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Evaluation of Factors that Impede the Use of Construction 4.0 Technologies for Construction Safety Management

Vimlesh Prabhu Desai[1], Lysette D'souza[2], Anil Singh[3], and Vikram Bhadauria[4]

[1]Professor, Management Studies Department, Agnel Institute of Technology and Design, Assagao, Goa, 403507, India, vimlesh.prabhudesai@gmail.com (corresponding author).

[2]Associate Professor, V M Salgaocar Institute of International Hospitality Education, Manora – Raia, Salcete, Goa, 403720, India, E-mail: lyseth_d@yahoo.co.in

[3]Clinical Professor, Department of Information Systems and Operation Management, College of Business, University of Texas, Arlington, Texas, 76019, USA, E-mail: anil.singh@uta.edu

[4]Associate Professor, Department of Information Systems and Computing Technologies, College of Business, Engineering, and Technology, Texas A&M University, Texarkana, Texas, 75503, USA, E-mail: vbhadauria@tamut.edu

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Abstract: The safety performance of the construction sector remains subpar despite the utilization of both conventional and new methodologies. Consequently, there is a decline in the standard of work, the efficiency of employees, and an escalation in project expenses and duration. In order to enhance safety, it is imperative for the industry to use cutting-edge digital technologies at every stage of the project's lifespan. The utilization of these technologies is not yet prevalent and, by far, may be a factor in the poor safety record in the construction industry. This study aims to identify and evaluate factors that impede the use of such technology to improve health and safety in construction management. Literature review and interviews with a few experts were able to garner 18 factors, which were evaluated by experienced industry professionals on a 5-point Likert scale using a questionnaire survey. The responses were analyzed using the relative importance index (RII) and factor analysis. The analyses indicated 'Employees' resistance and reluctance to change', 'high upfront investment', 'lack of awareness about digital technologies and their benefits', 'limited trained workforce to work on digital technologies', and 'poor data communication infrastructure facilities' as the top five barriers. Factor analyses churned out six groups: 'Organization readiness', 'Industry readiness', 'Country readiness', 'Technology related', 'Data related', and 'Investment related' on the basis of latent characteristics. The findings will aid firms, the government, and academia in directing resources and planning strategies to improve the usage of C4.0 technologies in safety and health management in the construction industry.

Keywords: Construction 4.0, construction, digital technologies, factor analysis, relative importance index (RII)

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1. Introduction

As construction projects get more intricate, the demand for alternative contemporary ways of construction necessitates innovative approaches in design and construction techniques (Cooke and Williams, 2009). Given the global context and the need to improve construction project management, alternatives must be explored. One such alternative is the adoption of digitization, Construction 4.0 (C4.0), which serves as a response to the Fourth Industrial Revolution, also known as Industry 4.0 or I4.0. C4.0 encompasses the utilization of intelligent and interconnected digital technologies within the realm of the construction sector (Kozlovska et al., 2021; Osunsanmi et al.,2020). C4.0 technologies enable communication between devices and stakeholders hence are termed 'smart'. The construction industry, though laggard in adopting innovation compared to other sectors (Aghimien et al., 2021), needs to move ahead aggressively in adopting smart technologies in order to maintain competitiveness. Prior research has indicated restricted adoption of digital technologies within the construction sector (Yap et al., 2019). C4.0 technologies include but are not limited to 'cyber-physical system' (CPS), 'radio-frequency identification' (RFID), 'internet of things' (IoT), 'automation', 'modularization', 'robotics', 'simulation and modelling' (e.g., building information modelling (BIM), 'augmented reality' (AR), 'virtual reality' (VR), 'mixed reality' (MR)), and 'digitization and virtualization' (e.g., cloud computing, big data, mobile computing) across the entire construction value chain.

The construction industry is complex and dangerous due to high levels of injuries and fatalities in comparison to other industries (Bavafa et al., 2018). About a quarter of work-related injuries can be attributed to the construction sector (Ambegaonkar, 2020). Accidents kill hundreds of construction workers each year (Nnaji and Karakhan, 2020); developed countries like the US reported 1 in 5 workplace deaths in 2021 in the construction industry due to accidents (BLS, 2023). This number is manifold in emerging economies (Jin et al., 2019). Health and safety on construction sites is a global concern (Furci and Sunindijo, 2020). The high rate of injury interferes with workers' mental and physical health. Construction workforce safety and well-being enhance productivity and job quality, resulting in high-performance infra-assets and civil works, enhancing citizen experience and boosting the economy. Adopting safety measures reduces work-related injuries /accidents thus lowering bodily harm at construction sites. Over the decades, the construction industry has developed and adopted several safety strategies, methods, and approaches, including behavioral and engineering approaches, to reduce worker injuries and fatalities. Behavioral techniques emphasize worker awareness of threats, while engineering approaches focus on using safety gears, including guard and safety rail systems, to protect workers (Nnaji and Karakhan, 2020), but poor safety performance still persists in the construction industry (Bhagwat and Delhi, 2023).

Tabatabaee et al. (2022) and Forcina and Falcones (2021) found that smart technologies promise to enhance safety management. Digital technologies improve safety by identifying and eliminating workplace dangers early in the project lifecycle, thus enhancing site safety (Tabatabaee et al., 2022). Xu and Wang (2020) demonstrated that surveillance camera safety simulation can analyze integrated human-machine-environment risk to deliver dynamic safety pre-warnings for timely corrective actions. Smart devices are purposefully engineered to leverage an integrated network of advanced technologies to automate, digitize, and enhance the systematic process of managing safety in workplaces (Okonkwo et al., 2023). These technologies are often used to develop systems to simulate hazard recognition or notify construction workers of imminent perils (Hou et al., 2021;; Nnaji and Karakhan, 2020). This helps identify potential dangers and develop effective mitigation plans.

Patel and Amlani (2022) opined that the success of C4.0 is considerably influenced by the willingness of employees and managerial personnel to embrace smart technologies. The growing advancement in the field of digital technologies has increased tremendous interest among practitioners, academicians and researchers to study its influence on business and workforce performance. The potential of digital technologies to contribute to efficient project management (Abioye et al., 2021) has made their adoption in construction projects imperative, but the adoption is, unfortunately, very low (Yap et al., 2022; Wang et al., 2020). Despite the praise for digital technologies' role in construction, in various literature, their practical acceptance is still at a nascent stage (Hwang et al., 2022; Karakhan et al., 2019). Thus the study's focus is on the impediments to adopting digital tools to improve construction safety management. The research, therefore, aims to achieve the following objectives;

1. To identify the factors impeding the use of C4.0 technologies in Construction Safety Management (CSM)
2. To evaluate, prioritize, and group similar factors based on commonality

To achieve the above objectives, the study aims to answer the following research questions,

1. What C4.0 technologies are critical to CSM?
2. What are the factors that impede the use of the above C4.0 technologies in CSM?
3. What is the relative importance of these factors?

Structure of the remainder of the paper: Section 2 examines the literature on digital technologies in CSM, Section 3 discusses the research approach for reaching objectives, and Section 4 presents and analyzes study findings. The study concludes with conclusions, implications, limitations, and future directions in Section 5.

2. Literature Review

2.1. Safety at Construction Sites

Construction sites are renowned for their perilous working conditions, making them one of the most treacherous working locations globally (Yap, 2022). This can be attributed, in part, to the dynamic, fast-paced, and hazardous nature of construction sites. The increased rate of accidents can also be attributed to traditional (labor-intensive) work procedures (Okpala and Nnaji, 2023) and a lack of technology advancements (Yap, 2022). These procedures involve hazardous behaviors, use of heavy equipment, and perilous working circumstances (Xu and Wang, 2020). Developed and Emerging economies alike are subject to fatal construction occupation injuries; US construction industry recorded 11% increase in fatal work injuries in 2022 as compared to 2021 (BLS, Dec 2023), Hong Kong construction industry contributed 75% of total worker fatalities (Shafique and Rafiq, 2019), European construction industry recorded 20% of the total workplace fatalities (Sadeghi et al., 2020), Malaysian construction industry recorded 37% of the total workplace injuries in 2021 (Zermane et al., 2023). As per the International Labor Organization (ILO), India has the highest number of fatal accidents on construction sites (Hafeez et al., 2023). The construction industry in India faces significant occupational safety issues due to a lack of legislation, inadequate site data, insufficient training, limited awareness, and poorly structured safety management systems (Krishna Rao et al., 2022). The construction workforce reported high rates of work-related musculoskeletal diseases (WMSDs) (Antwi-Afari et al., 2023) making CSM all the more an important concern in academic research and practice. The high prevalence rate of WMSDs results not only in work absenteeism, schedule delays, and heightened medical expenses but also contributes to income and productivity loss, as well as premature retirement (Antwi-Afari et al., 2023). Traditional safety management practices relying on human inspections and incident reporting have failed. Reactive attempts to address injury patterns are generally unsuccessful and time-consuming (Okonkwo et al., 2023).

2.2. Smart Technologies for CSM

With the growing importance of digital technologies in construction, integrating them into formal safety management systems is a possibility. Demirkesen and Tezel (2022) argue that the construction industry's intricate and constantly changing nature necessitates the rapid adoption of new technology to improve the current status of safety management in construction. Digital technologies use location tracking, collect safety and health data from construction workers and the environment, send it to a processing unit, and provide feedback for practical applications (Okonkwo et al., 2023). Digital technologies prevent accidents and increase quality control, communication, collaboration, and safety risk mitigation through proactive measures, saving time and money (Maskuriy et al., 2019). According to Choi et al. (2020), the technologies avoid accidents, increase exposure, simplify monitoring, checks and balances, and boost workflow. Malomane et al. (2022) and Afzal et al. (2021) believed digital technologies can detect and prevent dangers, boosting construction sustainability and controllability. Safety technologies increase health and safety management, site design, and logistics, as well as project outcomes through visualization and communication, according to Swallow and Zulu (2019).

Zhou and Ding (2017) developed an RFID and IoT-based safety barrier warning system to decrease accidents at Yangtze river crossing project underground construction sites. The devices communicate, retrieve, and store data for analytics on worker, machine, and material movement Malomane et al. (2022) suggested using unmanned aerial vehicles such as drones in construction projects to examine the worksite, monitor worker safety, follow vehicle movements, and scan for hazards. Khan et al. (2022) suggested CCTVs and sensor-based monitoring, such as wearable safety devices, as two primary technologies for monitoring unsafe construction-site behaviors. During the design process, BIM automatically identifies potential occupational dangers in building systems, categorizes them and generates prevention strategies to eliminate from the design or mitigate during construction phase (Nnaji and Karakhan, 2020). MR simulation can be used to identify and mitigate workplace hazards associated with construction tasks and machine operations (Cheng et al., 2020). Robotics and automation improve worker comfort and safety by speeding up, stabilizing, bracing, reaching, transferring, and minimizing repetitive tasks (Haupt et al., 2019). Virtual Reality allows users to visualize and communicate the impact of construction activities in existing facilities that may be overlooked using traditional methods (Zhang et al., 2017). VR also simulates a real safety work experience for construction safety training, allowing safety exercises to be conducted without a competent safety administrator (Lia and Leung, 2017). AR uses GPS and cameras to show real-time data geospatially, giving users up-to-date feedback projected on their phones or special helmets (Musarat et al., 2022). AI/ML can analyse huge amounts of data from sensors, cameras, and other sources on building sites to find trends, abnormalities, and risk issues that manual inspections could miss, enabling prompt mitigation (Ballal et al., 2024).

2.3. Barriers to the Acceptance of Smart Technologies for CSM

Diffusion of innovation (DOI) is a process of gradual dissemination of innovation to the members of the society (Rogers, 2003). The DOI theory denotes that certain internal and external factors influence the adoption of innovation.

Experts warn of human workers' obsolescence in the construction sector due to AI advancements (Anakpo and Kollamparambil, 2022). Due to their potential to eliminate construction tasks such as excavation, grading, and site work, robotics, and automation are facing intense pushback from management and workers (SmartMarket Report, 2017). As per the PwC report, automation has the capability to replace 40% of the jobs (Kokina and Blanchette, 2019). Ikuabe et al. (2020) found poor degree of awareness regarding digital technology in the construction industry, thus leading to use of limited technologies (Okpala et al., 2020). Given the unique attributes and intricacies of the construction sector, reforming business processes within the framework C4.0 requires large investments. From an economic standpoint, construction firms hesitate to spend because of the huge cost of equipment, training and educating the workforce, and maintaining infrastructure (Bademosi and Issa, 2021). Complex equipment and gadgets require significant technical abilities, which poses a huge challenge to the sector (Zabidin et al., 2020). Imparting training to the industry's huge unskilled/semi-skilled workforce is in itself a huge task. Fragmented stakeholders from different backgrounds, comprising the Construction industry value chain, collaborate to achieve project needs; the inherent complexity of such a value chain makes C4.0 implementation difficult.

High upfront cost (Osunsanmi et al., 2020; Nnaji and Karakhan, 2020), interoperability and standardization of IoT devices (Tabatabaee et al., 2022), poor standards of technical proficiency at the firm level (Osunsanmi et al., 2020; Okpala et al., 2020), extensive workforce training- cost, time and quality (Nnaji and Karakhan, 2020; Bademosi and Issa, 2021), absence of suitable and enforceable government regulations on use of digital technologies for CSM even in developed countries like US (Nnaji & Karakhan,2020; Okpala et al., 2019) were some of the barriers highlighted in previous studies. Häikiö et al.'s (2020) survey of over 4000 construction workers indicated that the primary issues for IoT wearable devices adoption in the workplace concern privacy and security. Lack of awareness about the need for safety gear was cited as one of the reasons for a three-fold increase in the construction causalities in Maharashtra, a State in the western peninsular region of India (Hafeez et al., 2023).

3. Research Methodology

This section outlines the methodology used for identifying and analysing factors impeding the use of digital technologies in CSM. A systematic literature review (SLR) was conducted to identify relative barriers, which were then presented to 6 experts, minimum 10+ years' experience in construction safety management, for validation and modification in the context of emerging economies. Thereafter, a questionnaire was distributed among construction industry professionals with 5+ years of construction safety management experience, finally RII and Factor analysis were used to rank and reduce the barriers to fewer numbers based on commonalities.

Phase1 – This phase consisted of identifying potential 'barriers' to the adoption of digital technologies for CSM. At first, a SLR on the topic was conducted to identify a rough list of barriers. Scopus, Web of Science, Google Scholar, and ProQuest were used to identify relevant articles. Even newspapers, trade/business magazines, dissertation reports, reports by independent agencies were also referred. The list thus obtained was then circulated to the 6 experts mentioned above for validation and modification. Their feedback ensured the reduction of bias, utilization of acceptable words, and alignment of the survey content with industry-specific technical terms. These experts were individually contacted and briefed about the study and the list. After sending the list they were once again reached to ensure compliance. The exercise generated 20 factors, see Table 1 below.

Table 1. Factors that impede the use of C4.0 technologies in CSM

Code	Factors	Meaning	Source
F1	Employees' resistance and reluctance to change	Employees turn down any effort to shift from the traditional way of doing things to new way.	Saka and Chan (2020)
F2	Lack of technology integration	Firms struggle with integrating work practices and technologies, lacking governance.	Asadzadeh et al. (2020); Bademosi and Issa (2021)
F3	High upfront investment	Significant implementation and maintenance costs coupled with uncertain potential benefits pose a major challenge for adoption.	Bademosi and Issa (2021)
F4	High cost of training	Training for C4.0 is time-consuming, resource-intensive, and costly.	Nnaji and Karakhan (2020)
F5	Poor data communication infrastructure facilities	Inadequate communication infrastructure hampers C4.0 adoption especially on construction sites.	Expert
F6	Dynamic Project characteristics	Construction projects vary in complexity, location, costs, duration, contractual arrangement, etc.	Al Omari et al. (2023)
F7	Lack of top management support	Lack of backing from top management towards adopting C4.0 technologies for CSM.	Nnaji and Karakhan (2020), Saka and Chan (2020)
F8	Lack of awareness about the digital technologies and their benefits	Limited industry awareness hinders technological solution adoption.	Shibani et al. (2020)
F9	Conflicting regulations across different geographies	Regulations around the digital space are in the forming stage and invariably conflict with one another in different regions.	Expert
F10	Decrease in worker productivity due to use of smart devices	The use of wearable devices can be painful and cumbersome, resulting in decreased productivity.	Antwi-Afari et al. (2018)
F11	Lack or no government legislations regarding use of C4.0 for CSM	Lack of government oversight and regulations hinder adoption of C4.0 technologies.	Bademosi and Issa (2021), Pradhananga et al. (2021)
F12	Limited trained workforce to work on digital technologies	Shortage of skilled personnel hampers C4.0 technologies acceptance and deployment.	Zabidin et al. (2020)

Table 1. Factors that impede the use of C4.0 technologies in CSM (Cont.)

Code	Factors	Meaning	Source
F13	Inter-organizational integration challenges	The nature of projects requires constant interaction with departments and partners across the value chain, which poses coordination challenges.	Expert
F14	Vendor support	Worries surrounding vendor support and reliability.	Nnaji and Karakhan (2020)
F15	Challenges in technology usage	Concerns pertaining to user interface, technology complexity, upgrades, standardization, incompatibility.	Okpala et al.(2020)
F16	Data security	Rising cyber-attacks raise doubts about the security of smart technologies' data.	Raj et al. (2020)
F17	Data privacy	Concerns about data usage, identity privacy, and legal issues in tracking employees.	Rey-Merchán et al. (2021)
F18	Data quality	Data integrity and consistency challenges arise with large, diverse, and shared datasets.	Raj et al. (2020)

Phase 2 – This phase consisted of administering a questionnaire survey. The survey method is a cost-effective and efficient method for collecting feedback from large samples for statistical analysis and prioritizing variables in construction safety management studies (Nnaji and Karakhan, 2020; Yap et al., 2022). A questionnaire prepared with the list of factors finalised from phase 1 was administered among construction industry professionals with a minimum of 4 years of experience in construction safety management. The questionnaire contained the following sections,

I. Demographic profile of the respondents, including information about firms

II. List of factors to be ranked on 5-point Likert scale; 5- very important, 4- important, 3- average, 2- below average, 1- not important

The research employed a purposive strategy to choose participants so as to ensure that they were capable of providing valuable insights for the study. Professionals working in construction firms that have a history of using digital technologies or who are attempting to use digital technologies for construction management were approached for the survey. A list of construction firms was obtained from industry / government databases. The authors used their two decades of industry experience and network plus social networking site www.linkedin.com to make initial contact with probable respondents. A mix of snowball and convenience sampling was employed to reach out to 361 participants who satisfied the required criteria.

Phase 3 – This phase consisted of data analysis.

The ranking of factors was performed using the Relative Importance Index (RII). According to Chan and Kumaraswamy (1997), the mean and standard deviation of factors are insufficient for assessing overall rankings due to their inability to capture any interrelationships among them, leading to the use of significance indexes such as the RII technique to rank the factors identified by respondents. Desai and D'souza (2024) used the RII technique to rank barriers and strategies to improve the well-being, safety, and health of women professionals in the construction industry. Following formula Eq. 1 was used to calculate RII,

$$RII\ (Relative\ Importance\ Index)\ = \frac{\Sigma W}{(N\ x\ A)} \tag{1}$$

W – Ratings given by respondents to each factor on a scale of '1 to 5'. A - The highest rank on the scale which in this case is '5', and N - number of total respondents

A data reduction technique was used to comprehend the underlying characteristics of the variables and group similar ones based on commonalities. Factor analysis is a technique used to analyse correlation patterns and identify underlying themes in data. It has been used in construction management studies to group variables into fewer numbers (e.g. Desai and D'souza, 2023; Yap et al., 2022). The Kaiser-Meyer-Olkin (KMO) index (≥ 0.50) and Bartlett's test (p-value < 0.05) were used to determine factor reliability, while the latent root criterion (Eigen values >1.0) determines the optimum number of groupings.

4. Result and Discussion

Though every effort was made to seek responses from participants with over four years of experience in safety management, there were some slippages' hence the authors screened for high-quality responses. Respondents with less than four years of experience in safety management were removed, only respondents knowledgeable about OSH management technologies were included, and responses that showed straight-lining were eliminated. After quality checks, 217 responses were considered acceptable, improving the reliability and validity of the study by removing irrelevant or less experienced participants. The response rate was 60.11%, which is considered good considering the respondents' busy schedules and lack of interest in academic research. The profile of the respondents is shown in the table below,

Table 2. Details of the respondents

Respondents' information	Groups	Number	Percent
Highest level of education	Graduate	132	60.83
	Post graduate	77	35.48
	Doctorate (PhD)	8	3.7
Total industry experience (years)	≥15	51	23.5
	≥10 & <15	77	35.48
	≥4 & <10	89	41.01
Experience in construction safety management (CSM) (years)	≥10	50	23.04
	≥7 & <10	98	45.16
	≥4 & <7	69	31.80

4.1. Ranking of Factors

Cronbach's alpha coefficient was 0.805, higher than the threshold of 0.70 (Hair et al., 2019), indicating each variable was internally consistent. Table 3 below presents ranks of the factors in ascending order,

Table 3. Ranking of factors that impede use of C4.0 in CSM

Rank	Code	RII	Rank	Code	RII
1	F1	0.943	9	F15	0.856
2	F3	0.933	10	F2	0.841
3	F8	0.926	11	F6	0.833
4	F12	0.921	12	F16	0.811
5	F5	0.911	12	F11	0.811
6	F17	0.899	13	F4	0.763
7	F18	0.879	14	F14	0.758
7	F7	0.879	14	F9	0.758
8	F13	0.859	14	F10	0.758

The top five factors that impede the use of C4.0 technologies for CSM were: Employees' resistance and reluctance to change, high upfront investment, lack of awareness about the digital technologies and their benefits, limited trained workforce to work on digital technologies, and poor data communication infrastructure facilities.

C4.0 technologies require employees to understand and acquire new skills. Fear of not being able to comprehend the technology and obsolesce of traditional working methods, ultimately leading to layoffs, creates resistance to change (Okonkwo et al., 2023). Ambiguity, loss of authority, or hesitancy to accept new ways of doing things contribute to aversion to change. Organizational culture significantly influences resistance to change, influenced by factors like risk-taking propensity, leadership styles, and attitudes towards collaboration and innovation (Shojaei and Burgess, 2022). The construction industry is hesitant to invest in new technology due to high expenses and no dedicated budget for innovation (Yap et al., 2022). This is further hindered by factors such as narrow profit margins, frequent cost overruns, complex projects, and uncertainty over return on investment (Bademosi and Issa, 2021). The lack of awareness of the different C4.0 technologies, their applications, and their benefits hamper their usage (Musarat et al., 2022). The scarcity of vendors also hinders the knowledge and widespread implementation of digital technology (Chauhan et al., 2021). Consequently, organizations are more reluctant to adopt new technologies. Lack of competency and untrained workers are major impediments to C4.0 adoption for CSM, according to Nnaji and Karakhan (2020). Firms prefer to stay with tried and tested methods rather than those that require training (Hwang et al., 2022). Firms are reluctant to use C4.0 technologies due to a lack of necessary supporting infrastructure for the seamless functioning of these technologies. The absence of crucial digital infrastructure, such as dependable internet access, sufficient bandwidth, high data speed, uninterrupted power supply, suitable hardware, and challenges in interfacing different components of the system, make firms rethink the mass use of digital technology (Kandasamy et al., 2023).

4.2. Factor Analysis

KMO value of 0.773 and Bartlett's test of sphericity result of p-value=0.000 indicated that the data set was suitable for factor analysis (Hair et al., 2019). Varimax rotation extracted six components with a cumulative variance of 82.85%, exceeding the recommended 60% for construct validity (Hair et al., 2019). Table 4 below shows the result of factor analysis.

Table 4. Rotated Component Matrix[a]

Factors	Principal Components (PC)						Variance explained (%)
	PC1	PC2	PC3	PC4	PC5	PC6	
F1	.911						
F7	.900						
F10	.814						
F13	.775						21.56
F8		.933					
F12		.873					
F6		.745					18.62
F9			.871				
F11			.846				
F5			.744				12.45
F2				.918			
F14				.899			
F15				.867			11.41
F3					.899		
F4					.851		10.66
F16						.911	
F18						.787	
F17						.777	8.15

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization
a. Rotation converged in 9 iterations

The assignment of the label of the latent factor was determined by the variables with higher factor loadings>0.50. The six principle components were labeled as,

- PC1 - Organisation readiness
- PC2 - Industry readiness
- PC3 - Country readiness
- PC4 - Technology related
- PC5 - Investment related
- PC6 - Data related

a. Organisation readiness – This group accounts for 21.56% of total variance and consists of,

- Employees' resistance and reluctance to change
- Lack of top management support
- Decrease in worker productivity due to the use of smart devices
- Intra-organizational integration challenges

Fear of unknown (Cinite and Duxbury, 2018), unwillingness to move out of comfort zone (Müller, 2019), conventional mindset with a strong drive to retain traditional methods (Demirkesen and Tezel, 2022; Saka and Chan, 2020), fear of job displacement / loss (Okpala et al., 2020) or disruption of established workflows (Müller, 2019), technology too complicated for users to adopt; all these contribute to employees' reluctance to adopting new methods of working. Thin profit margins in an environment of lowest cost bidding culture deter top management from spending money on pricey C4.0 technologies (Shojaei and Burgess, 2022; Delgado et al., 2019). There is a perception that these technologies are more suitable for large projects than medium- to small-sized projects. Insufficient budget allocation to cutting-edge technology to finish the work at a minimalistic cost pre-empts innovation, leading to a weak innovation culture (Pradhananga et al.,2021). Organizations, as well as workers, fear damage to costly wearable devices inhibiting their usage. Wearable gear and high-tech solutions make worker interaction difficult, thereby decreasing their productivity (Antwi-Afari et al., 2018). Since construction work is often scattered across various sites without much organization, introducing digital tools becomes a real challenge. The need to allocate resources for inter-departmental cooperation, the lack of a structured setup, and the fact that most work happens on-site make it tricky to smoothly bring in digital technologies. Construction projects vary a lot, and the ever-changing nature of the work makes it tough to use these tools consistently across different sites.

b. Industry readiness – This group accounts for 18.62% of the total variance and consists of,

- Dynamic Project characteristics
- Lack of awareness about the digital technologies and their benefits
- Limited trained workforce to work on digital technologies

b. Every project is unique in terms of deliverables, requirements, investment, construction technology used, number and workforce expertise, etc. Location and difficult terrain of projects make technology adoption a challenge (Demirkesen and Tezel, 2022). Tight project schedules and high uncertainty in the activities performed make project proponents bypass technology adoption. The productivity and economic benefits of investing in information technology have been continuously questioned (Brynjolfsson, 1993). At the industry level, there is limited awareness about the available technological solutions and their potential benefits (Smallwood et al., 2020). This also poses resistance to change from the stakeholders (Contractors/Employees/Management), as no knowledge or poor knowledge is dangerous. Unproven effectiveness raises industry concerns about testing new technologies (Yap et al., 2022). The shortage of skilled personnel to operate and maintain C4.0 technologies has been a huge constraint at the industry level. Training employees to use these technologies effectively can be time-consuming, and hiring an external agency/consultant can be expensive. Moreover, the lackadaisical attitude of workers towards acquiring new knowledge limits the scope of training.

c. Country readiness – This group accounts for 12.45% of the total variance and consists of,

- Poor data communication infrastructure facilities
- Conflicting regulations across different geographies
- Lack or no government legislation regarding the use of C4.0 for CSM

Weak data network infrastructure facilities such as pitiable internet strength, low bandwidth, unstable power, and poor network connectivity on construction sites work unfavorably for the adoption of C4.0 technologies (Chauhan et al., 2021). Incompatibility issues with other software or hardware used in the construction industry are pertinent concerns. Digital innovations in construction require regulatory reforms, increasing legal risks. The industry is most controversial, and digital transformation will only add fuel. CSM digital solutions involve software and apps, but license and liability constraints are unclear, discouraging project commitment to digital technology (Wuni et al., 2024). Regulations concerning the digital environment are currently in the process of being formed, which is preventing the spread of C4.0 across the nation (Kumar et al., 2021). Moreover, the continuously evolving technological landscape challenges regulators to create rules and regulations to protect customers. Insufficient rules and technical standards and variation in the maturity at the regulatory level across nations limit the optimum utilisation of smart technologies. The regulations of the land neither encourage nor enforce the use of C4.0 technologies for CSM (Raj et al.,2020). The lack of a clear definition of policies and associated incentives has led to a low rate of adoption.

d. Technology related – This group accounts for 11.41% of the total variance and consists of,

- Lack of technology integration
- Vendor support
- Challenges in technology usage

Firms find integration with existing work practices and with other technologies a challenge. Firms or projects have their own governance standards regarding SOPs to be followed in a project (Okonkwo et al., 2023). Being largely people driven, it becomes difficult to enforce a digital intervention among a large crowd and gather relevant data and retrospect on it to get meaningful outcomes. The integration of several technologies has not been adequately explored (Saka and Chan, 2020). Concerns about the availability of technical support, lack of trust in vendor reliability and assistance, non-user-friendly interface, requirement of certain basic knowledge in technology, frequent technology upgrades, and complexity in the use of technology impact the use of C4.0 technologies. Since C4.0 technologies are emerging, standardization initiatives are limited, limiting hardware and software. Incompatibility issues arise when software packages don’t converge (Swallow and Zulu, 2019). The successful deployment of technology depends on factors like ease of use, perceived ease, interoperability, usability, and applicability. The below-par performance of existing software to solve construction problems adds an additional layer of complexity to the capability of C4.0 technologies for CSM (Shojaei and Burgess, 2022).

e. Investment related – This group accounts for 10.66% of the total variance and consists of,

- High upfront investment
- High cost of training

The costs associated with the implementation and maintenance of digital technologies can be rather substantial (Abioye et al., 2021). Ngo et al. (2020) found that high investments are among the top three barriers to C4.0 technology adoption in the Singapore construction industry. With no information on possible benefits (Wuni et al., 2024), many construction companies, especially smaller ones, may find it tough to invest resources in these technologies. When it comes to construction projects, cost overruns are extremely prevalent. Due to the fact that contractors are still trying to figure out ways to successfully complete projects within the allotted budget, they are extremely selective when it comes to embracing new technology that needs financial inputs (Forcina and Falcone, 2021). As regards training, besides the significant amount of time and resources required to teach individuals the requisite skills and knowledge for the utilization of C4.0, the cost involved is equally high (Ngo et al., 2020). It is also possible that training will not result in a favourable cost-benefit ratio (Shojaei and Burgess, 2022). Sacks and Barak (2010) argue that firms must allocate resources to train and retrain their workforce in order to get workers skilled in technologies; nevertheless, these endeavours include expenses that many are reluctant to shoulder (Emmanuel et al., 2018).

f. Data related – This group accounts for 8.15% of the total variance and consists of,

- Data security
- Data privacy
- Data quality

Users have voiced increasing apprehensions regarding the security of data collected via smart devices (Nnaji and Karakhan, 2020). The increasing incidence of cyber-attacks raises doubt about data safety, and the lack of trust in the way data is stored and used adds to the worries. Ensuring that information and data are accessible exclusively to authorized users and software programs is crucial. Prior research has indicated that the absence of data security and privacy concerns has discouraged the adoption of certain digital technologies in construction projects (Aghimien et al., 2021). Häikiö et al. (2020) found that anxieties regarding the revelation of identity and associated data privacy impede technology adoption. The lack of legislation on 'personal data' protection raises ethical and legal issues with the tracking and monitoring of employees, as well as the management of the collected data (Malomane et al., 2022). When dealing with a large volume of data, heterogeneous data, and data that is constantly transferred from one person to another, maintaining data integrity and consistency becomes more difficult. Moreover, the fragmented nature of the industry leads to a diminished level of data quality (Yap et al., 2022).

5. Conclusion

The introduction of new ideas and ways of doing things in many sectors has resulted in operational flexibility, efficiency, and safety. Nevertheless, the construction industry has been sluggish in embracing technology innovations in CSM despite their ability to tackle safety issues. The sluggish adoption hinders the necessary changes required to boost workplace safety, mitigate hazards, and enhance productivity in high-risk construction sites.

An initial survey, followed by interviews with six experts, identified a total of 18 potential obstacles that hindered the adoption of C4.0 technologies in CSM. Later, a questionnaire poll conducted among construction professionals with at least four years of safety experience revealed the ranking of the factors. The top five factors with substantial impact were: Employee resistance and reluctance to change, High upfront cost, Lack of awareness about digital technologies and their benefit, Lack of trained workforce, and Poor data communication infrastructure facilities. In order to divulge the underlying characteristics of the factors, a factor analysis was conducted, which identified six distinct groupings. These groupings were termed organisation readiness, industry readiness, country readiness, data-related, investment-related, and technology-related.

Digital technology in CSM requires a collaborative culture, dedicated leaders with a human-centric mindset who walk the talk, and a focus on employee training and upskilling. Managers' and employees' awareness and understanding of the digital technologies' benefits improve their acceptance of new technologies. Achieving widespread adoption of digital technologies for construction health and safety will necessitate a more strategic, organized, and coordinated approach, owing to the fragmented character of the construction industry. Top management support, social acceptance, alignment with organizational culture, and legislations, will boost the applicability of C4.0 technologies (Tabatabaee et al., 2022). UK BIM implementation experience showcased the importance of training and education for the swift adoption of digital technology (Awwad et al., 2022).

The construction industry is expected to improve safety performance by adopting new safety technologies, similar to other industries. However, barriers need to be addressed across stakeholders – government, industry and organisations to ensure successful implementation. Factors explaining these barriers guide industry practitioners and legislators in evaluating the feasibility and readiness of safety management technologies. A shift towards a high-technology, high-skilled construction industry is needed for national development, economic growth, and higher income.

The study considered views of employees working in the private sector; professionals from government firms, public sector undertakings, etc., could provide diversity in the analysis. The study considered digital technologies in totality; specific technology, e.g., IoT, BIM, Robotics, wearable devices, etc., could provide more depth to the results. Other quantitative statistical methods, such as focused group discussion, the Delphi method, case study, etc., can be used to compare the results. The study considers factors pertaining to the construction sector; other sectors could provide factors different from the ones already considered. As an extension of the study, enabling factors for C4.0 technology adoption in CSM could be explored.

Author Contributions

Vimlesh Prabhudesai contributes to conceptualization, methodology, validation, analysis, investigation, data collection, draft preparation, manuscript editing, visualization, supervision, and project administration. Lysette Dsouza contributes to conceptualization, methodology, validation, analysis, investigation, data collection, draft preparation, manuscript editing, and project administration. Anil Singh contributes to conceptualization, methodology, software, validation, analysis, and manuscript editing. Vikram Bhadauria contributes to conceptualization, methodology, draft preparation, analysis, visualization, and manuscript editing. All authors have read and agreed with the manuscript before its submission and publication.

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Vimlesh Prabhudesai is a Professor at Agnel Institute of Technology and Design, Assagao, Goa, India. Advisor to the top management, Vimlesh is a strategist with 29+ years of corporate and academic experience. His expertise lies in business strategy, business development, international business, business process re-engineering, new business initiatives, and public-private partnerships. He is a SAP certified consultant in SCM (Supply Chain Management). Vimlesh is a member of EPPM Association.

Lysette Margaret D'souza is an Associate Professor at V M Salgaocar Institute of International Hospitality Education, Goa, India. She is a management graduate with over 20 years of experience across Academics and Industry. She has vast and rich experience in the areas of marketing management, organizational behaviour, international business and financial management. She also holds Thomas Profiling certification. Her research focuses on experiential marketing, strategic management and sustainability.

Anil Singh holds the following degrees: Doctor of Philosophy (Ph.D.) from The University of Texas at Arlington; Bachelor of Science from Goa University; Master of Management Studies from Goa University, India; Master of Information Systems from The University of Texas at Arlington; and Master of Science (M.Sc.) in accounting from Texas A&M Commerce. He has over five years of industry experience and is currently pursuing research and teaching at the University of Texas at Arlington. He is engaged in research on ERP trust, information technology in supply chains, and new technologies. He has published in Communications of the ACM, Journal of Information Systems Education, Journal of Accounting Education, and IEEE Transactions on Professional Communication.

Vikram S. Bhadauria is the chair of the information systems and computing technologies division in the College of Business, Engineering, & Technology at Texas A&M University, Texarkana. He received his Ph.D. in information systems from the University of Texas at Arlington. His current research includes cyber security, data analytics, sustainability, the Internet of Things, and self-driving technology adoption. His research publications have appeared in the Journal of the Association for Information Systems, Journal of Database Management, Computers in Human Behavior, Information and Computer Security, Industrial Management & Data Systems, International Journal of Productivity and Quality Management, Management Research Review, Supply Chain Management: An International Journal, etc. He has also won many research grants and presented papers at several international conferences.