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The Human Factor in Construction 4.0: Impact of Digital Transformation on Worker Awareness, Critical Thinking, and Accountability

Rizwan Farooqui[1], Abid Hassan[1], Muhammad Umer[2] and Syed Ahmed[1]
[1]Mississippi State University, [2]University of West Florida

The construction industry is undergoing a rapid digital transformation through technologies such as Building Information Modeling (BIM), Digital Twins, Artificial Intelligence (AI), robotics, and augmented and virtual reality (AR/VR), and wearable sensors. While these tools have improved coordination, safety, and productivity, their growing use is also creating unintended behavioral consequences. This study examines how increasing reliance on digital systems influences workers' situational awareness, critical thinking, and sense of accountability in technology-driven construction settings. Survey data from professionals with varying levels of technology exposure reveal early signs of automation bias and cognitive complacency. Respondents showed moderate awareness and critical thinking but lower accountability, suggesting that digital tools may be reducing independent vigilance and ownership of decisions. Scenario-based results further indicated that those with stronger accountability were more likely to verify automated recommendations, whereas others displayed over-trust in system feedback. These findings show that Construction 4.0 tools, if adopted uncritically, can erode essential human skills and weaken professional responsibility, posing risks to safety and decision quality. The study calls for a human-centered digital strategy that restores awareness, reinforces ethical accountability, and ensures automation complements, rather than replaces human judgment in modern construction practice.

Keywords: Construction 4.0, Automation Bias, Situational Awareness, Critical Thinking, Accountability

Introduction

Construction 4.0 is driving a major shift in how construction projects are planned and executed through the integration of Building Information Modeling (BIM), Artificial Intelligence (AI), Digital Twins, the Internet of Things (IoT), augmented and virtual reality (AR/VR), and robotics. These technologies aim to improve coordination, enhance safety, and increase productivity across project delivery. BIM is widely adopted for virtual modeling, collaborative planning, and waste reduction (Ait Ouchtout et al., 2025; Rashidian et al., 2023). When combined with AI, BIM supports predictive decision-making and operational optimization (Silitonga & Jin, 2024; Metwally et al., 2024). Digital Twins extend these capabilities by enabling real-time hazard detection and data-driven decision-making through synchronized digital replicas of assets (Khajavi et al., 2023). IoT sensors further contribute by providing continuous performance and compliance data from the field (Rahman et al., 2023), while robotics help address labor shortages and improve efficiency in repetitive and hazardous tasks (Schöberl et al., 2023). Together, these technologies are transforming construction toward a more integrated, data-driven, and efficient ecosystem (Nechyporchuk et al., 2023).

However, research from other high-reliability domains suggests that automation can influence human judgment, reduce situational awareness, and shift responsibility away from individuals (Day et al., 2023; Reale et al., 2023). While the technical benefits of Construction 4.0 are well documented (Ait Ouchtout et al., 2025; Silitonga & Jin, 2024; Rahman et al., 2023), its behavioral implications for construction professionals remain largely unexplored. This study examines how interaction with digital systems influences situational awareness, critical thinking, and accountability, and whether automation affects practitioners' tendencies to verify digital outputs, rely on system recommendations, or defer responsibility during Construction 4.0 workflows.

Background and Related Work

Although digital tools offer operational and safety benefits, emerging evidence shows that automation can also introduce behavioral risks. Studies in aviation and healthcare have linked automation bias to reduced alertness and over-trust in system outputs (Day et al., 2023; Reale et al., 2023). Similar patterns are now being observed in construction, where professionals may interpret the absence of system alerts as an indication of safety, leading to reduced direct monitoring of site conditions (Tikhomirov et al., 2023; Pillajo et al., 2023). These effects raise concerns that long-term dependence on automation may weaken situational awareness and degrade professional skills (Day et al., 2023; Reale et al., 2023).

Situational awareness remains critical for effective performance in technology-driven work environments. Tools such as BIM and AR/VR enhance visualization and improve spatial understanding (Brown et al., 2023; Marois et al., 2023), yet excessive dependence on digital visualization may cause professionals to overlook real on-site cues or place unjustified confidence in modeled information (Marois et al., 2023). These concerns highlight the need to balance technological input with direct environmental observation to maintain awareness.

Digital decision-support systems have improved analytical efficiency, enabling faster and more accurate design and planning processes (Jakobo & Taifa, 2025). However, automation can discourage independent reasoning when users rely on system outputs without questioning validity or context, potentially allowing errors to go undetected (Lei et al., 2023). Prior studies suggest that technology should augment—not replace—professional judgment to preserve critical reasoning in complex project environments (Jakobo & Taifa, 2025; Johansen et al., 2023).

The diffusion of responsibility in automated environments poses additional challenges (Cheong, 2024). As digital systems increasingly participate in decision-making, responsibility for errors can become ambiguous, and professionals may defer accountability to the system itself (Savaş, 2025). Limited transparency in algorithmic processes further complicates the ability to justify decisions, underscoring the need for human oversight and clearly defined responsibility boundaries (Savaş, 2025).

Long-term reliance on automation can also weaken core professional skills such as judgment, contextual awareness, and critical reasoning (Deliu, 2024). Although AI and robotics offer operational advantages, effective outcomes still depend on human interpretation and adaptation to dynamic site conditions, suggesting that digital tools should augment rather than replace human competence (Deliu, 2024). Calls for greater transparency, documentation, and shared responsibility in digital systems highlight emerging concerns about accountability and professional agency in technology-mediated environments (Wanyama et al., 2023; Adeusi et al., 2024).

Research Gap

While Construction 4.0 research has thoroughly documented the technical and operational gains associated with BIM, AI, Digital Twins, robotics, and AR/VR (Ait Ouchtout et al., 2025; Silitonga & Jin, 2024; Rahman et al., 2023), research examining how these tools shape human cognition and behavior in construction work settings remains limited. Systematic reviews suggest that although Construction 4.0 technologies are widely studied, there is less emphasis on understanding their impact on decision-making and human interaction with digital systems (Shafei et al., 2022). In particular, fewer studies have investigated how construction professionals engage with digital recommendations during day-to-day project decisions, such as when to verify system outputs, rely on automated guidance, or assume responsibility for outcomes, despite calls for greater insight into these behavioral dynamics. Collecting empirical evidence from current industry practitioners may help clarify how professionals interact with digital tools as technology becomes more embedded in workplace.

Objectives

This study focuses on the behavioral implications of Construction 4.0 technologies; specifically, how digital tools influence professional judgment and decision-making among construction practitioners. To examine these dynamics empirically, the study employs a survey instrument and scenario-based decision tasks administered to industry professionals with varying levels of exposure to digital systems. The objectives are to:

1. Analyze how reliance on Construction 4.0 technologies is affecting situational awareness.
2. Examine how interaction with automated systems influences critical thinking and independent decision-making.
3. Evaluate how digital tools reshape perceptions of accountability and professional responsibility.
   Assess how practitioners respond to technology-based decision scenarios to identify patterns of trust, verification, or skepticism toward automation.

The study introduces behavioral human-factor considerations into the Construction 4.0 discourse; an area primarily focused on productivity and efficiency. By identifying how digital tools can influence verification practices and perceived responsibility, the study highlights accountability as a potential protective factor against automation bias in construction settings.

Research Methodology

Research Design

The methodological workflow for this study is summarized in Figure 1, detailing the steps of construct identification, survey development, expert validation, deployment, and subsequent data analysis.

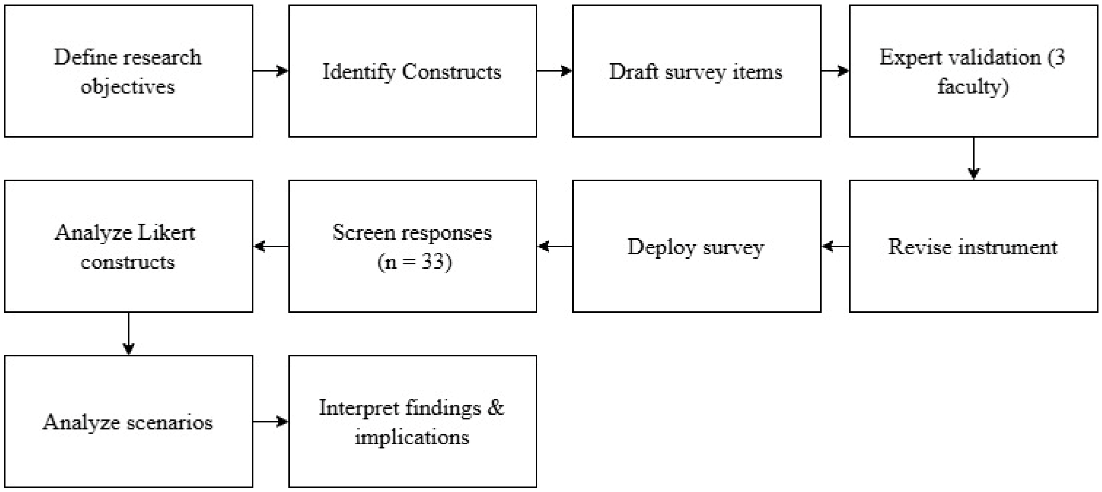

Figure 1. Research methodology flowchart

Survey Instrument Development and Validation

The survey instrument was designed to capture behavioral tendencies associated with the use of digital and automated tools in construction work environments. Four behavioral constructs were identified as relevant to emerging Construction 4.0 practices: technology reliance, situational awareness, critical thinking, and accountability. The instrument consisted of four components: (1) respondent demographics (company type, role, experience, and project sector), (2) exposure to Construction 4.0 technologies, (3) perceived behavioral impacts of technology on early-career employees, and (4) three scenarios involving decision-making under digital–human conflict. Survey items were drafted to reflect realistic construction workflows in which digital outputs may influence human judgment.

Example items included statements such as “Employees rely on system feedback before acting” (technology reliance), “Employees balance attention between digital models and field conditions” (situational awareness), “Employees critically question digital outputs” (critical thinking), and “It is clear who is responsible when digital tools are involved” (accountability). These items were rated using a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). The three scenarios presented respondents with project-based decisions in scheduling, safety planning, and cost estimating contexts. For each scenario, respondents selected from multiple-choice options reflecting different behavioral tendencies, such as reliance on automation, reliance on human expertise, or verification through additional checks.

Prior to deployment, the instrument underwent content and face validity review by three Construction Science faculty members, resulting in refinements to item clarity, wording, and contextual fit.

Participants and Sampling

Participants were recruited from across the US construction industry using a combination of professional networks, LinkedIn and other professional groups, and direct outreach to industry organizations including those on Industry Advisory Boards. The target respondents included project managers, site engineers, safety managers, supervisors, and executives from both general and specialty contracting firms as well as those from project management, construction management and owner firms. A purposive sampling approach was used to ensure diversity in experience levels and technology exposure. Participation was voluntary, and all responses were collected anonymously to encourage honest feedback.

Data Collection and Analysis

The survey was administered via Google Forms between June and August 2025 to construction professionals with exposure to digital tools, recruited through professional networks and industry contacts. Thirty-three eligible responses were retained, with screening requiring recent construction work and experience with digital platforms. Because the survey was distributed through open networks, the number of recipients is unknown and a response rate cannot be calculated. Descriptive statistics summarized responses, Cronbach's alpha assessed internal consistency, and Pearson correlations examined relationships among the four behavioral dimensions.

Data Overview

A total of 33 eligible responses were analyzed. Eligibility required respondents to report current or recent work in construction and exposure to digital or automated tools. Respondents represented multiple project roles (e.g., project managers, project engineers, superintendents, and field supervisors), and more than 80% reported over 15 years of industry experience. Ten positively worded items were reverse-coded so that higher scores consistently indicated greater reliance on automation, ensuring directional alignment for scoring and analysis. All items used a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).

Results and Discussion

Reliability and Internal Consistency

The Results are organized to correspond to the four study objectives. Objective 1 (technology reliance) and Objective 2 (situational awareness and critical thinking) are addressed through the Likert-scale behavioral constructs. Objective 3 (accountability) is examined through both construct responses and correlations. Objective 4 (decision-making) is addressed through the three scenario-based questions. This structure provides direct linkage between study objectives and the analytical findings.

Internal consistency was assessed using Cronbach's alpha (α) to determine how closely related items were within each construct.Table 1 shows that most constructs demonstrated acceptable reliability for exploratory behavioral research. Situational Awareness produced the highest reliability ($\alpha = 0.81$), indicating that items measuring perception and attention coherence well. Technology Reliance ($\alpha = 0.68$) and Critical Thinking ($\alpha = 0.60$) were moderately reliable, suitable for initial empirical studies. Accountability ($\alpha = 0.52$) had lower consistency, suggesting possible item revision in future iterations.

Table 1. Reliability Summary of Behavioral Constructs

Construct	Number of Items	Cronbach's α
Technology Reliance	5	0.68
Situational Awareness	5	0.81
Critical Thinking	5	0.60
Accountability	4	0.52

Cronbach's α values between 0.6–0.7 are considered acceptable for early-stage behavioral scales, while ≥ 0.8 reflects good internal consistency. Thus, the measures of awareness and technology reliance can be considered stable indicators of professional mindset. The modest reliability for the Critical Thinking (α = 0.60) and Accountability (α = 0.52) constructs suggests that these attributes may be interpreted differently across professional roles in digital project environments, resulting in more dispersed responses. This pattern indicates the need to further refine and clarify measurement items for these constructs in future survey iterations.

Construct-Level Descriptive Analysis

Table 2 presents the mean, standard deviation, and percentage of agreement (ratings ≥ 4) for each construct. Technology Reliance yielded the highest mean (3.35), suggesting a moderate inclination among professionals to depend on automated systems. Situational Awareness and Critical Thinking were slightly above neutral, indicating practitioners remain reasonably attentive and reflective despite digital reliance. Accountability had the lowest mean (2.86), suggesting participants recognize potential diffusion of responsibility in technology-mediated decisions.

Table 2. Construct-Level Descriptive Statistics

Construct	**Mean**	**SD**	**% Agree (≥ 4)**
Technology Reliance	3.35	0.67	20.6%
Situational Awareness	3.15	0.68	5.9%
Critical Thinking	3.02	0.70	11.8%
Accountability	2.86	0.62	5.9%

Behavioral constructs trended in different directions. Higher Technology Reliance scores indicated greater dependence on automation, whereas higher scores for Situational Awareness, Critical Thinking, and Accountability represented more desirable human factors. Respondents showed moderate reliance on automated tools while still retaining some independent judgment. The Technology Reliance mean (3.35) suggests growing comfort with automated recommendations, while lower means for Critical Thinking (3.02) and Accountability (2.86) indicate reduced verification and weaker ownership of decisions. These patterns align with early forms of automation bias and highlight the importance of maintaining human oversight as Construction 4.0 tools mature.

Item-Level Analysis

Item-level diagnostics were conducted to evaluate how each survey statement contributed to its respective construct's internal consistency. Table 3 summarizes the mean, standard deviation, item–total correlation, and the change in Cronbach's α if the item were deleted. Most items demonstrated satisfactory internal alignment (item–total correlation > 0.30), indicating that respondents interpreted the statements consistently within each behavioral dimension. A few items in the Critical Thinking and Accountability constructs showed lower correlations (< 0.25), suggesting potential ambiguity in wording or overlapping with other constructs.

Table 3. Item-Level Descriptive and Reliability Statistics

Construct	**Example Item (abbreviated)**	**Mean**	**SD**	**Item–Total Corr.**	**α if deleted**
Technology Reliance	Employees rely on system feedback before acting	3.52	0.88	0.41	0.64
	Employees remain equally vigilant with or without technology *(R)*	3.11	0.91	0.36	0.65
	Over-trust in automated alerts affects attention	3.42	0.82	0.40	0.66

Table 3. Item-Level Descriptive and Reliability Statistics

Construct	Example Item (abbreviated)	Mean	SD	Item–Total Corr.	α if deleted
Situational Awareness	Employees monitor both digital and site cues	3.27	0.74	0.49	0.75
	Balance attention between model and field *(R)*	3.10	0.79	0.44	0.76
	Identify missing details from digital systems *(R)*	3.03	0.72	0.53	0.77
Critical Thinking	Critically question digital recommendations *(R)*	2.98	0.81	0.26	0.58
	Adapt quickly to unforeseen on-site changes *(R)*	3.05	0.77	0.24	0.57
	Use AI data only after verifying accuracy	3.17	0.79	0.31	0.59
Accountability	Clear responsibility even with automated systems *(R)*	2.86	0.69	0.23	0.49
	Explain reasoning beyond "the system said so" *(R)*	2.95	0.72	0.21	0.48
	Address errors openly when relying on technology *(R)*	2.78	0.66	0.28	0.51

In table 3, R = Reverse-coded item. Most survey items aligned well with their intended constructs, with the exception of Accountability, which showed lower item–total correlations. This suggests that perceptions of responsibility under digital decision-making vary among practitioners, reflecting real-world ambiguity when technology mediates decisions on construction sites. These differences imply that responsibility may be context-dependent, with some professionals treating technology as a support tool and others deferring responsibility to automated outputs. This divergence highlights accountability as a critical human factor in Construction 4.0 adoption.

Scenario-Based Behavioral Outcomes

Three scenarios assessed responses when digital outputs conflicted with human judgment (Table 4). Participants largely verified information: 73% in Scheduling, 65% in Safety, and 68% in Cost Estimation, with only 3% accepting automated outputs without review.

Table 4. Scenario Response Summary

Scenario	Verify (%)	Partial/Discuss (%)	Accept/Trust (%)
1 – Digital Scheduling Optimization	73 %	27 %	3 %
2 – Digital Safety Planning	65 %	—	35 %
3 – Digital vs Human Cost Estimation	68 %	—	32 %

Verification rates across all three scenarios were consistently high, suggesting that most professionals continue to take a cautious and balanced approach to digital recommendations. Rather than accepting automated outputs at face value, respondents generally preferred to validate information before committing to a decision, especially in safety- and cost-related contexts. A smaller proportion of respondents accepted system outputs without additional review, reflecting growing comfort with automation rather than outright reliance. This pattern aligns with earlier behavioral scores, where moderate reliance on digital tools coexisted with continued use of human judgment.

Correlation Between Constructs and Scenarios

To explore the relationship between behavioral constructs and real-world decision tendencies, Spearman's rank correlations (ρ) were computed (Table 5).

- Accountability showed a significant positive relationship with verification behavior in Scenario 2 ($\rho = 0.36$, $p = 0.04$), suggesting that individuals who value accountability are more likely to validate both human and digital safety inputs.
- Critical Thinking displayed a negative association with automation acceptance in Scenario 1 ($\rho = –0.31$, $p = 0.08$), indicating that reflective professionals are less prone to unverified decisions.
- Other relationships followed predicted trends but were not statistically significant, likely due to the modest sample size.

Table 5. Spearman Correlations Between Constructs and Scenario Verification

Construct	**Scenario 1 ρ**	**Scenario 2 ρ**	**Scenario 3 ρ**
Technology Reliance	0.02	0.08	–0.14
Situational Awareness	–0.27	–0.01	–0.18
Critical Thinking	–0.31 †	0.06	–0.12
Accountability	–0.29	**0.36 ***	0.06

Correlations with p-values below 0.05 were considered statistically significant, while those between 0.05 and 0.10 indicated trend-level relationships. Accountability showed the strongest association with verification behavior, particularly in safety scenarios, indicating that individuals who feel responsible for outcomes are more likely to confirm digital information. Lower critical thinking scores corresponded with greater acceptance of automated recommendations. Although modest due to sample size, the directional consistency across scenarios provides preliminary evidence that human-factor attributes influence decision-making under Construction 4.0 tools.

Conclusion

This study provides early evidence that Construction 4.0 technologies can influence human behavioral tendencies such as verification, responsibility, and critical engagement. While respondents showed growing comfort with automated recommendations, lower levels of critical thinking and accountability suggest emerging vulnerability to over-reliance on digital tools. Accountability remained the strongest factor associated with verification behavior, underscoring the need to preserve clear ownership in decision-making as digital systems integrate further into project delivery.

This study is exploratory and subject to limitations. The sample size was modest ($n = 33$) and based on self-reported perceptions, which may limit generalizability across different organizational and technological contexts. Behavioral constructs were assessed perceptually rather than through direct observation, and the cross-sectional design identified associations rather than causality. Additionally, the analysis relied on descriptive statistics and correlations; no inferential or multivariate modeling (e.g., regression or factor analysis) was performed, which limits the analytical depth and restricts the ability to identify stronger structural relationships among behavioral constructs.

Future Work

Future studies should expand the sample, incorporate observational or system-level data, and apply more advanced analytical approaches (e.g., regression or factor analysis) to examine behavioral relationships with greater depth and over time. Combining perceptual and system data may support interventions that reinforce human judgment and accountability in Construction 4.0 environments.

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