agility, and cultivate differentiation capabilities. Digital transformation research also indicates that if enterprises can effectively integrate digital capabilities with sustainability strategies, it will contribute to improving ESG performance and long-term competitiveness [5,6].

2.2 Net-Zero Transition and ESG Governance in the Automotive Industry

Net-zero transition has become an important direction for the future development of the automotive industry. Because the life cycle of automotive products involves multiple-stage emissions—including manufacturing, supply chain, energy use, and recycling—corporate carbon reduction strategies have shifted from singular production improvements toward full life cycle management. Fugger et al. [1] noted that although automakers have proposed Scope 1–3 carbon reduction targets, differences still exist among enterprises in terms of the scope of emissions management, timeline planning, and intensity of carbon reduction, indicating that the automotive industry still requires a more complete governance mechanism.

On the other hand, ESG has become an important framework for measuring corporate sustainability capabilities. Vijaya et al. [2] pointed out that the core ESG factors in the automotive industry include corporate governance, environmental emission control, and sustainable product development, showing that enterprises' future competitiveness depends not only on financial performance but also on their sustainability governance capability. Related research also indicates that intelligent manufacturing and digital capabilities can enhance corporate ESG performance, allowing enterprises to strengthen their sustainability performance through information transparency and governance capabilities [10].

2.3 SIMS, Consumer Low-Carbon Use, and Collaborative Governance

Past automotive industry sustainability research has largely concentrated on internal corporate carbon reduction and supply chain management, with less exploration of the impact of the consumer use phase on corporate ESG objectives. However, the majority of a vehicle's environmental impact occurs during the use phase; therefore, how to guide consumers toward low-carbon use behaviors has become a critical issue in automotive enterprises' sustainability transformation.

Choi and Lowry [7] noted that the development of smart connected vehicles presents consumers with a trade-off relationship among sustainability value, information disclosure, and privacy protection. This suggests that future automotive enterprises must build consumer trust through digital information services to promote participation in sustainable behaviors. In addition, information sharing and smart digital platforms can also enhance carbon management transparency and cross-organizational collaboration capabilities [11,12].

Therefore, the value of SIMS lies not only in internal corporate management but in establishing a

collaborative governance mechanism among manufacturers, service systems, and consumers.

2.4 Literature Critique

Synthesizing the above literature reveals that existing studies have separately explored net-zero strategies, ESG governance, digital transformation, and consumer sustainable behaviors in the automotive industry, yet three deficiencies remain. First, past research has predominantly focused on internal corporate governance and supply chain management, with less exploration of consumer participation during the use phase. Second, although information systems research emphasizes digital platforms and decision support functions, it has rarely analyzed them within the context of automakers' ESG and competitive advantage formation. Third, consumer research has mostly focused on purchase intention, with less investigation into how enterprises guide low-carbon use through information mechanisms.

Therefore, this study takes SIMS as its core and explores how automakers integrate net-zero transition, ESG governance, and consumer collaborative participation through digital capabilities to further build sustainable competitive advantage.

III. RESEARCH METHOD

This study aims to explore how automakers use Smart Information Management Systems (SIMS) to integrate net-zero transition, ESG governance, and guidance for low-carbon use by consumers, thereby forming corporate competitive advantage. Because the implementation of SIMS is not merely a matter of technology adoption but involves multiple factors such as organizational strategy, information governance, sustainability management, and stakeholder interaction, this study adopts a qualitative research method to gain a deeper understanding of the practical logic and formation mechanisms of enterprises in the process of digital sustainability transformation.

This study employs a multiple case study design, conducting an in-depth analysis of automakers and their related service systems to explore the common characteristics and differences among different enterprises regarding SIMS implementation, ESG governance, and consumer interaction models. Compared with quantitative research, which focuses on verifying relationships between variables, qualitative research is more suitable for analyzing management phenomena that are still emerging and can reveal how enterprises integrate resources, adjust strategies, and build competitive advantage in complex environments.

This study uses purposive sampling to select interviewees with relevant experience, primarily including senior managers of automakers, directors of information and digital transformation, personnel involved in sustainability governance, and managers of dealership and after-sales service systems. Furthermore, to enhance the comprehensiveness of the research perspective, experts in ESG, sustainability management, and the automotive industry were also included to gain an understanding of the application value and future development directions of SIMS from different roles. Data collection was primarily conducted through semi-structured in-depth interviews, with the interview content focusing on topics such as the enterprises' motivations for implementing SIMS, how the system supports net-zero and ESG governance, how digital services guide consumers toward low-carbon use, and how SIMS is transformed into competitive advantage.

For data analysis, this study adopts thematic analysis to organize and interpret the data. The researchers first engaged in repeated reading of the interview transcripts and related documents to grasp the overall context of the enterprises' SIMS implementation. Subsequently, based on the research questions, key concepts were identified, and content with common meanings was grouped together to form research themes. Through cross-case comparative analysis, this study further explores the similarities and differences among different enterprises in terms of SIMS application models, ESG governance approaches, and consumer low-carbon interaction strategies, and constructs a theoretical framework explaining how automakers employ SIMS to form competitive advantage.

To ensure research quality, this study adopts data triangulation, cross-validating corporate interview data, expert opinions, and publicly available documents to enhance the credibility and

completeness of the research findings. At the same time, records of data organization and analysis were retained throughout the research process to establish the traceability of the research process. Regarding research ethics, all interviewees participated in the interviews after fully understanding the research purpose, and all research data were processed anonymously to ensure the security of the information of both interviewees and enterprises.

In summary, through a qualitative multiple case study method, this research conducts an in-depth analysis of how automakers transform SIMS from an information management tool into a mechanism for sustainability governance and competitive advantage formation, thereby supplementing the deficiencies in existing research on digital transformation, ESG governance, and consumer low-carbon participation in the automotive industry.

IV. RESEARCH FINDINGS AND ANALYSIS

4.1 The Strategic Background and Value Reconstruction of Automakers' SIMS Implementation

Through in-depth interviews and document analysis, this study found that the main purpose of automakers implementing Smart Information Management Systems (SIMS) has gradually shifted from traditional IT applications to corporate sustainability governance and competitive advantage building. Interviewees generally agreed that automotive industry competition in the past focused mainly on product performance, production efficiency, and market price. However, after the requirements for net-zero emissions and ESG governance gradually deepened, corporate competitive advantage has begun to shift toward data capability, sustainability governance capability, and customer relationship management capability.

The research results indicate that the core driving factors for SIMS implementation mainly stem from three aspects. First, external environmental pressure urges enterprises to re-examine their existing operational models. With increasing carbon management regulations, ESG rating requirements, and rising consumer sustainability awareness, automakers must establish more precise carbon emission monitoring and information disclosure capabilities. Second, internal management needs also drive the development of SIMS, especially in contexts where information related to manufacturing, energy management, after-sales service, and customer data is highly fragmented. How to enhance decision-making efficiency through system integration has become a critical issue in corporate digital transformation. Finally, enterprises are gradually recognizing that SIMS is not merely a tool for reducing operational costs but an important strategic resource that helps enterprises build long-term competitive advantage.

Therefore, this study found that the essence of automakers' SIMS implementation is not simply a technological upgrade but a process of transforming "information management capability" into "strategic governance capability."

4.2 The Mechanism of SIMS in Driving Net-Zero Transition and ESG Governance

Further findings reveal that SIMS primarily plays three functions in the sustainability transformation process of automakers: data integration, decision support, and governance transparency.

First, regarding data integration, the automotive industry involves multiple aspects such as R&D, production, supply chain, sales, and after-sales service. Traditional information systems tend to create information silos, making it difficult for enterprises to grasp complete life cycle carbon emission information. Through the integration of the Internet of Things, big data analytics, and smart platforms, SIMS enables enterprises to establish an information chain from product manufacturing to the use phase, thus improving the completeness of carbon management.

Second, in terms of decision support, SIMS can transform large volumes of operational data into managerial information, allowing enterprises to more quickly identify energy consumption, carbon emission sources, and improvement opportunities. Interviewees pointed out that the key to future competition among automotive enterprises lies not merely in whether they possess data but in whether they have the capability to transform data into strategic actions.

Third, concerning ESG governance, SIMS enhances the transparency of corporate sustainability

information, enabling enterprises to respond more effectively to the demands of external stakeholders. The research found that ESG is no longer just content disclosed in annual corporate reports; it is gradually becoming an important basis for daily management and decision-making.

Therefore, this study argues that the value of SIMS in net-zero and ESG governance does not stem from the technology itself but from whether it can help enterprises establish a closed-loop governance model of "data–decision–action."

4.3 The Collaborative Governance Model of SIMS Extending to Consumer Low-Carbon Use

Another important finding of this study is that the formation of automakers' sustainable competitiveness cannot remain solely within the enterprise but must be extended to the consumer use phase.

In the past, the relationship between automotive enterprises and consumers was primarily established on product sales and after-sales service. However, with the development of smart vehicles and digital services, the interaction between enterprises and consumers has gradually transformed into an ongoing information exchange relationship. Through SIMS, automakers can convert vehicle energy use, driving behavior, maintenance needs, and low-carbon use suggestions into information that consumers can understand.

The study found that consumer low-carbon participation is mainly influenced by three factors. The first is information comprehensibility. If the information provided by the system is too technical, it is difficult for consumers to translate it into concrete actions. The second is information credibility. Consumers must believe that the purpose of the information provided by the enterprise is to help them reduce their environmental impact, rather than merely for marketing. The third is interaction value. When low-carbon suggestions can simultaneously enhance usage convenience, reduce costs, or improve the service experience, consumers are more likely to form participation intentions.

Thus, this study proposes that the important value of SIMS lies in breaking through the traditional corporate ESG model, transforming sustainability governance from an internal corporate responsibility into a collaborative governance model involving the joint participation of "enterprise–service system–consumer."

4.4 The Formation Model of Automakers' Competitive Advantage Constructed by SIMS

Synthesizing the above findings, this study further constructs the formation model of automakers' competitive advantage through the use of SIMS.

The study found that the impact of SIMS on automakers' competitiveness is not generated directly but is formed gradually through three stages.

The first stage is "data capability formation." Through SIMS, enterprises integrate manufacturing, production, service, and usage information, establishing the data foundation required for sustainability governance.

The second stage is "governance capability transformation." Enterprises utilize data analysis and decision support functions to enhance net-zero management, ESG execution, and organizational collaboration capabilities.

The third stage is "competitive advantage formation." When enterprises can further establish interactive relationships with consumers through SIMS, they can develop service differentiation, brand trust, and customer value co-creation capabilities.

Thus, this study proposes: SIMS is not merely a digital tool for automakers but a strategic capability linking net-zero transition, ESG governance, and collaborative use with consumers.

This finding supplements prior automotive industry research that focused primarily on the manufacturing and supply chain ends, further proposing that the use phase and consumer participation are also important sources of sustainable competitive advantage for automotive enterprises.

V. CONCLUSION AND DISCUSSION

5.1 Research Conclusions

This study aimed to explore how automakers use Smart Information Management Systems (SIMS) to integrate net-zero transition, ESG governance, and guidance for low-carbon use by consumers, thereby building corporate competitive advantage. Through a

qualitative research method, this study found that SIMS is not merely an information technology tool but a strategic capability combining data governance, sustainability management, and stakeholder interaction.

The research findings reveal that the main purpose of automakers' SIMS implementation has shifted from traditional efficiency improvement toward the construction of sustainability governance capabilities. Through SIMS, enterprises can integrate information from the manufacturing, service, and use phases, enhancing carbon emission management transparency, strengthening ESG decision-making capability, and reducing governance constraints caused by information silos.

Furthermore, this study found that the contribution of SIMS to automotive enterprises' competitive advantage formation does not come solely from internal management improvements but extends further through consumer collaboration mechanisms. Enterprises can provide energy use information, maintenance suggestions, and low-carbon use feedback through digital services, guiding consumers to participate in sustainable behaviors and forming a low-carbon governance model involving the joint participation of "enterprise–service system–consumer."

Therefore, this study proposes the formation path of SIMS-enabled competitive advantage: Data integration capability → ESG governance capability → Consumer collaboration capability → Sustainable competitive advantage.

5.2 Theoretical Contributions

This study has three theoretical contributions.

First, it supplements the deficiency in automotive industry sustainability research, which has traditionally overemphasized the manufacturing end, supply chain, and corporate governance, by proposing that the use phase and consumer participation are also important factors in forming corporate ESG competitiveness.

Second, this study broadens the perspective of information management research by elevating SIMS from a traditional information support tool to a sustainability governance capability, explaining how digital capabilities can be transformed into corporate strategic capabilities.

Third, by integrating the perspectives of net-zero transition, ESG governance, and customer value co-creation, this study proposes a new model for the formation of automakers' future competitive advantage, supplementing research related to digital sustainability transformation.

5.3 Managerial Implications

This study provides three managerial insights for automakers.

First, enterprises should reposition the role of SIMS, not viewing it merely as an IT department project but elevating it to the level of corporate sustainability strategy, enhancing governance effectiveness through cross-departmental collaboration.

Second, enterprises should shift from traditional manufacturing-end carbon reduction to full life cycle management, incorporating production, service, and consumer use phases into the scope of sustainability management.

Third, enterprises should strengthen their interactive relationships with consumers through SIMS, so that low-carbon information is not merely corporate disclosure content but becomes an important service tool that helps consumers change their usage behaviors, thereby further enhancing brand trust and market differentiation capabilities.

5.4 Research Limitations and Future Directions

This study adopted a qualitative research method and primarily analyzed the mechanisms through which SIMS builds competitive advantage via case studies and in-depth interviews. Therefore, the research findings mainly reflect the experiences and organizational contexts of the interviewees, without further quantitative verification of their impact on corporate performance and carbon reduction outcomes.

Future research can further integrate quantitative methods, such as structural equation modeling, longitudinal tracking studies, or cross-national comparative analyses, to verify the impact of SIMS on ESG performance and competitive advantage. Moreover, future studies can also delve deeper from the consumer perspective into the

acceptance levels of low-carbon information services among different demographic groups, so as to establish a more complete model of sustainable collaborative governance in the automotive industry.

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