

Human-Centered Comparable to Technology-Driven Approaches in Reducing the Bullwhip Effect: A Cross-Industry Study

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ABSTRACT

Purpose: To assess the effectiveness of human-centered, technology-driven, and hybrid strategies in reducing the bullwhip effect (BWE) in Pakistan. The study examines whether the combination of both human and digital solutions leads to additional stability of the supply chain than independent methods. **Methodology:** The primary data was obtained through structured questionnaire given to 120 supply chain professionals using a quantitative research design. The Stata was used to analyze responses through Structural Equation Modeling and Ordered Logistic Regression. Multi-item Likert scales were used to operationalize variables and interaction terms were formed to determine the moderating effect of hybrid strategies. **Findings:** Findings support the reduction of the bullwhip effect by human-centered (HC) and technology-driven (TD) practices as a significant one. It is interesting to note that the hybrid model of HC and TD practices has shown greater and consistent effects. The multi-group analysis also shows that technology is dominant in every sector, whereas hybrid strategy is more influential in FMCG, which means that there are sector-specific dynamics. **Originality/Value:** The research adds to the scarce empirical literature on hybrid supply chain strategy in

developing economies. It pays attention to the industrial environment in Pakistan, which makes it more compelling in terms of the practical applicability of integrating human and technological potentials to increase supply chain resiliency and predictive accuracy.

Implications: The results provide practical recommendations to practitioners and policymakers who want to modernize supply chains. It is important to focus on the digital maturity and maintain strategic human contribution to achieve the best performance of a supply chain.

Keywords: Bullwhip Effect, Human-Centered Practices, Technology-Driven Practices, Supply Chain Resilience

1. Introduction

1.1. Background

In this modern fast-paced and networked supply chain environment, the demand variability and uncertainty have become a major concern, leading to the propagation of demand variations upstream, which is commonly referred to as the Bullwhip Effect (BWE) (Kelka, 2024). The bullwhip effect was first identified in the realm of the Beer Game simulation created at MIT, but it quickly grew into a key study in supply chain management literature, as it is a major source of inefficiency (Alabdulkarim, 2020). As a result of the BWE, there will be high inventory, long lead times, delays in production, underutilization of capacity, and exaggerated costs, and dissatisfaction on the part of the customers in the supply networks (Uhuka, 2022).

The underlying causes of the bullwhip effect are demand forecast inaccuracy, long lead time, information asymmetry, batch order, price volatility, behavioral biases and failure to coordinate supply chain entities (Lee, Padmanabhan, & Whang, 1997; Tamayo, Orjuela-Castro, & Herrera, 2023). Traditionally, companies have been using human-based solutions in fighting these problems including managerial intuition, forecasting through judgment, experience-based coordination, joint planning and management of relationships (Selzer, 2024). These have focused on trust, situational awareness and teamwork particularly in the new economies such as Pakistan where the digitalization has not yet gained momentum.

The emergence of Industry 4.0 has seen the supply chain move more toward technology-based solutions. These are Artificial Intelligence (AI) predictive analytics, block chain, big data analytics, Internet of Things (IoT) inventory visibility, Discrete

Wavelet Transform Artificial Neural Network (DWT-ANN) models forecasting, and Reinforcement Learning (RL) dynamic order optimization (Darbanian, Brandtner, Falatouri, & Nasser, 2024). These technologies promise a possible advance in accuracy, responsiveness and efficiency of forecasting.

However, regardless of these developments, there is still a big gap between the digital capacities and their application. The supply chain activities in the developing economies such as Pakistan tend to be in a duo-mode; that is, the traditional way of human-based coordination and the new way of technological integration. Although technology has the capability of automating and improving, judgment, experience, and contextual sensitivity that are brought by human decision-makers is often lacking. Thus, a combined, hybrid solution, which utilizes both human-based and technology-based methods, can be the most effective way to reduce the bullwhip effect. Although both human-based and technology-based supply chain strategies have received significant amount of research, there are hardly any studies that provide a comparative and sector specific analysis of these two approaches. As far as Pakistan is concerned, there is a two-fold challenge. To begin with, most companies are yet to embrace the modern way of doing things because of infrastructural and skill constraints. Second, the application of digital tools is on the rise, but their success in mitigating BWE has not been tested empirically in leading industries such as manufacturing, electronics and FMCG.

Furthermore, the literature usually pays attention to only one of the two issues (either technological (e.g., AI or block chain) or human (e.g., collaboration or judgment)) without exploring the potential of their synergy. Cross-industry empirical research evaluating the impact of industry characteristics like customer concentration, supply chain complexity and digital maturity on success of each approach is lacking. This poses a research gap that is critical and is sought to be filled in this study.

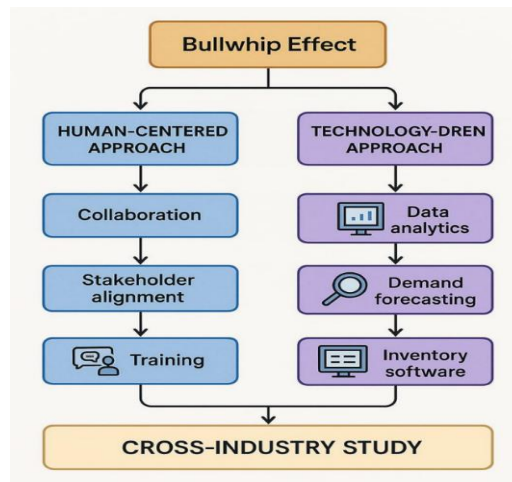


Figure 1: Human Centered vs Technology Driven Approach

1.2. Significance of the Study

The study is theoretically and practically important. Theoretically, it adds to the current body of knowledge by providing a unified view of two previously distinct areas human-centered and technology-driven supply chain strategies. It further enhances the existing literature, as the study bases its analysis in the setting of Pakistan, which is an emerging economy, with diverse industrial practices and infrastructural issues. Pragmatically, the results of the study will be helpful to supply chain managers, policymakers, and providers of technology solutions to know what interventions best fit their particular situations of operation. The lessons learnt can guide companies to create resilient, responsive and adaptive supply chains particularly during times of disruption or uncertainty. More so, study offers digital transformation guidelines, which are specific to the state of preparedness in various sectors.

1.3. Scope of the Study

This research is based on three key strategic industries in Pakistan which include manufacturing, FMCG and electronics. The industries are known to have high product flow, a complicated customer demand structure, and differing levels of digital maturity. research focuses on both upstream and downstream dynamics with specific focus on forecasting, inventory management, coordination practices, and technology implementation. unit of analysis involves supply chain managers, planners, and decision-makers in organizations across these industries. research method is quantitative in nature, consisting of a structured questionnaire and data analysis by STATA.

2. Literature Review

2.1. Overview of the Bullwhip Effect

The bullwhip effect (BWE) is the increased volatility of demand along the upstream supply chain. Small variations in customer demand may result in ever-growing order variations at the manufacturer, wholesaler and supplier levels (Salwa & Zulfikri, 2024). This causes imbalances in the inventory, cost escalation, lower levels of service and inefficiency within the chain. Since the global supply chains are increasingly interconnected, volatile, and need to be addressed, it is important to consider the bullwhip effect. The two main strategies reflected in literature are technology-based solutions that involve the use of digital transformation and advanced analytics and human-based solutions that focus on coordination, communication, and trust.

2.2. Theoretical Framework

The study relies on the Systems Theory and Socio-Technical Systems Theory, which offer an all-inclusive perspective in viewing and analyzing the supply chain operation dynamics and the bullwhip effect. Systems Theory claims that the supply chain is an interdependent system, in which different actors, such as suppliers, manufacturers, retailers, and customers, communicate via exchange of information, materials, and decision-making (Nair, Narasimhan, & Choi, 2009). Under this system, the bullwhip effect can be seen as a misrepresentation of the demand that will get worse as you go upstream. In this framework, the key role is played by effective information processing and feedback system to ensure the system stability and responsiveness (Lai & Lin, 2017). Echoing this is the Socio-Technical Systems Theory that states that the performance of organizations is optimized when the social (human) and technical (digital) subsystems are aligned and optimized (Sony & Naik, 2020). Regarding supply chains, this means that human intelligence, teamwork, and managerial instincts should be efficiently combined with the use of smart digital technologies, including artificial intelligence, big data analytics, and block chain to deliver the best outcomes (Chew & Mohamed Zainal, 2024). In addition, the paper takes into account the impact of Contingency Theory, which implies that the success of any strategy is based on the external environment and the context of an organization (Tosi Jr & Slocum Jr, 1984). The relationship between the mitigation strategies and the bullwhip effect outcomes can be moderated by factors like the size of the firm, type of the sector, concentration of customers and the level of digital maturity.

2.3. Technology-Based Solutions of Minimizing Bullwhip Effect

To reduce the bullwhip effect, technological interventions are being used more frequently in the form of data-based forecasting, real-time monitoring, automation, and integration of the system.

In the study of Jaipuria and Mahapatra (2014), the DWT-ANN forecasting model was tested, which had better results in handling nonlinear and volatile data compared to ARIMA, thereby reducing the forecasting error and the bullwhip effect (BWE). Liu, Fang, Xiao, and Shi (2025) analyzed panel data of 2,159 Chinese manufacturing companies, and it was established that digital transformation has a considerable impact in minimizing the BWE. In the study of Rozhkov, Alyamovskaya, and Zakhodiakin (2025), the Recurrent Proximal Policy Optimization (RPPO) algorithm was used to optimize the decisions of orders and it performed better than the traditional inventory policies.

Matos (2024) results indicated that the forecasting accuracy increased by 14 percent and the supply chain agility increased, which indicates that secure digital tools can be used to overcome data privacy issues. Delgoshaei and Ariffin (2024) proposed a block chain-based model of product distribution, which is specific to uncertain markets. Leng, Liu, Ren, and Tsyvinski (2025) suggested a theoretical framework where closed-form solution proved that the production delays have a considerable effect on the BWE, particularly in upstream sectors.

2.4. Human-Oriented Reduction of the Bullwhip Effect

Although technology provides us with effective tools, human factor is critical. A number of studies indicate the significance of trust, communication, managerial decision-making and behavioral insights. Bogale and Desta (2025) conducted a systematic review of sustainable supply chain practices to combat BWE. The most significant human-related strategies that were identified were communication, coordination, collaborative forecasting, and data-sharing among the stakeholders. Cindy and Zai (2025) showed that effective inventory management and information sharing by people influenced the performance of retailers positively by lowering BWE.

In study by Tekka (2024), the construction industry in Tanzania was examined and it was found that BWE is reduced considerably in project-based supply chains because of teamwork, project planning, and improved coordination of stakeholders. Chen, Liang, Yang, and Zhu (2024) revealed that demand bullwhip ratio has a significant increased

effect on cost of uncertain demand, particularly in the firms with high fixed costs. To an extent, this result confirms the necessity of active managerial changes and improved communication practices.

Hybrid Perspectives: Combining Human and Technological Solutions

Bullwhip effect (BWE) is a multidimensional issue and cannot be solved alone using technology or human intuition. A body of literature is increasingly addressing the use of hybrid solutions, i.e., the combination of data-driven and people-oriented solutions to build stronger, more adaptable, and resilient supply chains. Such studies recognize that although artificial intelligence, digital platforms, and advanced analytics are capable of optimizing forecasting and coordination, human sense, collaboration, and managerial control are still crucial in terms of providing sustainability, adaptability, and ethical decision-making. Although block chain is an effective way of ensuring secure flow of information, its effectiveness is determined by the readiness of the supply chain actors to share information (Rejeb, Keogh, Simske, Stafford, & Treiblmaier, 2021). Likewise, ERP systems may not work when employees are not trained and do not buy-in. Research always highlights the necessity of balanced solutions utilizing the accuracy of machines and the judgment of human beings.

ULMER and ROSE investigates the role of distributors and digital platforms in assisting SMEs in optimizing the surplus inventories of chips, in case of shortages, through better data visibility and system integration. Qian, Yan, and Li (2025) highlights the relevance of technological fit and similarity of innovations between companies and their suppliers in decreasing the BWE. The research indicates that not only systems compatibility leads to operational efficiency and reduced variability but also human-based coordination of innovation practices. Matos (2024) underlines the role of managerial interpretation of insights, user trust, and training in order to utilize such technologies. It therefore promotes an augmented intelligence paradigm, in which human supervision is used to make ethical, strategic, dynamic application of predictive tools. In this scenario, Unilever case is of special interest because it demonstrates how an international FMCG company integrated enterprise systems, such as EDI, ERP, and RFID, with cooperative contracts and engagement with the stakeholders to reduce the bullwhip effect (Xu, 2012). In an AI-based learning environment, Rozhkov et al. (2025) demonstrates how reinforcement learning can be used to optimize orders in a stochastic supply chain. This

sentiment is also echoed by Salwa and Zulfikri (2024), which indicates that although digital visibility tools (block chain, neural networks, ERP) decrease variability, the challenges of integration tend to be human-related, i.e., they are caused by organizational silos, low digital maturity, and change refusal. Although AI, block chain, ERP, and RL systems provide accuracy, fast delivery, and scalability, human thought, faith, flexibility, and collaborative governance are required to interpret the context, ethical use and sustainability in the long run. In view of this, we have formulated the following hypothesis:

H1: Human-centered practices significantly reduce the bullwhip effect.

H2: Technology-driven practices significantly reduce the bullwhip effect.

H3: Firms that use a hybrid approach experience a lower bullwhip effect compared to those using either approach alone.

Table 1: Bibliography

Sr.N o	Title	Problem Statement	Approach	Technique	Results	Drawbacks	Remarks
1	An Improved Demand Forecasting Method To Reduce Bullwhip Effect In Supply Chains	Inefficient inventory management due to demand forecasting	Integrated DWT and ANN	Hybrid Model of DWT-ANN	Reduced MAPE and root mean square error	Require Advance Computational resources	Further research required

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| 2 | Big Data And Inefficient Focus on Simulation All V's are Big data Further
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| 6 | The Impact Of Bullwhip Effect Inventory Level Information Sharing Retailer Operational Performance Mediated By Supply Chain Performance | Poor retailer performance due to uncoordinated inventory and info sharing | Empirical analysis | Survey and SEM | and Stronger supply chain performance improves retailer outcomes | Limited generalizability across industries | Needs sector-specific validation |
| 7 | The Impact Of Information Sharing Factors On The Bullwhip Effect Mitigation: A Systematic Literature Review | Unclear factors in effective sharing for bullwhip mitigation | Systematic literature review | Content and thematic analysis | and Key info-sharing factors identified for reducing bullwhip | Subjectivity in literature selection | Suggests future empirical testing |
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| 8 | Efficient Management Of Excess Inventory The Industry: Role Of Standardized Data Transparency Between Distributors, Digital Platforms, And SMEs : A Systematic Literature | Excess inventory issues due to lack of data standardizati on | Systematic literature analysis | Data mapping and synthesis | Transparen cy reduces chip sector inventory risks | Focus on chip industry only | Could expand to other tech sectors |
| 9 | Stabilizing By Learning: The Value Of Technologica l Similarity With The Supply Base For Bullwhip Effect | Volatile supply chains due to lack of tech alignment | Quantitativ e modeling | Similarity index modeling | Technologi cal similarity reduces bullwhip intensity | Requires longitudinal data | Potential for AI-based prediction |
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10	The Bullwhip Effect Stock Returns	Market And inefficiencies linked to supply chain variability	Econometric analysis	Regression on stock return data	Bullwhip indicators predict stock return patterns	Assumes consistent investor behavior	Explore causality further
11	The Impacts Of Bullwhip Effects On Supply Chain And Construction Project's Performance	Performance delays and inefficiencies in construction projects due to bullwhip effects	Empirical and case analysis	Project performance correlation analysis	Bullwhip significantly reduces construction performance	Limited to specific project types	Needs broader industry studies
12	A Novel Study Of The Impact Of Supply Chain Complexity On The Bullwhip Effect	High complexity in supply chains exacerbates bullwhip effects	Simulation modeling	Complexity index simulation	Greater complexity amplifies the bullwhip effect	Assumes linear complexity-bullwhip relationship	Further real-world validation needed

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| 16 | The Bullwhip Effect, Demand Uncertainty, And Cost Structure | How demand uncertainty and cost structures amplify bullwhip effects | Theoretical modeling | Cost-demand uncertainty framework | Bullwhip is more severe under high fixed costs and uncertain demand | Limited empirical validation | Test in real-world industries |
| 17 | From Variability To Visibility: Mitigating The Bullwhip Effect In Modern Supply Chains | Lack of visibility causes high variability and inefficiencies | Digital integration strategies | Data visibility tools and metrics | Visibility tools reduce variability and bullwhip | Technology cost and integration barriers | Adopt digital twin or block chain |
| 18 | Effects Of Time Aggregation, Product Aggregation, And Seasonality In Measuring Bullwhip Ratio | Difficulty in accurately measuring bullwhip due to temporal and categorical factors | Quantitative analysis and simulations | Aggregation impact modeling | Aggregation and seasonality distort bullwhip measurement | Context-specific results | Refine models for industry-specific applications |
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19	Optimizing Supplier Order Sizes To Mitigate The Bullwhip Effect In A Food Supply Chain: A Case Study Based Approach	Unoptimized order sizes increase bullwhip in food supply chains	Case study with simulation	Inventory and supplier simulation models	Order size Data	Replicate with larger food chains	
					optimization lowers and food chain simulation bullwhip accuracy		
20	The Bullwhip: Time-To-Build And Sectoral Fluctuations	Time-to-build lags in production generate sectoral volatility and bullwhip	Closed-form mathematical modeling	Time-to-build shock propagation model	Upstream sectors show amplified volatility due to delayed adjustment	Abstract assumptions may limit real-world use	Further simulation with variable time-lags needed

3. Research Methodology

3.1. Research Philosophy and Approach

This research paper is based on the positivist research paradigm that presupposes that knowledge can be extracted based on observable and measurable facts. The positivist position advocates the application of quantitative methodology, and the researcher will be able to determine patterns, relationships, and causality between variables concerning supply chain practices and the bullwhip effect. The study is deductive in nature, because it aims at testing the theoretical propositions (based on the literature available) regarding the relationship between the supply chain practices (human-centered and technology-driven) and their effects on the bullwhip effect. Structured data collection and statistical analysis were used to derive and test hypotheses.

3.2. Population and Sampling

The industries that have been chosen as part of this research, namely Manufacturing, FMCG, and Electronics, were selected due to the level of complexity of their supply chains, being susceptible to changes in demand, and the difference in the extent to which they have adopted digital technologies. These industries are a wide range of practices in Pakistan: manual, relationship-based coordination in the traditional manufacturing industry to high-tech digital tools in modern FMCG and electronics companies. Additionally, purposive sampling method was adopted to make sure that respondents are aware of supply chain activities and decision-making procedures in their companies. Both SMEs and large firms were attempted to be included in order to get a wide range of practices.

3.3. Data Collection Method

The structured questionnaire was the main instrument of data collection that was based on validated instruments and adjusted to the existing literature. Attitudes, perceptions, and practices were captured in a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The survey was conducted online and also on paper depending on the accessibility and digital preparedness of the firm using Google Forms and paper-based surveys. Follow up calls and visits were done so as to have increased response rates.

3.4. Operationalization of Variables

Table 2: Variable and Measurement

Variable	Type	Operational Definition
Bullwhip Index	Effect Dependent	Degree of demand amplification across the supply chain
Human-Centered Score	Independent	Use of intuition, trust, experience, collaboration in supply chain management
Technology-Driven Score	Independent	Use of AI, ERP, block chain, dashboards in SCM processes
Hybrid Strategy	Independent	Use of both human and technology inputs simultaneously
Firm Size	Control	Scale of an organization's operations measured by the number of employees

Sector Type	Control	1: Small
		2: Medium
		3: Large
Industry or domain in which the firm operates		1: Electronics
		2: Manufacturing
		3: FMCG
Digital Maturity	Control	Extent to which a firm has adopted digital technologies into its supply chain operations
		1: Low
		2: Medium
		3: High

3.5. Ethical Considerations

All the participants were informed of the purpose of the study and gave voluntary consent. The identity of the respondents and the organizational information remained confidential and was only used in academic purposes. The data was stored in encrypted files and only the researcher could access the files.

3.6. Data Analysis Techniques

The study is quantitative in nature and uses STATA in the analysis of data. First, the data were cleaned and searched in terms of missing values. To guarantee internal consistency, descriptive statistics and reliability analysis (based on Cronbach alpha) were conducted. Composite scores were the averages of responses to corresponding Likert items held on each latent construct.

The Structural Equation Modeling (SEM) in STATA was used to analyze the connection between variables and determine the appropriateness of the conceptual model. After this, Ordered Logistic Regression (OLOGIT) was applied to the ordinal characteristic of the dependent variable, which is the bullwhip effect. The moderating effect of hybrid approaches that relied on both human-centered and technology-driven strategies was tested by computing interaction terms and including them in the model. Lastly, Multi-Group Analysis (MGA) was performed to contrast the results of the models in various industry sectors (Manufacturing, FMCG and Electronics) to establish the sector-specific differences in the bullwhip mitigation models.

3.7. Research Model

$$BWE = \beta_0 + \beta_1(Human) + \beta_2(Tech) + \beta_3(Hybrid) + \beta_4(Controls) + \epsilon \quad (1)$$

where:

- BWE – Bullwhip Effect
- Human = Human-Centered Practices
- Tech = Technology-Driven Practices
- Hybrid = Hybrid Integration (interaction/moderator)
- Controls = Firm size, Sector type
- ϵ = Error term

Furthermore, to test if hybrid integration moderates the relationship between human/tech practices and the bullwhip effect, Interaction terms (e.g., Human $\times$ Hybrid, Tech $\times$ Hybrid) will be created and added to the regression.

$$BWE = \beta_0 + \beta_1 (Human \times Hybrid) + \beta_2 (Tech \times Hybrid) + \beta_3(Controls) + \epsilon \quad (2)$$

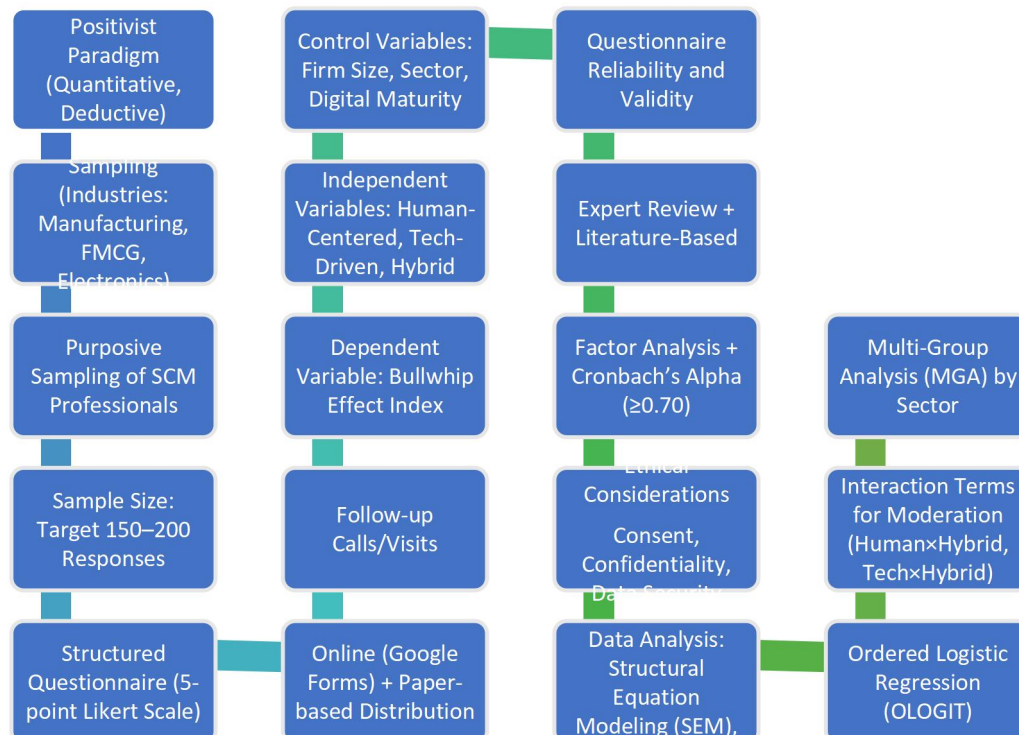


Figure 2: Research Methodology Flowchart

4. Results and Discussion

4.1. Sample Characteristics

In the descriptive analysis of the sample characteristics, table 3, the size of the firm,

industry sector, and digital maturity were analyzed to give contextual knowledge of the firms that participated in the analysis. The statistics indicated that the most represented firms were medium-sized firms (51-250 employees) with 45 responses, followed by the small-sized firms (1-50 employees) with 41 responses and the large-sized firms (251+ employees) with 34. In terms of sector distribution, the largest group was FMCG firms ($n = 45$), electronics ($n = 40$) and manufacturing firms ($n = 35$) were also well-represented, which guarantees cross-sectoral insights. Regarding digital maturity, most companies ($n = 52$) were at low digital maturity, which means that little use of digital tools and practices in the supply chain activities was observed. There were also firms with high ($n = 35$) and medium ($n = 33$) digital maturity, which allowed comparing them with different levels of technological development. This difference in terms of firm size, industry, and digital integration offers a solid basis in the analysis of the influence of organizational and technological characteristics on the bullwhip effect. The descriptive statistics of categorical proxies reveal meaningful patterns across the sampled firms. The average industry score ($M = 1.94$) indicates a higher representation from the manufacturing sector, followed by electronics and FMCG. The mean firm size ($M = 2.04$) suggests that medium-sized firms dominate the sample, with fewer small and large firms. Regarding digital maturity, the average score ($M = 1.86$) reflects that most firms possess low to medium levels of digital integration in their supply chain operations, highlighting room for improvement in technology adoption across sectors.

Table 3: Firm Characteristics

Proxy	Industry	Size	Maturity
1	41	40	52
2	45	35	33
3	34	45	35
Mean	1.941667	2.041667	1.858333
Standard Deviation	0.0722738	0.0770571	0.769661

Figure 3 illustrates the mean scores of key variables across the three industrial sectors: Electronics, Manufacturing, and FMCG. The bullwhip effect was reported to be highest in the Electronics sector, followed by FMCG, and lowest in Manufacturing. Notably, hybrid strategies—combining human-centered and technology-driven approaches—

consistently received the highest mean scores (~ 4.0) across all sectors, reflecting their strong adoption and perceived effectiveness in mitigating supply chain inefficiencies. The Manufacturing sector, despite having relatively lower scores for technology-driven strategies, showed the lowest bullwhip effect, suggesting that human-centered practices, when combined with hybrid approaches, can yield optimal outcomes. In contrast, the Electronics and FMCG sectors, although exhibiting high reliance on hybrid strategies, still reported moderate bullwhip levels, indicating a potential mismatch between strategy application and operational complexity. Overall, the results underscore the critical role of hybrid strategies, while also pointing to sector-specific nuances in their effectiveness.

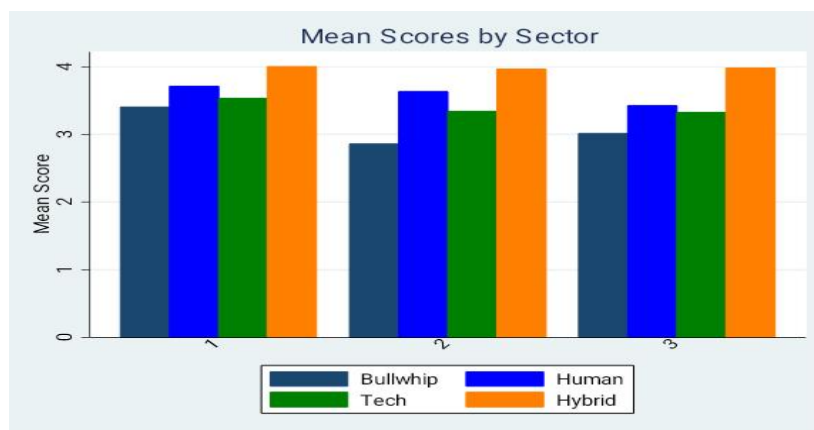


Figure 3: Mean Scores by Sector

To further illustrate the relationship between digital maturity and the bullwhip effect, a box plot (figure 4) was constructed. The plot compares the distribution of bullwhip effect scores across three levels of digital maturity. While the median values remain fairly consistent across the three categories, the spread of the data varies. Digital maturity level 3 shows the widest interquartile range, indicating higher variability in bullwhip effect outcomes among highly digitalized firms. In contrast, level 2 exhibits a narrower distribution, suggesting more consistent performance in mitigating the bullwhip effect. These visual insights complement the tabular findings by emphasizing that although higher digital maturity does not always guarantee lower bullwhip effect values, it is associated with a broader range of operational outcomes, possibly influenced by how effectively digital tools are implemented and integrated.

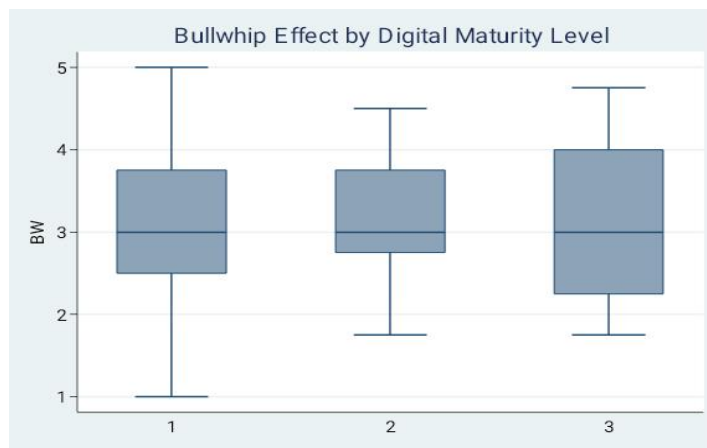


Figure 4: Bullwhip Effect by Maturity

4.2. Cronbach Alpha

In order to evaluate the internal consistency and reliability of the survey instrument, Cronbach alpha was calculated on all constructs as shown in table 4. The overall scale has a Cronbach alpha of 0.8231, which means high internal reliability (0.80 is usually a good value). The statistics of individual items indicate that the deletion of any one item would not lead to a significant increase in the overall alpha, which implies that all the items are in line with the overall scale.

The item-test correlations (B1 to B4) of the bullwhip effect indicators were between 0.5355 and 0.7121, which indicates strong correlations with the overall scale and indicates that they are suitable to measure the construct reliably.

The reliability of the human-centered practices (HCP1-HCP5) and technology-driven practices (TDP1-TDP5) was also high with the Cronbach alpha values between 0.8079 and 0.8152. These numbers justify the internal consistency of the items that are used to gauge the human and technological methods of managing the bullwhip effect. Even though hybrid approach (H1-H5) showed relatively low item-test correlations (ranged between 0.0503 and 0.3145), the subset has acceptable consistency with Cronbach alpha values greater than 0.82 in each of the items. This implies that, although the individual contributions are a little weaker, the items nevertheless form a scale. Internal consistency was also tested on control variables; Industry, Size and Maturity. Although their item-test correlations were quite low (e.g., 0.1384 in the case of Size), their inclusion did not impact negatively on the reliability of the scale, which suggested that the overall measurement structure would be robust.

Table 4: Cronbach Alpha

Item	Obs	Sign	Item-test Correlation	Item-rest Correlation	Average Interitem Covariance	Alpha
Industry	120	–	0.2299	0.1533	0.1822726	0.8248
Size	120	–	0.1384	0.0546	0.185794	0.8289
Maturity	120	+	0.1139	0.0300	0.1867784	0.8298
B1	120	+	0.5893	0.5083	0.1622996	0.8094
B2	120	+	0.5355	0.4496	0.1655929	0.8126
B3	120	+	0.7121	0.6556	0.1580629	0.8025
B4	120	+	0.6007	0.5228	0.1620885	0.8087
HCP1	120	+	0.4831	0.3991	0.1693811	0.8152
HCP2	120	+	0.5389	0.4539	0.1654195	0.8124
HCP3	120	+	0.5459	0.4696	0.1665853	0.8119
HCP4	120	+	0.6164	0.5439	0.1629082	0.8079
HCP5	120	+	0.5511	0.4774	0.166765	0.8116
TDP1	120	+	0.6432	0.5739	0.1605946	0.8063
TDP2	120	+	0.6281	0.5590	0.1620111	0.8073
TDP3	120	+	0.6078	0.5300	0.1614993	0.8083
TDP4	120	+	0.6966	0.6280	0.1580885	0.8034
TDP5	120	+	0.5965	0.5145	0.1614899	0.8090
H1	120	+	0.1745	0.0943	0.1843534	0.8271
H2	120	–	0.1008	0.0182	0.1872602	0.8300
H3	120	–	0.3145	0.2347	0.1786231	0.8221
H4	120	–	0.1217	0.0385	0.1864492	0.8294
H5	120	+	0.1286	0.0503	0.1860958	0.8284
Test Scale					0.1708877	0.8231

4.3. Pairwise Correlation

Table 5 shows the correlation matrix of the important variables employed in this research that include the bullwhip effect (BW), human-centered practices (HC), technology-driven practices (TD) and hybrid strategies (HYBRID). The bullwhip effect is positively

correlated with human-centered practices as well as technology-driven practices, which indicates a statistically significant positive association that implies that firms that engage in human-centered practices or technology-driven practices to a greater extent are likely to have trouble in reducing demand variability, perhaps because of incomplete or misaligned implementations. Further, the correlation between HC and TD is substantial and positive, which means that organizations prefer using a combination of those two methods and not one of them in isolation.

Table 5: Correlation Matrix

Variables	(1)	(2)	(3)	(4)
(1) BW	1.000			
(2) HC	0.417*	1.000		
(3) TD	0.612*	0.491*	1.000	
(4) HYBRID	0.092	-0.100	-0.089	1.000

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

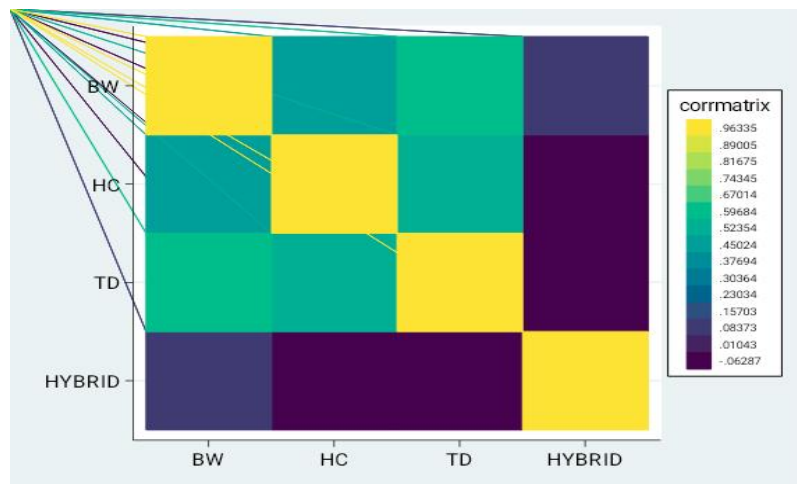
Interestingly, the hybrid variable that is the combined application of human-centered and technological strategies is weakly and statistically insignificantly correlated with the other variables, including BW. This could mean that the effectiveness of the hybrid approach is not linear and it needs additional analysis in terms of the interaction effect or moderated models to determine its actual impact on the bullwhip reduction. These relationships indicate that the dynamics of supply chain are quite complex and that although individual strategies can be inadequate, there is potential that has not been tapped yet when the strategies are implemented collectively.

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<http://amresearchreview.com/index.php/Journal/about>*Figure 5: Heatplot*

To visually interpret the relationship among the studied constructs, a correlation heatmap was generated using STATA. As depicted in the figure 5, BW shows moderate positive correlations with HC and TD, suggesting that both human-centered and technology-driven approaches have measurable associations with the bullwhip effect. Notably, BW shares a relatively weak and negative correlation with the hybrid approach, indicating a distinct pattern compared to the individual strategies. This could imply that the hybrid strategy functions differently and potentially more effectively in disrupting the bullwhip effect. Additionally, HC and TD are moderately correlated with each other, while both show weak correlations with the hybrid strategy. These findings support the premise that hybrid strategies represent a distinct mechanism for mitigating supply chain inefficiencies, warranting deeper investigation into their standalone impact.

4.4. Overall Goodness of Fit

The model fit statistics in table 6 show that the hypothesized model and the observed data fit very well. The Root Mean Square Error of Approximation (RMSEA) = 0.000 with a 90 percent confidence interval of 0.000 to 0.000 and a PCLOSE = 1.000, which is highly indicative of the fact that the approximating error of the model is insignificant and definitely within the acceptable range (RMSEA < 0.05). The Comparative Fit Index (CFI) and Tucker Lewis Index (TLI) is at the highest possible level of 1.000 showing that the model fits perfectly compared to the baseline model. The Standardized Root Mean Square Residual (SRMR) value is also at 0.000 and this further proves that the model has very little residual variance, therefore, a near perfect fit of the observed covariance's. The Chi-

square difference test between the saturated and the baseline model provides the statistically significant value ($\chi^2(6) = 67.72, p < 0.001$), which proves that the hypothesized model significantly outperforms the null one. The values of information criteria, Akaike Information Criterion (AIC) of 1762.02 and Bayesian Information Criterion (BIC) of 1784.32, can be used as benchmarks in the future to compare models in the refinements. All in all, all the results prove the model to be a good representation of the underlying data structure and suitable to interpret and test hypothesis.

Table 6: Goodness of Fit

Fit Statistic	Value	Description
Likelihood Ratio		
chi_ms(3)	10.783	Model vs. saturated
p>chi2	0.000	
chi2_bs(6)	67.72	Baseline vs. saturated
p>chi2	0.000	
Population error		
RMSEA	0.000	Root mean squared error of approximation
90% CI, lower bound	0.000	
Upper bound	0.000	
pclose	1.000	Probability RMSEA ≤ 0.05
Information criteria		
AIC	1762.021	Akaike's information criterion
BIC	1784.321	Bayesian information criterion
Baseline comparison		
CFI	1.000	Comparative fit index
TLI	1.000	Tucker-Lewis index
Size of residuals		
SRMR	0.000	Standardized root mean squared residual
CD	0.431	Coefficient of determination

4.5. Structural Equation Modelling:

The structural equation modelling (SEM) findings in table 7 show that there is a strong indication of the predictors of the bullwhip effect (BW) using a sample size of 120

observations. Technology-driven practices (TD) are the most statistically significant exogenous variables that influence the level of reduction of bullwhip effect ($p < 0.001$) and can be considered as a key factor in demand-supply imbalance. Likewise, the hybrid approach (HYBRID) that is a combination of human-centered and technological practices also has a considerable impact on the bullwhip effect ($\beta = 0.304$, $p = 0.038$), which is why the concept that the integrated strategy is more effective than the individual one should be encouraged.

Human-centered practices (HC) also show a positive impact (0.166), yet this finding is not significant ($p = 0.064$), implying that human intuition and experiential knowledge has a positive influence, although less so compared to technological interventions. Of the control variables, the type of industry, firm size, and digital maturity do not significantly predict the bullwhip effect ($p > 0.05$), which means that the effect is not strongly differentiated in this context by these contextual variables in this sample. The error term variance ($\text{var}(e.BW) = 0.397$) shows that there is moderate amount of unexplained variability and the overall model fit is satisfactory. The log-likelihood of -873.01073 and the statistically significant likelihood ratio test ($p < 0.001$) shows that the proposed structural model fits the data significantly better in comparison with the null model.

These results support the main hypotheses that the technology-driven and the hybrid strategies work as equals to minimize the bullwhip effect and the hybrid integration has synergistic benefits. The findings give a solid empirical background to the need to adopt blended approaches that couple the technological devices with human judgment in the management of supply chain volatility.

Endogenous variables

Observed: BW

Exogenous variables

Observed: HC TD HYBRID Industry Size Maturity

Fitting target model:

Iteration 0: log likelihood = -873.01073

Iteration 1: log likelihood = -873.01073

Structural equation model

Number

of obs = 120

Estimation method = ml

Log likelihood = -873.01073

OIM						
	Coef.	Std.Err.	z	P>z	Interval]	
					[95%Con	f.
Structural						
BW <-						
HC	0.166	0.090	1.850	0.064	-0.009	0.342
TD	0.562	0.082	6.830	0.000	0.401	0.724
HYBRID	0.304	0.147	2.070	0.038	0.017	0.592
Industry	-0.114	0.074	-1.530	0.125	-0.260	0.032
Size	0.018	0.070	0.260	0.798	-0.119	0.155
Maturity	0.043	0.069	0.620	0.532	-0.093	0.179
_cons	-0.533	0.728	-0.730	0.464	-1.960	0.893
LR test of model vs. saturated: chi2(0) =	10.783					Prob >
chi2 =	0.0000					

Table 7: SEM Results

The structural equation picture in figure 2 draws a picture of relationships between human-centered practices (HCP), technology-driven practices (TDP), hybrid strategies, and the bullwhip effect (BWE) and controls the firm-level factors, including industry, size, and digital maturity. Each of the measurement items (e.g., HCP1-HCP5, TDP1-TDP5, H1-H5, B1-B4) has a good loading on the corresponding latent construct, and therefore, the convergent validity of the measurement is strong. Factor loadings are usually above 0.60 and a few above 0.70 (e.g., HCP3 = 0.71, TDP4 = 0.85), and thus measurement is reliable.

On the structural level, technology-driven practices (TDP) have a high positive path coefficient of decreasing the bullwhip effect (0.67), which proves the hypothesis that digital solutions play a significant role in alleviating the variability of demand. On the same note, the hybrid construct that reflects the combination of human judgment and technological tools also exhibits a positive impact on BWE reduction (beta = 0.58). By

contrast, human-centered practices (HCP) demonstrate a less strong direct association ($\beta = 0.28$), which implies that there is not much standalone effect when digital enablers are available. Industry ($\beta = -0.16$), size ($\beta = 0.011$) and digital maturity ($\beta = 0.047$) are among the control variables with the least effect on BWE showing that the main factor leading to improvement is the internal practices as opposed to the firm characteristics.

The model presented substantiates the theoretical model that a combination of human and technological methods is more effective than a single one, which further emphasizes the significance of the hybrid strategies to the realization of supply chain resilience in the Pakistani context in the manufacturing, FMCG, and electronics industries.

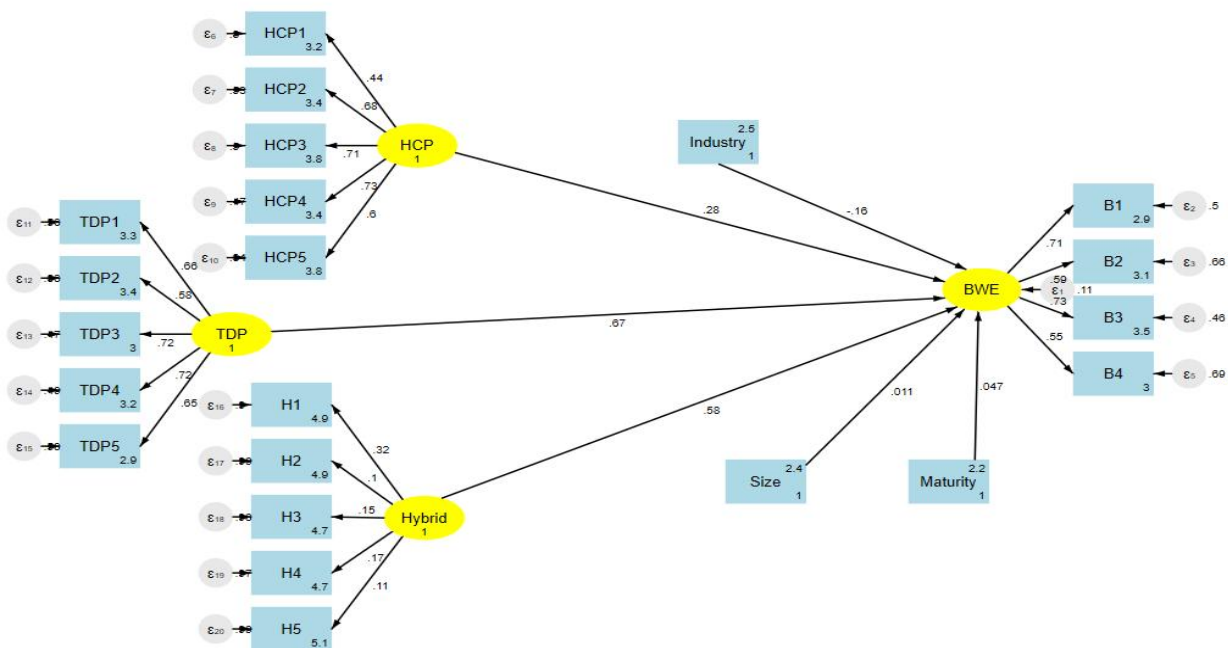


Figure 6: SEM Diagram

4.6. Ordered Logistics Regression

In order to evaluate the association between human-centered practices, technology-driven approaches, hybrid integration, and bullwhip effect, we used ordered logistic regression (ologit) since the dependent variable was an ordinal (measured on a Likert scale). Before estimating the model, all the assumptions required were tested including the proportional odds (parallel lines) assumption, which was tested using Brant test. Additionally, the presence of multicollinearity was checked using variance inflation factors (VIFs), where all

of them were below the critical levels showcasing no multicollinearity among predictors. Linktest was also done to test the specification of the model and it was revealed that the model was properly specified.

Furthermore, to test whether hybrid integration moderates the relationship between human-centered or technology-driven practices and the bullwhip effect, interaction terms were created (e.g., Human $\times$ Hybrid, Tech $\times$ Hybrid). These interaction terms were included in the regression model to examine whether the effect of human or technological practices on the bullwhip effect changes depending on the level of hybrid integration. The inclusion of interaction terms allowed for a deeper understanding of conditional relationships, helping to assess whether combining human intuition with technological tools leads to more significant reductions in the bullwhip effect than either approach alone. The results from these models were analyzed to interpret the nature, strength, and direction of the moderation effects.

Table 8: Ordered Logistic Regression

	(1)	(2)
VARIABLES	BW	BW
HC	0.560** (0.280)	
TD	1.694*** (0.272)	
HYBRID	1.006** (0.443)	
Industry	-0.328 (0.210)	-0.369* (0.210)
Size	0.0429 (0.194)	-0.0502 (0.190)
Maturity	0.0949 (0.194)	0.0595 (0.193)
human_hybrid		0.103 (0.0674)

tech_hybrid 0.394***
(0.0661)

Observations 120 120

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

The regression outcomes in table 8 provide valuable insights on how human-centered practices (HC), technology-driven practices (TD), hybrid integration, and bullwhip effect (BW) relate. In Model 1, HC (0.560, p < 0.05) and TD (1.694, p < 0.01) positively affect reducing the bullwhip effect statistically significantly, which means that they contribute to alleviating the demand amplification fluctuations when they are intensified. On the same note, BW reduction is also greatly positively correlated with hybrid practices (1.006, p < 0.05).

Model 2 acknowledges moderating effects because of the presence of the interaction terms. Although the interaction between human practices and hybrid integration (human_hybrid) is insignificant, the interaction between technology practices and hybrid integration (tech_hybrid) is positive and very significant (beta = 0.394, p < 0.01). This implies that the hybrid integration has a strong influence in enhancing the impact of technology practices in minimizing the bullwhip effect as opposed to its interaction with human practices. Industry is also significant at 10 percent level as a control variable indicating a slight sectoral variation in the occurrence of the bullwhip effect.

On the whole, the results are in favor of H1 and H2: both human and technological practices decrease the bullwhip effect. In addition, H3 has been partially confirmed because the moderating effect of hybrid integration is statistically significant only along with technological practices.

4.7. Multi-Group Analysis

This research used sector-wise regression to analyse the difference in the effect of human-centered practices (HC), technology-driven practices (TD) and hybrid integration on the bullwhip effect (BW) in the Electronics, Manufacturing and FMCG sectors in Pakistan. Table 9 highlights important information on how the effectiveness of each strategy differs with the industry. Technology-driven practices in the Electronics sector showed a high

and statistically significant correlation with the minimization of the bullwhip effect (1.396, $p < 0.01$). Nonetheless, human-centered practices and hybrid integration had positive and statistically insignificant coefficients. When interaction terms were added, tech x hybrid interaction was found significant ($\beta = 0.320$, $p < 0.05$) which means that the hybrid mechanisms integration significantly enhances the effect of technological practices in demand fluctuations management and inefficiencies reduction in electronics supply chains. In the case of the Manufacturing sector, technology-based practices once more came out as a very strong predictor of less bullwhip effect ($\beta = 1.614$, $p < 0.01$). Human-centered and hybrid approaches alone did not prove to be statistically significant. Interestingly, the interaction term between tech and hybrid was also significant ($\beta = 0.416$, $p < 0.01$) which showed that hybrid integration increases the effectiveness of technology in reducing the bullwhip effect. The interaction between human and hybrid was not significant and this means that the integration of human practices with hybrid integration does not make a significant contribution to bullwhip mitigation in this industry. Both human-centered (0.974 , $p < 0.1$) and technology-driven practices (2.260 , $p < 0.01$) were shown to be statistically significant in the FMCG sector, i.e., both of these approaches can independently contribute to the reduction in the bullwhip effect. In addition, the sector was the only one to demonstrate the importance of both interaction terms: human x hybrid ($\beta = 0.236$, $p < 0.1$) and tech x hybrid ($\beta = 0.437$, $p < 0.01$). These results demonstrate the sensitivity of the FMCG industry to the hybrid integration strategies and indicate that the combined use of human and technological practices results in the most efficient outcomes regarding the reduction of the variability and disruptions of the supply chains.

Table 9: Sector Wise Regression Results

VARIABLES	Electronics		Manufacturing		FMCG	
	(1)	(2)	(3)	(4)	(5)	(6)
	BW	BW	BW	BW	BW	BW
HC	0.637		0.110		0.974*	
	(0.583)		(0.452)		(0.574)	
TD	1.396***		1.614***		2.260***	

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	(0.525)		(0.413)		(0.655)	
HYBRID	1.020		0.612		1.468	
	(0.883)		(0.681)		(0.909)	
Size	0.0995	0.0129	-0.0711	-0.122	0.141	-0.00963
	(0.321)	(0.314)	(0.342)	(0.336)	(0.439)	(0.425)
Maturity	0.361	0.328	0.165	0.0994	-0.0548	-0.152
	(0.351)	(0.350)	(0.327)	(0.314)	(0.406)	(0.402)
human_hybrid		0.122		-0.0235		0.236*
		(0.142)		(0.103)		(0.142)
tech_hybrid		0.320**		0.416***		0.437***
		(0.132)		(0.104)		(0.142)

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

On the whole, these findings support the assumption that technology-driven practices have always been effective in all sectors, whereas human-oriented practices are sector-specific and are most effective in FMCG. Hybrid approach is a moderating factor and more so when coupled with technology and this is especially effective in industries that have high volatility of demand like FMCG. These findings indicate that the customization of supply chain strategies to industry-specific dimensions which utilizes hybrid integrations can go a long way in further cutting down the bullwhip effect in the major industrial sectors in Pakistan.

4.8. Discussion

This paper considered how human-centered practices, technology-based approaches, and the combination of both can reduce the bullwhip effect (BWE) in the three key industries in Pakistan, including manufacturing, FMCG, and electronics. It used SEM and ordered logistic regression to analyze the data and the results gave a strong empirical evidence of the effectiveness of these methods- especially hybrid models- in managing demand variability in the supply chain.

The findings prove H1, which stated that the BWE is significantly decreased due to human-centered practices. The effect size was lower than that of the technological strategies, but the coefficient of HC was positive and significant, especially in FMCG

industry. This is consistent with the current literature that reveals the significance of behavioral coordination, communication and trust in minimizing demand amplification (Akkermans & Vos, 2003; Salwa & Zulfikri, 2024). More aligned supply chain activities are possible through human based strategies like improved forecasting judgment, stakeholder alignment and experiential decision-making (Brau, Aloysius, & Siemsen, 2023; Tokar, 2010), particularly within high variability and low technology infrastructure environments.

Moreover, H2 was also supported strongly. The highest and most constant impact was observed in technology-driven practices, especially ERP, EDI, AI-based forecasting, and big data analytics, which were significant in all sectors. This aligns with the previous research that claims that advanced IT systems enhance the real-time data visibility, forecasting accuracy, and response time (Alonge et al., 2023; Hofmann, 2013). As an example, a study conducted by Weerabahu, Samaranayake, Nakandala, and Hurriyet (2023) revealed that digital maturity is directly linked to the decrease in uncertainty in the supply chain and demand distortion.

However, the technological dimension produced the largest coefficients in this study and this indicates the dominant position of this dimension in predictive and adaptive planning.

Additionally, H3 was put to test the effectiveness of hybrid strategies was also supported. The interaction terms (human x hybrid and tech x hybrid) were positively correlated with BWE reduction with the tech x hybrid interaction being significant in all three sectors and human x hybrid being especially effective in the FMCG sector. The results can be used to support claims in the new literature that promotes the concept of integrated approaches. Ghosh, Dutta, and Abotaleb (2024) state that hybrid models that combine human intuition and machine learning capabilities are more effective than individual models. The hybrid model enables companies to experience the benefits of machine-based analytics and also include flexibility and human contextual judgment, which are essential in the unstable market such as Pakistani.

At the sector level, the FMCG industry was the most benefited by hybrid integration probably because of the high variability of demands and quick turnover of inventories. Manufacturing and electronics also experienced positive influence of technology but they demonstrated comparatively modest benefit of hybrid configurations.

This could be an indication of the discrepancy in digital preparedness and employee flexibility within the industry.

In addition, the regression models did not show statistically significant predictors of firm size and digital maturity. This may imply that the scale and maturity influence the operational capacity, but the strategic alignment of human and technological practices is more critical when mitigating BWE. This observation is contrary to the past research (e.g., Sanders (2007)) that focuses on the influence of the size of the organization on the adoption of technology and the increasing significance of cross-functional integration irrespective of size.

5. Conclusion

The study shed light on the multifaceted interaction among human intuition, digital technologies, and their synergistic effect on managing the bullwhip effect (BWE) in supply chains in the Pakistani major industrial sectors including manufacturing, FMCG, and electronics. The analysis showed that although both the approaches of human-centered and technology-driven solutions are effective on their own in terms of reducing the BWE, the combination of the two, where the strategic human control and technological accuracy are combined, is showing the most consistent and significant effects. Digital tools do not substitute human judgment; instead, they complement it and allow firms to become more responsive and accurate in responding to changes in demand with higher levels of coordination. The results confirm that successful supply chain resilience is not about the selection between human and technological capabilities but about integrating them in a manner that generates flexible, intelligent systems. In the environments where demand is volatile, infrastructure is lacking, and the digital environment is changing, this synergy is not just a competitive advantage but a requirement.

Limitations

The study has a number of limitations in spite of its contributions. To begin with, its cross-sectional design restricts the possibilities to make inferences about long-term causalities. The use of survey-based presents a possibility of response bias especially since the respondents may not be equally knowledgeable about organizational supply chain systems. In addition, the study is restricted to three industries in Pakistan; therefore, the results cannot be applied to other industries with varying dynamics or to more digitally

developed economies. Moreover, although hybrid integration proved to be effective, the study did not examine which combinations of technologies and human roles are the most effective, which is an opportunity to conduct research in the future.

Recommendations

Going by the findings, the recommendation is that companies should be proactive in developing and executing hybrid supply chain strategies that would combine human strengths with technological innovations. This involves the investment in AI-based forecasting systems and ERP platforms as well as the training of the employees in the area of decision-making and data interpretation. It is also important to tailor strategies to the needs of the industry. As an example, demand sensing and real-time analytics can be more beneficial to FMCG companies, whereas electronics companies can concentrate on inventory synchronization and lead time reduction. Also, policymakers and business associations ought to focus on enhancing digital infrastructure, particularly to small and medium enterprises (SMEs) so that they can embrace hybrid systems effectively.

Research Implications

The study adds to theoretical and practical understanding of supply chain management. In theory, this strengthens an emerging body of thought that hybrid strategies are more flexible and perform better in complicated and uncertain supply chains, especially in emerging markets. In practice, the results provide a roadmap to companies that are interested in mitigating the bullwhip effect by investing in people and technology equally. This evidence can help supply chain managers to make strategic decisions regarding the allocation of resources and the development of interventions depending on the specifics of their operation. The study shows policymakers that it is necessary to promote digital transformation with selective support, particularly in those areas and industries where digital maturity is still low. The development of hybrid capabilities in SMEs will be essential to the development of national supply chain resilience.

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