ITU A|Z • Vol 22 No 3 • November 2025 • 775-794

Critical success factors for and barriers against Occupational Health and Safety 4.0 in the construction industry

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Received: August 2024 • Final Acceptance: April 2025

Abstract
Construction industry (CI)'s poor occupational health and safety (OHS) performance drives the need for CI to adapt relevant industry 4.0 technologies effectively. This paper aims to identify critical success factors (CSFs) for and barriers against adaptation of OHS4.0 to CI. With this aim, following the literature review, four rounds of two groups of Delphi surveys, and interviews were conducted. The first group of four rounds of Delphi survey (DS) focused on identification of the barriers whereas the second group of four rounds of DS focused on identification of the CSFs. Results of both DSs have been commented on, and validated through interviews with experts. The results of these four rounds of two groups of DS and interviews revealed barriers and CSFs under three main interrelated categories (i.e. cost, human resources (HR), and managerial aspects). These barriers and CSFs can provide input to the strategies at the company, CI, and country levels for supporting achievement and widespread of OHS4.0 in CI. This study can be useful to all stakeholders of OHS4.0 in CI.

Keywords
Barriers, Critical success factors, Construction industry, Industry 4.0, OHS4.0.

doi: 10.58278/0.2025.111

1. Introduction

Safety problems is a source of concern in the construction industry (CI) (Machfudiyanto et al., 2019). There are higher rates of worker injuries and deaths in CI than other industries (Nnaji and Karakhan, 2020). Different statistical data on the workplace fatality rate in CI reveal poor performance of CI. For example, according to the Health and Safety Authority (2024), CI is responsible for up to 29% of all workplace fatalities. Similarly, according to Zhang et al. (2015), CI accounts for 36% of all workplace deaths in the United States. Furthermore, according to the Occupational Safety and Health Administration (2021) nearly half of all fatal occupational injuries in the United States are experienced by construction workers. Among CI's self-reported work-related illnesses musculoskeletal disorders outstands with its high percentage of %52 (HSE, 2024). Financial and non-financial costs are associated with workplace injuries and illnesses (HSE, 2024). Rate of employees experiencing recent or chronic work-related musculoskeletal disorders is approximately 2.0% which is higher than workers in all industries (1.2%) (HSE, 2024). Statistical data on nonfatal accidents, and illness further verify poor performance of CI. For example, according to Health and Safety Authority (2024), CI is among the top five industries sectors for non-fatal accidents and illnesses. Furthermore, from the economic perspective, fatalities, injuries and illness in workplaces result in economic loss as supported by Lipnicka (2020) who indicated that loss of around 4% of the global Gross Domestic Product due to OHS related diseases, injuries, and fatalities.

CI can benefit from alignment of CI with the digitalization of production through Industry 4.0 (I4) (Suferi & Rahman, 2021). Many factors, however, prevent CI from adopting I4 (Taher, 2021). Previous studies underlined the need to improve knowledge and to conduct studies regarding the factors limiting use of technology for OHS management in CI (Nnaji & Karakhan, 2020). Despite slightly widespread of adoption/use of technology for OHS management in CI, there is industry-wide resistance to its use (Nnaji & Karakhan, 2020). More than 70% of construction firms reported difficulties in implementing recent technologies, according to a global survey, suggesting a notable slowdown in CI's digitalization (Mitchell, 2023). CI has unique barriers against implementing new technologies due to its nature, including value chain fragmentation (Hwang et al., 2021).

Even if many studies (e.g., Al-Turk & Weheba, 2022; Demirkesen & Tezel, 2021) have emphasised importance of identifying barriers, there is lack of studies on barriers against adaptation of the OHS4.0 to CI. As there are many barriers against adoption of I4Ts (Industry4.0 technologies), it can be useful to identify and eliminate them (Luthra & Mangla, 2018). Investigating challenges preventing adoption of I4 by construction companies can be an opportunity to raise awareness of and develop strategies on how to deal with them (Demirkesen & Tezel, 2021). Furthermore, there is need for investigating main barriers against I4Ts' successful implementation and adoption in CI (Al-Turk & Weheba, 2022). Identifying barriers against effective implementation of OHS management at sites is necessary to cope with them (Eigege et al., 2020). Overcoming barriers against the adoption of technology can contribute to construction safety performance into safety management in CI (Nnaji and Karakhan, 2020).

Many studies (e.g. Nwaiwu et al., 2019) have emphasised importance of Critical Success Factors (CSFs) for different purposes. There is, however, lack of studies on CSFs for adaptation of the OHS4.0 to CI. Pozzi et al. (2023) emphasised the need for academic contributions to CSFs for I4 implementation and improvements. Identifying CSFs can lead to prioritization and awareness of critical variables for CI to be competitive (Sarvari et al., 2021). For example, Nwaiwu et al. (2019) analyzed factors for the I4 implementation in the Czech Small Medium Enterprise (SME) manufacturing sector, stating that factors identified as critical for a successful transition and adaptation should be prioritized. Furthermore, Sukathong et al. (2021) examined CSFs affecting adoption of technologies for SMEs. Additionally, determining CSFs for effective management of SMEs in CI can contribute to project success and efficiency (Sarvari et al., 2021). Vrchota et al. (2020) emphasized importance of identifying CSFs for project management and analyzing its relationship with I4. Machfudiyanto et al. (2019) argued that identifying CSFs affecting safety can improve performance.

Many studies (e.g., Sony et al., 2021) have emphasized that both barriers against and CSFs should be evaluated together. For example, Sony et al. (2021) emphasized that studies critically examining benefits of, challenges in, and success factors for I4 beyond conceptually defining it are necessary. There is need to identify and analyze the barriers against and CSFs for adoption of I4 and CSFs (Moeuf et al., 2020). Even if it is important to understand the barriers against and the CSFs for the adaptation of I4Ts to OHS in CI, there is a gap in the literature with respect to researches on determination of barriers against and CSFs in the context of the adaptation of OHS4.0 in CI. Integrated thinking of these CSFs and barriers can support construction companies' strategies and policies for embedding OHS4.0 into their OHS activities and processes. This paper aims to identify barriers against and CSFs for the adaptation of the OHS4.0 to CI.

2. Factors to be considered for the adaptation of OHS4.0 to CI

2.1. Cost related factors as barriers and CSFs

Financial constraints are critical in the I4T adoption (Zabidin et al., 2021). Poor understanding of the cost and benefit for I4 adoption appears to be a difficulty (Ling et al., 2020). Companies perceive economic and financial barriers to be among the barriers against adoption of technologies (Cugno et al., 2021). Similarly, the main barrier against adoption of technologies (e.g. AR, VR) to CI is that they are considered to be expensive (Delgado et al., 2020a). In CI, there are many barriers (e.g. high investment cost) causing many companies not to invest in BIM (Oesterreich & Teuteberg, 2018). When presenting case studies on efficiency of visualisation technologies in creating communication and putting construction site safety plans into action, Azhar (2017) emphasised extra expense of creating a BIM model. High initial investment cost of incorporating technology into an organization is a barrier against adoption of technologies for OHS in CI (Cai et al., 2020; Nnaji & Karakhan, 2020; Sony et al., 2021).

Before deciding to incorporate new technologies into construction safety, detailed cost-benefit analysis is required (Yap et al., 2021). In this regard, there are many real-life examples revealing benefits obtained from technology investments. For example, "construction 2025" started by the UK government, and called for construction projects to be completed 50% faster, and with a reduction of 33% in initial construction cost and the asset's lifetime cost (UK government, 2013). Another real life example is the Manchester Town Hall Building project, which is among the government's pilot BIM schemes, and which has shown the value of digital engineering by reducing cost of needless temporary work, and saving time of nine months (UK government, 2013).

2.2. Human resources related factors as barriers and CSFs

Human resources practices can help adopt new technologies to the company (Sukathong et al., 2021). For example, 'human' factor can be considered among CSFs for the IoT implementation (Hakim et al., 2021). Low level of awareness of I4, however, is a barrier which should be overcome by training (Eğilmez & Koca, 2018). For example, barriers against the adaptation of AR and VR include lack of sufficient number of graduates equipped with the necessary skills, and lack of teams having appropriate competencies related with these technologies (Delgado et al., 2020b). Training the human capital that will use the relevant technology in accordance with the labor market can be considered a challenge (Cugno et al., 2021). Eigege et al. (2020) emphasized insufficient training of staff as a barrier against OHS adaptation to the processes. Construction companies targeting implementation of I4Ts in their processes must train their workers (Moshood et al., 2020). Proper training of HR is a success factor for successful implementation of I4 (Nwaiwu et al., 2019). Education and training have emerged as an important issue as adoption of I4 requires a set of new skills and responsibilities (Khan et al., 2022). Companies need to have staff who meets the requirements of I4 skills and technical knowledge (Sony et al., 2021).

While a strong safety culture is important to maintain employee awareness and compliance when improving OHS, there are issues related with inadequate training, funding constraints and project pressures (Labaran et al., 2024). While robots and automated machinery have the potential to substitute or support workers through improved flexibility, and safety, employees will be working on tasks which require management, accountability, decision-making, and human-machine interaction and which can expose workers to increased psychosocial stress and health and safety hazards that are inherent in automated tools (Leso et al., 2018). Even if concern over the future of jobs and wages grow as robots and other technologies are incorporated into the various stages of construction projects, current roles are expected to be changed while new ones are expected to be developed (Soto et al., 2019). Regarding real life examples, according to Autodesk and the Associated General Contractors of America's survey, 70% of construction companies have difficulty in finding qualified craftworkers to hire in case of an increase in demand for construction (AGC 2017). Furthermore, 8.7 million workers in Sri Lanka have high absenteeism and turnover rates due to unsafe acts, unsafe behaviours, and poor working conditions (NIOSH, 2017).

2.3. Management related factors as barriers and CSFs

Insufficient management support, government support and lack of policies and global standards are barriers against organizations in the adoption of I4 (Eğilmez & Koca, 2018). Among the critical challenges in adopting Construction4.0 is the lack of effective contracts, government policies and standardization due to the inherent nature of CI (Luthra & Mangla, 2018). Organizations fail to fully explain their digital company vision and missions, roadmaps and strategies regarding the transition to I4 (Luthra & Mangla, 2018). Fundamental deficiencies in organizational alignment and strategic management can be considered among the main barriers against I4 integration (Taher, 2021). Main barriers against I4 can be expressed as cultural resistance and inability of organizational processes to be transformed effectively (Cugno et al., 2021).

Top management's support is important for technology management, especially in terms of the resources required for the company (Sony et al., 2021). Top management's commitment leads an organization to policies and activities supporting achievement of its goals (Sukathong et al., 2021). Commitment of/support by top management and compliance with organizational strategies are among the CSFs (Khan et al., 2022). Management must be determined to adapt developing technologies to its processes for competitiveness in the international market (Karimulla, 2020). Furthermore, integration of corporate culture with lean management is among the success factors for the I4 adoption in companies (Pozzi et al., 2023). Additionally, managing cybersecurity is important for organizations and it is a CSF for implementation of I4 (Sony et al., 2021).

Wanjiku (2015)'s case study's findings demonstrated contribution of management priorities, attitude, and practices to health and safety outcomes (Wanjiku, 2015). Furthermore, as another real-life example, in Anambra State, Okoye et al. (2016)'s research investigated construction workers' compliance with and knowledge of OHS through questionnaires applied to construction workers at fifteen sites, and revealed importance of management (Okoye et al., 2016). Shafei et al. (2025)'s case study revealed that Construction4.0 technology projects highlighted BIM's adaptability and efficiency in addressing OHS issues. As another case study, Zhang et al. (2015)'s research which used a prototype to test a BIM framework with automatic safety rule checking algorithms in two case studies involving models of a Finnish office and residential building project, revealed successful implementation of the safety rule-checking platform designed for fall-hazard detection and prevention in BIM.

3. Method

This paper aims to identify barriers against and CSFs for the adaptation of OHS4.0 to CI. Following the literature review, four rounds of two groups of Delphi surveys (DS), and interviews were conducted (Figure 1). Figure 1 outlines the research flow where arrows' directions indicate the order/flow of the research process. The criteria determined based on the literature review were refined through four rounds of two parallel DSs. The first group of the DS focused on determination of barriers against the adaptation of OHS4.0 to CI (Figure 1). The second group of the DS focused on determination of the CSFs for the adaptation of OHS4.0 to CI (Figure 1). Furthermore, upon the accomplishment of four rounds of two groups of DSs, interviews with 10 experts have been performed to get detailed comments on and validate the DS results (Figure 1). These interviews were performed online (Figure 1).

Four rounds of the two groups of DSs followed the same process in each round. All rounds can be briefly described as follows:

The first round of both groups of DSs focused on the selection of the most important criteria among the criteria obtained from the literature. In the first round of the first group DS, participant experts were asked to mark minimum 5 and maximum 10 criteria that they considered as most important from the list of 191 criteria obtained from the literature review. Similarly, in the first round of the second group DS, participants were asked to do the same on the CSR list (311 criteria obtained from the literature review). Furthermore, at the end of the first round of both group of the DSs, participant experts were asked to indicate additional criterion/criteria/barrier(s) under the 'other' option in case they had further suggestions. At the end of the first round, the criteria which have not been selected have been removed from the lists whereas the selected criteria, and additional criteria specified under the 'other' option have been included in the lists for the second round of both group of DSs.

In the second round of both groups of DSs, for each group of DS, experts were asked to rethink the criteria list prepared as a result of the first round of their Delphi group to select minimum 5 and maximum 10 criteria which they consider as most important. As a result of this second round, in each DS group,

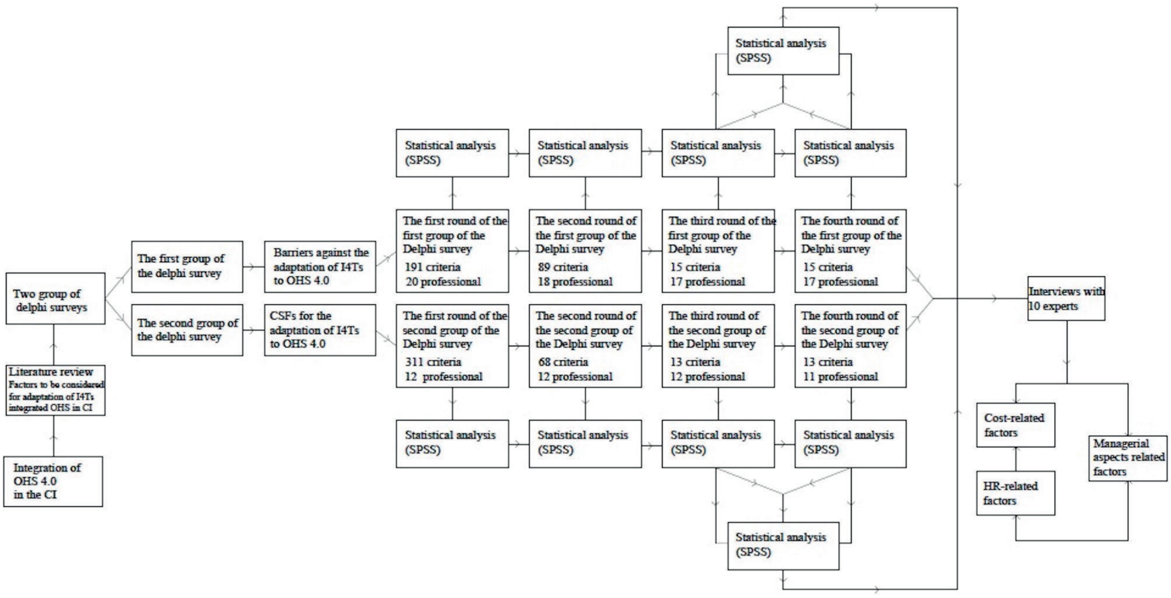

Figure 1. *Flowchart of the research method.*

criteria selected by less than 20% of experts were removed from the list, in compliance with Tatlici & Sertyesilisik (2023)'s research, as the basis for the third round.

In the third round of both groups of DSs, experts were asked to score all remaining criteria in their DS group in a 5 point Likert where 1 referred to the criterion they considered to be the least important whereas 5 referred to the criterion they considered to be the most important. Cronbach's alpha values were calculated for both DS groups.

In the fourth round of both groups of DSs, each DS group expert has received a table containing the results of the 3rd round of his/her DS group to compare her/his scores with the average results. In the first column of the table provided, the average of the answers given by all experts to each criterion was provided, and in the other column, the participant could see her/his scores given in the 3rd round of her/his Delphi group. In the last column, each expert was asked to score the criteria between 1 to 5 again considering criteria' mean values and the scores she/he assigned in the third round of her/his Delphi group.

For both groups of DSs, data gathered in the 3rd and 4th rounds were entered into the Statistical Package for the Social Sciences (SPSS®) computer program. When analyzing data, the Delphi method should focus on the group's opinion rather than on the individuals' opinion (Yeung et al., 2007; Chan et al., 2001). Therefore, similar to Yeung et al. (2007) and Chan et al. (2001), Kendall's concordance analysis was used to measure the consistency of the group's opinion in the third and fourth rounds. Compatibility increased as Kendall's Coefficient of Concordance increased from 0.263 to 0.313. Additionally, similar to Yeung et al. (2007), criteria were not eliminated in the 3rd and 4th rounds and consistency was measured. In both groups of DSs, the compliance coefficient of the 3rd round was lower than the one of the 4th round. It was observed that the compliance coefficient increased and that the experts' answers became similar to each other in the 4th round. Complying with Tatlici & Sertyesilisik (2023), corresponding weights were calculated for both groups of DSs. Additionally, the results of the 3rd and 4th rounds were transferred to the SPSS® program, and test of normality, Skewness and Kurtosis tests and Pearson's correlations tests were performed. As the data were normally distributed in both groups, Pearson's correlation analysis was performed. Similar to Yeung et al. (2007), in the correlation matrix tables, less than half of the criteria that are correlated with each other at the 5% significance level are correlated with each other (Table 4, Table 6). Therefore, the criteria have been ranked based on the corresponding weights. Results of both DSs have been commented on, and validated through interviews with experts.

Sample of both groups of DSs and of the interviews consisted of participants who have experience and/or publications in the relavant field in CI and academics who have academic publications in this research related field. Table 1 provides the profile of the sample sets for all research methods (i.e. both groups of the DSs, and interview) applied within the scope of the study.

As seen in Table 1, participants have many years of experience in either private or public construction. All participants are OHS specialists. Majority of them have engineering or architecture education background. The sample has been approved by the ethics committee and jurry members. Participation to the study has been completely voluntary. Experts having publications on this topic were identified through literature review and contacted via e-mail. CI participants in the sample were reached via the LinkedIn webpage.

4. Results

4.1. The first group of the Delphi Study

The first round: 20 experts contributed to the first round. Criteria which have not been selected by the participants have been eliminated whereas criteria which have been selected by at least one participant were proceeded to the next round together with the additional criteria suggested by the experts. As the number of remaining criteria in the list prepared based on the literature for the second round was 84 and as

Table 1. Profile of the research participants.

Profile of the first group of the delphi survey's participants				
expert ID	**experience**	**sector**	**education background**	**specific job title**
F1	between 1-5 years	private/construction	undergraduated (other)	OHS specialist
F2	between 6-10 years	private/construction	graduated (engineer, MSc)	OHS specialist
F3	between 1-5 years	public/university	graduaded (other, MSc)	Academic
F4	between 11-20 years	private/construction	graduated (engineer, PhD)	OHS specialist, owner
F5	between 1-5 years	public/construction	graduated (other, MSc)	OHS specialist
F6	between 1-5 years	private/construction	undergraduated (other)	OHS specialist
F7	between 6-10 years	private/construction	graduated (engineer, MSc)	OHS specialist
F8	between 11-20 years	private/construction	undergraduated (other)	OHS specialist
F9	between 1-5 years	private/construction	undergraduated (engineer)	OHS specialist
F10	between 1-5 years	private/construction	undergraduated (engineer)	OHS specialist
F11	between 6-10 years	private/construction	graduaded (other, MSc)	OHS specialist
F12	between 11-20 years	private/construction	graduated (engineer, MSc)	OHS specialist
F13	between 11-20 years	public/construction	graduated (other, MSc)	OHS specialist
F14	21 years and above	public/ university	graduated (engineer, PhD)	Academic
F15	between 11-20 years	private/construction	undergraduated (engineer)	OHS specialist
F16	between 6-10 years	private/construction	graduated (architect, MSc)	OHS specialist
F17	between 6-10 years	private/construction	graduated (other, MSc)	OHS specialist
F18	21 years and above	private/construction	graduated (engineer, MSc)	OHS specialist
F19	between 6-10 years	private/construction	graduated (engineer, MSc)	OHS specialist
F20	between 11-20 years	private/construction	graduated (engineer, MSc)	OHS specialist
Profile of the second group of the delphi survey's participants				
S1	between 6-10 years	private/construction	graduated (engineer, MSc)	OHS specialist, owner
S2	between 11-20 years	private/construction	graduated (engineer MSc)	OHS specialist
S3	between 11-20 years	private/construction	graduated (engineer, MSc)	OHS specialist
S4	21 years and above	private/construction	undergraduated (architect)	OHS specialist
S5	between 6-10 years	private/construction	graduated (other, MSc)	OHS specialist
S6	between 11-20 years	private/construction	undergraduated (engineer)	OHS specialist
S7	between 1-5 years	private/construction	graduated (other, MSc)	OHS specialist
S8	between 6-10 years	private/construction	graduated (architect, MSc)	OHS specialist
S9	between 11-20 years	private/construction	undergraduated (engineer)	OHS specialist
S10	between 6-10 years	private/construction	undergraduated (other)	OHS specialist
S11	between 1-5 years	private/construction	graduated (other, MSc)	OHS specialist
S12	between 11-20 years	private/construction	graduated (engineer, MSc)	OHS specialist
Profile of intervieewees				
A	16 years	private/construction	graduated (engineer, PhD)	OHS specialist, owner
B	10 years	private/construction	graduated (engineer MSc)	OHS specialist
C	15 years	private/construction	graduated (engineer, PhD)	OHS specialist
D	10 years	private/construction	graduated (architect,MSc)	OHS specialist
E	18 years	private/construction	undergraduated (other)	OHS specialist
F	9 years	private/construction	undergraduated (engineer)	OHS specialist
G	22 years	private/construction	undergraduated (architect)	OHS specialist
H	10 years	private/construction	graduated (other, MSc)	OHS specialist
I	19 years	private/construction	undergraduated (engineer)	OHS specialist
K	8 years	private/construction	undergraduated (other)	OHS specialist

experts added 5 more criteria to the other option at the end of the criteria list, a list of 89 criteria was created for the second round of the first group of DS (Figure 1).

The second round: 18 experts participated in this round and they were asked to rethink the criteria list to select minimum 5 and maximum 10 criteria which they consider as most important. As a result, all criteria selected by less than 20% of experts were removed from the list. The criteria selected by more than and/or equal to 20% of the participants (Table 2).

The third round: Experts were asked to score/weight all 15 criteria in the remaining criteria list (Table 2). Cronbach's alpha value of the 3rd round was found to be 0.872 and reliable. They were asked to score the criteria in a 5 point Likert where 1 point refers to the barrier they considered to be the least important and 5 points refer to the barrier they considered to be the most important. 17 experts participated in the 3rd round. As a result, none of the criteria was eliminated (Table 2) as the mean value of the criterion with the lowest score was 2.35 in the assessment based on 5 points.

The fourth round: The reliability analysis of the fourth round of the first group DS was found to be 0.871 (Cronbach's alpha value) and reliable. 17 experts participated to the 4th round. Results of the 4th round of the first group of DS are presented in Table 2. As the criterion having the lowest average was 2.71 and as data were collected at a 5-point Likert scale, all criteria remained above 2.5. Therefore, none of the criteria was eliminated.

Table 2 summarizes the results of the second, third and fourth rounds of the first group DS, and provides the criteria selected by participants in percentage (for the 2nd round) and the mean rating, mean rank, rank and corresponding weighting values (for the 3rd and 4th rounds).

When the 3rd and 4th rounds are compared, the Kendall fit coefficient increased from 0.263 to 0.313, meaning that the consistency increased (Table 2). When the 3rd and 4th rounds were compared on the criteria basis, the first four important factors remained the same, and the ranking of the other factors remained almost the same (Table 2).

Table 3 shows the results of the reliability analyses of the 3rd and 4th rounds of the two-group DS, and reveals that both rounds of the two-group DS were reliable.

Table 4 contains the results of the correlation analysis of all criteria in the 3rd and 4th round of the first group DS.

As seen in Table 4, similar to Yeung et al. (2007) and Tatlici & Sertyesilisik (2023)'s studies, the results of correlation analyzes confirm the necessity of evaluating the criteria based on corresponding weights. Therefore, the criteria have been ranked based on the corresponding weights (Table 4).

4.2. The second group of the Delphi Study

The first round: 12 experts participated in the first round and marked the most important criteria among 311 criteria obtained from the literature review. The criteria that the experts had never marked were removed from the list and 67 criteria obtained from the

Table 2. *Results of the 2nd, 3rd and 4th rounds of the first group DS.*

	Round 2	Round 3				Round 4			
	% of experts	Mean rating	Mean rank	Rank	Corresponding Weighting	Mean rating	Mean rank	Rank	Corresponding Weighting
High initial investment costs (Oesterreich and Teuteberg, 2018)	89	4,53	12.09	1	0,090	4,53	12.09	1	0,086
Low understanding of I4 (Luthra and Mangla, 2018)	61	4,06	10.65	2	0,081	4,24	11.24	2	0,081
Lack of education (Karimulla, 2020)	50	4,00	10.62	3	0,080	4,06	10.53	3	0,077
Lack of understanding that the adoption of technologies will yield great advantages in the long run (Karimulla, 2020)	61	3,88	10.21	4	0,077	3,88	9.71	4	0,074
Poor management support (Luthra and Mangla, 2018)	33	3,35	8.09	6	0,067	3,71	9.06	5	0,071
Lack of necessary talents, skills and knowledge about I4 (Ling et al., 2020)	33	3,35	7.85	7	0,067	3,71	8.65	6	0,071
Company's weak digital operations vision and strategy (Luthra and Mangla, 2018)	39	3,24	7.65	8	0,065	3,65	8.74	7	0,069
High cost of adoption (Ling et al., 2020)	44	3,47	8.65	5	0,069	3,53	8.18	8	0,067
Inability of companies to keep up with developments in technology (Karimulla, 2020)	44	3,24	7.62	9	0,065	3,35	7.56	9	0,064
Difficulty in demostrating the cost-benefit relationship or lack of work on the subject (Oesterreich and Teuteberg, 2018)	28	3,00	6.74	11	0,060	3,18	6.38	10	0,060
Poor long-term planning (Karimulla, 2020)	22	3,12	6.85	10	0,062	3,12	6.26	11	0,059
The complexity of new Technologies (Karimulla, 2020)	50	2,94	6.62	12	0,059	3,12	6.18	12	0,059
Poor research and development on I4 adoption (Luthra and Mangla, 2018)	28	2,82	5.94	14	0,056	3,00	5.62	13	0,057
Lack of digital culture (Luthra and Mangla, 2018; Eğilmez & Koca, 2018)	28	2,88	6.21	13	0,057	2,82	4.97	14	0,054
Reluctance of companies to use new Technologies (Luthra and Mangla, 2018)	22	2,35	4.24	15	0,047	2,71	4.85	15	0,052
Number of experts Kendall's Coefficient of Concordance(W) Level of significance		17 0.263 0.001				17 0.313 0.001			

Table 3. *The Cronbach's Alpha value results of rounds 3 and 4.*

Reliability Statistics			
	Cronbach's Alpha Round 3	Cronbach's Alpha Round 4	N of items
The first group of the delphi survey	.872	.871	15
The second group of the delphi survey	.892	.889	13

literature remained. Experts added 1 more criterion to the other option in the criteria list. A list of 68 criteria was prepared for the next (second) round.

The second round: 12 experts participated to the second round. All criteria which have been selected by less than 25% of experts participated were removed from the list. A list containing 13 criteria was prepared for the 3rd round of the second group DS.

The third round: The Cronbach's alpha value was 0.892 and reliable (Table 3). 12 experts participated in the 3rd round of the second group of the DS. As a result, none of the criteria was eliminated.

The fourth round: The 4th round of the second DS's reliability analysis is 0.889 and reliable (Table 3). 11 experts participated in the fourth round.

Table 5 summarizes the results of the 2nd, 3rd and 4th rounds of the second group DS.

In Table 5, the percentages of experts for all criteria in the second round are given, and for the third and fourth rounds, the mean rating, mean rank, rank and corresponding weighting values are given in detail for comparison. When the third and fourth rounds are compared, the Kendall fit coefficient increased from 0.264 to 0.363, meaning that the consistency increased. Furthermore, when the third and fourth rounds were compared on the criteria basis, the first four important factors remained the same, and the ranking of the other factors remained almost the same.

Table 6 contains the results of the correlation analysis of each criterion in the third round and fourth round of the second group DS.

As seen in Table 6, similar to Yeung et al. (2007) and Tatlici & Sertyesilisik (2023)'s studies, as correlation analyses results confirm the necessity of evaluating the criteria based on their corresponding weights, the criteria have been ranked accordingly.

Figure 2 summarizes the results of the two groups of DSs and reveals the barriers and CSFs with their corresponding weightings and related group.

4.3. Interview with experts

Complying with the results of the fourth rounds of both DSs, all interviewees confirmed that the main group of barriers and CSFs are related with cost, human resources and management aspects. All interviewees supported both group of DSs results. All interviewees confirmed that the identified criteria can be grouped under cost, human resources, and management

Table 4. *Matrix of correlation among the first group of the DS's 3rd and 4th round criteria.*

Matrix of correlation among the First Group of the Delphi Survey's (FDS) 3rd Round criteria

	FDS1	FDS2	FDS3	FDS4	FDS5	FDS6	FDS7	FDS8	FDS9	FDS10	FDS11	FDS12	FDS13	FDS14	FDS15
FDS1	1	.117	-.122	.172	.202	-.007	.053	.140	**.516***	**.545***	-.072	-.244	-.089	.116	-.437
FDS2		1	.237	.172	.282	.228	.290	-.325	.049	.192	-.378	.000	.072	.280	.258
FDS3			1	**.497***	.043	.418	**.526***	.172	.244	.208	.228	.045	.377	.294	.324
FDS4				1	.285	.348	-.019	.368	.165	.110	.356	.000	.428	.446	.013
FDS5					1	**.665****	.375	.288	.469	.331	.272	**.555***	.302	**.587***	.270
FDS6						1	.566*	.210	**.652****	.473	**.540***	**.697****	**.708****	**.664****	**.642****
FDS7							1	.113	**.544***	.314	.090	.478	.201	.120	.225
FDS8								1	.405	.376	.452	.286	.300	.143	.066
FDS9									1	**.810****	.372	**.537***	**.491***	.473	.284
FDS10										1	.341	.166	.277	.536	.224
FDS11											1	.410	.475	**.619****	.255
FDS12												1	**.660***	.420	**.647***
FDS13													1	**.594***	**.728****
FDS14														1	.457
FDS15															1

Matrix of correlation among the First Group of the Delphi Survey's (FDS) 4th Round criteria

	FDS1	FDS2	FDS3	FDS4	FDS5	FDS6	FDS7	FDS8	FDS9	FDS10	FDS11	FDS12	FDS13	FDS14	FDS15
FDS1	1	.248	.045	.451	.061	-.147	-.198	-.125	.320	**.513***	.037	-.048	.143	.112	-.390
FDS2		1	.077	.383	.171	-.029	.281	-.275	.114	.215	-.287	.025	-.075	.200	.103
FDS3			1	**.537***	.66	**.684****	.324	.140	.391	.288	.350	.267	**.502***	.344	.442
FDS4				1	.375	.330	.214	.069	.317	.263	.348	.343	.387	**.590***	.143
FDS5					1	.282	**.569***	.189	.405	.443	.338	**.614***	.056	.463	.190
FDS6						1	.332	.442	.452	.400	**.691****	**.599***	**.709****	**.586***	**.707****
FDS7							1	.146	**.493***	.267	.264	**.657****	.000	.009	.238
FDS8								1	.194	.213	**.611****	**.540***	.324	.249	.407
FDS9									1	**.811****	.384	**.612****	**.537***	.327	.344
FDS10										1	.277	.451	.434	.342	.276
FDS11											1	**.722****	.643**	**.591***	.338
FDS12												1	**.425**	.456	**.360**
FDS13													1	**.554***	**.562***
FDS14														1	**.518***
FDS15															1

Table 5. *Results of the 2nd, 3rd and 4th rounds of the second group DS.*

	Round 2	Round 3				Round 4			
	% of the expert	Mean rating	Mean rank	Rank	Corresponding Weighting	Mean rating	Mean rank	Rank	Corresponding Weighting
Top management support (Moeuf et al., 2020; Suferi and Rahman, 2021; Hakim et al., 2021)	92	4,92	11.25	1	0,100	5,0	11,45	1	0,097
User training and education (Moeuf et al., 2020)	83	4,25	8.83	2	0,086	4,45	9,09	2	0,086
Project team competence (Moeuf et al., 2020)	58	4,17	8.58	3	0,085	4,27	7,95	3	0,082
Financial capabilities (Moeuf et al., 2020; Ling et al., 2020; Bhatia and Kumar, 2020; Dikhanbayeva et al., 2021; Sukathong et al., 2021)	50	3,92	7.54	4	0,080	4,18	7,82	4	0,081
Organisational culture (Moeuf et al., 2020)	50	3,67	6.63	7	0,075	4,09	7,59	5	0,079
Clear goals and objectives (Moeuf et al., 2020)	67	3,83	6.75	5	0,078	4,09	7,36	6	0,079
Continuous improvement (Moeuf et al., 2020; Pozzi et al., 2023)	50	3,67	6.46	8	0,075	4,00	6,86	7	0,077
Employee training (Nnaji and Awolusi, 2021)	50	3,75	7.04	6	0,076	4,00	6,86	7	0,077
Change management (Moeuf et al.,2020; Yadav et al., 2021; Suferi and Rahman, 2021; Sony et al., 2021)	42	3,67	6.38	9	0,075	3,91	6,59	8	0,075
Cost-benefit (Oesterreich and Teuteberg, 2018; Nnaji and Awolusi, 2021)	50	3,58	6.46	10	0,073	3,64	5,59	9	0,070
IT and Innovation (Moeuf et al., 2020)	25	3,33	5.17	12	0,068	3,55	5,50	10	0,069
Effectiveness (Nnaji and Awolusi, 2021)	25	3,33	5.50	11	0,068	3,45	4,73	11	0,067
Cultural (Dikhanbayeva et al., 2021)	25	3,08	4.42	13	0,063	3,18	3,59	12	0,061
Number of experts Kendall's Coefficient of Concordance(W) Level of significance		12 0.264 0.001				11 0.363 0.001			

Table 6. *Matrix of correlation among the second group of the DS's 3rd and 4th round criteria.*

Matrix of correlation among the Second Group of the Delphi Survey's (SDS) 3rd Round criteria.

	SDS1	SDS2	SDS3	SDS4	SDS5	SDS6	SDS7	SDS8	SDS9	SDS10	SDS11	SDS12	SDS13
SDS1	1	-.313	.63	.237	1.512	-.098	-.346	.196	-.033	.107	.293	.460	.322
SDS2		1	.506	.000	.756**	.787**	.609*	.112	.190	-.122	-.129	.139	.185
SDS3			1	.450	.506	.575	.431	.778**	.572	.369	.171	.184	.529
SDS4				1	.048	.255	.180	.541	.861**	.659*	.645*	.504	.577*
SDS5					1	.511	.612*	.275	.293	.086	.018	.019	.259
SDS6						1	.744**	.447	.499	.201	.242	.339	.477
SDS7							1	.447	.378	.406	.497	.276	.674*
SDS8								1	.605*	.717**	.533	.104	.672*
SDS9									1	.504	.500	.485	.557
SDS10										1	.846**	.142	.614*
SDS11											1	.534	.819**
SDS12												1	.623*
SDS13													1

Matrix of correlation among the Second Group of the Delphi Survey's (SDS) 4th Round criteria.

	SDS1	SDS2	SDS3	SDS4	SDS5	SDS6	SDS7	SDS8	SDS9	SDS10	SDS11	SDS12	SDS13
SDS1	a	a	a	a	a	a	a	a	a	a	a	a	a
SDS2	a	1	.642*	.422	.696*	.742**	.742**	.295	.516	.046	.016	.153	-.050
SDS3	a		1	.132	.677*	.328	.493	.576	.143	.041	-.064	-.236	.078
SDS4	a			1	.593	.737**	.369	.467	.642*	.564	.637*	.606*	.489
SDS5	a				1	.553	.737**	.770**	.642*	.437	.505	.329	.489
SDS6	a					1	.667*	.274	.638*	.114	.239	.503	.249
SDS7	a						1	.547	.638*	.343	.359	.251	.374
SDS8	a							1	.571	.615*	.705*	.169	.763**
SDS9	a								1	.418	.604*	.657*	.499
SDS10	a									1	.814**	.361	.622*
SDS11	a										1	.607*	.903**
SDS12	a											1	.547
SDS13	a												1

*, Correlation is significant the 0.05 level (2-tailed).
**, Correlation is significant the 0.01 level (2-tailed).
a , can not be computed because at least one of the variable is constant.

related main headings. Furthermore, all interviewees emphasized that these main groups are interrelated with each other. All interviewees agreed that the first 3 barriers and CSFs are the most important (Figure 2). Specific emphases of the interviewees including their strategy and policy recommendations can be executively highlighted as follows:

Cost: Problems can be solved more easily if employers are explained about possible benefits of technology-based OHS4.0 and importance of switching to OHS4.0 despite its high initial investment costs as the benefits can surpress the costs (A). Employers may concern about issues such as high costs and uncertainty about their earnings

BARRIERS

Rank	Barriers	Corresponding weighting	Related group
1	High initial investment costs (Oesterreich and Teuteberg, 2018)	(.086)	cost
2	Low understanding of Industry 4.0 (Luthra and Mangla, 2018)	(.081)	human resources
3	Lack of education (Karimulla, 2020)	(.077)	human resources
4	Lack of understanding that the adoption of technologies will yield great advantages in the long run (Karimulla, 2020)	(.074)	human resources
5	Lack of necessary talents, skills and knowledge about Industry 4.0 (Ling et al., 2020)	(.071)	human resources
6	Poor management support (Luthra and Mangla, 2018)	(.071)	management
7	Company's weak digital operations vision and strategy(Luthra and Mangla, 2018)	(.069)	management
8	High cost of adoption (Ling et al., 2020)	(.067)	cost
9	Inability of companies to keep up with developments in technology (Karimulla, 2020)	(.064)	management
10	Difficulty in demonstrating the cost-benefit relationship or lack of work on the subject (Oesterreich and Teuteberg, 2018)	(.060)	cost
11	The complexity of new technologies (Karimulla, 2020)	(.059)	human resources
12	Poor long-term planning (Karimulla, 2020)	(.059)	management
13	Poor research and development on Industry 4.0 adoption (Luthra and Mangla, 2018)	(.057)	management
14	Lack of digital culture (Luthra and Mangla, 2018; Eğilmez & Koca, 2018)	(.054)	management
15	Reluctance of companies to use newtechnologies (Luthra and Mangla, 2018)	(.052)	management

CRITICAL SUCCESS FACTORS

Rank	Critical Succes Factors	Corresponding weighting	Related group
1	Top management support(Moeuf et al., 2020; Suferi and Rahman, 2021; Hakim et al., 2021)	(.097)	management
2	User training and education(Moeuf et al., 2020)	(.086)	human resources
3	Project team competence(Moeuf et al., 2020)	(.082)	human resources
4	Financial capabilities(Moeuf et al., 2020; Ling et al., 2020; Bhatia and Kumar, 2020; Dikhanbayeva et al., 2021; Sukathong et al., 2021)	(.081)	cost
5	Organizational culture(Moeuf et al., 2020)	(.079)	management
6	Clear goals and objectives(Moeuf et al., 2020)	(.079)	management
7	Continuous improvement(Moeuf et al., 2020; Pozzi et al., 2023)	(.077)	management
8	Employee training(Nnaji and Awolusi, 2021)	(.077)	human resources
9	Change management(Moeuf et al.,2020; Yadav et al., 2021; Suferi and Rahman, 2021; Sony et al., 2021)	(.075)	management
10	Cost-benefit(Oesterreich and Teuteberg, 2018; Nnaji and Awolusi, 2021)	(.070)	cost
11	IT and innovation(Moeuf et al., 2020)	(.069)	management
12	Effectiveness(Nnaji and Awolusi, 2021)	(.067)	management
13	Cultural(Dikhanbayeva et al., 2021)	(.061)	management

Figure 2. *Criteria's corresponding weightings and their related groups as a result of the two groups of the DSs.*

(K). Cost-benefit analysis needs to be understood (I). As companies' financial capabilities and condition are important, price policies of OHS4.0 technologies can have potential to affect management's investment decision (H).

Regarding interviewees' recommendations, policy makers should support owners and contractors through investment supports and tax incentives to enable them to overcome cost-related obstacles (A, B, C, G, H, K). Government's ability to develop various investment strategies could enable construction companies to increase their investments in technologies (A, B, C, G, H, K). As while employers provide training to their staff, and as the training provided has a cost, G and H drew attention to the necessity and importance of developing various strategies to support business owners and contractors with various additional support items (e.g. tax exemptions for training expenses).

Human resources: The most important barrier against OHS4.0 is the lack of awareness (B). Increased understanding of I4 can be possible through education (A, B). Even the most unskilled workers need to have a certain level of training and skills in terms of OHS4.0 (G). In order for managers to support OHS4.0, they must be educated and have the necessary knowledge and skills (H). As employers tend to perceive OHS expenses as an extra cost item, it is important to inform and train all project stakeholders, including employers, about the necessity of taking OHS measures (G). Creating effective training content for OHS4.0 is necessary and important (C). Training using VR glasses can be beneficial for OHS4.0 (C). Training should be organized in various ways regarding each employee's motivation, competencies and awareness of technology, ability to work in a team, and desire to learn (G). Employees' being able to work in a team, their awareness of adaptation to OHS and OHS4.0, and motivation are important (G). Employees' psychology needs to be considered in the context of OHS4.0 (E, K). Workers may worry about job and earnings losses due to the substitution of their work by robots (K).

Regarding intervieweees' recommendations, A, C, E, F, H, I, and K emphasized the need to develop strategies for the human resources training. C highlighted the need to create new OHS training methods incorporating technologies into training content. There are various new training methods and the need to adapt new methods (e.g. gamification) (C). Developing strategy suggestions (e.g. supporting the psychology of employees) is important (E). OHS trainings remain theoretical and their content should be developed with examples from sites (E). Good communication skills and teamwork for problem solving are needed and development of human resources-based strategies is important (F, I and K). G emphasized the necessity of companies to create an OHS culture and importance of developing training strategies to create it. H highlighted job concerns and the need for developing staff-focused strategies for a sustainable OHS4.0 understanding. Developing more private sector-academia collaborations and strategies for identification and solution of barriers and CSFs for OHS4.0 is important (I).

Management: All occupational risks have potential to be managed in an organization and each staff has responsibility for reducing OHS problems (A). Top management support is important (C). It can affect the cost significantly (B). The relationship between management and cost is strong as management must decide almost everything related to cost (K). Management support is important to ensure cultural change needed for OHS4.0 adoptation effectively (H). Companies need to adapt a new culture to adapt these OHS4.0 technologies (C). The culture of OHS and OHS4.0 has not been fully adopted (G). Cultural change is required in companies and digital culture is not effective enough in CI (H). All stakeholders' participation in OHS4.0 culture is important to widespread it (H). OHS experts can encourage employers to adopt OHS4.0 (C). OHS experts should be independent from the company and employed by the government so that they can perform their duty effectively and transparently (G, K).

Regarding interviewees' recommendations, all interviewees emphasized that there is a need to develop strategies related to management. To encourage cultural change, studies can be conducted to inform/raise awareness of top management/business owners and contractors primarily by OHS experts authorized by government authorities (A, H). Adopting management approaches (e.g. TQM, lean) can be seen as a strategy for OHS4.0 (A, B, G, H). As although OHS experts explain company owners that technology integration is essential for OHS, it can be difficult to convince them, there should be mandatory standards (C). Government incentives and guarantees are important as the high initial investment costs can make company owners reluctant to invest in technology (C). Policies should be developed to ensure that OHS management is completely independent from companies (F, G). Auditing mandatory standards is important (F, G, H). Furthermore, government supports for OHS and OHS4.0 are needed (K). Regulations and standards are important for OHS4.0 adaptation (D). Government incentives (e.g., financial support, relevant laws and regulations) can support the top management and to achieve a visible and continuous change (C). It is necessary to audit the implementation of laws (G, K, I).

5. Discussion

Figure 3 provides the classification of the CSFs and barriers based on Figure 2 so that the groups to which each criterion is related to can be seen clearly as Figure 2 provides the rankings of these criteria based on their corresponding weightings and their relation to the three main groups (i.e. cost, management, human resources).

Identified barriers and CSFs have been discussed under the following headings based on Figure 3.

5.1. Cost related barriers, CSFs and strategies

Criteria 1, 8 and 10 are the top three cost-related barriers, whereas criteria 4 and 10 underline financial capabilities and cost-benefit as among the top CSFs related to cost (Figure 2 and Figure 3). For widespread of OHS4.0 in CI, it is important to overcome cost-related barriers while supporting CSFs. Among the most critical issues for companies to invest in technologies is financial conditions (Zabidin et al., 2021). Cost-benefit stands out as both a barrier and a CSF (Figure 3). Companies may not want to invest their limited budgets in technologies that they are not sure will benefit them (Oesterreich and Teuteberg, 2018; Nnaji and Awolusi, 2021). Therefore, to establish the understanding of I4, it may be beneficial to develop understanding regarding the solution to cost-benefit-related problems (Ling et al., 2020). Regarding financial capabilities (e.g. Moeuf et al., 2020; Ling et al., 2020) barrier (Figure 3), financial issues affect companies' I4 integration (Dikhanbayeva et al., 2021). Regarding cost-benefit (Oesterreich and Teuteberg, 2018; Nnaji and Awolusi, 2021) barrier and CSF (Figure 3) various studies have emphasised importance of cost-benefit analysis for different reasons [e.g. investment in BIM technology (Ling et al., 2020; Oesterreich and Teuteberg, 2018)]. As a CSF, companies can make a cost-benefit assessment before investment (Nnaji and Awolusi, 2021).

	Cost	Human Resources	Management
BARRIERS	1 High initial investment costs (Oesterreich and Teuteberg, 2018) (.086) 8 High cost of adoption (Ling et al., 2020) (.067) 10 Difficulty in demonstrating the cost-benefit relationship or lack of work on the subject (Oesterreich and Teuteberg, 2018) (.060)	2 Low understanding of Industry 4.0 (Luthra and Mangla, 2018) (.081) 3 Lack of education (Karimulla, 2020) (.077) 4 Lack of understanding that the adoption of technologies will yield great advantages in the long run (Karimulla, 2020) (.074) 5 Lack of necessary talents, skills and knowledge about Industry 4.0 (Ling et al., 2020) (.071) 11 The complexity of new technologies (Karimulla, 2020) (.059)	6 Poor management support (Luthra and Mangla, 2018) (.071) 7 Company's weak digital operations vision and strategy (Luthra and Mangla, 2018) (.069) 9 Inability of companies to keep up with developments in technology (Karimulla, 2020) (0.64) 12 Poor long-term planning (Karimulla, 2020) (.059) 13 Poor research and development on Industry 4.0 adoption (Luthra and Mangla, 2018) (.057) 14 Lack of digital culture (Luthra and Mangla, 2018; Eğilmez & Koca, 2018) (.054) 15 Reluctance of companies to use newtechnologies (Luthra and Mangla, 2018) (.052)
CRITICAL SUCCESS FACTORS	4 Financial capabilities (Moeuf et al., 2020; Ling et al., 2020; Bhatia and Kumar, 2020; Dikhanbayeva et al., 2021; Sukathong et al., 2021) (.081) 10 Cost-benefit (Oesterreich and Teuteberg, 2018; Nnaji and Awolusi, 2021) (.070)	2 User training and education (Moeuf et al., 2020) (.086) 3 Project team competence (Moeuf et al., 2020) (.082) 8 Employee training (Nnaji and Awolusi, 2021) (.077)	1 Top management support (Moeuf et al., 2020; Suferi and Rahman, 2021;Hakim et al., 2021) (.097) 5 Organizational culture (Moeuf et al., 2020) (.079) 6 Clear goals and objectives (Moeuf et al., 2020) (.079) 7 Continuous improvement (Moeuf et al., 2020; Pozzi et al., 2023) (.077) 9 Change management (Moeuf et al.,2020; Yadav et al., 2021; Suferi and Rahman, 2021; Sony et al., 2021) (.075) 11 IT and innovation (Moeuf et al., 2020) (.069) 12 Effectiveness (Nnaji and Awolusi, 2021) (.067) 13 Cultural (Dikhanbayeva et al., 2021) (.061)

Figure 3. *Classification of CSFs and barriers into three main groups.*

Regarding strategies for overcoming cost related barriers, policy makers need to consider the cost related barriers and CSFs. For example, governments can support contractors and owners through subsidies/subsidy plans to ensure adoption of OHS4.0 in CI. Setting policy scenarios and quantitatively modelling stakeholder responses to policy scenarios are necessary for effectiveness study of the combined subsidy and fee policy (Xie et al., 2023). Subsidies can be for encouraging creative solutions or preventing particular risks (EU-OSHA, 2007-2012). Studies conducted by OSHA show that when illnesses, injuries, and fatalities decrease, there is an average return on investment of $5 for every $1 spent on construction safety programs (CAHill Tech, 2022). Many contractors are, however, unaware that investment in safety can yield a substantial return on investment (CAHill Tech, 2022).

All interviewees supported cost-related CSFs for and barriers against the widespread of OHS4.0 in CI, importance of effective training and increasing all stakeholders' awareness of OHS4.0, and accurate cost-benefit analysis. They have highlighted that problems related to investment costs can make employers reluctant to adopt new technologies. Furthermore, A, B, C, G, H, and K recommended policy makers to provide investment strategies, investment supports, and tax incentives to support contractors to overcome cost-related barriers and to encourage them to invest in technologies.

5.2. Human resources related barriers, CSFs, and strategies

When all barriers (i.e. criteria 3, 4, 11 and 13) and CSFs (i.e. criteria 2 and 8) (Figure 2, Figure 3) are evaluated together, training of all employees in CI can be important for the adaptation and widespread of OHS4.0. From the perspective of talent, know-how and skills of human resources, Criteria 2, 5 and 9 are barriers whereas criterion 3 is a CSF (Figure 3).

Overcoming barriers 4 and 11 can be supported through staff training. It is necessary to increase the level of awareness of CI employees and develop their awareness of adopting technologies. Insufficient training of staff is among the barriers against the adaptation of I4 (Eigege et al., 2020; Karimulla, 2020). Employees' training is important to support I4 adoption (Nnaji and Awolusi, 2021; Moeuf et al., 2020). The barrier that new technologies are generally thought to be complex (Karimulla, 2020) can be overcome by providing adequate training to the staff and equipping them with appropriate skills. Regarding project team competence, Moeuf et al. (2020) highlighted that skills and expertise of employees play key role in the success in I4 projects.

As operating technologies necessitate digital skills and multitasking abilities, skilled workers become indispensable, governments and businesses are recommended to invest in improvement of workers' intellectual capacities (Bispo and Amaral, 2024). Lipnicka (2020) proposed a training model that aims to educate employees on how to deal with injuries, allowing employees to easily adopt the latest safety standards. Gamification represents the next evolution in training approaches (Lipnicka, 2020). As digital technologies are used in OHS4.0 to collect, combine, and evaluate sensor data, safety executives can minimize damage and stop additional incidents when they have real-time access to data (Haleem et al., 2025).

Hwang et al. (2021)'s case study in Singapore to identify challenges in adoption of smart technologies in CI and to develop strategies, emphasized importance of strategies for training skilled construction workers and providing government incentives.

All interviewees agreed with both groups of the DS results on the human resources related CSFs and barriers. They emphasized importance of human resources to support safety and OHS4.0 in CI. They highlighted that accidents and near misses can be affected by employee's education, training, skills, competencies, abilities and their psychology and perception.

Regarding human resources related strategies, A, C, E, F, H, I, and K emphasized the need to develop strategies for the human resources training. Recommendations [e.g. new training methods (e.g. gamification)' adaptation (C); developing training strategies to create an OHS culture (G)] for improvement of OHS training have been provided. Need for addressing employment concerns of the personnel and development of personnel-focused strategies for a sustainable OHS4.0 understanding has been emphasized (H). Developing more private sector-academia collaborations and strategies (I).

5.3. Management aspects related barriers, CSFs and strategies

Criteria 6, 7, 12, 14, and 15 are barriers whereas criteria 1, 5, 6, 7, 11, 12 and 13 are CSFs from the management aspect perspective (Figure 3). Management support is important for the adoption of I4 (Luthra and Mangla, 2018). Regarding top management support (Moeuf et al., 2020; Suferi and Rahman, 2021; Hakim et al., 2021), for example, knowing the factors related to the impacts of and opportunities for I4 can contribute managers to improve I4 application (Pozzi et al., 2023). Management support and related policies, regulations, laws, and management policies can support OHS4.0 adaptation and widespread in CI. To adopt I4, company management must be determined and willing to progress with these technologies (Karimulla, 2020). It is important for company management, governments, policy makers to be determined for adopting certain policies to overcome the barriers. Regarding clear goals and objectives (Moeuf et al., 2020), for example, Bhatia and Kumar (2020) emphasized that managers should develop strategies focusing on certain CSFs, rather than focusing on all factors.

Regarding policies to foster managerial support and direct cultural change, Policies can be developed to encourage administrative support and direct cultural change to overcome management-related problems. Multinational corporations have taken proactively steps to incorporate workarea safety into their organizational culture (Haleem et al., 2025). Contractors can establish interventions integrating development of safety culture with engineering advancements (Feng, 2013). Government and business leaders should encourage collaboration/communication among engineering firms in CI to establish a competitive market environment that accommodates businesses having different resources and development approaches (Zhang et al., 2023). Furthermore, Martinez et al. (2020)'s case study, indicated that unmanned aerial vehicles could significantly influence safety regulations integrated safety planning and monitoring process of high-rise building construction projects by assisting safety managers.

All interviewees agreed on the CSFs for and barriers against adaptation of OHS4.0 to CI. Interviewees indicated that any OHS initiative that the management does not support cannot be successful and continuous and that management can have the potential to affect the cost and human resources related CSFs and barriers.

Regarding management related strategies, all interviewees emphasized that there is a need to develop strategies related to management. Adopting management approaches can be seen as a strategy for OHS4.0 (A, B, G, H). Government incentives and guarantees to encourage companies to invest in technology (C); policies to ensure independency of OHS management from companies (F, G); auditing mandatory standards (F, G, H); policies to direct cultural change (F, G, H); diversifying financial supports to encourage contractors and business owners to invest, enhancing employer awareness, and relevant academy-private sector collaborations (I) have been recommended.

6. Conclusion

This paper aimed to identify barriers against and CSFs for the adaptation of the OHS4.0 to CI. Following the literature review, four rounds of two groups of the DSs, and interviews were performed. 15 barriers and 13 CSFs have been identified and examined in an integrated way under 3 main headings (i.e., cost, human resources, management aspects). Interviewees have validated the DS results. All interviewees confirmed that the list of 15 barriers and 13 CSFs are correct and that the first three factors in the barriers and CSFs lists were the most important ones. They agreed on the classification of these factors under three main groups (i.e. cost, human resources, and management). They indicated that these three main groups are integrated and that they cannot be considered separately. Figure 4 illustrates interactions among CSFs and barriers.

Regarding cost related barriers and CSFs, criteria 1, 8, and 10 were identified to be among the top three cost-related barriers whereas criteria 4 and 10 were identified to be among the top three cost related CSFs (Figure 4). Regarding human resources related barriers and CSFs, criteria 2, 3, 4, 5, and 11 ranked among the top human resources related barriers whereas criteria 2, 3, 8 were ranked as top human resources CSFs (Figure 4). Criteria related to talent-knowledge-skills, and education were considered to be important by DS participants and interviewees. Furthermore, regarding management aspects related barriers and CSFs, criteria 6, 7, 9, 12, and 13 were identified among the management aspect related barriers whereas criteria 1, 5, 6, 7, 9, 11, 12, and 13 were identified among the management aspects related CSFs (Figure 4).

As interviewees emphasized the three main headings (i.e. cost, human resources and managerial aspects related CSFs and barriers) interact with each other and that even if legal regulations may be sufficient in terms of OHS, technology and OHS4.0 integrated OHS standards are needed. Furthermore, they highlighted that government incentives and inspections can encourage employers to adopt OHS4.0. When handled with careful financial planning and analysis, cost-related barriers can become enablers. Barriers related to human resources (e.g. inadequate training) highlight the necessity of workforce education, skill development, and industry-academia cooperation. Crucial are management-related concerns (e.g. resistance to digitization, lack of leadership support).

In order to successfully implement OHS4.0, the paper emphasizes interdependence of these barriers/CSFs/main headings identified and importance of addressing them all at once. To overcome these barriers and to support the adoption of OHS4.0 technologies, strategies are needed, including government incentives, extensive training programs, and strong managerial commitment. This paper encourages increased awareness among all CI stakeholders and supports strong legal frameworks that incorporate digitalization into safety standards. Significance of cost-benefit analyses, managerial commitment, and continual education have been emphasized to create a digital culture. As effective

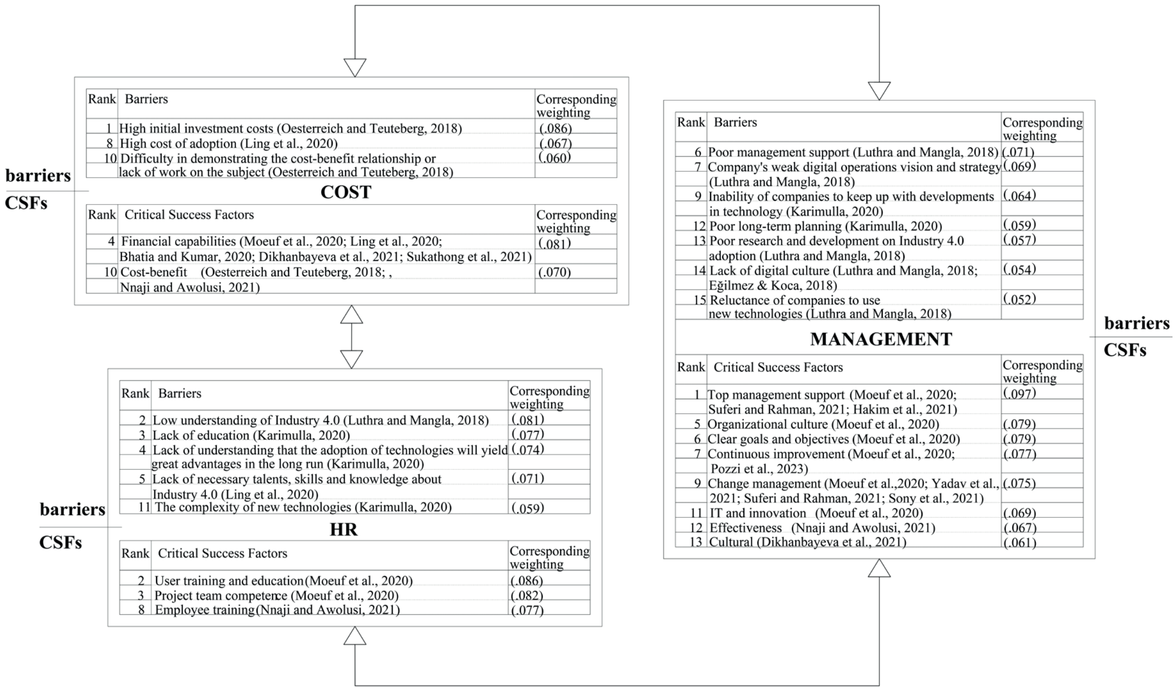

Figure 4. *Interactions among the CSFs and barriers.*

strategies on the cost, human resources and management need to be developed to promote the adoption of OHS4.0 in CI, it is recommended to develop future strategies under these main headings covering proposals for reducing cost, establishment of frameworks for designing and delivering effective training programs, policies to foster managerial support and drive cultural change, guidance for policymakers in incentives. Strategies considering barriers and CSFs in an integrated way can support achievement and widespread of I4Ts integrated OHS4.0 in CI. This study is expected to be useful to all stakeholders of OHS4.0 in CI and act as a potential guide for interested parties.

Acknowledgement

This research paper is part of Ms. Nur Efsan ERUSTA's PhD dissertation which is supervised by Prof. Dr. Begum SERTYESILISIK.

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