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Unveiling the Barriers to Industry 4.0 Adoption towards Sustainable Supply Chain in the Construction Industry

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Abstract

Industry 4.0 technologies promise substantial sustainability gains for construction supply chains, yet adoption rates in emerging-economy construction markets remain low, constrained by a complex and poorly systematised set of barriers spanning technological, organisational, economic, institutional, environmental, human-resource and social domains. This study identifies, classifies and ranks the barriers to Industry 4.0 adoption in sustainable supply chain management (SSCM), develops a taxonomy of adoption barriers, and proposes a mitigation-oriented adoption framework for construction organisations. A structured questionnaire was purposively administered to 285 built-environment professionals with a minimum of ten years' experience in Edo and Delta States, Nigeria; 184 valid responses were analysed (64.7% response rate). Thirteen barrier items spanning social, economic and environmental sub-scales were subjected to Cronbach's alpha reliability testing, the Kaiser–Meyer–Olkin (KMO) measure, Bartlett's test of sphericity, and Principal Component Analysis (PCA). Environmental barriers displayed the strongest single-component structure (KMO = 0.626; first component eigenvalue = 1.945, 48.63% variance), followed by economic barriers (KMO = 0.638; eigenvalue = 1.735, 43.38%) and social barriers (KMO = 0.504, non-significant Bartlett's test, $p = 0.458$). The most severe individual barriers were public communication deficits (loading = 0.751), resource depletion in steel-intensive processes (0.742), logistics/cash-flow inefficiency (0.729) and inefficient institutional policy (0.721). A seven-category taxonomy which includes technological, organisational, economic, institutional, environmental, human-resource and social was developed to classify all thirteen empirical items. It was concluded that Institutional and communication-related barriers currently constrain adoption at least as much as purely technical or financial constraints. A phased mitigation framework combining policy reform, stakeholder communication and targeted financing is proposed to accelerate sustainable Industry 4.0 adoption in construction supply chains, with particular relevance for developing-country contexts.

Keywords: Industry 4.0; adoption barriers; sustainable supply chain management; principal component analysis; construction industry; barrier taxonomy

Introduction

Industry 4.0 technologies are widely credited with the capacity to transform supply chain sustainability, yet their diffusion across construction supply chains remains markedly uneven, particularly in emerging economies (Chauhan, Singh & Luthra, 2021; Kamble, Gunasekaran & Sharma, 2018). While much of the literature has focused on documenting the sustainability potential of individual technologies, a parallel and equally important body of work has identified the barriers that prevent construction organisations from realising this potential in practice (Bag, Yadav, Dhamija & Kataria, 2021; Luthra & Mangla, 2018). These barriers are seldom purely technical; they span organisational readiness, regulatory environments, financing structures and workforce capability, and they interact in ways that narrative reviews often fail to disentangle (Ghadge, Kara, Moradlou & Goswami, 2020). Construction supply chains present a particularly demanding adoption context. Their project-based, temporary organisational structures limit the cumulative learning and capital amortisation that digital transformation typically requires (Serpell & Heredia, 2012; Khan, Schaefer & Milisavljevic-Syed, 2022), while

the sector's historically low digital maturity relative to manufacturing compounds the difficulty of technology adoption (Hofmann, Sternberg, Chen, Pflaum & Prockl, 2019). In Nigeria and comparable developing-country contexts, these structural constraints are further amplified by infrastructural deficits, policy uncertainty and skills shortages (Rajae, Mohammed, Mohamed, Kenza & Said, 2021).

Despite the practical urgency of understanding these barriers, the literature offers relatively few empirically grounded, statistically weighted rankings of barrier severity specific to construction SSCM. Most treatments remain qualitative or conceptual, cataloguing barriers without establishing their relative statistical significance for a defined respondent population (Kamble et al., 2018; Moktadir, Ali, Paul & Shukla, 2021). This gap constrains the ability of managers and policymakers to prioritise limited mitigation resources. This investigation addresses this gap directly. Its specific aim is to identify challenges in adopting Industry 4.0 technologies in sustainable supply chain management, and, in pursuing this aim, to (i) synthesise the literature on adoption barriers across technological, organisational, economic, institutional, environmental, human-resource and social domains, (ii) statistically identify and rank barrier severity using survey data from experienced construction professionals, (iii) develop a taxonomy that organises the empirically identified barriers within this broader classification, and (iv) propose a practical, mitigation-oriented adoption framework. The remainder of the article proceeds as follows. Section 2 reviews the barrier literature. Section 3 details the methodology, including full statistical specification. Section 4 presents results. Section 5 discusses findings against prior studies, with attention to developing-country and construction-sector implications, also setting out practical applications and Section 6 concludes.

This study contributes to the literature in three ways. Firstly, it offers a seven-domain barrier taxonomy, technological, organisational, economic, institutional, environmental, human-resource and social, that consolidates classifications that are typically treated separately across the literature (Kamble et al., 2018; Raj et al., 2020). Secondly, it applies Principal Component Analysis, rather than simple mean-ranking, to derive a statistically weighted severity ordering that accounts for the underlying covariance structure among barrier items, reducing the risk that severity rankings are driven by idiosyncratic response bias in any single item (Field, 2013). Thirdly, it grounds the analysis in a construction-specific, emerging-economy sample, a context in which barrier research remains comparatively sparse relative to manufacturing-sector studies from developed economies (Rajae et al., 2021; Chauhan et al., 2021).

Literature Review

Adoption barrier research in Industry 4.0 has evolved from single-factor studies toward multi-dimensional frameworks capable of capturing the interacting technical, financial and institutional forces that inhibit technology uptake (Kamble et al., 2018; Raj, Dwivedi, Sharma, Lopes de Sousa Jabbour & Rajak, 2020). Chauhan et al. (2021) demonstrate empirically that barriers rarely act independently; financial constraints frequently amplify technological barriers by limiting the resources available for the skills training that technology adoption requires. This interaction effect underpins the case for a taxonomy-based, rather than a flat list-based, treatment of barriers. The Technology–Organisation–Environment (TOE) framework (Tornatzky & Fleischer, 1990) provides a further theoretical scaffold for organising these interacting barriers. Under TOE, adoption is jointly determined by the characteristics of the technology itself (technological context), the internal readiness and resources of the adopting firm (organisational context), and the external institutional, economic and competitive environment (environmental context). Mapped onto the present study, technological and human-resource barriers correspond to the technological context; organisational barriers correspond directly to the organisational context; and economic, institutional, environmental and social barriers collectively populate the environmental context. This mapping clarifies why barrier mitigation cannot be addressed by a single organisational function and provides the theoretical justification for the cross-domain severity ranking developed in Section 4.

The various barriers domains includes technological barriers indicates that High skill, data and time requirements are consistently identified as primary technological constraints (Pande & Adil, 2022). Ghobakhloo (2019) similarly finds that inadequate technical infrastructure and integration difficulty with legacy systems are leading determinants of slow Industry 4.0 uptake. There is Organisational barriers shown by a lack of

information and awareness regarding technology benefits, alongside the absence of a coherent digital strategy, constrains adoption independent of financial capacity (Fracarolli Nunes & Lee Park, 2017; Müller, Maier, Veile & Voigt, 2017). Cooper and Zmud's (1990) technology-diffusion model remains influential in framing organisational readiness as a precondition for successful implementation. There is Economic barriers that is characterized by inefficiency in logistics systems, constrained cash flow, escalating stakeholder demands and a shortage of circular-economy enterprises are frequently cited economic constraints (Martins, Bourgault & Zaccour, 2021; Hossain, Wang, Amin & Duan, 2020). Bastas and Liyanage (2018) emphasise that construction firms face the compounded difficulty of integrating economic, environmental and social agendas simultaneously, rather than pursuing sustainability upgrades sequentially. There is Institutional barriers where inefficient or absent policy frameworks, and weak regulatory incentives for circular-economy participation, are repeatedly identified as institutional constraints (Kamble et al., 2018; Araújo, Pereira & Fontes, 2020). Popović, Barbosa-Póvoa, Kraslawski and Carvalho (2017) attribute part of this institutional gap to the absence of adequate quantitative sustainability indicators against which policy compliance can be assessed. There is Environmental barriers in which resource depletion, greenhouse gas emissions from warehousing, rising carbon footprints and demolition-related environmental harm constitute the environmental barrier domain (Toufani, Bostan & Aliakbari, 2018; Bartolini, Bottani & Grosse, 2019; Tseng, Tan, Chiu, Chien & Kuo, 2021). Aghelie (2020) situates these barriers within a broader concern for the sustainability management of resource-intensive industries such as steelmaking, which supplies construction. Also, there is Human-resource barriers which include workforce reskilling gaps and shortages of digitally literate personnel constrain adoption independent of the availability of technology itself (Ras, Wild, Stahl & Baudet, 2017). This domain overlaps substantially with the technological barrier domain but is treated separately here given its distinct managerial remedy (training and recruitment rather than infrastructure investment). Social barriers exist too where public communication deficits and a tendency among some organisations to limit sustainability engagement to public communication rather than substantive practice are documented as social barriers (Fracarolli Nunes & Lee Park, 2017; Popović et al., 2017; Nantee & Sureeyatanapas, 2021).

There is a barrier interaction and interdependence which is a recurring theme across the barrier literature is that individual constraints seldom operate in isolation; rather, barriers interact and, in some cases, compound one another (Kamble et al., 2018; Chauhan et al., 2021). Kamble et al. (2018) apply interpretive structural modelling to demonstrate that certain barriers function as “driving” forces that intensify others further down a dependence hierarchy—for instance, weak institutional policy incentives reduce the perceived economic case for investment, which in turn constrains the budget available for workforce reskilling. This layered interdependence has two implications for the present study. First, it justifies treating barrier severity as a multi-domain rather than single-cause phenomenon, consistent with the taxonomy-based approach adopted here. Second, it suggests that mitigation strategies targeting only the most “visible” barrier (often assumed, in narrative reviews, to be cost) may fail if underlying institutional or organisational driving forces remain unaddressed, a possibility examined empirically in Section 4 and addressed directly in the mitigation framework of Section 6.

Table 1: Comparative Literature Table: Barrier Domains, Representative Barriers and Key Sources

Barrier Domain	Representative Barrier(s)	Key Sources
Technological	High skill, data and time requirement; legacy-system integration	Pande & Adil (2022); Ghobakhloo (2019)
Organisational	Lack of information/awareness; absent digital strategy	Fracarolli Nunes & Lee Park (2017); Müller et al. (2017); Cooper & Zmud (1990)
Economic	Logistics/cash-flow inefficiency; stakeholder demands; circular-economy shortage	Martins et al. (2021); Hossain et al. (2020); Bastas & Liyanage (2018)
Institutional	Inefficient policy; weak regulatory incentives	Kamble et al. (2018); Araújo et al. (2020); Popović et al. (2017)

Environmental	Resource depletion; GHG emissions; carbon footprint; demolition waste	Toufani et al. (2018); Bartolini et al. (2019); Tseng et al. (2021); Aghelie (2020)
Human-Resource	Reskilling gap; shortage of digitally literate personnel	Ras et al. (2017)
Social	Public communication deficits; superficial sustainability engagement	Fracarolli Nunes & Lee Park (2017); Nantee & Sureeyatanapas (2021)

In various barrier researchs there have been a measurement challenge. This methodological difficulty recurs across the barrier literatures and raises the concerns the reliable measurement of barrier constructs that are conceptually heterogeneous. Several studies report modest internal-consistency coefficients for multi-item barrier scales, particularly where a scale intentionally spans distinct sub-domains, for example, combining technical and policy-related items within a single “social” or “institutional” construct (Kamble et al., 2018; Moktadir et al., 2021). Rather than treating such heterogeneity purely as a psychometric weakness, several authors argue it reflects the genuinely multi-causal nature of adoption resistance, and recommend factor-analytic decomposition, rather than reliance on a single aggregate score, as the more informative analytical strategy (Field, 2013; Hair, 2006). This recommendation directly informs the analytical approach adopted in Section 3, in which each barrier sub-scale is decomposed via PCA rather than summarised by a single mean severity score. Institutional theory offers a complementary lens for interpreting the institutional and social barriers identified in this study. DiMaggio and Powell's (1983) concept of institutional isomorphism suggests that organisations often adopt new practices not purely for efficiency reasons but in response to coercive (regulatory), mimetic (peer-driven) and normative (professional-body-driven) pressures. Applied to Industry 4.0 adoption, weak coercive pressure which is reflected in the inefficient policy environments reported by Kamble et al. (2018) and Araújo et al. (2020), this would be expected to slow adoption even where firm-level economic incentives are favourable, since organisations lack an external compliance driver to prioritise investment. This perspective reinforces the case, developed in Section 6, for policy-level as well as firm-level intervention: institutional barriers are unlikely to be resolved through firm-level technology investment alone, since their root cause lies in the external regulatory and professional environment rather than in internal organisational capability.



Figure 1: Conceptual synthesis of the literature showing six interacting barrier to adoption of Industry 4.0 Technologies in sustainable construction supply chains.

The illustration highlights the interdependence of barriers and the need for integrated mitigation strategies. The existing barrier studies rarely combine (a) a comprehensive, literature-derived taxonomy spanning all seven domains above with (b) a statistically weighted severity ranking derived from primary survey data specific to

construction SSCM (Kamble et al., 2018; Muktadir et al., 2021). This study integrates both, using PCA to empirically weight barrier severity within a taxonomy explicitly designed to support managerial prioritisation.

Methodology

This study reuses the quantitative, cross-sectional survey design, population and sample described for the parent research programme (Creswell & Creswell, 2017; Babbie, 2016). A structured questionnaire was purposively administered to 285 built-environment professionals such as architects, quantity surveyors, civil/structural engineers, builders and surveying/geoinformatics practitioners with a minimum of ten years' professional experience in Edo and Delta States, Nigeria. Fifty-five valid, fully completed instruments were returned (64.7% response rate). All respondents (100%) had prior exposure to at least one Industry 4.0 technology, supporting their competence to evaluate adoption barriers from direct organisational experience. The barriers section of the questionnaire comprised thirteen closed-ended items organised into three empirical sub-scales, social (5 items), economic (4 items) and environmental (4 items) challenges all measured on a Likert-type severity scale. Items were derived from the literature reviewed in Section 2 and refined through expert review (Fink, 2019). For the purposes of this article, the thirteen empirical items were subsequently mapped onto a broader seven-domain taxonomy (technological, organisational, economic, institutional, environmental, human-resource, social) to align the empirical structure with the classification conventions of the wider barrier literature (Section 4.4).

To ensure reliability analysis, Internal consistency of each barrier sub-scale was assessed using Cronbach's alpha:

$$\alpha = [k / (k - 1)] \times [1 - (\sum \sigma_i^2 / \sigma^2)] \quad (1)$$

where k is the number of items in the sub-scale, σ_i^2 is the variance of item i , and σ^2 is the variance of the summed sub-scale score. Values of $\alpha \geq 0.70$ are conventionally regarded as acceptable, 0.60–0.70 as marginal, and below 0.60 as weak (Hair, 2006; Pallant, 2016).

The Kaiser–Meyer–Olkin measure of sampling adequacy was computed for each sub-scale:

$$KMO = \sum \sum r_{ij}^2 / [\sum \sum r_{ij}^2 + \sum \sum a_{ij}^2] \quad (2)$$

where r_{ij} is the zero-order correlation and a_{ij} is the partial correlation between variables i and j . Bartlett's test of sphericity examined the null hypothesis that the correlation matrix is an identity matrix:

$$\chi^2 = -[(n - 1) - (2p + 5)/6] \times \ln|R| \quad (3)$$

where n is sample size, p is the number of items, and $|R|$ is the determinant of the correlation matrix. A significant result ($p < 0.05$) supports proceeding to component extraction (Bartlett, 1954; Field, 2013).

The principal component analysis and factor done was that for each barrier sub-scale, the standardised data matrix X ($n = 184$ respondents) was decomposed via its covariance/correlation matrix $S = (1/(n - 1))X^T X$, with components extracted from the eigenvalue decomposition $S v_k = \lambda_k v_k$. Component scores were computed as $Z = XA$, and the underlying common-factor model is expressed as $X = \Lambda F + \varepsilon$, where Λ is the loading matrix, F the vector of component scores, and ε the vector of unique variances. The Kaiser criterion ($\lambda_k > 1$) governed component retention, corroborated by scree-plot inspection.

The three barrier sub-scales (social, economic, environmental) were analysed as separate PCA runs which consistent with the original instrument design, a cross-category severity ranking required a common metric. Barrier severity, V_i , for barrier item i was defined as the absolute value of its loading on the first (dominant) extracted component within its sub-scale:

$$V_i = |L_{i1}| \quad (4)$$

where L_{i1} is the loading of item i on Component 1 of its respective sub-scale. Absolute value was used because several items (e.g., “high skill, data and time requirement”) loaded negatively while remaining substantively

significant contributors to the underlying dimension. Category-level severity, C_j , for barrier category j was additionally computed as the percentage of variance explained by the dominant component of that category's PCA solution, providing a second, category-level severity metric:

$$C_j = (\lambda_{1j} / \sum_k \lambda_{kj}) \times 100\% \quad (5)$$

where λ_{1j} is the eigenvalue of the first component within category j and $\sum_k \lambda_{kj}$ is the sum of all eigenvalues (equal to the number of items) within that category.

Table 2: Statistical Decision Criteria Applied in the Analysis

Criterion	Threshold	Source
Cronbach's alpha (α)	$\alpha \geq 0.70$ acceptable; 0.60–0.70 marginal	Hair (2006); Pallant (2016)
KMO measure of sampling adequacy	$KMO \geq 0.60$ acceptable; < 0.50 unacceptable	Kaiser (1974)
Bartlett's test of sphericity	$p < 0.05$ statistically significant	Bartlett (1954)
Eigenvalue (component retention)	$\lambda_k > 1$ (Kaiser criterion)	Kaiser (1960)
Factor loading cut-off	$ L_{ik} \geq 0.50$ substantive	Hair (2006)
Cumulative variance explained	$\geq 60\%$ desirable for social-science data	Hair (2006)

Results

Table 3 summarises reliability and sampling-adequacy statistics for the three barrier sub-scales. The economic ($\alpha = 0.556$) and social ($\alpha = 0.565$) sub-scales fell below the conventional 0.70 threshold, while the environmental sub-scale ($\alpha = 0.643$) approached but did not reach it. These moderate reliability values are consistent with the conceptually heterogeneous nature of the barrier items within each sub-scale and are interpreted further in Section 5. Sampling adequacy was good for environmental barriers ($KMO = 0.626$, $\chi^2(6) = 29.12$, $p < 0.001$) and economic barriers ($KMO = 0.638$, $\chi^2(6) = 17.10$, $p = 0.009$), but only marginal for social barriers ($KMO = 0.504$), whose Bartlett's test was not statistically significant ($\chi^2(10) = 9.80$, $p = 0.458$).

Table 3: Reliability and Sampling Adequacy Results by Barrier Sub-Scale

Sub-Scale	Items	Cronbach's α	KMO	Bartlett's χ^2	Sig.
Social Challenges	5	0.565	0.504	9.803 (df=10)	0.458
Economic Challenges	4	0.556	0.638	17.096 (df=6)	0.009
Environmental Challenges	4	0.643	0.626	29.119 (df=6)	< 0.001

Environmental barriers displayed the most concentrated single-component structure, with Component 1 alone explaining 48.63% of variance (eigenvalue = 1.945). Economic barriers similarly loaded onto a single dominant component (43.38% variance, eigenvalue = 1.735). Social barriers required two components to reach a comparable cumulative variance (52.58%; Component 1 = 26.70%, Component 2 = 25.88%), reflecting the more heterogeneous character of this sub-scale, which spans both technical/informational and policy/communication concerns.

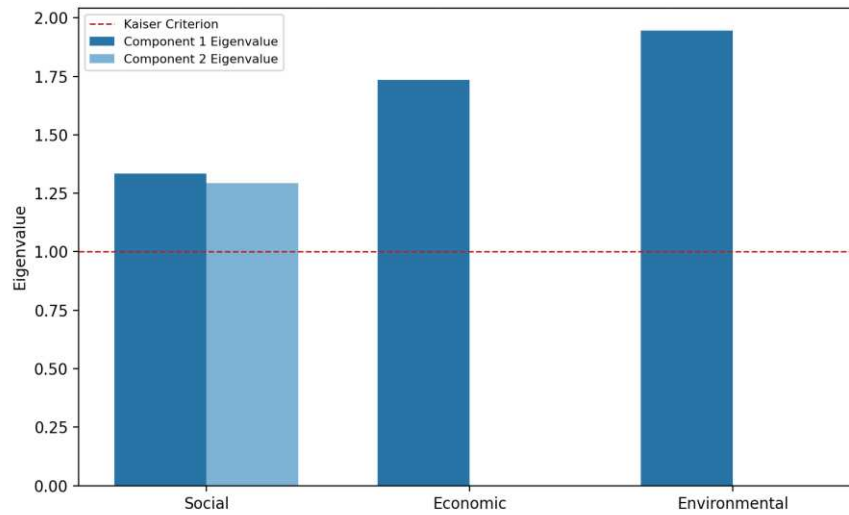


Figure 2: Eigenvalue Comparison Across Barrier Categories

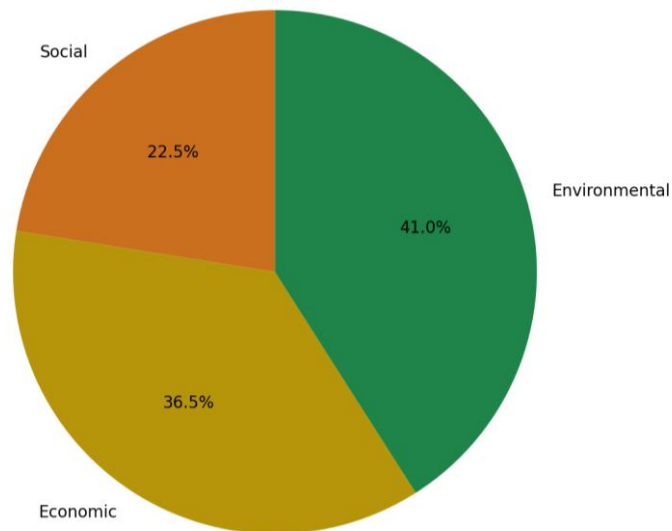


Figure 3: Relative Explanatory Strength of the Dominant Component Across Barrier Categories

Table 4: Component Matrix of Factor Loadings (Social Barriers)

Barrier Item	Component 1	Component 2
High skill, data and time requirement	-0.690	0.398
Lack of information	0.661	0.224
Pollution and high energy consumption	0.599	0.032
Public communication (deficits)	0.232	0.751
Inefficient policies	-0.093	0.721

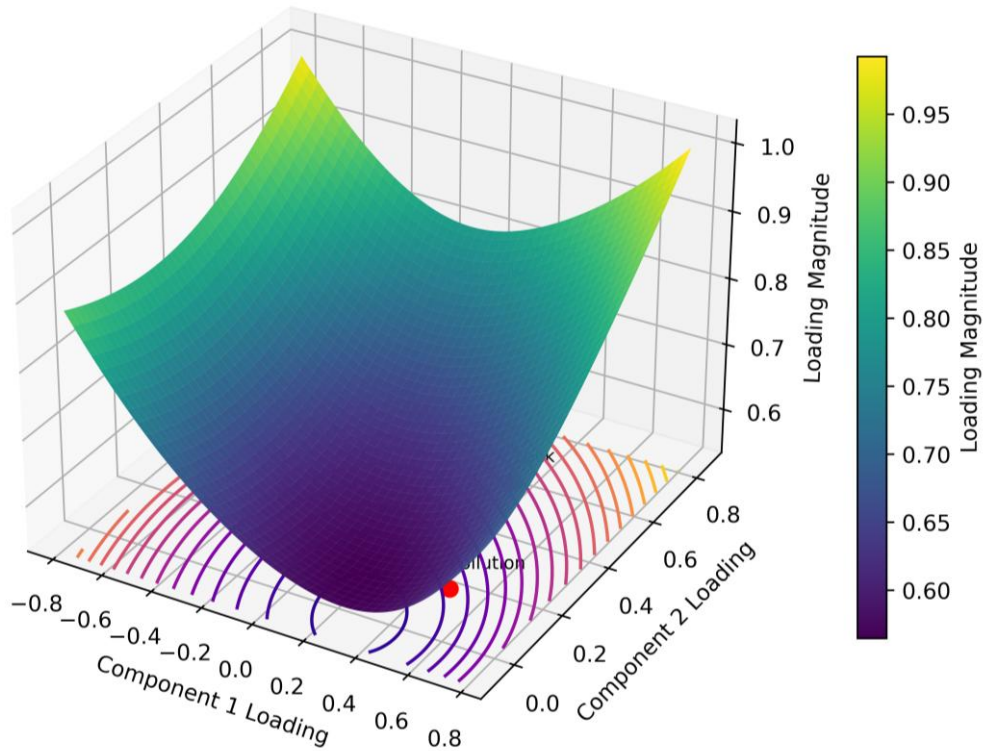


Figure 4: Three-dimensional contour heat map illustrating the spatial distribution of standardized factor loadings for the social barriers identified by principal component analysis.

Warmer colours indicate higher loading magnitudes, while contour gradients highlight regions of stronger component influence. The visualization demonstrates

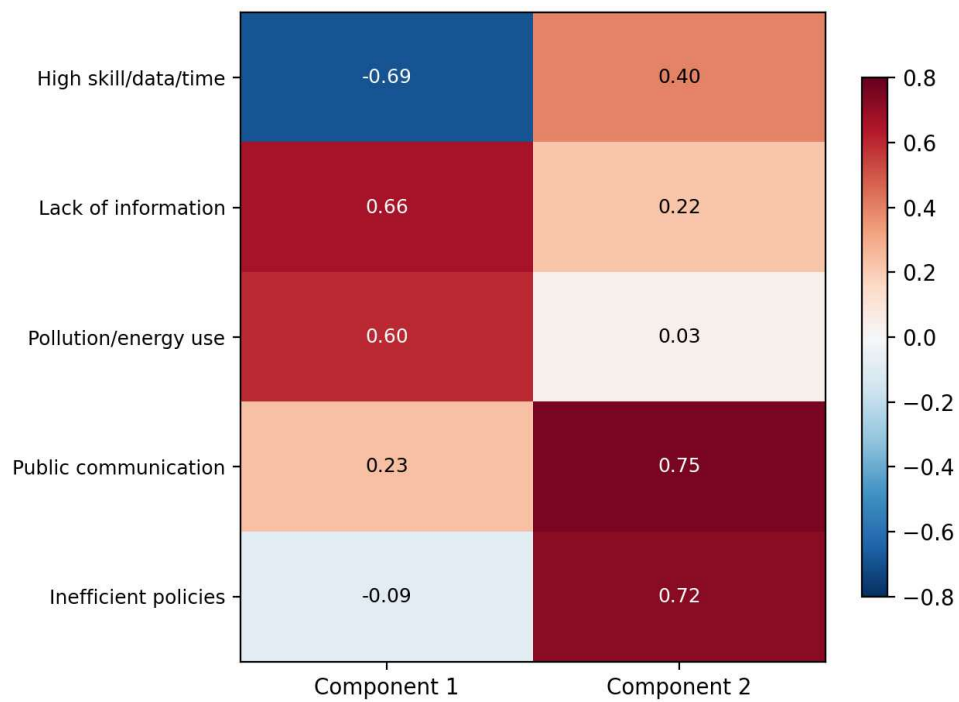


Figure 5: Heat Map of Component Loadings for Social Barriers

Table 5: Component Matrix of Factor Loadings (Economic and Environmental Barriers)

Domain	Barrier Item	Loading
Economic	Inefficiency in logistics system and lack of cash	0.729
Economic	Increasing stakeholders and social demands	0.663
Economic	Difficulties combining demand for faster economic growth	0.659
Economic	Shortage of circular-economy enterprises	0.574
Environmental	Resource depletion in steelmaking industries	0.742
Environmental	Warehouses as top contributors to GHG emissions	0.723
Environmental	Increasing carbon footprint	0.723
Environmental	Environmental problems in demolition processes	0.590

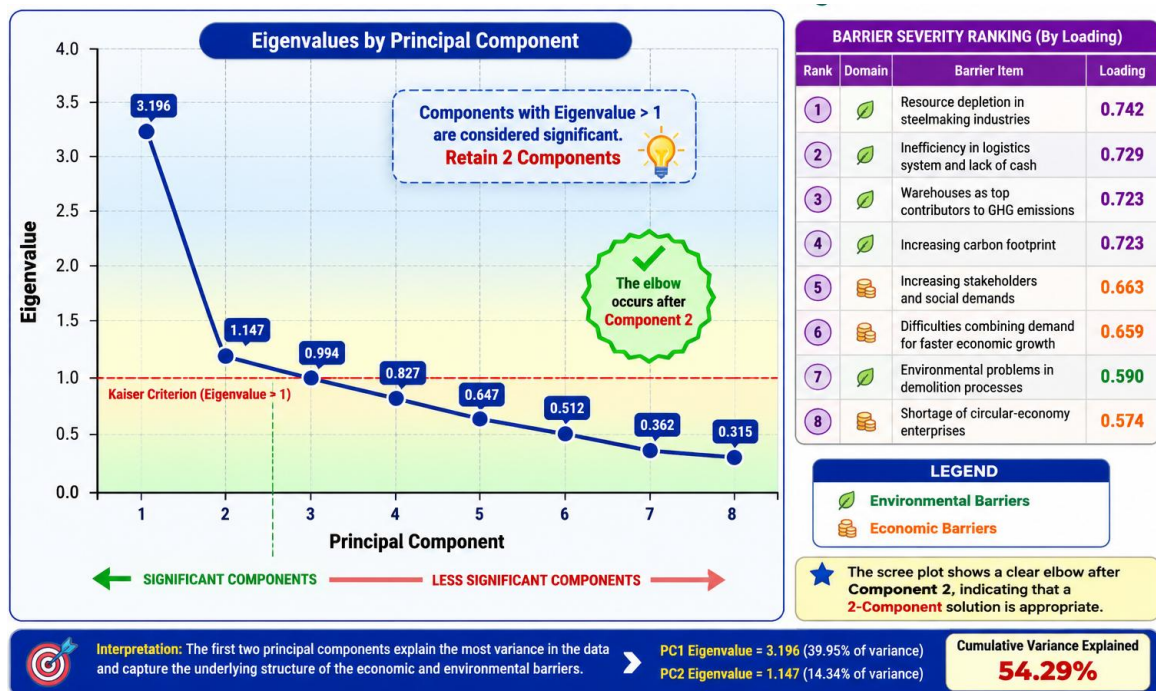


Figure 6: Colorful scree plot illustrating principal components and barrier loading interpretation for the economic and environmental barriers.

Barrier severity ranking is shown in Table 6 which ranks all thirteen empirically identified barriers by severity (V_i , Equation 4) and classifies each within the seven-domain taxonomy developed in Section 2. Public communication deficits (0.751), resource depletion in steel-intensive processes (0.742), logistics/cash-flow inefficiency (0.729) and inefficient institutional policy (0.721, taken from the social sub-scale Component 2) emerge as the four most severe barriers, spanning social, environmental, economic and institutional domains respectively demonstrating that no single domain dominates barrier severity.

Table 6: Barrier Taxonomy and Severity Ranking

RANK	BARRIER	TAXONOMIC DOMAIN	SEVERITY (L)	SUB-SCALE
1	Public communication deficits	Social	0.751	Social
2	Resource depletion (steelmaking)	Environmental	0.742	Environmental
3	Logistics inefficiency & cash constraints	Economic	0.729	Economic
4	Inefficient institutional policies	Institutional	0.721	Social
5	GHG emissions from warehousing	Environmental	0.723	Environmental
5	Rising carbon footprint	Environmental	0.723	Environmental
7	High skill, data & time requirement	Technological / Human-Resource	0.690	Social
8	Escalating stakeholder demands	Economic / Social	0.663	Economic
9	Lack of information / awareness	Organisational	0.661	Social
10	Conflict of rapid growth vs. sustainability	Economic	0.659	Economic
11	Shortage of circular-economy enterprises	Institutional / Economic	0.574	Institutional
12	Pollution & high energy consumption	Environmental	0.599	Social
13	Demolition-related environmental harm	Environmental	0.590	Environmental

TAXONOMIC DOMAIN LEGEND	SEVERITY SCALE GUIDE (L)	KEY INSIGHT
Social Environmental Economic Institutional Technological / Human-Resource Organisational	 0.75+ Very High 0.60 – 0.74 High 0.45 – 0.59 Moderate 0.30 – 0.44 Low < 0.30 Very Low	The top barriers are predominantly social, environmental, and economic in nature, requiring integrated strategies across policy, technology, finance, and stakeholder engagement.

This is a colourful infographic table illustrating the taxonomy of barriers, their severity ranking, taxonomic domains, and associated sub-scales.

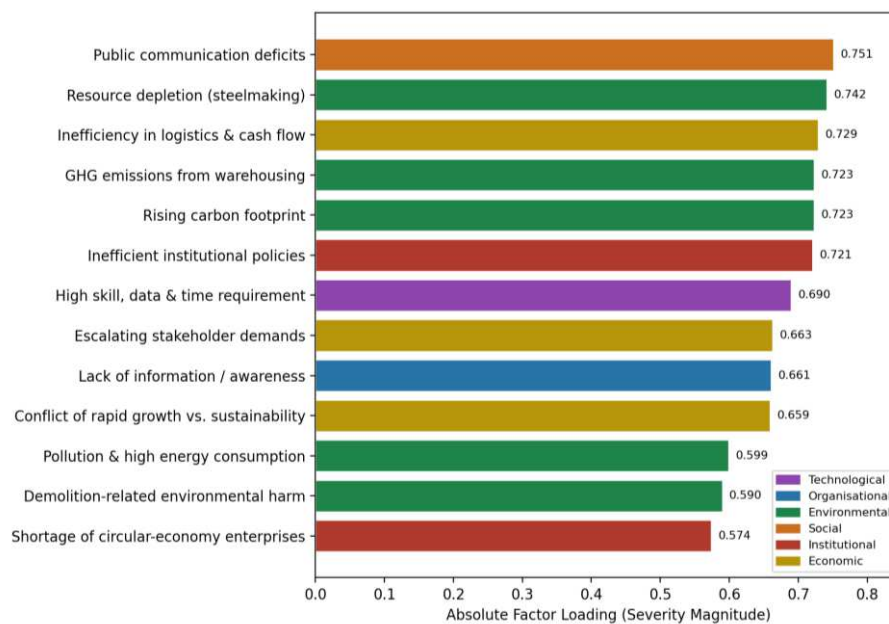


Figure 7: Severity Ranking of Barriers to Industry 4.0 Adoption in Sustainable Supply Chain Management

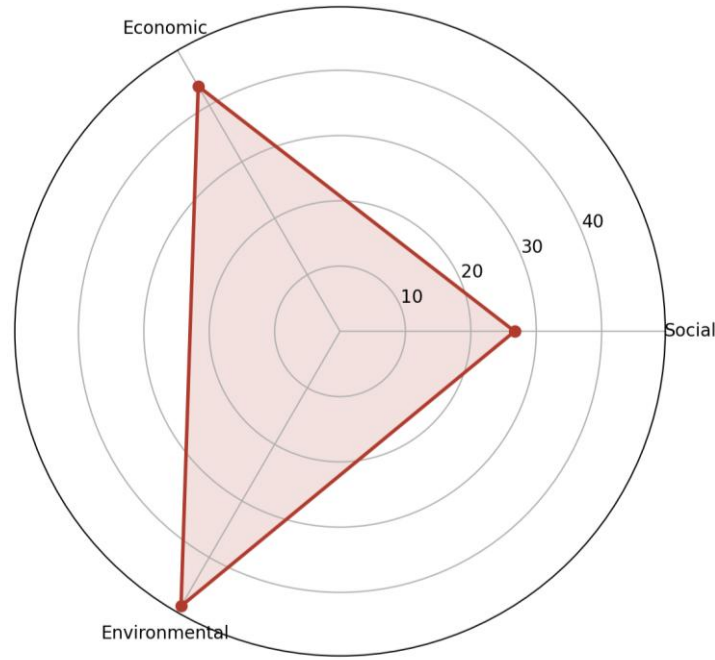


Figure 8: Dominant-Component Variance Explained by Barrier Category (%)

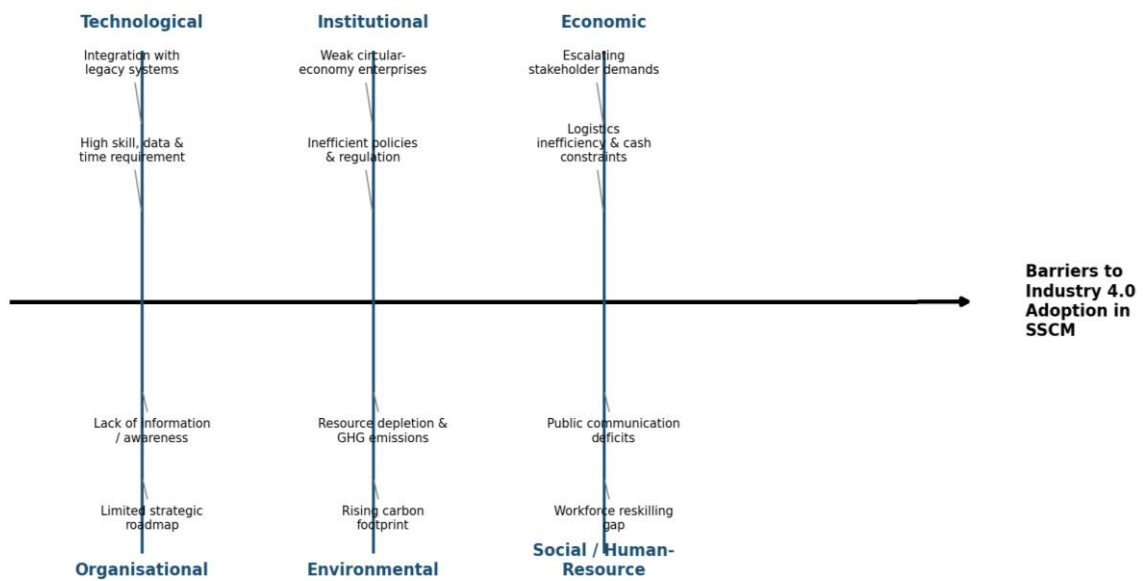


Figure 9: Fishbone (Ishikawa) Diagram of Barrier Categories Affecting Industry 4.0 Adoption

The taxonomy in Table 6 and Figure 6 reveals that the four lowest-severity barriers—shortage of circular-economy enterprises (0.574), demolition-related environmental harm (0.590), pollution and high energy consumption (0.599), and the conflict between rapid growth and sustainability (0.659)—are drawn predominantly from the institutional and economic domains, whereas the highest-severity barriers span social, environmental and economic domains in near-equal measure. This pattern is consistent with the interdependence argument developed in Section 2.3: rather than a single dominant barrier category, the data indicate a distributed severity profile in which mitigation efforts concentrated on any one domain (for example, cost alone) would leave the majority of high-severity barriers unaddressed.

Results Summary

S/N	Objectives	Key Findings	Most Significant Items
1	To determine the reliability and suitability of the barrier data for factor analysis.	The environmental and economic barrier sub-scales showed acceptable sampling adequacy, while the social barrier sub-scale exhibited weaker adequacy.	Environmental: $\alpha = 0.643$, KMO = 0.626; Economic: $\alpha = 0.556$, KMO = 0.638; Social: $\alpha = 0.565$, KMO = 0.504.
2	To identify the principal dimensions underlying the adoption barriers.	Environmental barriers exhibited the strongest component structure, followed by economic barriers, while social barriers required two components.	Environmental variance = 48.63%; Economic = 43.38%; Social = 52.58% (two components).
3	To identify the most severe barriers affecting Industry 4.0 adoption.	Public communication deficits ranked as the most severe barrier, followed by resource depletion in steelmaking industries, logistics/cash-flow inefficiency, and inefficient institutional policies.	Public communication (0.751); Resource depletion (0.742); Logistics/Cash-flow (0.729); Inefficient policies (0.721).
4	To rank the identified barriers according to their severity.	The severity ranking revealed that the most critical barriers were distributed across social, environmental, economic, and institutional domains.	Highest-ranked barriers: Public communication, Resource depletion, Logistics/Cash-flow, Inefficient policies.
5	To classify the barriers into a taxonomy for Industry 4.0 adoption.	The identified barriers were classified into seven major domains, demonstrating that adoption challenges are multidimensional.	Social, Environmental, Economic, Institutional, Technological, Organisational, and Human-Resource domains.

Discussion

The finding that environmental and economic barrier sub-scales exhibit strong, single-component structures (48.63% and 43.38% variance respectively) while social barriers require two components is consistent with Bastas and Liyanage (2018), who observe that construction firms face compounded, multi-agenda sustainability pressures that resist reduction to a single underlying cause. The two-component social structure separating technical/informational barriers (Component 1) from communication/policy barriers (Component 2) mirrors the organisational-readiness versus institutional-environment distinction drawn by Cooper and Zmud (1990) in the broader technology-diffusion literature. The prominence of public communication deficits as the single most severe barrier item extends Fracarolli Nunes and Lee Park (2017), who observed that some construction organisations limit sustainability engagement to public communication rather than substantive operational change; the present findings suggest the inverse problem may be equally significant namely, that inadequate communication of genuine sustainability efforts and technology benefits within and across organisations itself constitutes a primary adoption barrier. This nuance is not always distinguished in prior qualitative treatments and represents a modest extension of the existing literature.

The high severity of environmental barriers, particularly resource depletion in steel-intensive construction processes, corroborates Aghelie (2020), who documents acute sustainability concern within steelmaking industries feeding into construction supply chains. This finding diverges somewhat from studies conducted in more digitally mature manufacturing contexts (e.g., Frank, Dalenogare & Ayala, 2019), where technological and financial barriers typically dominate; the present results suggest that in construction-specific, emerging-economy contexts, environmental resource constraints may carry comparable or greater weight than purely technological barriers. The low reliability of the economic ($\alpha = 0.556$) and social ($\alpha = 0.565$) sub-scales warrants cautious interpretation. Rather than indicating measurement failure per se, such values are common

where a sub-scale intentionally spans conceptually distinct sub-domains (e.g., communication and policy within “social”) that do not share a single common cause, precisely the situation motivating the seven-domain taxonomy developed here. This is consistent with Chauhan et al. (2021), who caution against treating adoption barriers as a homogenous construct. For developing-country construction firms specifically, the co-dominance of institutional (inefficient policy) and economic (cash-flow, logistics) barriers alongside environmental constraints suggests that technology-focused interventions alone e.g., subsidising hardware acquisition—are unlikely to be sufficient. This aligns with Rajae et al. (2021), who argue that infrastructural and policy environments in developing economies condition the effectiveness of any purely technological intervention. For construction firms specifically, the elevated severity of environmental barriers tied to resource-intensive inputs (steel, concrete) implies that supply chain-level, rather than firm-level, interventions may be required to meaningfully reduce this barrier category. When viewed through an institutional-theory lens, the high severity of inefficient institutional policy (0.721) is consistent with DiMaggio and Powell's (1983) argument that weak coercive institutional pressure slows practice diffusion independent of firm-level economic rationale. This suggests that the barrier is not primarily a matter of individual firm capability or willingness, but of an external institutional environment that has not yet generated sufficient regulatory or professional-body pressure to compel adoption, a distinction with direct consequences for where mitigation responsibility should sit, discussed further in Section 6. The implication for developing countries is that the prominence of institutional and economic barriers in this Nigerian construction sample is consistent with a broader pattern documented across developing-economy Industry 4.0 studies, in which weak regulatory infrastructure and constrained access to affordable financing compound the technological barriers that dominate discourse in developed-economy contexts (Kamble et al., 2018; Raj et al., 2020). Unlike manufacturing-sector studies from more digitally mature economies, where the principal reported constraint is often a skills or technology gap alone (Frank et al., 2019), the present findings suggest that in developing-country construction markets, policy and financing gaps must be addressed concurrently with, rather than subsequent to, technology investment. This has direct implications for donor agencies and development finance institutions active in construction-sector digitalisation programmes: financing instruments that bundle capital access with policy-advocacy support are likely to outperform hardware-only grant schemes.

The implication for developing firms within the construction sector specifically, project-based organisational structures mean that barrier mitigation strategies effective in manufacturing settings where firm boundaries and asset ownership are stable cannot be transplanted without adaptation (Serpell & Heredia, 2012). The environmental barrier domain's dominance in this study, driven substantially by resource-intensive inputs such as steel, implies that individual contracting firms have limited unilateral capacity to reduce this barrier category, since material sourcing decisions are frequently made upstream by suppliers or specified by clients. This reinforces the case, developed further in Section 6, for supply chain-level rather than firm-level mitigation of environmental barriers, and for construction firms to engage collaboratively with material suppliers on sustainability specifications rather than treating environmental barrier mitigation as an internal operational matter alone. These findings should be interpreted in light of several limitations. The sample ($n = 184$), while drawn from experienced professionals, is geographically concentrated in Edo and Delta States and numerically modest, constraining the stability of the extracted component structure and limiting generalisability to other regional or national contexts. The below-threshold reliability of the economic and social sub-scales, discussed above, indicates that some items within these sub-scales may benefit from refinement in future instrument iterations. Finally, the cross-sectional design captures barrier severity at a single point in time; barrier salience may shift as organisations progress through adoption phases, a dynamic that longitudinal research is better positioned to capture. The severity ranking and taxonomy developed in Sections 4 and 5 translate into a set of domain-specific mitigation strategies, summarised in Table 7. Rather than presenting an undifferentiated list of recommendations, the matrix deliberately assigns responsibility to the organisational function or external actor best positioned to act on each barrier domain, reflecting the institutional-theory observation that barriers rooted in the external environment (institutional, economic) require different remediation pathways than barriers rooted in internal organisational capability (technological, human-resource, organisational).

Table 7: Mitigation Strategy Matrix

 BARRIER DOMAIN	 MITIGATION STRATEGY	 RESPONSIBLE ACTOR
 SOCIAL / COMMUNICATION	Establish structured internal and cross-partner communication protocols on sustainability performance and technology benefits	 Senior management; project leads
 ENVIRONMENTAL	Prioritise supply chain-level material efficiency programmes and low-carbon sourcing for steel-intensive inputs	 Procurement; supply chain partners
 ECONOMIC	Phased financing models (leasing, shared-service platforms) to ease cash-flow constraints of technology acquisition	 Finance function; industry associations
 INSTITUTIONAL	Engage industry bodies to advocate for clearer digital-transformation and circular-economy policy incentives	 Industry associations; regulators
 TECHNOLOGICAL	Pilot technologies on bounded, well-scoped tasks before enterprise-wide rollout to manage skill/data demands	 IT/digital transformation leads
 HUMAN-RESOURCE	Structured reskilling programmes aligned to the technology-adoption roadmap	 HR; training providers
 ORGANISATIONAL	Develop an explicit digital-transformation strategy document with defined milestones	 Executive leadership
 OVERALL GOAL: Address barrier domains through targeted mitigation strategies to accelerate technology adoption, strengthen sustainability outcomes, and enhance long-term competitiveness. 		

This is a colourful graphical illustration table of the mitigation strategy matrix together with the underlying source table.

Construction organisation leaders should treat the severity ranking in Table 6 as a prioritisation device rather than an exhaustive risk register. Because the four highest-severity barriers span four different domains (social, environmental, economic and institutional), no single departmental function can address adoption barriers unilaterally; a cross-functional digital-transformation steering group, combining procurement, finance, HR and communications, is recommended as a governance mechanism. For developing-country construction firms in particular, the co-occurrence of institutional and economic barriers suggests that firm-level action should be paired with collective, industry-association-level advocacy for clearer policy incentives, since individual firms have limited capacity to resolve institutional barriers independently (Kamble et al., 2018). Firms should also resist the temptation to treat communication as a peripheral concern: given that public communication deficits ranked as the single most severe barrier, embedding structured, ongoing communication about both sustainability performance and technology roadmaps, both internally and with supply chain partners should be treated as a core adoption enabler rather than an afterthought. The practical adoption framework in Figure 7 synthesises these recommendations into a phased sequence from barrier identification and taxonomic classification, through severity prioritisation and root-cause interpretation, to a mitigation strategy matrix and a phased roadmap moving from awareness to institutionalisation.

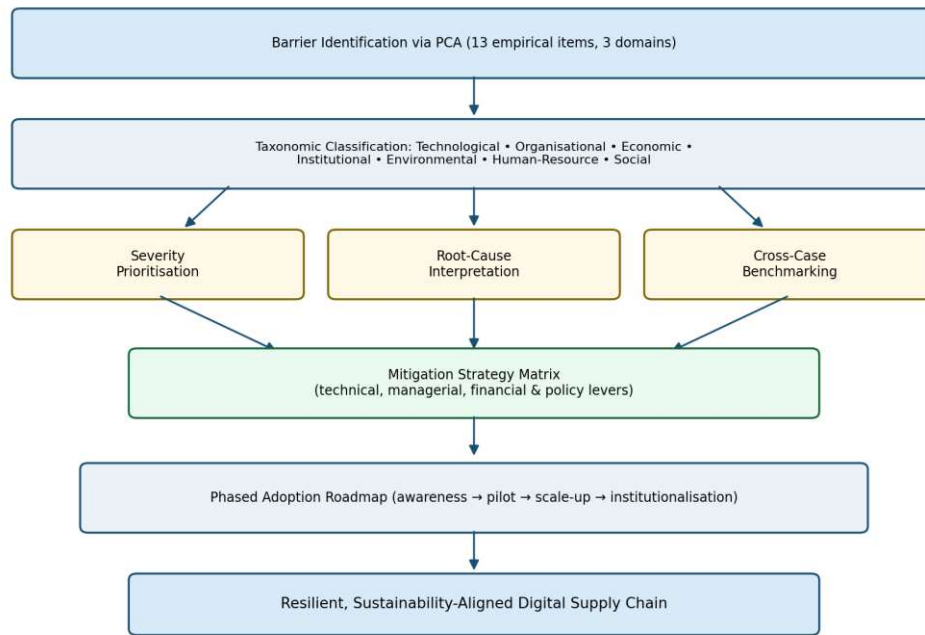


Figure 10: Practical Framework for Overcoming Adoption Barriers to Industry 4.0 Technologies in Sustainable Supply Chain Management

The phased roadmap depicted in Figure 7 is deliberately sequenced to respect the interdependence among barriers documented in Section 2.3. The awareness phase targets the organisational and social domains directly, using structured communication to build the internal case for investment before capital is committed. The pilot phase then targets technological and human-resource barriers through bounded, low-risk implementation, generating the internal evidence base needed to secure further investment. The scale-up phase addresses economic barriers through the phased financing instruments summarised in Table 7, while the institutionalisation phase—requiring the longest time horizon—addresses institutional and environmental barriers through sustained policy engagement and supply chain-level sustainability agreements. Construction organisations attempting to compress this sequence, for instance by pursuing scale-up before securing organisational buy-in during the awareness phase, are, based on the barrier-interdependence evidence discussed in Section 2.3, more likely to encounter the institutional and communication-related resistance identified as the most severe barriers in this study.

Conclusion

This study identified, classified and ranked the barriers constraining the adoption of Industry 4.0 technologies in construction sustainable supply chain management. Using PCA of survey data from 184 experienced construction professionals, the study found that environmental and economic barriers exhibit the strongest, most internally coherent structures, while social barriers are more heterogeneous, spanning distinct technical/informational and communication/policy sub-dimensions. Public communication deficits, resource depletion in steel-intensive processes, logistics/cash-flow inefficiency and inefficient institutional policy emerged as the four most severe individual barriers, collectively demonstrating that adoption constraints are genuinely multi-domain rather than concentrated in any single category such as cost or technical skill. The study's principal contributions are a seven-domain barrier taxonomy that integrates prior fragmented classifications, an empirically weighted severity ranking derived from primary construction-sector data, and a practical mitigation and adoption framework linking barrier diagnosis to managerial action. Future research should test the generalisability of this taxonomy and ranking across other developing-country construction markets, examine the temporal dynamics of barrier severity as organisations progress through adoption phases, and evaluate the effectiveness of the mitigation strategies proposed in Table 7 through longitudinal or intervention-based study designs. More broadly, the distributed severity profile documented here in which no

single barrier domain accounts for the majority of adoption resistance challenges managerial narratives that frame Industry 4.0 adoption primarily as a cost or technology-access problem. Construction organisations, industry associations and policymakers seeking to accelerate sustainable digital transformation are therefore encouraged to pursue coordinated, multi-domain interventions rather than single-lever solutions, and to treat the taxonomy and framework developed in this study as a diagnostic starting point for organisation-specific barrier assessment rather than a universally fixed severity ordering.

Recommendations

Based on the findings of this study, the following recommendations are proposed. Firstly, construction organizations should strengthen internal and external communication regarding digital transformation initiatives, as inadequate public communication emerged as the most severe barrier to Industry 4.0 adoption. Clear communication strategies can improve stakeholder awareness, acceptance, and collaboration. Secondly, government should formulate and implement supportive policies that encourage Industry 4.0 adoption through incentives such as tax reliefs, grants, low-interest financing, and regulatory frameworks that promote digital innovation within the construction industry. Also, construction firms should improve logistics management and financial planning by investing in digital systems that enhance supply chain visibility, optimize resource allocation, and improve cash flow management, thereby reducing major economic barriers to technology adoption. Thirdly, industry stakeholders should promote environmentally sustainable practices throughout the construction supply chain, particularly by encouraging responsible material sourcing, efficient resource utilization, and carbon reduction initiatives to address the major environmental barriers identified in this study and Professional institutions, educational institutions, and industry associations should invest in continuous digital skills development through specialized training, certification programmes, and awareness campaigns that prepare construction professionals for Industry 4.0 technologies and improve organizational readiness. Finally, Future studies should investigate additional barriers using larger and more geographically diverse samples, while examining how these barriers evolve as organizations progress through different stages of Industry 4.0 implementation. Such studies could also employ longitudinal research designs to provide a deeper understanding of barrier dynamics over time.

Declarations

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The authors declare that they have no competing interests, financial or otherwise.

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The study was conducted in accordance with the relevant guidelines and regulations as stipulated by the Federal University of Technology, Owerri, ensuring adherence to ethical standards.

Ethics Approval

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