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A Practical Model for Measuring and Mitigating Safety Risks of Using UAS in Construction

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February 2022

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CPWR is the research and training arm of NABTU. Production of this document was supported by cooperative agreement OH 009762 from the National Institute for Occupational Safety and Health (NIOSH). The contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH.

Report #20-5-PS

Abstract
In recent years, Unmanned Aerial Systems (UAS) have become very popular in the construction industry due to their versatility and ease of use in data collection. Other benefits of using UAS on job sites include cost savings and improved safety. As research has increasingly focused on how UAS can assist on multiple tasks during different construction phases, the potential negative safety outcomes for construction workers have not been studied adequately. This small study aimed to begin filling this gap by developing a practical model to establish, assess, and improve mitigation programs that construction companies have for controlling safety risks generated as a result of using UAS. The components of the model—including the safety factors and mitigation methods—were identified, verified, and quantified through a mixed approach that relied on a review of literature and a three-round Delphi process.

Key Research Findings
- This study identified potential safety risks of using UAS on construction job sites and derived and verified a hierarchical structure of the causal risk factors.
- It established the relative importance of verified causal risk factors.
- It identified and verified, through a Delphi process, safety practices to control each causal risk factors.
- It developed a practical assessment model for measuring and improving safety control programs for UAS-assisted construction projects.

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Introduction

The construction industry is a major component of the U.S. economy, contributing approximately 5% of the nation's gross output in 2020 (BEA 2021). Construction is also faced with multiple challenges, including skilled worker shortages, a long history of poor productivity, and – most importantly – unsatisfactory safety performance. The industry is one of the nation's most hazardous: of the 5,333 worker fatalities reported in the U.S. in 2019, 1,061 of them were associated with construction activities (OSHA 2019). In other words, although construction accounts for less than 5% of the U.S. workforce, it is responsible for nearly 20% of the total worker deaths (BLS 2019). To improve dangerous workplace conditions and to encourage safe and productive construction activities, both researchers and practitioners have increasingly explored and applied a variety of emerging technologies (Guo et al. 2017, Li et al. 2018). Construction has historically been slow to adopt technology compared to other industries. However, the use of Unmanned Aerial Systems (UAS), a.k.a. drones, grew by 239% in construction in just one year, making construction the fastest commercial adopter of this technology (DroneDeploy 2018).

Given their ease of use, mobility, and cost-effectiveness, UAS can assist with multiple tasks over different construction phases. During site preparation, they can support project planning by performing mapping and surveying tasks, as well as tracking materials and equipment on site for logistics management purposes (Kang et al. 2019). Drones can also be used for site security surveillance and collecting multi-temporal information during construction, which can then be used for progress tracking, quality control, and safety management purposes (Siebert and Teizer 2014, Irizarry and Costa 2016, Hamledari et al. 2017). Furthermore, during operations and maintenance phases, UAS can help with periodic structural inspections and assessment (Nasrollahi et al. 2018, Xu and Turkan 2019). UAS can be used to observe construction sites from viewpoints that are not accessible to humans, providing a more comprehensive and objective angle to reduce errors and document progress (Tobias 2020). Besides, implementing UAS could also reduce the dangers associated with inspecting hard-to-access areas.

UAS prices vary from a couple hundred to a couple thousand dollars based on their sensors and other features, such as object avoidance system and autopilot. Contractors therefore have flexibility to choose the most appropriate device for specific tasks within certain budget restrictions (Opfer and Shields 2014). According to a technology survey with 2,690 construction practitioners, the percentage of the industry considering budget as a barrier to implement UAS in construction has decreased from 53.6% in 2014 to 38.1% in 2017 to 35.4% in 2019 (JBKnowledge 2019).

Although the benefits of using UAS are proven for a variety of applications in different industries, such benefits come at a price. Over the past two years, the Federal Aviation Administration (FAA) has consistently received more than 100 sighting reports of unsatisfactory UAS operations each month from pilots, citizens, and law enforcement authorities (FAA 2021). For example, an Australian triathlete sustained minor head injuries after being hit by a drone, which was used for capturing images of the competitors completing a triathlon (Tailliar 2014). One year later, a drone capturing aerial footage of the Seattle Pride Parade crashed into a building and fell into the crowd, leaving one person unconscious and injuring two others (Miletch 2017). In 2016, a drone crashed at the top of the Space Needle observation tower in Seattle, right before the New Year's Eve celebrations and almost hit the firework technician (Murphy 2017). Although reports of injuries and fatalities due to drone operations in construction are rare, as their use in the industry is still in its infancy, the aforementioned incidents raise a flag about the potential risks of using drones in construction.

FAA regulations to ensure the safety of the public during routine commercial use of small UAS call for certified pilots and cover the operational aspects only. Given the complex dynamic work environment in construction, there may be problems if the UAS operator is the only person following the regulations and taking the responsibility for onsite safety. However, there is currently no standard or set of rules that the industry can follow to safely operate UAS on job sites. Without those standards, safety programs vary between contractors, in areas such as what elements should be included and what measures should be taken to deal with potential risks.

Thus, there is an urgent need for contractors, either those using or those interested in using UAS on their job sites, to determine whether their safety control program is effective. Previous research studies on the topic have touched on a few potential negative safety impacts from using UAS on construction job sites, but those potential impacts and corresponding mitigation plans have not yet been studied adequately.

The primary goal of this study is to develop a practical model to measure and improve the effectiveness of safety control programs for UAS-assisted construction projects. The components of the model are designed to enable professionals and practitioners to: 1) understand and recognize the risks associated with the use of UAS in construction, as well as the causal factors; 2) measure and evaluate the effectiveness of their safety control programs; and 3) adjust and update their safety control programs using effective mitigation strategies. This model is a significant practical contribution to help the industry improve working conditions and mitigate hazards on construction job sites - all of which are expected to improve safety performance across the industry.

RESEARCH METHODOLOGY

To establish a practical model to mitigate the safety risks associated with using UAS on construction job sites and improve the effectiveness of the control methods, this study took a mixed-methods research approach, combining a review of state-of-the-art literature and a Delphi process. The research workflow is shown in Figure 1. The key accomplishments as well as the corresponding results for each stage (shown Figure 1) are detailed in the next section.

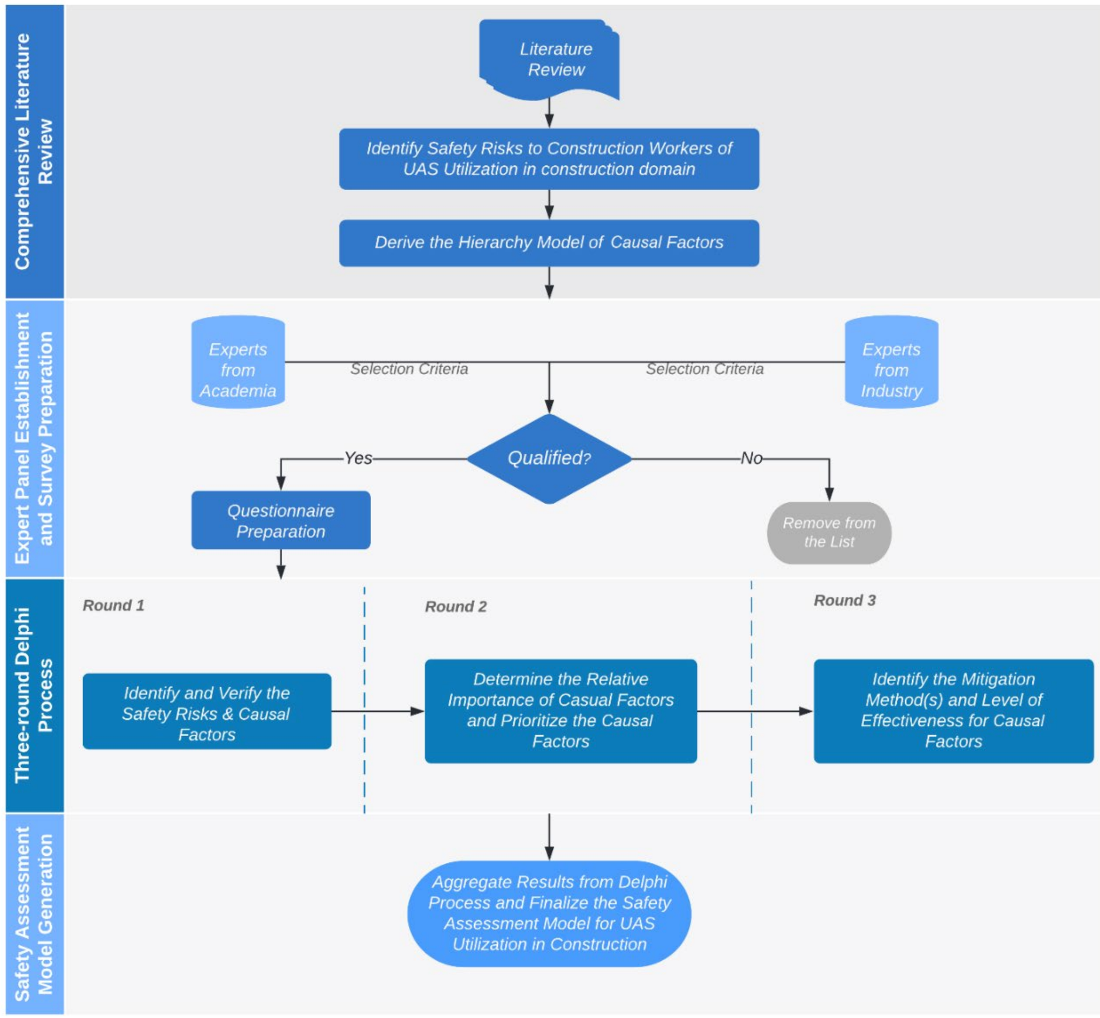


Figure 1. Research Workflow

ACCOMPLISHMENTS AND RESULTS

Stage 1: Comprehensive Literature Review - Identify potential safety risks to construction workers from using UAS on jobsites and develop a hierarchy model of causal factors

To identify all possible safety risks to construction workers associated with the use of UAS on construction sites, the research team reviewed the literature on the topic. Safety risks that construction workers might be exposed to can be divided into two main categories: unsafe work environment and unsafe worker behavior.

As machines of substantial mass and velocity flying above a construction site, UAS can create an unsafe work environment by posing a risk of crash or collision with workers or other objects on the site. This risk can be caused by multiple reasons, including UAS system failure. The safety level of UAS relies largely on both hardware and software performance (Plioutsias et al., 2017). Any failures related to design, manufacture, or lack of maintenance (e.g., algorithm flaw or defective components) could create dangerous conditions for workers underneath, such as unintended acceleration, abrupt falling, or being out-of-control (Vasic et al. 2013, Opfer and Shields 2014). In addition, some UAS features such as Global Positioning Systems (GPS) and communication networks could easily be interrupted in a complex construction environment, where concrete and metallic materials are common and there may be power lines and/or trees

(Vasic et al., 2013). Adverse weather conditions could increase the possibility of UAS system failures as well. High wind, for example, could reduce UAS stability, making it difficult for the pilot to operate (Opfer and Shields 2014, Martinez et al. 2021). Also, considering sand and gravel stockpiles are common on construction sites, high wind could also elevate dust and particulate, which could damage sensors or moving parts of the UAS (Vasic et al., 2013); wind, moisture and extreme temperatures could threaten the circuits and other sensitive UAS components (e.g., battery) (Howard et al., 2018, Namian et al. 2021).

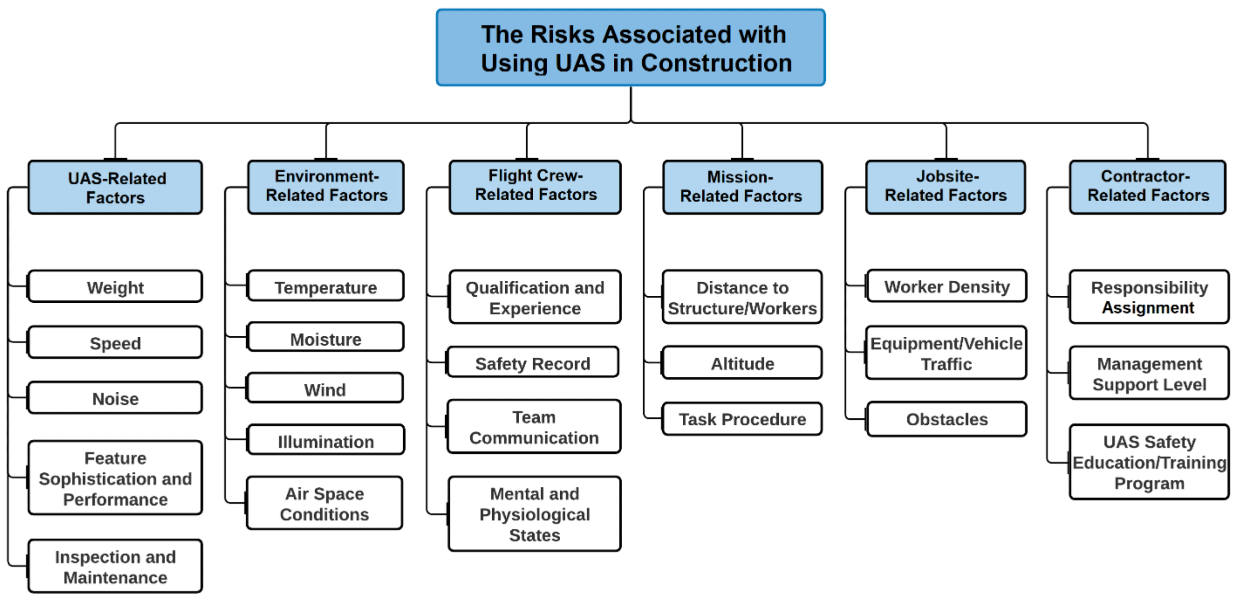
Working in extreme weather environments could potentially cause physical problems (**e.g., sunstroke**) that decrease the flight team's ability to operate the UAS, increasing the collision risks with construction workers or structures (Aliyari 2020). Operational errors could also stem from operator's lack of experience (Melo Costa 2020, Kim and Irizarry 2019). To be a commercial UAS remote pilot, an FAA certificate must be obtained. However, this certificate requires a knowledge test only, not a demonstration of hands-on operating skills. Given the dynamic nature of construction sites, being unfamiliar with UAS or lack of experience working under such complex circumstances could increase the stress level of operators and affect their situational awareness and decision making (Kim et al. 2020, Gheisari et al. 2018). Furthermore, onboard sensors' limited view angle and a lack of sensory cues such as sound may impact operators' ability to make timely decisions during emergencies (e.g., bird attack and signal interference) (McCarley and Wickens 2004, Opfer and Shields 2014). . Although the FAA requires a safety observer to monitor the pose of the UAS and ensure it is operated in a safe environment, errors could still occur due to possible visual illusions and inefficient communication between the observer and the pilot.

Based on the abovementioned reasons, construction workers could be hit by out-of-control UAS, resulting in fatal or non-fatal injuries. In addition, UAS collisions with structures (e.g., temporary structures) might cause structural damages or even collapses, which could harm the workers on those structures or injure workers around it due to flying debris (Howard et al., 2018). Moreover, if UAS crash in or near highly flammable construction materials or volatile liquids, catastrophic property damage could occur (e.g., fire), which would threaten construction workers as well as public safety (Opfer and Shields 2014).

In addition to possibly creating a hazardous work environment, UAS use on construction projects could also distract workers, leading to unsafe behaviors (Gheisari and Esmaeili 2019, Moud et al. 2019, Xu et al. 2020). Depending on the goal of the flight mission and the battery capacity, UAS are task-irrelevant stimuli to construction workers (Namian et al. 2018), and such stimulus could potentially raise their curiosity and distract them. Additionally, UAS noise and the changes in noise frequency due to its motion (e.g., acceleration, climb, and hover) could distract workers. Such auditory distraction around construction workers could easily turn to visual distraction because of tracking the sound source (Nnaji and Gambatese 2016, Moud et al. 2019), particularly for small-size UAS in the distance. According to the distraction theory (Hinze 1996), distracted workers are less likely to recognize job site hazards and are more likely to be involved in workplace accidents. This theoretical proposition has been empirically tested and validated by a previous research study (Namian et al. 2018), which proved that distracted workers recognized significantly fewer hazards than undistracted workers and are, therefore, more likely to get injured or injure fellow workers.

In addition, UAS use in construction projects could stress workers out. The camera sensors mounted on UAS would not only collect necessary images and videos for project progress monitoring, materials management, or safety inspection, but also record the workers' behaviors. Although the workers' productivity might be improved since they would be working under constant surveillance, the increased workload could lead to physical (e.g., fatigue) and psychological (e.g., anxiety or anger) stress, and therefore increase workers' vulnerability to accidents. Besides, in cases such as safety inspections, UAS may be near construction workers. Such a scenario could make construction workers feel that their safety is threatened (Moud et al. 2019). In other words, construction workers are forced to perform two tasks simultaneously – their work at hand and protecting themselves from being hit by the UAS. This might be extremely dangerous, especially for those working at heights.

After identifying the safety risks associated with the use of UAS that construction workers might be exposed to, the researchers hierarchically structured causal factors at different levels (Figure 2). The identified causal factors were classified into six categories, referred to as superior-level factors, based on their sources: (1) UAS-related, (2) environment-related, (3) flight crew-related, (4) mission-related, (5) job-site-related, and (6) contractor -related. Each superior causal factor has one sub-factor set that are referred to as subordinate level factors, as shown in Figure 2. It is worth noting that other challenges associated with using UAS in construction, such as trespassing and privacy issues, are important but not related to construction workers' safety, and therefore are not included in the hierarchy structure. This study only takes rotary-wing UAS into account since they are the most commonly used type due to their ability to vertically take-off and hover.



Stage 2. Expert Selection and Qualification

To achieve the research objectives, the Delphi method was employed to identify, verify, and quantify the safety risk factors and the corresponding mitigation measures associated with using UAS in the construction industry. The Delphi method, a systematic procedure to achieve a reliable consensus among a selected panel of experts, has been widely implemented across numerous domains. The Delphi method is especially heavily used in construction safety and risk management research since experimental or analytical techniques cannot be used due to the ethical considerations. Given that the reliability of a study where the Delphi technique is used largely depends on the quality of the experts' responses, the selection of qualified and knowledgeable experts is crucial (Hallowell and Gambatese 2010, Belton et al. 2019). To ensure diverse perspectives were embraced in this study, experts from both academia and industry specializing in varied but relevant fields (construction safety management, human-technology integration, drone utilization in construction) were considered. Involving both academics and industry professionals could not only assure a diverse range of scientific and practical responses but also prevent potential biases in the data.

To identify the potential experts from academia, the selection criteria mainly relied on the authorship of journal and conference papers related to construction safety, human-technology integration, and drone utilization in construction. The number of publications and membership in nationally recognized committees in the abovementioned research areas were considered as well when determining potential experts from academia. The researchers invited each of the potential academics via email to participate in this study. From a total of twenty-three experts identified from academia, nine agreed to participate.

Unlike the experts from the academia, who can be identified based on their publications in a certain research area, the work experience and contact information for professionals from industry were not easy to obtain. Thus, for the selection of industry professionals, the research team enlisted the support of the Associated General Contractors of America (AGC) industry liaison Erin Wirkkala in the School of Civil and Construction Engineering at Oregon State University, who distributed invitation emails to school alumni and industry partners. The target population was specified as professionals with knowledge and experience in UAS and/or construction safety. To maximize the number of professionals participating in the study, the research team asked email recipients to forward the invitation to someone they know who has knowledge and experience in the relevant areas. Given that the snowballing method was used to invite industry professionals, the actual number of recipients was impossible to track. However, fifty-four experts with a variety of expertise and background agreed to participate in this study.

To validate the qualification of the participants as members of the Delphi panel, requirements and a relative point system identified by Hallowell and Gambatese (2010) were adopted to generate the abovementioned background survey and to assess whether a participant is an expert. The relative point system was used because it offers flexibility for qualifying experts for studies that require not only academic background but also industry experience. The criteria used in this point system were modified to enable both academics and industry professionals to exhibit their expertise in UAS use and construction safety areas through diverse facets. The weight of each of the criteria was determined based on the relative time commitment required to complete each of the achievements. The modified criteria and their weights that were used to filter experts are shown in Table 1.

Hallowell and Gambatese (2010) recommended that panelists score at least four criteria and obtain a minimum score of eleven points to qualify as an expert in a Delphi study. Forty-four out of fifty-four survey participants from the industry did not satisfy these criteria and were removed from the potential panelist list. At the end of this validation process, 19 participants (9 from academia and 10 from industry) were determined to be qualified for the expert panel. In terms of the panel size, there is no agreed-upon number given the different goals and disciplines of studies. However, an expert panel size of eight to twelve was recommended in a previous construction safety study that used the Delphi method (Hallowell and Gambatese 2010). Considering the possibility of experts dropping out in subsequent rounds of the survey, the number of panelists identified in this study was conservative, practical, and manageable. The results of the qualification process for the 19 participants are presented in Table 1 and indicated that all satisfied the minimum required scores and had a level of experience in relevant areas. It is worth noting that 12 of the experts are registered as FAA remote pilots.

Table 1. Criteria and Point System used for Expert Qualification (n = 19)

Criteria (Score) / Participants	**Professional Experience** (1/year)	**Advanced Degree** (4/BS, 6/MS, 10/Ph.D.)	**Publication** (2/Journal, 2/Book or Book Chapter, 0.5/Conference Paper, 0.5/Industry Publication)	**Member of a Committee** (1/Committee)	**Leadership Position** (3/Each)	**Conference Presentation** (0.5/Presentation)	**Professional Registration** (3/Registration)	**Total Score** (Minimum 11)
1	10	PhD	J:18, BC: 4, CP:16, IP:4	2	0	10	2	87
2	13	PhD	J:32, BC:1, CP48, IP:10	4	2	45	1	153.5
3	31	PhD	J:84, BC:7, CP:73, IP:57	2	2	>150	1	374
4	25	PhD	J:79, BC:12, CP:140, IP:16	1	0	>190	0	391
5	12	PhD	J:21, BC:1, CP:15, IP:10	1	0	15	1	90
6	10	PhD	J:4, CP:4	0	0	8	0	34
7	1.5	PhD	J:7, CP:10	3	0	7	2	43
8	9	PhD	J:13, CP:16	3	0	13	0	62.5
9	12	PhD	J:4, BC:1, CP:10, IP:1	2	2	5	2	54
10	18	BS	0	2	1	5	2	35.5
11	22	MS	J:1	1	0	2	1	35
12	10	BS	0	1	0	2	0	16
13	38	BS	0	3	0	15	2	58.5
14	10	BS	IP:6	0	0	0	2	23
15	23	MS	IP:3	0	2	3	1	41
16	25	BS	0	1	4	30	2	63
17	4	MS	J:2	2	3	8	1	32
18	13	BS	J:2, IP:2	2	1	25	2	45.5
19	6	BS	0	1	0	7	0	14.5

Note: Criteria and score system used in this table are adapted and modified from Hallow and Gambatese (2010)

Stage 3: Conduct a Three-round Delphi Survey to Identify, Verify, and Quantify the Causal Factors of UAS Safety Risks to Construction Workers and the Corresponding Mitigation Methods

Round 1. Identify and Verify the Causal Factors of Safety Risks to Construction Workers Associated with UAS Use on Construction Job sites

The primary goal of the first-round survey in the Delphi process was to identify and verify the causal factors of safety risks associated with using UAS on construction sites. The questionnaire was designed to collect the experts' level of agreement with the causal factors the research team identified (see Figure 2). A 5-point Likert scale was used for evaluation, where "1" indicates "strongly disagree" and "5" indicates "strongly agree." In addition, the experts were welcomed to add any other factors to those listed in Figure 2. A detailed description of each factor was provided in the questionnaire. The questionnaire was administered in Qualtrics, a web-based survey tool, and distributed to the expert panel via email.

Overall, 17 out of 19 experts (89.5%) agreed with the categorization of the causal factors associated with using UAS on construction job sites and confirmed that the causal factors under each category were comprehensive. Only two of the experts disagreed with this categorization. One of them indicated that the job site employees were missing and should be added as a new category, given that employees are usually trying to locate the UAS when they hear the whir and ignore other surrounding hazards. The researchers addressed this expert's comment by explaining such considerations were included in "noise" and "UAS safety education and training program" factors. The other expert who disagreed with the identified structure, arguing that UAS are safe, and zero issues were observed during operations in construction if safety check was performed before and after each flight. This opinion indicates that the operators could over-trust UAS, which is one of the most common human judgment errors (OSHA 2019). The majority of the experts agreed or strongly agreed that UAS noise can be a new distraction source for construction workers. It is also worth noting that two of the experts remained neutral, arguing that adding UAS into an already dynamic work environment with various sources of distractions (e.g., high level of workplace noise, flashing lights, crowded workspaces, and other site conditions) would make no difference.

One expert suggested adding “operation license” as a subfactor to the “Flight crew related” category, pointing out that in some cases UAS are operated by individuals who do not have an FAA certificate. The research team modified the structure based on the expert’s comment by combining the license issue with the “experience” factor as “qualification and experience.”

After the structure of causal factors of safety risks associated with using UAS on construction sites was modified, it was sent back to the experts for review. The statistical information of experts’ responses is presented in Table 2. Standard deviation was used to measure consensus and a standard deviation less than 1.5 was considered to indicate that the consensus was reached.

Table 2. Average and Standard Deviation of Level of Agreement on Identified Causal Factors (n = 17)

Causal Factors		Mean	Standard Deviation	Causal Factors		Mean	Standard Deviation
UAS Related Factors	Weight	4	0.92	Environment Related Factors	Temperature	3.62	1.24
	Speed	3.88	0.98		Moisture	4.25	0.71
	Noise	3.38	1.45		Wind	4.63	0.52
	Feature Sophistication and Performance	3.75	1.01		Illumination	3.63	1.10
	Inspection and Maintenance	3.80	0.85		Air Space Condition	4.13	0.64
Mission Related Factors	Distance to Structures/Workers	4.13	0.99	Flight Related Factors	Qualification and Experience	4.10	0.62
	Altitude	3.80	1.21		Safety Record	3.87	1.02
	Task Procedure	4.13	1.30		Team Communication	3.87	1.02
Jobsite Related Factors	Worker Density	3.75	1.02		Mental and Physiological States	4.13	0.64
	Equipment/Vehicle Traffic	3.50	1.07	Contractor Related Factors	Responsibility Classification	4.25	1.04
	Obstacles	4.00	0.76		Management Support Level	3.88	0.99
					UAS Safety Education/Training Program	3.60	1.30

Note: 1 = Strongly Disagree, 5 = Strongly Agree

<u>Round 2. Prioritize the Causal Factors</u>

The objective for the second-round survey in the Delphi process was to collect the experts’ opinion about the relative importance of all verified causal factors (listed in Figure 2) based on the risks they pose to the safety of construction workers. Assessing the risk is an important part of the decision-making process, since it could serve as a basis for managerial decisions in two ways: (1) it helps identify the most serious risk(s) and then allocate precautions and limited resources in a more efficient manner, and (2) it provides the direction for possible actions, procedures, and practices to reduce risks by uncovering the identified causal factors (Kindinger and Darby 2000). Ranking causal factors based on the level of risks they pose to the safety of construction workers is a complex multi-criteria decision-making problem (MCDM) involving multiple interrelated and interdependent factors. This process was even harder for the expert panelists participating in this study, as there is no historical data since UAS use in construction is in its infancy stage.

Considering that risk assessment is highly subjective and risk analysts in the construction industry prefer using everyday language rather than precise numbers, a method called Fuzzy Analytical

Hierarchy Process (FAHP) was chosen for preparing the questionnaire and analyzing the responses in this round of the survey. FAHP enabled the experts to compare any two causal factors based on the level of risk they pose to the safety of construction workers using languages such as English and Spanish. In addition, it allows the conversion of everyday language to a set of values (fuzzy numbers) including the most possible value as well as the upper and lower bounds of the linguistic variables, which is why it is considered suitable and effective for simulating human judgment and improving the assessment accuracy. This round's questionnaire was prepared to include seven questions corresponding to seven groups of causal factors in the hierarchical structure presented in Figure 2 (one for the superior causal factors and six for the subordinate causal factors). Each question was designed as a pairwise comparison table to enable experts to assess the relative importance of any two causal factors in each group. The linguistic scales that were provided to experts for comparison are adapted from Saaty (1980) (Figure 3). As indicated above, the collected data was analyzed using FAHP as well. Figure 4 presents the data analysis workflow using FAHP.

Importance Level	*Extremely* ***More*** *Important*	*Strongly* ***More*** *Important*	*Moderately* ***More*** *Important*	*Slightly* ***More*** *Important*	*Equally Important*	*Slightly* ***Less*** *Important*	*Moderately* ***Less*** *Important*	*Strongly* ***Less*** *Important*	*Extremely* ***Less*** *Important*
Scale	**9**	**7**	**5**	**3**	**1**	**1/3**	**1/5**	**1/7**	**1/9**

Figure 3. Linguistic Scale Provided to Experts for Pairwise Comparison

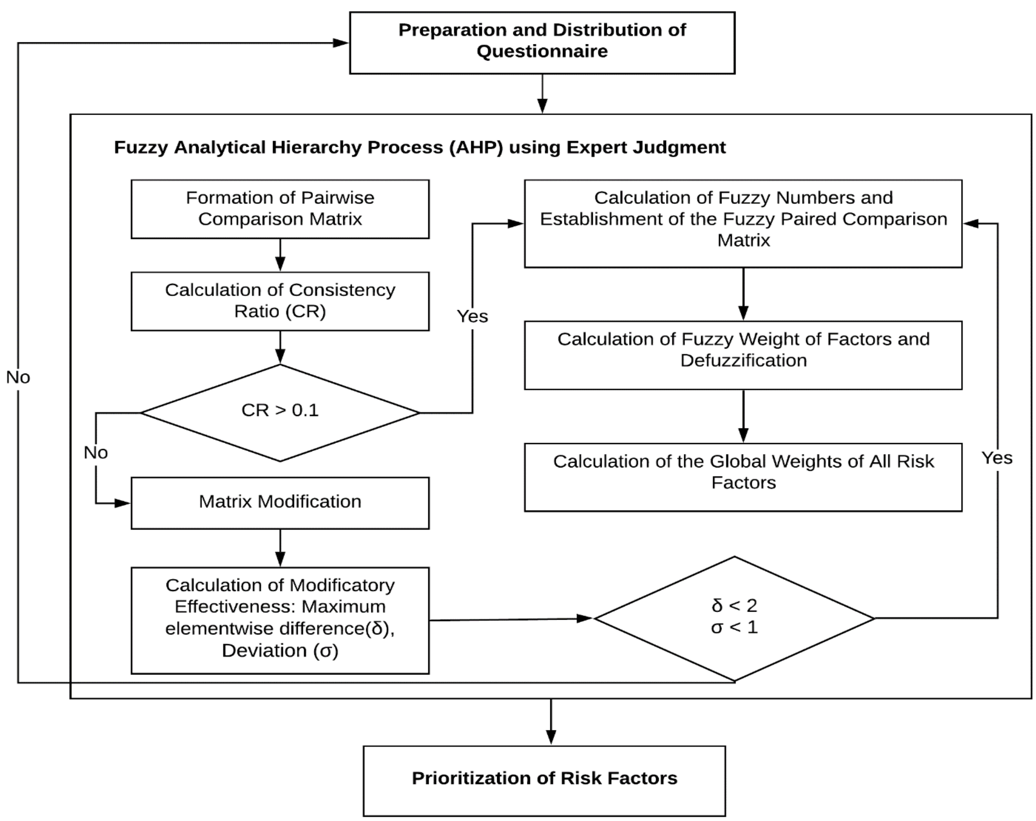


Figure 4. The Data Analysis Workflow using FAHP

Formation of Pairwise Comparison Matrix. Expert opinions were directly extracted from the survey responses (the pairwise comparison tables) to form half of the pairwise comparison matrix. Given the symmetry characteristics of the pairwise comparison, the other half were completed by the research team using reciprocal numbers corresponding to experts' judgment.

Calculation of Consistency. Ideally, if the experts are perfectly consistent, they would not contradict themselves on any of the pairwise comparisons. For example, if an expert rates A as four times more important than B and two times more important than C, then C should be two times more important than B. However, such fully rational and consistent judgments are hard to obtain considering the limitations of human judgment and the complexity of the practical problem. To ensure the quality of each response, the research team used the consistency ratio (CR) introduced by Saaty (1980) and checked to see whether the expert responses are at an acceptable level of consistency to satisfy the CR≤0.1 condition. (More details about the calculation of consistency can be found in the paper by Liu et al. (2017).) If the CR is not satisfied, the algorithm proposed by Xu and Wei (1999) is used to modify the matrix with acceptable modificatory effectiveness by satisfying two criteria: 1) the maximum elementwise difference (δ) being less than 2, and 2) matrix deviation (σ) being less than 1. If such conditions can be reached, it is considered that the matrix modification has satisfactory effectiveness, which has an acceptable CR while preserving most of the information from the original matrix. Otherwise, the matrix should be returned to the experts to ask them if they would reconsider their judgments. This procedure should be repeated until a matrix with satisfactory CR is obtained.

Calculation of Fuzzy Numbers and Formation of the Fuzzy Paired Comparison Matrix. The linguistic language used by the experts to describe the relative importance of any two causal factors are converted to a fuzzy number (f) as described below (Kazemi et al., 2015):

$$f_{ij} = (a_{ij}, b_{ij}, c_{ij})$$

$$b_{ij} = \left(\prod_{k=1}^{n} (RI)_{ijk}\right)^{1/n}$$

where $(RI)_{ijk}$ is the relative importance (RI) of factor i over factor j provided by the k^{th} expert; a_{ij}, b_{ij}, and c_{ij}, respectively, are minimum value, geometric mean, and maximum value of the RI of factor i over factor j provided by n number of experts. Based on the calculated fuzzy number, a fuzzy paired comparison matrix (F) is formed as described below:

$$F = \left[f_{ij}\right]_{m\times m}$$

where m is the number of factors that pair-wisely compared in a given category.

Calculation of Fuzzy Weight of Factors and Defuzzification. Relative fuzzy weights (W) of factors are calculated as:

$$W_i = R_i \oslash (R_1 \oplus \ldots \oplus R_m)$$

$$R_i = [f_{i1} \otimes \ldots \otimes f_{im}]^{1/m}$$

where R_i is the geometric row mean for the i^{th} row in F; $\oplus$, $\oslash$, and $\otimes$ represent fuzzy addition, division, and multiplication, respectively. Details regarding fuzzy arithmetic can be found in the paper by Kwiesielewicz (1998) and Kazemi et al. (2015).

Calculation of the Global Weights of Sub-Factors. The global weight of each subordinate causal factor equals the product of local weight of this factor and the local weight of its superior causal factor. For example, global weight for weight listed under UAS related factors is 0.0617, which is the product of local weight of this factor (0.233) and the local weight of its superior level 1 risk factor (0.265).

In this round, the research team received responses from 17 of the 19 qualified expert panelists. Out of the 17 responses, the original CR check for eight responses was not satisfied (CR>0.1). After matrix modification implementing the algorithm proposed by Xu and Wei (1999), all eight modified responses reached a satisfactory modificatory effectiveness and all 17 responses received an acceptable level of consistency. The final weights and rank of the causal factors that were used to assess risks when using UAS in construction are presented in Table 3. From the results, among all superior causal factors, UAS-related factors are considered as the most critical risk factor group, with a local weight of 0.265. UAS-related factors are followed by environment, flight crew, job site, and mission-related factors with local weights of 0.226, 0.172, 0.130 and 0.115, respectively. The contractor-related factors are identified as the least important safety risk factor group with a local weight of 0.092. Based on the calculated global weights, "wind level," "UAS weight," "UAS inspection and maintenance," "UAS' operational speed," and "distance to structures/workers" are ranked as the top five subordinate causal factors. Considering that the three of the five most important risk factors are associated with the aircraft itself, it would be beneficial to establish a procedure for UAS equipment selection with satisfactory quality and features for assisting with different construction tasks. The findings indicated that the contractor-related factors are the least important causal factor group. This may be because contractors hire a specialty vendor/subcontractor to perform UAS-related tasks in most cases. However, the authors argue that transferring such risks to a third party may not be the best way to protect workers and structures, and that contractor-related factors should be investigated further.

Table 3. Results of Causal Factors Prioritization of UAS Safety Risks to Construction Workers

Level 1 Risk Factors	Local Weight	Level 2 Risk Factors	Local Weight	Global Weight	Rank
UAS-Related Factors	0.265	Weight	0.233	0.0617	2
		Speed	0.215	0.0570	4
		Noise	0.128	0.0339	18
		Feature Sophistication and Performance	0.188	0.0498	6
		Inspection and Maintenance	0.230	0.0610	3
Environment-Related Factors	0.226	Temperature	0.149	0.0337	19
		Moisture	0.146	0.0330	20
		Wind	0.318	0.0719	1
		Illumination	0.166	0.0375	14
		Air Space Conditions	0.208	0.0470	10
Flight Crew-Related Factors	0.172	Qualification and Experience	0.289	0.0497	7
		Safety Record	0.282	0.0485	9
		Team Communication	0.218	0.0375	15
		Mental and Physiological States	0.203	0.0349	16
Mission-Related Factors	0.115	Distance to Structures/Workers	0.435	0.0500	5
		Altitude	0.267	0.0307	21
		Task Procedure	0.298	0.0343	17
Jobsite-Related Factors	0.130	Worker Density	0.361	0.0469	11
		Equipment/Vehicle Traffic	0.305	0.0397	13
		Obstacles	0.334	0.0434	12
Contractor-Related Factors	0.092	Responsibility Classification	0.254	0.0234	22
		Management Support Level	0.216	0.0199	23
		UAS Safety Education/Training Program	0.530	0.0488	8

Round 3. Identify the Mitigation Method(s) and Their Level of Effectiveness

The objective for the third-round survey in the Delphi process was to collect experts' opinion about the mitigation methods or safety practices that could be implemented to control each of the verified causal factors that might expose construction workers to new hazards as a result of using UAS on job sites. In addition, the experts were asked to provide the corresponding effectiveness level for each of the mitigation methods. Given that there are 23 causal factors in total, providing mitigation method(s) for all of them would not be an easy task for the experts, and it could potentially decrease the response rate or the quality of the responses. Therefore, the research team designed the questionnaire with several control methods for mitigating each of the causal factors, which were identified from previous studies or industry publications including news articles, blogs, and reports published by professional organizations in the construction industry. Besides being able to select from the provided mitigation method(s), the experts could also add another method along with their assessment of its effectiveness. A 3-point scale was used to classify the level of effectiveness, where 1 indicates "slightly effective", 2 indicates "moderately effective", and 3 indicates "highly effective". The researchers did not include "not effective" as part of the rating scale given that the selection of a mitigation method would indicate that the expert thinks that the method is effective to some extent. In other words, the experts skipped any of the mitigation methods if they consider them ineffective and/or undesirable.

Out of the 17 panelists who participated in round 2, 13 fully completed the survey in this round. With respect to the identification of mitigation methods, a consensus level of 50% was used to determine whether a method should be retained. In other words, a mitigation method was retained if it was selected or brought up by more than seven experts. As a result of this process, all the 70 mitigation methods, to control a total of 23 causal factors, were retained. In addition, control methods that were added by the panelists were reviewed and sorted to consolidate the ones that were the same or very similar. At the end of this process, two new mitigation methods were identified and included in the final set of mitigation methods. One was "to choose a UAS with a brand/manufacturer with a positive public/customer perception of quality and maintenance," which was raised by eight of the experts for mitigating the "Inspection and Maintenance of UAS" factor. The other control recommended by the experts was "to use a UAS with some level of dust resistance," which was suggested by seven of the experts for reducing the negative safety impact on construction workers caused by the "wind" factor. All 72 mitigation methods are listed in Tables 4-9.

For those mitigation methods that were retained, their level of effectiveness was determined by using the median value of the responses by all experts who provided a response. Median value was used because, unlike the mean, it is less likely to be influenced by outliers (Hallowell and Gambatese 2010). However, the calculated median value for a given causal factor was not always an integer matching the three levels of effectiveness provided, since a causal factor could receive ratings from more than seven respondents. In two instances, a mitigation method received a median value of 1.5, which was considered slightly effective (1 point) to control that risk factor, while another mitigation method received a median value of 2.5, which was considered highly effective (3 points) . As described previously, the standard deviation was used to determine whether the consensus was achieved. A consensus was considered reached if the standard deviation was less than 1.1. The identified mitigation methods with their perceived level of effectiveness are summarized in Tables 4 through 9 based on different groups of causal risk factors.

Table 4. Safety Practices with Perceived Effectiveness Level for Mitigating UAS-related Risk Factors

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Weight	Equipping UAS with recovery systems (e.g., parachute systems and/or airbag system)	Choosing a lighter UAS meeting the requirement for a specific task	Compliance with FAA rules (UAS weight no more than 55 lbs)
Speed		Using a UAS that has a range of speed modes including a low-speed mode; Using a UAS equipped with blades protection (e.g., blade guards)	Compliance with FAA rules (UAS maximum speed is 100 mhp); Identification of the maximum operation speed for UAS for a specific task
Noise	Provide ear protection equipment to onsite employees while UAS in operation	Choose a UAS with a minimum level of noise emmision based on the noise generated by the current construction work	
Feature Sophistication and Performance	ADS-B technology (Automatic Dependent Surveillance-Broadcast)	Autopilot systems	Global Positioning System; Obstacle aviodance sensors; Return-to-Home feature; Geofensing
Inspection and Maintenance		Join an aircraft maintenance program and schedule inspection and maintenance following manufacturer recommendations	Choose a UAS with a brand/manufacturer with a positive public/customer perception of quality and maintenance; Inspect the outer shell and other components for abnormalities such as damage or cracking before and after every flight

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points)

Table 5. Safety Practices with Perceived Effectiveness Level for Mitigating Environment-related Risk Factors

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Temperature		Shorten flight times; Take precautions to prevent operators from having hypothermia or sunstroke; Warm the UAS battery when operating it in a cold environment and take longer breaks between flights in a environment	Check the weather forecast and monitor any changes; Follow the operating temperature designated by the manufacturer
Moisture		Using a UAS with some level of waterproofing	Check the weather forecast and monitor any changes; Do not operate a UAS in the rain or snow
Wind		Using a UAS with some level of dust resistance	Check the weather forecast and monitor any changes; Do not operate a UAS when the wind speeds are higher than the maximum limit recommended by the manufacturer
Illumination		Plan the UAS operation in a way that minimizes direct exposure to the sun	Eye protection for the flight crew (e.g., sunglass); Use sunshade over the screen when planning and during the flight
Air Space Conditions		Collect information about UAS activities in surrounding areas; Make the UAS more visible to reduce the risk of a bird attack (e.g., use a colorful or reflective tape)	Use only one UAS on the construction site at a time; Use a UAS equipped with approved aviation anti-collision lighting

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points)

Table 6. Safety Practices with Perceived Effectiveness Level for Mitigating Flight Crew-related Risk Factors

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Qualification and Experience		Hire a UAS pilot who is enrolled in a recurrent training program	Hire an FAA-certified UAS pilot; Hire a UAS pilot with a certain number of flight hours hands-on experience; Hire a UAS pilot with experience in working on construction sites
Safety Record		Establish the criteria for selecting UAS operators based on their safety records (e.g., accident/incident history)	
Team Communication	Use redundant equipment such as a second ground station if possible to avoid communication loss between the controller and the UAS	Use extra visual observer(s); Provide communication tools between the operator and the observer(s) (e.g., two-way radio, wireless headset technology); Establish hand signals and use them effectively among the flight crew in situations such as high noise envrionment	
Mental and Physiological States		Establish the process to valuate the physical and emotional state of the flight crew members (e.g., mental acuity test)	

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points)

Table 7. Safety Practices with Perceived Effectiveness Level for Mitigating Mission-related Risk Factors

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Distance to Structures/Workers		Establish the requirement for minimum UAS operational distance from the structure	Establish the requirement for minimum UAS operational distance from workers who are not directly participating in the operation of the UAS
Altitude		Maintaining a visual line of sight during the operation	Compliance with FAA regulations (operating UAS within 400 ft above the ground or within 400 ft of a structure)
Task Procedure		Conduct a test flight; Minimize the number of objectives for each flight; Develop a contingency plan responding to any emergency cases during the operation	Develop and verify a pre-flight checklist; Provide the task procedure and flight plan in writing

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points)

Table 8. Safety Practices with Perceived Effectiveness Level for Mitigating Jobsite-related Risk Factors

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Worker Density	Limit the number of employees on job sites during UAS operations		Ensure that the workers are under a coverd structure or inside a stationary vehicle during UAS operation
Equipment/Vehicle Traffic		Set up a limited-access zone or swing radius around heavy equipment with barricades or fencing; Keep equipment/vehicle idle while UAS is operating	Create clear paths for site traffic using barricades/cones/flagging/signs
Obstacles		Establish the requirement for safe operational UAS distance to each identified obstacle	Identify all obstacles including both stationary (e.g., powerline) and dynamic (e.g., crane) that might affect UAS performance

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points)

Table 9. Safety Practices with Perceived Effectiveness Level for Mitigating Contractor-related Risk Factors

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Responsibility Classification			Clearly identify the responsibility of different parties involved in UAS operation on construction site, for either operating UAS in-house or outsourcing; Obtain insurance for both the equipment and personnel
Management Support Level		Increase construction personnel involvement in UAS operation (e.g., engage construction personnel in the flight crew for support); Develop a corresponding contingency plan	Monitor and manage workplace housekeeping (e.g., flammable explosive materials); Provide site orientation/site walk to the flight crew and ensure that the UAS operator is fully aware of any safety "keep out" zones or other limits on the construction site; Update the operators about any site changes for necessary changes on the flight plan; Ensure all personnel on-site wear personal protective equipment (PPE)
UAS Safety Education/Training Program		Provide continuous UAS Safety education to workers/employees to improve their situational awareness, hazards recognition, and mitigation	A Pre-Flight briefing to inform onsite workers of the purpose of the UAS activity and the overall flight route

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points)

Stage 4: Develop a Practical Risk Mitigation and Effectiveness Assessment Model of UAS Utilization in Construction

Based on the results collected from the literature review and the Delphi process, a practical risk mitigation and effectiveness assessment model for using UAS construction sites was developed. To develop such a model, a performance index (PI) was used to aggregate all the risk factors and the mitigation methods that can be implemented to control those risk factors (Ng and Skitmore 2005). The PI represents the mitigation effectiveness score that could be assigned to each risk factor based on the method implemented to mitigate such risk factor, which is defined as follow:

$$PI_{ij} = \frac{\sum_{k=1}^{3} N(RMI_{ij})_{level_k} \times S(level_k)}{\sum_{k=1}^{3} N(RMA_{ij})_{level_k} \times S(level_k)} \times 100$$

where PI_{ij} indicates the performance index of the j^{th} subordinate factors within group i shown in Figure 2; $N(RMI_{ij})_{level_k}$ is the number of risk mitigations with level k effectiveness that are implemented to control factor ij, $N(RMA_{ij})_{level_k}$ is the number of risk mitigations with level k effectiveness that are available to control factor ij, and $S(level_k)$ represents the score assigned for level k effectiveness.

Based on the above mitigation effectiveness score for one risk factor, the total mitigation performance considering all mitigation methods implemented to reduce the potential safety risks resulting from using UAS on construction sites can be obtained by using the following equation:

$$PI_{total} = \sum_{i=1}^{6} \sum_{j=1}^{in} (PI_{ij} \times LW_i \times LW_{ij})$$

where LW_i is the local weight of the i th factors in superior factors obtained from the second round of Delphi survey, and LW_{ij} is the local weight of the j^{th} subordinate factors within group i, and n is the number of sub-factors within group i.

The risk mitigation and effectiveness model for UAS use on construction sites is structured such that a score is calculated based on the extent to which a construction company fulfills the suggested mitigation methods. According to the abovementioned calculation, the highest score of this model (PI_{total}) is 100, which indicates that the construction company has implemented all suggested mitigation methods to control each of the identified causal factors. Given that implementing all the identified safety practices is not realistic, three safety levels were developed. The description of each level is provided in Table 10.

Table 10. Risk Mitigation and Effectiveness Model Criteria

Score	Safety Level	Diagnosis	Action
0 - 32	Low	Minimum safety level of using UAS in construction	Mitigation methods with higher effectiveness are needed to control some or all risk causal factors
33-67	Intermediate	Moderate safety level of using UAS in construction	Mitigation methods with higher effectiveness are needed to control some risk causal factors
67 - 100	High	Desirable safety level of using UAS in construction	Adjust as needed

Dissemination Plan

The researchers wrote a peer-reviewed conference paper based on the results of this project, which will be included in the proceedings of the ASCE Construction Research Congress (CRC2022), one of the prime international conferences in construction engineering and management. Furthermore, the results of this study are planned to be disseminated to the construction research community via peer-reviewed articles in journals such as ASCE Journal of Construction Engineering and Management or Safety Science.

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