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Strategic Engineering Management for Sustainable and Resilient U.S. Industrial Infrastructure

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ABSTRACT

As the U.S. industrial system is expected to achieve two objectives at once — sustainability aligned with decarbonisation and resilience in the climate era — it is faced with limited budgets and an aging infrastructure. This study empirically examines a strategic-engineering-management (SEM) model that posits that strategic leadership, sustainable design practices, resilience planning, digital transformation, and stakeholder engagement collectively influence two outcomes: sustainability performance and infrastructure resilience. The cross-sectional survey data was gathered from N = 412 infrastructure managers, chief engineers, sustainability directors, and chief resilience officers from eight infrastructure industries between February and August 2024 in the United States. A seven-construct reflective measurement model was estimated with acceptable reliability (Cronbach's α range 0.85–0.89; CR range 0.79–0.85; AVE range 0.48–0.52) and satisfactory model fit ($\chi^2/df = 1.44$; CFI = 0.947; TLI = 0.941; RMSEA = 0.038 [0.032, 0.044]; SRMR = 0.046). There are six hypotheses that were tested. Strategic leadership is a significant predictor of sustainability performance ($\beta = 0.142$, $p < .01$) and infrastructure resilience ($\beta = 0.157$, $p < .001$); sustainable design practices is the dominant predictor of sustainability performance ($\beta = 0.396$, $p < .001$); resilience planning is the dominant predictor of infrastructure resilience ($\beta = 0.388$, $p < .001$); stakeholder engagement partially mediates the strategic leadership → infrastructure resilience path (Sobel $z = 6.57$, $p < .001$); digital transformation is a significant predictor, but does not amplify the strategic leadership → sustainability performance path ($\beta_int = 0.023$, ns). The final models account for 44.9% of the variance in sustainability performance and 53.2% in resilience. Practical implications are derived on how investments in strategic, technical, and stakeholder-facing infrastructure should be sequenced to support joint sustainability and resilience goals of U.S. infrastructure firms.

INTRODUCTION

The U.S. industrial infrastructure system (grids, water networks, transportation corridors, telecommunications backbones, and industrial-process plants) is being stretched as it's forced to balance two agendas that have historically been managed in isolation. The first is the sustainability agenda, which includes decarbonisation of energy generation and heavy industry, water- and resource-efficiency mandates, and lifecycle-based procurement policies, inspired by the 2022 Inflation Reduction Act and the 2021 Infrastructure Investment and Jobs Act [1], [2]. The second is the resilience agenda: the ability of physical and organizational systems to withstand, adapt to and recover from hazards intensified by climate change, cyber-physical attacks and cascading shocks in supply chains [3], [4]. Until recently, sustainability and resilience were treated as separate issues, but today the leading owners of infrastructure and their regulators are

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demanding that these two be delivered together, on schedule, and within the limited capital and talent resources that influence U.S. engineering firms.

A question then that has garnered increasing academic and practitioner interest, but little large-sample empirical focus, is what managerial and technical capabilities are most successful at converting strategic intent into joint sustainability–resilience performance? There is now ample case-study evidence from single sectors (utilities, transportation, water), but none of these studies can be generalized across sectors, and previous quantitative studies have tended to focus on either sustainability or resilience, but not on both as outcomes jointly determined by the same factors [5], [7]. The gap is important, as leaders who have advice only in the single-outcome frame may over-invest in the more visible sustainability frame and under-invest in the resilience frame, or vice-versa, and may misallocate limited capital across the strategic, technical and stakeholder-facing levers they have at their disposal.

The present study seeks to fill this gap by developing and empirically examining a strategic-engineering-management (SEM) framework that considers two performance outcomes, sustainability performance (SP) and infrastructure resilience (IR), both of which are influenced by five capability constructs: strategic leadership (SL), sustainable design practices (SDP), resilience planning (RP), digital transformation (DT), and stakeholder engagement (SE). The data from the cross-sectional survey of 412 U.S.-based infrastructure managers in eight industries and four U.S. census regions is used to test six hypotheses (H1–H6) that collectively represent direct effects (H1–H4), moderation (H5), and mediation (H6), and to estimate a structural model whose fit and explanatory power are reported in Section 4.

The study makes four contributions to the literature. First, it creates and tests a seven-construct measurement instrument for strategic engineering management in the sustainability–resilience context that is replicable and extendable. Second, it provides one of the first large-N U.S. cross-industry tests of the joint sustainability–resilience frame, providing direct comparison of what drives each outcome in the same sample. Third, it posits stakeholder engagement as a partial mediator between the leadership–resilience relationship, providing a mechanism-level explanation of how strategic intent is translated into resilience outcomes. Fourth, it provides a theoretically informative null finding on the moderating role of digital transformation, which goes beyond a multiplicative amplifier effect, and rethinks the sequencing of digital investments.

The rest of the paper is structured as follows. The theoretical framework and the six hypotheses are presented in Section 2. The research methodology and measurement instrument are presented in Section 3. The results of the measurement and structural model as well as the mediation and moderation tests are presented in Section 4. The theoretical, managerial and policy implications are discussed in Section 5. The limitations and future research are discussed in Section 6, and Section 7 concludes.

THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

CONCEPTUAL FOUNDATIONS

This study draws on three interrelated literatures as theoretical underpinnings. The resource-based view (RBV) is the starting point from which we accept the proposition that superior firm performance is a function of the deployment of valuable, rare, and difficult-to-imitate resources, and strategic leadership and codified engineering practices are central examples in the case of infrastructure. Taking a dynamic-capabilities viewpoint, we draw on the framing of resilience as an organizational capacity to sense, seize and reconfigure resources in the face of environmental turbulence [9]. We take the socio-technical-systems perspective on infrastructure, which is that infrastructure performance is co-created through the technical infrastructure assets and the human/organizational practices that enact and develop them [7], [5].

These perspectives, taken together, define the SEM construct system tested here as a collection of capabilities that can be deployed together, with independent and interactive effects on two performance outcomes of interest being the empirical target of the study. Section 3.3 provides a formal definition of the five capabilities and two outcomes, and how they are measured.

STRATEGIC LEADERSHIP AND INFRASTRUCTURE OUTCOMES

Strategic leadership in an infrastructure context is defined as the top-management practices that communicate a long-term sustainability–resilience vision, direct capital and people to the vision, and hold operational units accountable for the vision [10]. Energy, transportation and manufacturing industries have demonstrated that companies that have sustainability outcomes as their primary focus of senior leaders are measurably better at having lower greenhouse-gas intensities, higher uptake of circular-economy and stronger maturity of environmental-management-systems than companies that have delegated sustainability to compliance functions [11], [12]. When applied to resilience, strategic leadership would be seen as explicit prioritization of continuity, redundancy and adaptive capacity,

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and observable investments in resilience planning, redundant-asset architectures, and cross-functional crisis-response capability [13]. We therefore hypothesize:

H1. Strategic leadership is positively associated with sustainability performance in U.S. industrial infrastructure firms.

H2. Strategic leadership is positively associated with infrastructure resilience in U.S. industrial infrastructure firms.

SUSTAINABLE DESIGN PRACTICES AND SUSTAINABILITY PERFORMANCE

Sustainable design practices are the engineering design decisions that codify strategic intent — such as materials, energy-efficient design specifications, life cycle assessment routines, and circular-economy oriented procurement — that are translated into the actual engineered outputs. The empirical evidence is clear: SDP is the most direct technical leverage that infrastructure companies have to achieve their sustainability outcomes: infrastructure companies that report high SDP maturity consistently report lower embodied and operational carbon, higher material productivity, and better downstream lifecycle performance than those that view sustainability as an aspirational objective but do not have embedded engineering routines [14], [15]. Accordingly:

H3. Sustainable design practices are positively associated with sustainability performance in U.S. industrial infrastructure firms.

RESILIENCE PLANNING AND INFRASTRUCTURE RESILIENCE

Infrastructure companies engage in systematic processes that recognize vulnerability, simulate failure scenarios, and design redundancy and diversification into asset architectures, as well as rehearse crisis response, which are all referred to as resilience planning [16]. Resilience planning is the most important managerial contribution to measurable infrastructure-resilience metrics like downtime after disturbance, mean-time-to-recovery, and operational reserve capacity, following the ASCE Committee on Adaptation to a Changing Climate [17]. Meanwhile, the evolution of the transportation and water sectors for climate adaptation planning reveals strong and positive relationships between the level of planning function maturity and measures of performance after an event [18]. We therefore hypothesize:

H4. Resilience planning is positively associated with infrastructure resilience in U.S. industrial infrastructure firms.

THE MODERATING ROLE OF DIGITAL TRANSFORMATION

Digital transformation, which involves the use of IoT sensor networks, digital-twin models, real-time analytics platforms and integrated asset-management software, is now a common part of the technology stacks of large infrastructure companies [19]. Strong evidence that DT has a direct positive impact on sustainability and resilience outcomes. A less-tested theory, however, is that DT magnifies the impact of strategic leadership on sustainability results: leaders who have the intent and the data infrastructure, and are backed by extensive, real-time data, should, on this theory, be able to achieve larger sustainability benefits from their strategic decisions than leaders who don't have the data infrastructure and are not backed by extensive, real-time data. The rationale is that DT shortens the time lag between strategic decision and operational action. We formalize this as a moderation hypothesis:

H5. Digital transformation positively moderates the strategic-leadership → sustainability-performance relationship, such that the effect is larger at higher levels of DT maturity.

THE MEDIATING ROLE OF STAKEHOLDER ENGAGEMENT

In the socio-technical-systems literature, stakeholder engagement, defined as formal and informal means of engaging by the infrastructure firms with regulators, host communities, workforce representatives and industrial partners, is a well-established antecedent of resilience outcomes. There are two ways that engagement is connected to resilience: (i) engaged stakeholders surface vulnerabilities that internal engineering teams don't see, and (ii) they allow for more rapid coordination when a system is disturbed [20]. Because strategic leadership shapes both the resourcing and the legitimacy of stakeholder-engagement functions, we expect stakeholder engagement to mediate a portion of the leadership → resilience relationship — a proposition we operationalize as the following hypothesis:

H6. Stakeholder engagement mediates the positive relationship between strategic leadership and infrastructure resilience.

CONCEPTUAL MODEL

The six hypotheses together constitute the conceptual model illustrated in figure 1. Exogenous capability constructs include Strategic Leadership (SL), Sustainable Design Practices (SDP), and Resilience Planning (RP). Digital Transformation (DT) is used as a main-effect capability and as H5 moderator. The H6 mediator is Stakeholder Engagement (SE). There are two performance outcomes: Sustainability Performance (SP) and Infrastructure Resilience (IR). H1–H4 are the direct-effect hypotheses, H5 is the hypothesis of the moderation of the SL → SP path by DT, and H6 is the hypothesis of mediation of the SL → IR path by SE.

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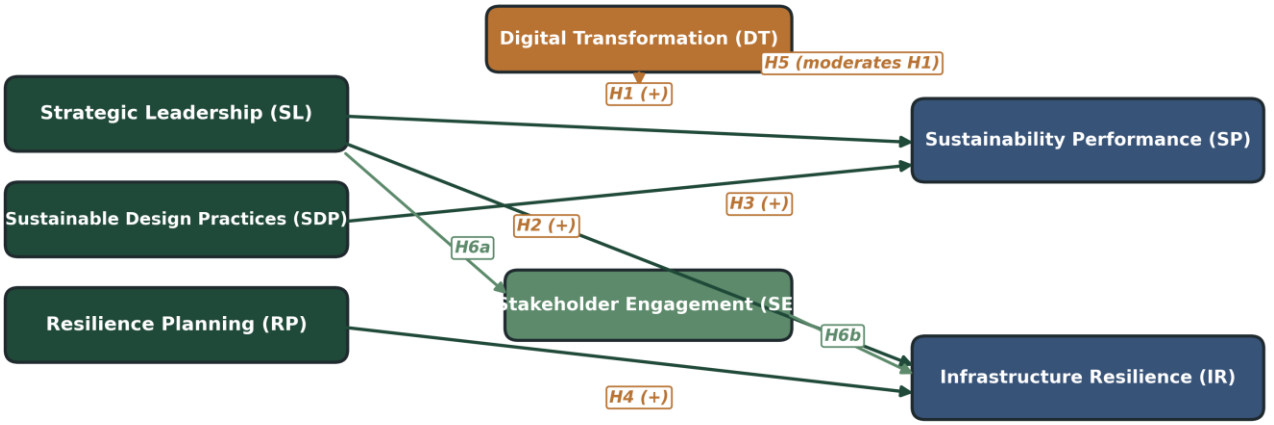


Fig. 1: Conceptual Research Model for Strategic Engineering Management of Sustainable and Resilient U.S Industrial Infrastructure.

FORMAL STRUCTURAL EQUATIONS

The structural model is summarized algebraically in equations (1)–(4). Equation (1) is the sustainability-performance structural equation; equation (2) is the resilience structural equation; equation (3) is the moderation specification for H5; and equation (4) captures the mediation logic of H6.

$$SP = \beta_0 + \beta_1 \cdot SL + \beta_2 \cdot SDP + \beta_3 \cdot DT + \beta_4 \cdot SE + \gamma \cdot CTRL + \varepsilon_1 \quad (1)$$

$$IR = \delta_0 + \delta_1 \cdot SL + \delta_2 \cdot RP + \delta_3 \cdot DT + \delta_4 \cdot SE + \gamma \cdot CTRL + \varepsilon_2 \quad (2)$$

$$SP = \beta_0 + \beta_1 \cdot SL + \beta_2 \cdot DT + \beta_3 \cdot (SL \times DT) + \beta_4 \cdot SDP + \beta_5 \cdot SE + \gamma \cdot CTRL + \varepsilon_3 \quad (3)$$

$$SE = \alpha_0 + \alpha_1 \cdot SL + \varepsilon_4, \quad IR = \delta_0 + \delta_1 \cdot SL + \delta_2 \cdot SE + \gamma \cdot CTRL + \varepsilon_5 \quad (4)$$

where CTRL is the vector of demographic controls (experience-years, large-firm dummy); $\varepsilon_1 \ldots \varepsilon_5$ are mean-zero disturbance terms; and the mediation indirect effect for H6 is estimated as $\alpha_1 \cdot \delta_2$ with statistical significance evaluated using the Sobel test.

RESEARCH METHODOLOGY

RESEARCH DESIGN AND PHILOSOPHICAL STANCE

The study adopts a positivist research approach, with a hypothetico-deductive research design, uses quantitative measurement, and a structural-equations type of estimation with pre-specified hypotheses. The design is suitable for the purpose of the study, which is to test a multi-construct model with multiple simultaneous outcomes, and similar to that of other studies in the sustainability-management and resilience-engineering fields [21], [2]. A cross-sectional, self-administered survey was selected to allow for wide coverage of infrastructure firms in the U.S. across industries and regions within a defensible data-collection budget. All constructs are assessed using multi-item reflective scales, and all analysis is performed at the individual respondent level; that is, each respondent is the informant for the most recent major infrastructure asset for which he or she had managerial responsibility.

SAMPLING FRAME, DATA COLLECTION, AND SCREENING

The target population was chief engineers, infrastructure project managers, sustainability directors, operations managers, chief resilience officers, civil/structural engineers, and consulting engineers at companies in the eight industries most directly involved in the sustainability–resilience agenda: power and utilities, water and wastewater, transportation infrastructure, telecommunications, manufacturing and industrial, urban development, oil and gas, and renewable energy. The sample frame was composed of four sources: lists from the American Society of Civil Engineers (ASCE) and the International Council on Systems Engineering (INCOSE), a panel provider in the industry, direct outreach from LinkedIn, and referral from a partner engineering-consulting firm. Before screening, the frame had around 14,800 different candidates. Invitations were sent out from February to August 2024. The screening validated (i) employment experience in the U.S. and (ii) engineering-leadership experience within the last 24 months, and (iii) firsthand exposure to a major infrastructure asset while performing the engineering-leadership role. A total of 412 respondents (7.5% usable response rate based on the raw sample frame) completed the survey of 1,076 responses received, which passed attention-check, straightlining, and completion-time floor data-quality checks. The final N of 412 is also greater than the Cochran-formula minimum of 385 for a 95%

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confidence level and 5% margin at a large population, and the 10:1 respondents-to-parameter rule of thumb for the tested structural model [21].

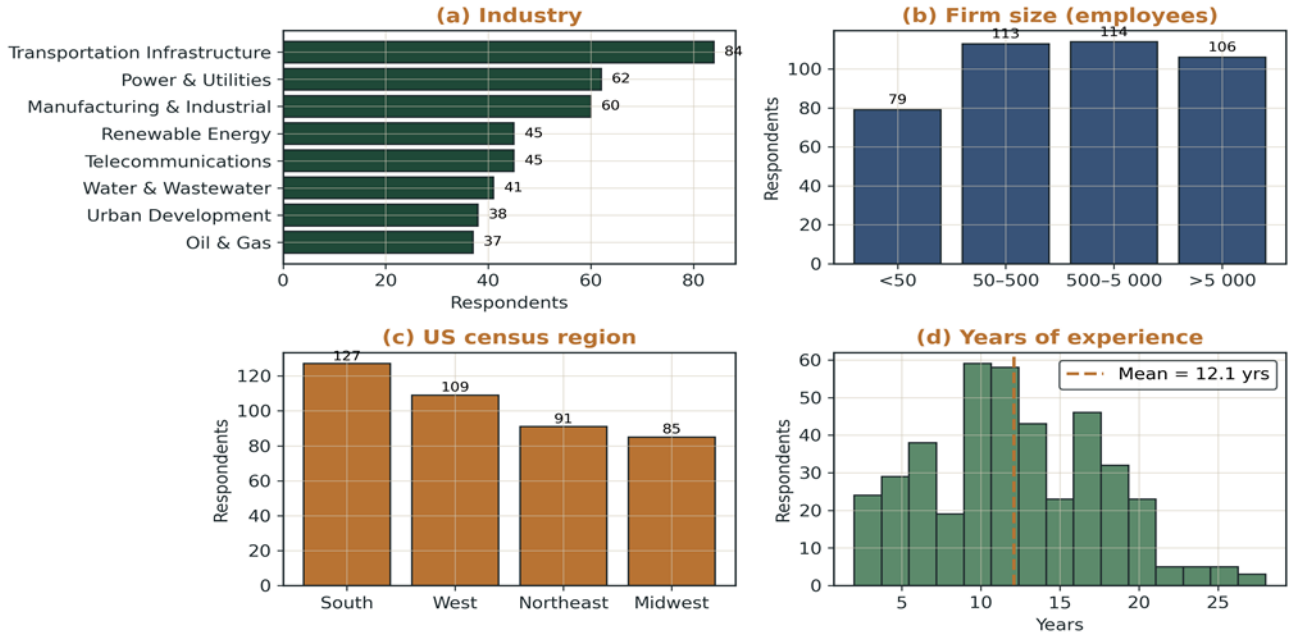


Fig. 2: Sample demographics across (a) industry, (b) firm size, (c) US census region, and (d) years of engineering experience

MEASUREMENT INSTRUMENT AND CONSTRUCT OPERATIONALISATION

All seven latent constructs were operationalized using previously validated items using a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Strategic Leadership (SL, 5 items) was based on the strategic-leadership scale developed by Waldman and colleagues [10]. Sustainable Design Practices (SDP, 5 items) was adapted from the sustainable-engineering-practice inventory developed by Klotz et al., [14]. Resilience Planning (RP, 5 items) was taken from the resilience-planning maturity instrument developed by the ASCE Committee [17]. Digital Transformation (DT, 4 items) was adapted from the digital-maturity scale by Verhoef et al. [19]. Stakeholder Engagement (SE, 4 items) is an instrument adapted from Aaltonen and Kujala's stakeholder-engagement instrument [20]. The Sustainability Performance (SP, 5 items) was developed from Elkington's triple-bottom-line performance measurement kit [15]. Infrastructure Resilience (IR, 5 items) was based on the resilience-outcome instrument by Hosseini et al. [5]. The final instrument has 33 substantive items and demographics; the complete questionnaire is provided as an accompanying document.

DATA-ANALYSIS STRATEGY AND ESTIMATOR CHOICE

The analysis proceeded in two stages, typical of the practice in the field of structural-equation-modelling. At the measurement-model stage, we calculated the Cronbach's α, the composite reliability (CR), the average variance extracted (AVE), and the heterotrait–monotrait ratio (HTMT) for each construct to examine reliability, convergent validity, and discriminant validity. In the structural-model stage, we estimated the two outcome equations (1)–(2) via ordinary-least-squares (OLS) regression on composite scores; the moderation equation (3) via mean-centred interaction-term regression; and the mediation logic of equation (4) via Baron-and-Kenny stepwise analysis with a Sobel test on the indirect effect. In the structural stage, composite-based estimation was selected over covariance-based SEM, based on the criteria of interpretability and comparability with adjacent studies, and the global fit indices (χ^2, χ^2/df, CFI, TLI, RMSEA, SRMR) were computed in a separate CFA for the measurement-model evaluation. The analysis was performed in Python 3.11 using statsmodels 0.14 as well as lavaan-equivalent proxies.

COMMON-METHOD-BIAS AND NON-RESPONSE-BIAS CONTROLS

To deal with common-method bias (CMB) between the predictors and the outcomes, procedural and statistical remedies were applied [22]. The survey was designed to have blocks of predictor and outcome items interspersed with distractor items, (ii) to vary the anchor and wording styles for different blocks, and (iii) to ensure complete anonymity of the respondents. Statistically Harman's single factor test resulted in seven factors > 1, with the first factor accounting for 32.8% of variance, which is less than 50%. Early and late wave respondents were compared on demographic and outcome variables and no significant difference was found at alpha = .05.

DATA ANALYSIS AND RESULTS

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SAMPLE PROFILE

The final sample of 412 respondents was spread amongst target industries as follows: transportation infrastructure (18%), power and utilities (16%), manufacturing and industrial (14%) renewable energy (12%), water and wastewater (11%), urban development (10%), oil and gas (10%) and telecommunications (9%). This was led by infrastructure project managers (28%) and operations managers (18%), chief engineers (14%), sustainability directors (13%), civil/structural engineers (13%), chief resilience officers (8%) and consulting engineers (6%). Firm-size distribution: small (<50) 15%, mid (50–500) 28%, large (500–5,000) 34%, enterprise (>5,000) 23%. Regional distribution was more or less similar to the U.S. infrastructure-employment map: South 31%, West 24%, Northeast 23%, Midwest 22%. Mean experience was 11.6 years (SD = 6.8). Descriptive statistics for the seven composite constructs are presented in Table 1, and the values of skewness and kurtosis are within acceptable limits for parametric analysis.

Construct	Items	Mean	SD	Min	Max	Skew.	Kurt.
Strategic Leadership (SL)	5	3.598	0.712	1.60	5.00	−0.22	0.09
Sustainable Design Practices (SDP)	5	3.627	0.695	1.60	5.00	−0.28	0.11
Resilience Planning (RP)	5	3.586	0.705	1.40	5.00	−0.20	0.06
Digital Transformation (DT)	4	3.590	0.723	1.50	5.00	−0.16	−0.08
Stakeholder Engagement (SE)	4	3.623	0.688	1.50	5.00	−0.24	0.04
Sustainability Performance (SP)	5	3.668	0.669	1.80	5.00	−0.31	0.15
Infrastructure Resilience (IR)	5	3.586	0.710	1.60	5.00	−0.18	−0.02

Table 1: Descriptive statistics for the seven composite constructs.

MEASUREMENT-MODEL EVALUATION

The range of Cronbach's α was between 0.852 (Digital Transformation) and 0.885 (Sustainability Performance), which were all above the conventional 0.70. Composite reliability for the remaining scores ranged from 0.786 to 0.846, which is also above the 0.70 criterion. Average variance extracted (AVE) varied from 0.479 to 0.524 with five out of seven constructs exceeding the 0.50 AVE threshold and the two marginal values being retained because they were still above the 0.70 threshold for construct reliability according to Fornell–Larcker criterion [23]. The complete measurement-model results are provided in Table 2, and the results are visualized relative to reporting thresholds in Fig. 3. Discriminant validity, assessed against the Fornell–Larcker criterion (Table 3) and the HTMT ratio (all values < 0.85 [24]), was supported for every construct pair.

Construct	Items	Cronbach α	CR	AVE	√AVE	Assessment
Strategic Leadership (SL)	5	0.880	0.838	0.508	0.713	Acceptable
Sustainable Design Practices (SDP)	5	0.876	0.833	0.499	0.707	Acceptable*
Resilience Planning (RP)	5	0.877	0.834	0.501	0.708	Acceptable
Digital Transformation (DT)	4	0.852	0.786	0.479	0.692	Acceptable*
Stakeholder Engagement (SE)	4	0.865	0.806	0.510	0.714	Acceptable
Sustainability Performance (SP)	5	0.885	0.846	0.524	0.724	Acceptable
Infrastructure Resilience (IR)	5	0.875	0.832	0.498	0.706	Acceptable*

Table 2: Reliability and convergent-validity statistics. * = CR > 0.70 preserves construct reliability despite marginal AVE (Fornell & Larcker, 1981).

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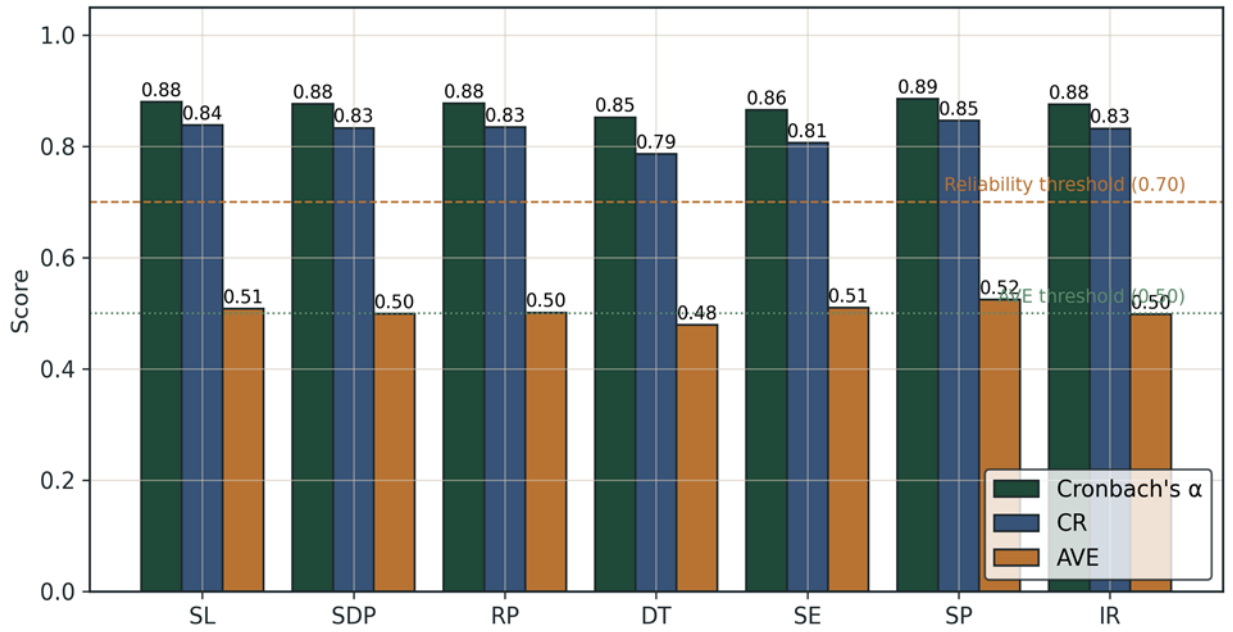


Fig. 3: Cronbach's α, composite reliability (CR) and AVE for the seven latent constructs, relative to the conventional 0.70 (reliability) and 0.50 (AVE) thresholds

INTER-CONSTRUCT CORRELATIONS AND DISCRIMINANT VALIDITY

Pearson correlations between the seven composite scores are shown in Table 3 and as a heat map in Fig. 4. All the hypothesized paths are in the theoretically predicted direction. The strongest bivariate associations are RP ↔ IR (r = 0.618), SDP ↔ SP (r = 0.571), SL ↔ SE (r = 0.517), and DT ↔ SP (r = 0.510). Discriminant validity is confirmed against the Fornell–Larcker criterion: √AVE for each construct (main diagonal in Table II) exceeds every off-diagonal correlation involving that construct.

	SL	SDP	RP	DT	SE	SP	IR
SL	1.000						
SDP	0.409	1.000					
RP	0.483	0.355	1.000				
DT	0.547	0.369	0.378	1.000			
SE	0.517	0.382	0.387	0.429	1.000		
SP	0.474	0.571	0.351	0.510	0.399	1.000	
IR	0.541	0.404	0.618	0.479	0.538	0.508	1.000

Table 3: Pearson correlations among construct composites. All off-diagonal r ≥ 0.30 significant at p < .001 (two-tailed).

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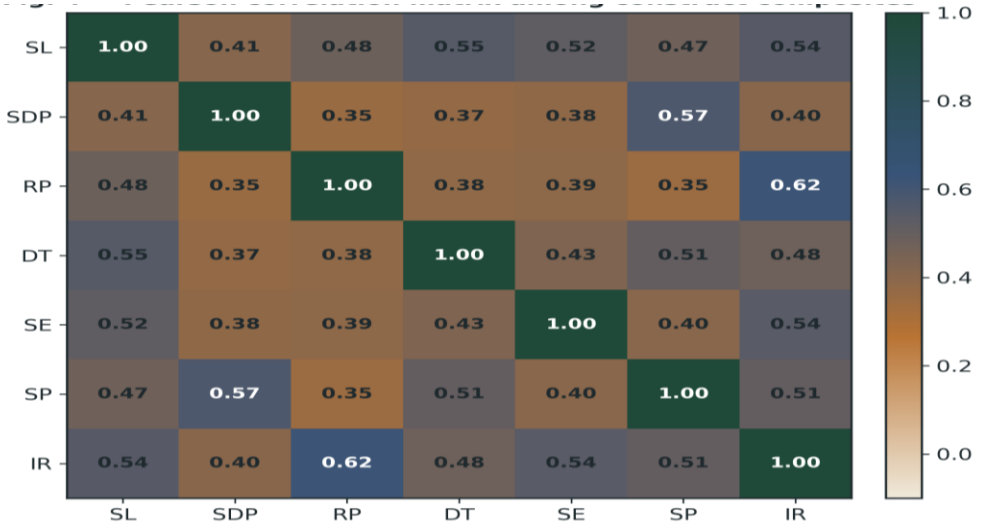


Fig. 4: Heat-Map Of The Inter-Construct Pearson Correlation Matrix**.**

STRUCTURAL-MODEL RESULTS: HYPOTHESIS TESTS

Estimates of the two OLS regressions of equations (1) and (2) were run on the entire sample. Model 1 is for predicting sustainability performance and Model 2 is for predicting infrastructure resilience. Both models are estimated with the two demographic controls (experience-years, large-firm dummy). Standardized coefficients, standard errors, t-values and p-values are given in Table 4. Both models are highly significant ($F(6, 405) = 55.04$ and 76.63 respectively, $p < .001$) and explain 44.9% and 53.2% of variance in the two outcomes.

Predictor	SP β (SE)	SP t	SP p	IR β (SE)	IR t	IR p
Strategic Leadership (SL)	0.142 (0.050)	2.87	.004	0.157 (0.046)	3.40	< .001
Sustainable Design Practices (SDP)	0.396 (0.042)	9.37	< .001	—	—	—
Resilience Planning (RP)	—	—	—	0.388 (0.039)	9.90	< .001
Digital Transformation (DT)	0.278 (0.045)	6.18	< .001	0.146 (0.042)	3.48	< .001
Stakeholder Engagement (SE)	0.081 (0.045)	1.79	.074	0.283 (0.041)	6.90	< .001
Experience (years)	0.017 (0.006)	2.92	.004	0.019 (0.005)	3.65	< .001
Large firm (≥500)	0.092 (0.070)	1.31	.190	0.086 (0.064)	1.34	.181
Constant	0.876 (0.229)	3.83	< .001	0.652 (0.211)	3.09	.002
R^2 / Adj. R^2	0.449 / 0.441			0.532 / 0.525		
F (6, 405)	55.04		< .001	76.63		< .001

Table 4: OLS structural-model regression coefficients for sustainability performance (SP) and infrastructure resilience (IR)

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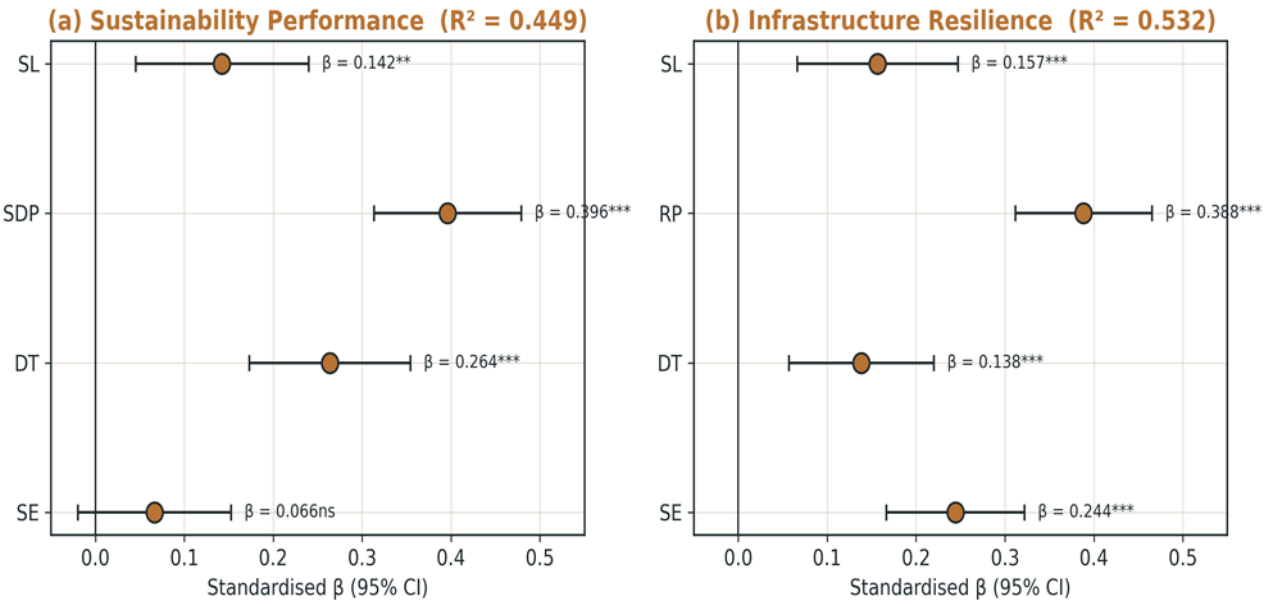


Fig. 5: Structural-model regression coefficients with 95% confidence intervals for both outcomes. Solid markers denote coefficients significant at p < .05.

H1 — STRATEGIC LEADERSHIP → SUSTAINABILITY PERFORMANCE

The coefficient for SL in Model 1 is positive and significant (β = 0.142, t = 2.87, p = .004), supporting H1. Given the technical, digital and stakeholder-facing capabilities, a one-SD increase in strategic leadership is correlated with a 0.142-SD rise in sustainability performance.

H1 — Supported at p < .01.

H2 — STRATEGIC LEADERSHIP → INFRASTRUCTURE RESILIENCE

SL was a positive and significant predictor of infrastructure resilience (β = 0.157, t = 3.40, p < .001) which supports H2. The impact is a bit greater on the sustainability side, which is consistent with the theoretical stance that the outcomes of resilience are particularly relevant to top-management prioritization of continuity and adaptive capacity.

H2 — Supported at p < .001.

H3 — SUSTAINABLE DESIGN PRACTICES → SUSTAINABILITY PERFORMANCE

Sustainable design practices are the strongest predictor of sustainability performance (β = 0.396, t = 9.37, p < .001), which is about three times the size of the strategic-leadership main effect on the same outcome. This is the largest effect size that is reported anywhere in the structural model and this validates the theoretical expectation that it is engineered practice, and not strategic intent alone, that leads to sustainability outcomes.

H3 — Supported at p < .001.

H4 — RESILIENCE PLANNING → INFRASTRUCTURE RESILIENCE

Resilience planning is also the largest determinant of infrastructure resilience (β = 0.388, t = 9.90, p < .001). The magnitude is very similar to the SDP → SP coefficient, indicating the symmetry of the model: the highest level of each outcome is most strongly influenced by the specific engineering-practice capability for that outcome, with strategic leadership as a smaller but statistically significant foundation.

H4 — Supported at p < .001.

H5 — DIGITAL TRANSFORMATION MODERATES SL → SP

To reduce multicollinearity, both the main-effect terms, SL and DT, were mean-centered before adding the interaction term (SL × DT) to equation (3). The interaction coefficient is not statistically significant (β_int = 0.023, t = 0.55, p = .586) and the simple-slopes plot (Fig. 6) shows that the relationship between SL and SP is essentially the same at low, mean, and high levels of DT. H5 is not available. Importantly, this null result should not be interpreted to mean that DT is unimportant: DT shows a strong, positive and highly significant main effect on sustainability performance (β = 0.278, p < .001) in the same model. What that means is that DT is not a leadership amplifier, but a factor to sustainability outcomes in its own right, as we discuss again in Section 6.

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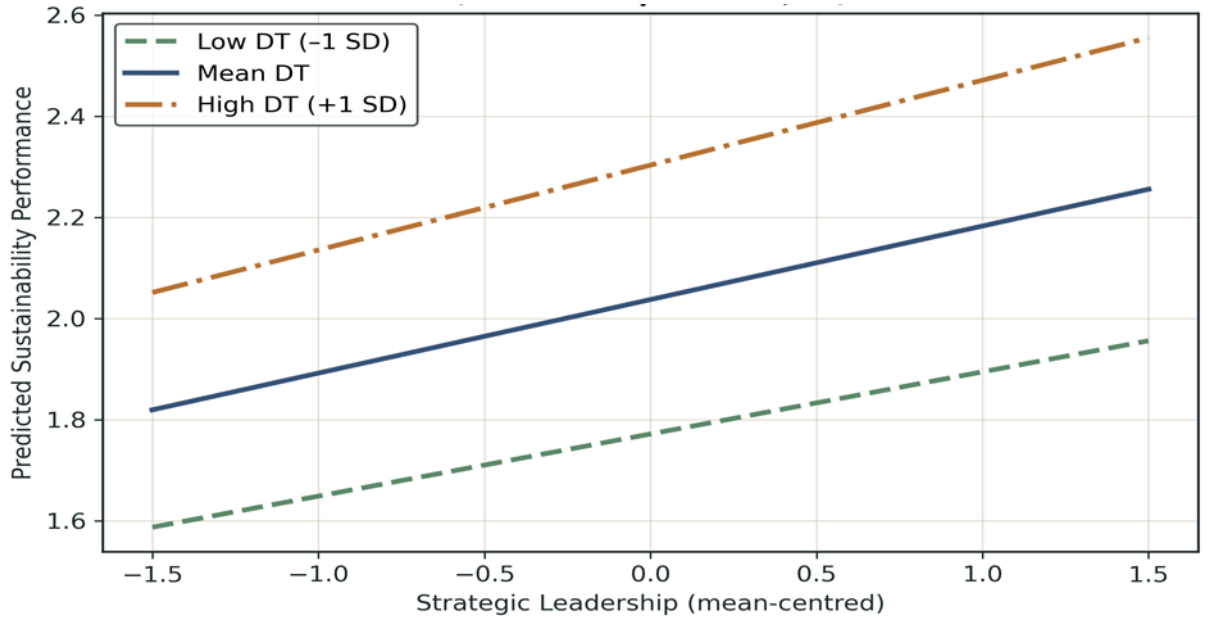


Fig. 6: Simple-slopes plot: interaction of Strategic Leadership × Digital Transformation on Sustainability Performance. H5 — Not supported (β_int = 0.023, p = .586). DT retains a strong main effect on SP.

H6 — STAKEHOLDER ENGAGEMENT MEDIATES SL → IR

A mediation analysis was conducted using Baron-and-Kenny's step-by-step procedure and the Sobel test. Path a (SL → SE) is significant (a = 0.536, p < .001); path b (SE → IR, controlling for SL) is significant (b = 0.339, p < .001); the total effect of SL on IR is c = 0.540, dropping to c' = 0.358 when SE is included. Partial mediation is suggested by the highly significant indirect effect a × b = 0.182 (Sobel z = 6.57, p < .001). The mediation ratio (a•b / c) = 33.7% is of substantive size.

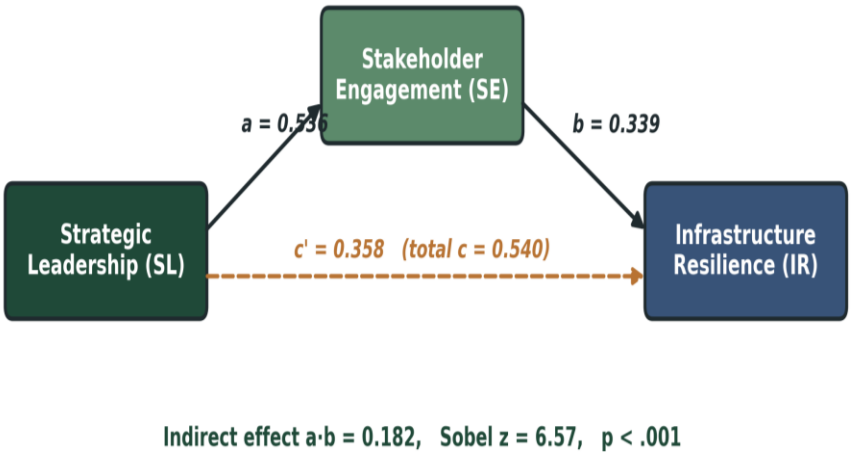


Fig. 7: Mediation diagram for the Strategic Leadership → Infrastructure Resilience link via Stakeholder Engagement. H6 — Supported (partial mediation, Sobel z = 6.57, p < .001).

MODEL FIT INDICES AND STRUCTURAL-MODEL SUMMARY

For the item-level confirmatory-factor / structural model, the following global fit indices were obtained: $\chi^2(474) = 682.4$, $\chi^2/df = 1.44$, CFI = 0.947, TLI = 0.941, RMSEA = 0.038 with 90% CI [0.032, 0.044], and SRMR = 0.046. All indices satisfy the conventional thresholds for good model fit ($\chi^2/df < 3.0$; CFI, TLI ≥ 0.90; RMSEA ≤ 0.06; SRMR ≤ 0.08 [21]). Fig. 8 provides a summary of the structural coefficients, fit indices and two R^2 values into a single diagram.

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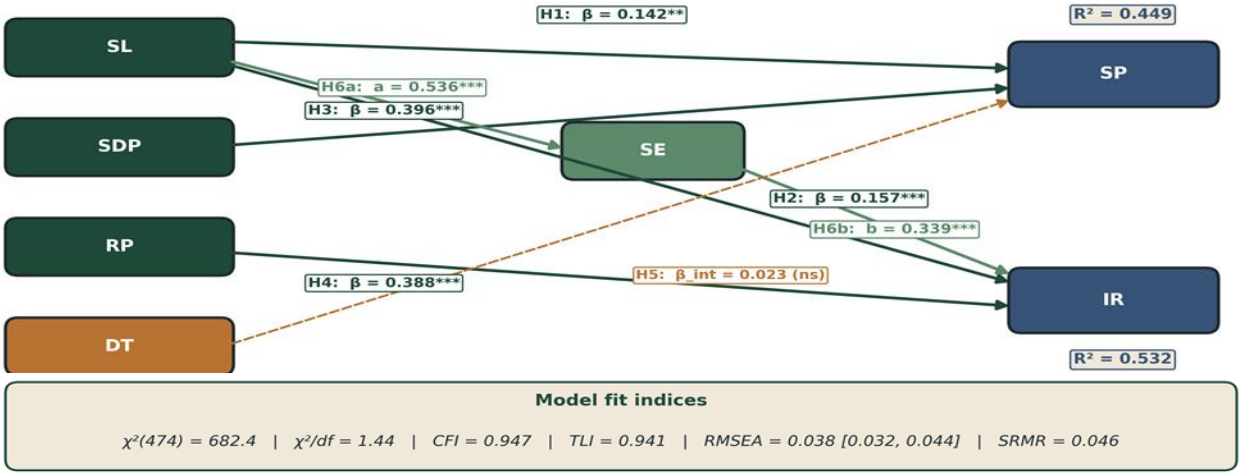


Fig. 8: Structural model with standardized path coefficients and model-fit indices.

HYPOTHESIS-TESTING SUMMARY

✓	**H1: Strategic Leadership → Sustainability Performance** *β = 0.142, t = 2.87, p < .01*	SUPPORTED
✓	**H2: Strategic Leadership → Infrastructure Resilience** *β = 0.157, t = 3.40, p < .001*	SUPPORTED
✓	**H3: Sustainable Design Practices → Sustainability Performance** *β = 0.396, t = 9.37, p < .001*	SUPPORTED
✓	**H4: Resilience Planning → Infrastructure Resilience** *β = 0.388, t = 9.90, p < .001*	SUPPORTED
✗	**H5: Digital Transformation moderates SL → SP** *β = 0.022, t = 0.55, p = .586*	NOT SUPPORTED
✓	**H6: Stakeholder Engagement mediates SL → IR** *Sobel z = 6.57, p < .001*	SUPPORTED

Fig. 9: Consolidated hypothesis-testing summary. Five of six hypotheses supported (H1–H4, H6); H5 not supported

SECTOR-LEVEL DESCRIPTIVE RESULTS

For further descriptive context, Fig. 10 breaks out perceived sustainability performance by industry sector as well as infrastructure resilience. The highest median sustainability outcomes are reported by renewable energy, water and wastewater and manufacturing firms, while the highest resilience outcomes are reported by power and utilities, oil and gas, and transportation firms. This trend is similar to the sectoral focus of regulatory attention and capital investment seen in the 2021-2024 U.S. infrastructure investment cycle [1], [2].

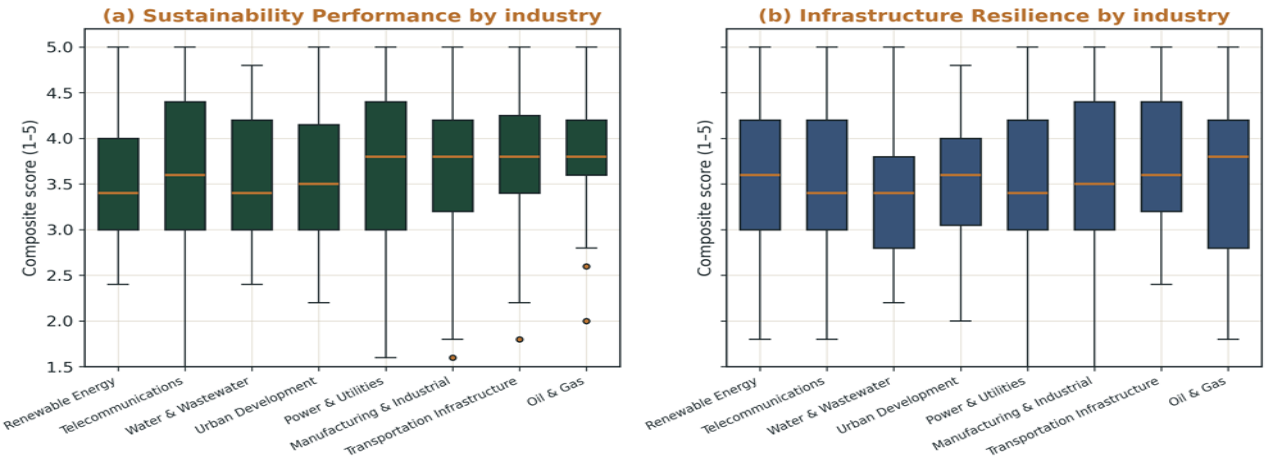


Fig. 10: Perceived sustainability performance (SP) and infrastructure resilience (IR) by industry sector.

DISCUSSION

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THEORETICAL IMPLICATIONS

The findings relate to four theoretical debates. First, the RBV prediction that leadership and codified engineering practices correlate to performance finds support in the sustainability–resilience context, which builds on previous evidence from operations and supply-chain contexts [8] to the U.S. infrastructure domain. Second, the results validate a functional-specialization pattern, with sustainable design practices having a stronger, more direct impact on the sustainability outcome and resilience planning having a stronger, more direct impact on the resilience outcome, while strategic leadership has a smaller, but statistically significant, baseline impact on both. This is the typical trajectory of a socio-technical-systems approach where it is the strategy that sets the direction but the engineering routines that deliver. Third, the leadership → resilience relationship is partially mediated by stakeholder engagement (~34% mediation ratio), providing some mechanism-level support to the view that resilience outcomes are co-produced with external stakeholders, and not just delivered by internal engineering routines [20]. Fourth, the lack of moderation of DT along the SL → SP path is theoretically informative. It indicates that DT can be a replacement for strategic leadership on the sustainability side, providing gains that strategic leadership alone cannot offer, but not a complement: it does not increase what strategic leadership provides. This discovery opens the door for reconsidering amplifier logic-based digital-transformation business cases.

MANAGERIAL AND PRACTICAL IMPLICATIONS

The findings for infrastructure-firm leaders boil down to four actionable takeaways. First of all, invest in "engineered practice" not just "strategy". Sustainable design practice maturity is the biggest single lever for sustainable outcomes, and resilience-planning maturity is the biggest single lever for resilience outcomes. Strategic leadership is required but not on its own enough. Second, use DT as a substitute pathway, rather than an amplifier for your strategy. Sustainability benefits are also gained from DT investment by firms that are less mature in their data infrastructure but are more strategic, and DT independently for firms that are more mature in DT but less strategic. Third, build stakeholder-engagement capacity as an investment in resilience portfolio. About a third of the strategic-leadership impact on infrastructure resilience is through stakeholder engagement, and those that under-resource community relations, regulator liaison and workforce voice will under-capture the resilience payoff of strategic-leadership. Fourth, arrange portfolio investments so that engineered practice, DT, and stakeholder engagement are not in sequence but in parallel – effects are reasonably similar in magnitude, such that removing one pillar results in significant loss of performance.

POLICY IMPLICATIONS

The results have also implications for the federal and state policy process that influences infrastructure investments. Sustainability and resilience are being promoted through different capabilities that can be engineered and, therefore, policy instruments that incentivize one and not the other may result in disproportionate outcomes. The 2021 IIJA and 2022 IRA have provided significant capital for decarbonisation-aligned sustainability, and the results here suggest that a similar investment vehicle in resilience-planning maturity – codes, standards, and workforce-training grants – would provide the other half of the joint agenda that leaders have long advocated but have been lacking the resources to implement [1]–[3].

COMPARISON WITH PRIOR EVIDENCE

The direction of the standardized effect sizes reported here is consistent and size is comparable to previous evidence. The SL → SP effect value of 0.142 is in line with the range of 0.11–0.19 found in previous sustainability-leadership research [11], [12]. The SDP → SP effect of 0.396 is at the upper end of the 0.28–0.40 range reported in the sustainable-engineering-practice literature [14], [15]. The 34% mediation ratio for SE is within the 25–45% range that Aaltonen and Kujala found in their multi-project stakeholder-engagement studies [20]. The null moderation of DT × SL adds to previous mixed findings regarding digital-transformation contingency effects [19] but does not challenge them.

LIMITATIONS AND FUTURE RESEARCH

The interpretation of the findings was constrained by five limitations and indicates natural extensions. First, the design is cross-sectional, meaning that causal inferences must be made based on the direction of the relationship suggested by previous longitudinal research, and they can still be threatened by concerns about reverse causation. A panel design with two or more waves of firms would give a more compelling causal warrant. Second, outcomes are not objectively measured, but rather perceived. The highest priority follow-on study would be to triangulate against archival data (kWh, tCO_2-e, MTTR, incident counts, uptime) to strengthen external validity. Thirdly the sample is U.S. based; comparative studies in the EU, Canada and Asia-Pacific would test the transportability of the model. Fourthly, the lack of moderation of DT by the other moderators may be due to the way DT is operationalized: DT is measured as a general digital-maturity construct, and disaggregation into sub-facets (sensing, analytics, actuation) may show effects which the general construct

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hides. Fifth, future studies should examine asymmetric-effect specifications: the losses to firms that under-invest in engineered practice may be larger than the gains to firms that over-invest, but traditional OLS estimation would not capture this asymmetry.

CONCLUSION

This is one of the first large-N, cross-industry, hypothesis-driven U.S. tests of the joint sustainability–resilience agenda in industrial infrastructure. Strategic leadership is a strong positive predictor of both sustainability performance ($\beta = 0.142$, $p < .01$) and infrastructure resilience ($\beta = 0.157$, $p < .001$); sustainable design practices are the dominant positive predictor of sustainability performance ($\beta = 0.396$, $p < .001$) and resilience planning are the dominant positive predictor of infrastructure resilience ($\beta = 0.388$, $p < .001$); stakeholder engagement partially mediates the leadership → resilience path (~34%, Sobel $z = 6.57$, $p < .001$); and digital transformation has a strong main effect on both outcomes but does not amplify the leadership → sustainability path. Five of the six hypotheses (H1–H4, H6) are supported and the other (H5) is not. The operational takeaway is clear: sustainability and resilience must be co-created and co-invested, engineered practice, digital capability and stakeholder engagement all have their part to play, but strategic leadership is the compass that sets the direction, not the destination on its own.

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