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# The development of a safety assessment model for using Unmanned aerial systems (UAS) in construction

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ABSTRACT

In recent years, Unmanned Aerial Systems (UAS) have become very popular in the construction industry due to their versatility, ease of use, cost-effectiveness, and safety advantages. Several research studies investigated UAS use to assist with various tasks through different construction phases. However, the potential negative safety impacts to construction workers associated with UAS use in construction jobsites have not been studied adequately. Therefore, this study aims to fill this gap by developing a practical model to establish, assess, and improve the risk mitigation programs that construction companies have to control safety risks associated with UAS use in construction with a specific focus on workers' occupational safety and health. The components of the model including the safety factors and mitigation methods were identified, verified, and quantified through a mixed approach relied on a review of the literature and a three-round Delphi process. The proposed model is expected to enable practitioners working in the construction industry to 1) understand and recognize the risks associated with the use of UAS in construction as well as their causal factors, 2) measure and evaluate the effectiveness of their own safety control programs for UAS-assisted projects, and 3) adjust and update their own safety control programs using effective mitigation strategies.

## 1. Introduction and motivation

Unmanned Aerial Systems (UAS), commonly known as drones, have become increasingly popular in recent years. Asof late 2021, in the United States (U.S.) alone, 338,974 commercial, and 522,839 recreational drones have been registered with the Federal Aviation Administration (FAA) (FAA, 2021a). The number of remote pilot certificates issued in the U.S. is more than doubled since the small UAS regulations (Part 107) went into effect in 2016 (FAA, 2021a). Thanks to such regulations, innovation and research related to the technology development of UAS increased significantly. This was reflected in the upsurge of the patents related to UAS technology that started in 2016 (AUVSI, 2019). Rapid improvements in UAS technology enabled industry practitioners and academics to evaluate its use for a diverse set of applications in various industries including construction. Accordingly, UAS market size has increased consistently. Based on a recent market research report, the global commercial UAS market is projected to be USD 27.4 billion by the end of 2021 and is forecasted to be more than doubled of that amount by 2026 (Markets and Markets Research, 2021).

The construction industry has historically been lagging behind other industries in technology adoption. However, the UAS use in construction sector skyrocketed, with a 239 % increase within just one year, making the construction industry the fastest commercial adopter of UAS (DroneDeploy, 2018). The popularity of UAS use in the construction industry is mainly due to its characteristics that include being easy-to-operate, time-efficient, affordable, and enabling access to hard-to-reach areas. First, UAS operation has a lower barrier to entry compared to the operations of manned aircraft, considering that only a knowledge test is needed to operate UAS for commercial uses. Besides, UAS can move faster than humans and transfer real-time data in a format of video, digital or thermal images, or point clouds depending on the type of sensors they are equipped with. Concerning cost, UAS prices vary from a couple of hundred to a couple of thousand dollars in the market based on the type of sensors equipped and the feature complexity (e.g., object avoidance system, autopilot system). Various pricing options provide more flexibility for construction contractors to choose the most appropriate device for specific tasks within certain budget restrictions (Opfer and Shields, 2014). In addition, from the annual survey of thousands of construction practitioners, the percentage of contractors that consider the cost as a barrier for implementing new technology in construction

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has decreased gradually from 2014 to 2019 (JBKnowledge, 2019). This decreasing trend is expected to continue as technology, including UAS, is renovated rapidly, which enables them to automate different types of construction workflows (JBKnowledge, 2019). Lastly, the UAS to collect data from hard-to-access areas reduces errors and enables to document project information efficiently while providing a more comprehensive dataset compared to that can be obtained through manual data collection on the ground (Tobias, 2020). Additionally, UAS use could protect onsite staff from exposure to the dangers associated with tasks that require climbing or reaching hard-to-access areas.

The use of UAS for various construction tasks over different construction phases has increased tremendously due to the aforementioned advantages. During the pre-construction phase, UAS can be used to collect spatial and temporal information for mapping, surveying, and project planning tasks (Siebert and Teizer, 2014; Bang et al., 2017; Jiang et al., 2020; Martinez et al., 2021a). During construction phase, it can be used for various tasks including site security surveillance (Zhou et al., 2018), progress monitoring (Bognot et al., 2018; Álvares and Costa, 2019), logistics management (Kang et al., 2019), site communication (Zhou et al., 2018), quality monitoring (Kielhauser et al., 2020), and safety management purposes (De Melo et al., 2017; Gheisari and Esmaeili, 2019; Kim et al., 2020; Martinez et al., 2021b). Most recently, it was also used to help maintain social distancing on construction job sites during the COVID-19 global pandemic (Cardno, 2020). In the post-construction phase, UAS can be used to periodically inspect structures for maintenance purposes and to evaluate damages for post-disaster assessment (Adams et al., 2014; Zhang et al., 2020). In summary, UAS are proven to be capable of producing rich data with less expense and satisfactory accuracy for various construction applications.

While the benefits of using UAS have been proven for various construction applications such as progress monitoring and rapid data collection from hard-to-reach places, concerns and challenges associated with its use were brought up as well. Unauthorized trespassing and invasion of public privacy were the two main concerns highlighted in previous studies (Zhou et al., 2018; Gheisari and Esmaeili, 2019; Namian et al., 2021). Considering that UAS are operated at a certain height above the construction job site, it is possible that they could capture sensitive data from neighbors or breach their property rights, especially when the construction sites are in congested areas. Moreover, since UAS is a relatively new technology, insurance coverage was determined to be another challenge as the risks associated with UAS use in construction have not yet been identified rigorously (Zhou et al., 2018). Furthermore, the safety risks associated with UAS in construction received increasing attention as well. >100 sighting reports of unsatisfactory UAS operations have been received by the FAA every month over the past two years (FAA, 2021b). Some of them resulted in human injuries and property damages. For instance, a UAS capturing aerial footage of the Seattle Pride Parade crashed into a building and fell into the crowd injuring two people, while leaving another person unconscious (Miletch, 2017). A year later, a small UAS crashed at the top of the Space Needle observation tower in Seattle, right before the New Year's Eve celebrations in 2016, and almost hit the firework technician (Murphy, 2017). Considering that UAS use in construction is still in its infancy stage, injuries, and fatalities due to UAS operations reported in the construction industry are rare. However, the abovementioned incidents underscore the risks that this technology might pose to construction workers, who work in one of the most dangerous industries worldwide.

Currently, the FAA in the United States regulate the commercial UAS applications. Considering the unique characteristics (e.g., dynamic work environment and unique safety challenges) of the construction industry, the regulations, and standards for safe UAS operations that construction industry relies upon are limited. To ensure that the UAS use in construction does not pose additional safety risks to construction workers, there is a need to investigate the safety risks and corresponding mitigation methods specifically for UAS use in construction domain. In addition, an evaluation tool is also needed to assess if the current safety programs and procedures are effective for workers' safety and health. Therefore, this paper proposes a practical model to evaluate and improve the safety control programs, if needed, for UAS-assisted construction projects. The components of the model would enable practitioners working in the construction industry to 1) understand and recognize the safety risks associated with the use of UAS in construction as well as their causal factors, 2) measure and evaluate the effectiveness of their own safety control programs for UAS-assisted projects, and 3) adjust and update their own safety control programs using effective mitigation strategies. This is a significant practical contribution that can help construction stakeholders identify safety risks that UAS might pose to construction workers and take precautionary measures to control them accordingly, all of which are expected to lead to improved safety performance across the industry and maximize the benefits of UAS use in construction.

## 2. Background and objectives

### 2.1. Construction safety performance and UAS for safety applications

Construction industry, with an annual spending of $1,230 billion, is one of the most important components of the U.S. economy (BLS, 2019). However, construction industry is also one of the most dangerous industries due to its stubbornly high number of occupational fatalities. In 2019, out of 5,333 worker fatalities reported in the U.S., 1,061 of them occurred in the construction industry (OSHA, 2019). That is, construction industry, which accounts for less than 5 % of the entire U.S. workforce is responsible for almost 20 % of the worker fatalities (BLS, 2019). While these fatalities can be attributed to several reasons, four of the leading causes of fatal accidents on construction sites are falls, being struck by objects, being caught in or between objects, and electrocutions. These four reasons account for over half of the fatalities in construction and are known as the "fatal four". Considering the safety risks in construction, safety management is one of the most crucial tasks. It helps to keep construction safety performance at an acceptable level by identifying potential hazards and unsafe behavior and acting in a timely fashion. According to the Occupational Safety and Health Administration (OSHA), project safety personnel need to walk through the entire construction site repeatedly to observe construction operations, structures, and workers' behavior visually (Woodcock, 2014). However, this process can be very slow if the number of inspectors onsite is limited and/or the construction site is large and complex (Gheisari and Esmaeili, 2019; Martinez et al., 2020). Hence, UAS, due to its ability to collect and transfer real-time visual data, has been explored in the previous studies for the purpose of safety inspection and management.

In early studies on using UAS for safety applications, its usability and feasibility of recognizing hazards on construction sites were explored. For example, Irizarry et al. (2012) used a camera equipped UAS as a safety inspection tool on a construction site to detect hardhats automatically in drone images and concluded that UAS was able to assist safety inspections by providing safety personnel with real-time images and videos as well as voice interaction with construction workers. Irizarry and Costa (2016) and Gheisari and Esmaeili (2016) also investigated the feasibility of using UAS for safety inspections by implementing user-centered approaches, which gathered opinions of safety personnel on using UAS for various safety-related operations. The safety monitoring and control practices that can be improved by using UAS were identified based on the safety managers' responses (Gheisari and Esmaeili, 2016). UAS-integrated safety inspection concept was first proposed by Gheisari et al. (2014). This study confirmed that UAS equipped with relevant sensors can support safety managers by providing data faster as well as enabling to collect data from locations that are not easy to access. Tuttas et al. (2017) conducted a study that compared UAS, and handheld camera use onsite and concluded that UAS is more favorable due to its ability to capture images from unique angles at various elevations, which provides a comprehensive view of a construction site, therefore the status of the project. To improve the benefits of using UAS for safety inspections, Kim et al. (2016) identified and evaluated the factors potentially affecting the performance of UAS-assisted construction safety inspections. Kim et al. (2020a) investigated the user requirements and operational challenges for using UAS on construction job sites. Kim et al. (2020b) documented the operational considerations and procedures through field tests conducted with the industry practitioners and proposed a conceptual UAS-integrated construction safety management workflow. Martinez et al. (2020) conducted a case study to investigate the steps required to integrate UAS in current planning and monitoring processes and concluded that UAS integration has the potential to enhance the identification and assessment of hazards (e.g., unsafe behavior and conditions at height) in high-rise building projects. Also, safety managers involved in this study indicated that UAS provided the most useful type of data for safety planning and monitoring tasks. In another study, De Melo et al. (2017) conducted two case studies to assess the applicability of UAS for collecting visual asset data from jobsites and evaluate the compliance of safety items based on safety regulations. The authors also claimed that the photos and videos collected by UAS can be used as training materials to increase workers' safety awareness. This study also highlighted the difficulty of integrating UAS in safety management systems given the manual data analysis and the large amount of data collected. To solve this problem, Rey et al. (2021) developed a smart inspection method using UAS data and computerized digital inspection tools, which could reduce the time required to analyze UAS data and generate an inspection report in an efficient manner.

### 2.2. Research Problem and Objectives

The previous studies contributed to a better understanding of using UAS to improve current construction safety inspection and management processes. However, UAS use in construction may introduce new safety risks. For example, Martinez et al. (2021) considered the potential fall hazards that UAS can create and thus developed a customized UAS with a super zoom camera and a parachute recover system to enable it to capture very detailed visual data from a safe location without exposing anyone to UAS-associated hazards. Although the studies in recent years have pointed out the safety concerns related to using UAS in construction, no study to date investigated the potential safety risks associated with using UAS in construction from the perspective of workers' safety and health. In addition, the causal factors of such safety risks have been overlooked in the literature. Furthermore, the current regulations and standards for safe UAS operations in the construction industry are limited. The U.S. construction industry relies on the current FAA regulations that provide general guidelines for commercial UAS use. Unfortunately, such high-level guidelines are insufficient for assuring the safety of construction workers considering the unique safety challenges of the construction industry. Therefore, to ensure that the UAS use in construction does not pose additional safety risks to construction workers, an evaluation tool is needed to assess whether the current safety programs and procedures are effective for workers' safety and health to control the safety risks associated with UAS use in construction, which is missing in the current literature.

To this end, the primary goal of this study is to develop a practical model to assess the safety level of UAS use in construction from the perspective of construction occupational safety and health (OSH) management. Accordingly, several research questions were brought up: (1) what are the potential OSH risks associated with using UAS in construction as well as the causal factors causing such risks? (2) which factors are more important when assessing the OSH risks, and (3) what mitigation methods can be implemented to manage each of the causal factors and what are their levels of effectiveness? To answer these research questions and achieve the research goal, four specific objectives (OB) are set as follows:

OB#1: Investigate and identify the potential OSH risks associated with UAS integration in construction workflow and the corresponding causal factors;
OB#2: Verify the potential causal factors leading to identified OSH risks associated with UAS integration in construction workflow;
OB#3: Quantify the importance level of the verified causal factors leading to identified OSH risks; and
OB#4: Identify and quantify the potential mitigation strategies for controlling each of the identified causal factors.

The necessary information to develop a safety assessment model for UAS use in construction was obtained while also achieving these objectives. The developed model includes an evaluation procedure, which can be performed at a task level of integration in construction workflow from the perspective of workers' safety and health.

## 3. Research methodology

This study used a mixed-methods approach that relied on a comprehensive literature review and a three-round Delphi survey to achieve the research goal and objectives. A literature review was conducted to identify the potential OSH risks associated with UAS integration in construction workflow and to derive the causal factors (OB#1). The Delphi method was used to collect information needed to construct the components of the safety assessment model (OB#2 - OB#4). The Delphi method is a well-structured and interactive procedure to achieve a reliable consensus from a selected panel of experts on a specific problem. This method is considered powerful for situations when empirical evidence is lacking, or experimental research is unethical or unachievable (Hallowell and Gambatese, 2010). In the present study, the Delphi method was chosen since (1) there is no empirical research on how UAS use in construction affects workers' safety and health, and (2) experimental research on-site is unrealistic due to ethical considerations. Fig. 1 illustrates the research workflow, and the detailed methods used in the present study are described in subsections below.

### 3.1. Review of literature

Prior to the Delphi process, the potential safety risks that UAS could pose to construction workers and the causal factors of those risks were identified through a literature review. To do so, relevant scientific publications were identified using three scholarly databases based on availability to authors, namely, Web of Science, ScienceDirect, and the American Society of Civil Engineers (ASCE). The keywords that used to search articles were "Unmanned aerial system" as well as its common variants ("Unmanned aerial vehicle", "UAS", "UAV", and "Drone") and "occupational safety and health" along with its variants ("safety risks" and "safety challenges"). A total of 287 articles were identified through the literature search. Based on the screening of the abstracts and removing duplicative articles from different databases, 42 articles were carefully reviewed; however, only 19 articles that reported negative safety outcomes associated with using UAS in construction were reviewed and used to develop the Delphi survey.

### 3.2. Expert selection process

The reliability of a study that uses the Delphi technique is largely dependent on the quality of expert responses. Accordingly, the selection of qualified and knowledgeable experts is crucial (Hallowell and Gambatese 2010, Belton et al. 2019). To ensure that diverse perspectives are embraced in this study, experts from both academia and industry with expertise in relevant fields (construction safety management, human-technology integration, UAS utilization in construction) were considered to be a part of the expert panel. The inclusion of both the academics and industry professionals from different fields of expertise did not only contribute to the diversity of scientific and practical viewpoints but also

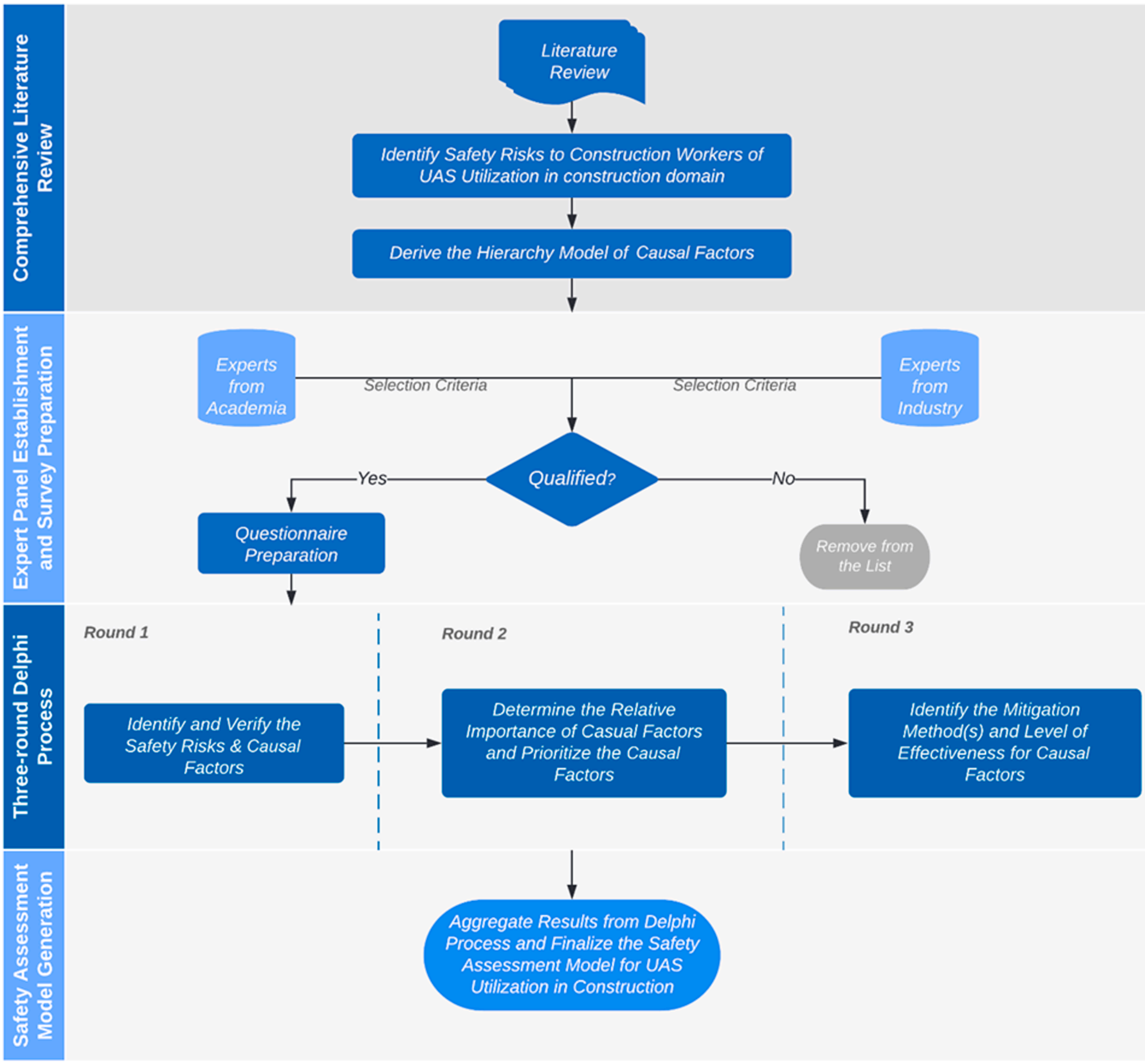


**Fig. 1.** Research Workflow.

minimized the bias.

To identify the potential experts from academia, the selection criteria were primarily based on the authorship of journal articles and conference proceedings on construction safety, human-technology integration, and UAS utilization in construction. The number of publications and their relevance to this study was considered as well when determining the potential experts from academia. Based on such criteria, the authors identified twenty-three experts from academia. To select industry professionals with relevant experience to participate in the study, the research team enlisted the support of the Associated General Contractors of America (AGC) industry liaison in the School of Civil and Construction Engineering at Oregon State University (OSU), who distributed invitation emails to school alumni and industry partners. Professionals with expertise and experience in drones and/or construction safety were identified as the target population. 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 pertinent areas. Since industry professionals were invited using such snowballing approach, it was impossible to track the actual number of invitations.

Nine out of twenty-three experts identified from academia and fifty-four experts from industry with a variety of expertise and background agreed to participate in this study, as they completed the background survey included in the invitation email. The background survey, as a part of the first round of the Delphi survey, was conducted to determine whether the experts who were agreed to participate are qualified to be Delphi panelists of this study. The criteria and point system proposed by Hallowell and Gambatese (2010) were adapted and modified in this study to both prepare the background survey and assess the participants' expertise. This point system was used because it offers flexibility for qualifying experts in studies requiring expertise with both academic and industry backgrounds in the construction domain.

### 3.3. Delphi process

There is no agreed guidance on the optimal number of rounds in Delphi studies. The number of rounds varied from two to six was found in previous studies depending on the complexity of the problem (Yeung and Colleague, 2009; Ameyaw et al., 2014). However, most of the Delphi studies have reached the desired consensus after two to three rounds (Lucko and Rojas, 2010; Ameyaw et al., 2014). Therefore, three rounds of Delphi survey are considered reasonable as was the case in this study. One questionnaire per Delphi round was developed to obtain feedback from the qualified Delphi experts regarding the components of the proposed assessment model (OB#2 - OB#4). Each questionnaire was approved by the Institutional Review Board (IRB) at OSU. All three questionnaires were developed in Qualtrics, an online survey platform, and distributed to the experts via email. The information gathered from three rounds of Delphi survey was analyzed using descriptive statistics and a modified Fuzzy Analytical Hierarchy Process (FAHP). Using advanced statistical data analysis and combining Delphi with other modeling methods such as Fuzzy sets and Analytical Hierarchy Process (AHP) are expected to yield stronger and more reliable findings (Ameyaw et al., 2014). Details regarding the data analysis are discussed in the results section.

## 4. Results

This section presents the results of the literature review, the expert qualification process, and the three-rounds of the Delphi survey.

### 4.1. Results from the literature review

A comprehensive review of the literature on the topic revealed that no study to date investigated the risks UAS may pose to construction workers and identified the corresponding causal factors in a systematic manner. Accordingly, this section focuses on a theoretical understanding of the negative safety outcomes of UAS use in construction from the perspective of workers' safety and health. The safety risks associated with the use of UAS discussed in this section are for rotary-wing UAS since they are the most commonly used UAS type in construction mainly due to their capabilities of hovering and vertical take-off and landing. The following subsections provide detailed information from the literature review and discuss the safety risks associated with the use of UAS in construction projects as well as the causal factors of those risks.

#### 4.1.1. UAS safety risks to construction workers

From the literature, both direct and indirect risks that UAS can potentially pose to construction workers have been identified. Direct risks were considered as physical contact with workers because of UAS crashes or collisions. Indirect risks were considered as non-contact UAS effects on workers including mental or psychological impacts that may lead them to unsafe behaviors and health issues.

As flying machines that are capable to assist with various construction tasks and operate above the construction site, UAS could potentially collide and crash with entities such as workers, flying objects, and structures that share the same airspace with them. Fall, struck-by, caught-in, and electrocutions are considered as the "fatal four" reasons that cause construction workers to die in the workplace (Gheisari and Esmaeili, 2019). Potential UAS collisions and crashes may worsen the situation on job sites by creating more "fatal four" hazards or other types of hazards for construction workers. There are three main potential accidents scenarios, which are discussed below:

• *Collision with workers on site*: UAS can be unstable due to such as out-of-control or fall due to internal (e.g., system malfunction) or external error (e.g., navigation disruption). As flying machines that are operated above construction workers, the UAS with unstable conditions can potentially create a struck-by hazard for the workers by physical contact with them (Irizarry et al., 2012; De Melo and Costa, 2019; Gheisari and Esmaeili, 2019; Martinez et al., 2020). Such unintended physical contact may result in fatal or non-fatal injuries.

• *Collision with mid-air objects*: As UAS have become more popular for hobby and commercial uses, an increasing number of UAS must share the same uncontrolled airspace. That is, UAS used for assisting construction tasks can accidentally collide with other UAS, which are used for either construction applications or recreational purposes near the construction job site (Gheisari and Esmaeili, 2019; Martinez et al., 2020). Besides, birds can be another threat to small UAS since they may attack the aircraft thinking that it is their prey (Rey et al., 2021). Such collisions with mid-air objects can cause functional errors or even disintegration of UAS that may result in out-of-control or abrupt falling (partially or entirely). Those situations create struck-by flying objects or falling object hazards for the construction workers underneath the UAS. Consequently, the construction workers can be harmed by the spinning rotor blades or other sharp falling parts of UAS and have physical injuries such as bruises, lacerations, or puncture wounds. Severe consequences such as unconsciousness or even death also could happen to workers if the workers are not wearing their personal protection equipment (PPE) properly and have certain body parts (e.g., head or neck) exposed to such UAS collisions.

• *Collision with other construction entities*: The construction sites are dynamic, complex, and often congested. UAS that are out of control or falling can potentially crash with various construction entities and cause secondary accidents that may severely injure construction workers. For example, UAS may crash with temporary structures (e.g., falsework or scaffolding) on-site that may cause structural damages or even collapse (Xu et al., 2020; Jeelani and Gheisari, 2021). This situation may put construction workers, who are either on those structures or on the ground in that area, at risk. Workers who are standing on those structures can be injured due to fall accidents caused by the sudden damage or collapse (Jeelani and Gheisari, 2021). Such accidents may also create struck-by hazards to the workers on the ground, who may be hit by the debris of collapsed structures. Besides, some of the construction materials stored on-site are highly flammable such as petrol, paints, and adhesives (Xu et al., 2020). The spark generated by the UAS crash in such an area may ignite those materials and catch fire. Aside from the flammable materials, electrical features and facilities are also common on construction sites, such as grounding, wiring, and high-voltage powerlines (De Melo and Costa, 2019; Gheisari and Esmaeili, 2019; Xu et al., 2020). UAS contact with exposed electrical features may result in serious electrical hazards for the workers working in that area. In an adverse scenario, a flash and small explosion resulting from a UAS crash may cause sparks and result in a fire eventually. These scenarios may create significant safety issues for the workers on-site given the abundant amount of wood materials that are easily found on construction sites, which the fire can spread to. Construction workers trapped in such conditions may also have respiratory issues, burning, or even fatal injuries.

In addition to direct risks resulting from physical contact with the UAS or other objects generated from the collision or crash, the use of UAS in construction projects could also pose indirect risks to construction workers. Two main potential accident scenarios are discussed below:

• *Visual and auditory distraction*: As a relatively new and rapidly updated technology, UAS integration in construction activities can cause unwanted distractions to construction workers (Gheisari et al., 2014; Irizarry and Costa, 2016; Alizadehsalehi et al. 2018; Moud et al. 2019). UAS motion and sound are task-irrelevant and discrete/infrequent stimuli to construction workers. They are considered task-irrelevant because the current UAS operations are mainly for inspecting the aspects of project performance rather than be the processes involved in the focal tasks performed by construction workers. Such stimuli are considered discrete or infrequent because the current UAS technology cannot be operated consistently due to battery capacity limitations. Besides, humans are slow to react to task-irrelevant stimuli with an irregular frequency than to those with regular frequency (Namian et al. 2018). In the case of UAS use in construction, the UAS motion may increase construction workers' curiosity and divert their visual attention away from their task at hand. In addition, the buzzing UAS sound and sound changes due to different motions such as acceleration, climb, and hover could distract workers as well. Such auditory distraction can quickly turn into visual distraction as a result of workers tracking the sound source, particularly when a small size UAS is used and when it is operating far from the workers (Namian et al. 2018; Kim et al., 2019). According to the distraction theory, distracted workers are less likely to recognize the jobsite hazards and are more likely to make mistakes and involve in workplace accidents (Namian et al. 2018). In summary, visual and auditory distractions may lead construction workers to behave unsafely and either injure themselves or other construction workers.

• *Psychological and physical stress*: Other than possibly distracting workers due to its motion and sound, UAS use in construction could also stress construction workers out (Xu et al., 2020). The camera sensors mounted on UAS do not only collect images and videos for various project management tasks (e.g., progress monitoring, materials management, or safety inspection) but also record workers' behaviors unavoidably. Such unintended data collection may increase workers' stress level and mental workload and lead them to think that they are under surveillance (Xu et al., 2020; Jeelani and Gheisari, 2021). According to the Hawthorne Effect (McCarney et al., 2007), people feel under time pressure and try to complete their tasks quickly when they perceive as being under surveillance. Although it seems that the workers' productivity may increase because of the time pressure, the increased workload could potentially lead to both physical (e.g., fatigue) and psychological stress (e.g., anxiety), and therefore, increase workers' vulnerability to accidents. Besides, in some cases such as safety inspections, UAS might be operated near construction workers. In such a scenario, construction workers may feel that their own safety is compromised (Moud et al. 2019). In other words, construction workers would be forced to perform two tasks simultaneously – their work at hand and protecting themselves from being hit by the UAS. This can be extremely dangerous for construction workers, especially for those workers who are working at heights.

#### *4.1.2. Causal risks associated with UAS use in construction*

Based on the system safety theory (Leveson, 2002), a construction job site is considered as an integrated system with construction workers, equipment, and management. This theory states that safety performance is affected by a set of parameters related to the behavior of the system's different components (Larsson et al., 2010). Therefore, considering a UAS-assisted construction project, the safety performance of the project is affected by various factors that are part of this system. According to this theory, the causal factors of the safety risks associated with UAS use that construction workers might be exposed to are classified into six categories, which are referred to as superior level factors based on their sources: (1) UAS-related, (2) environment-related, (3) flight crew-related, (4) mission-related, (5) jobsite-related, and (6) contractor-related. Each superior causal factor has one sub-factor set that includes several subordinate level factors, which is shown in Fig. 2. It is worth noting that other challenges associated with UAS use in construction such as trespassing and public privacy issues, although important, are not related to construction workers, and therefore, they are not included in the list of identified risk factors. Also, this study considers the risks associated with rotary-wing UAS use since it is the most commonly used UAS due to its capability of vertical take-off and hover, which is more suitable for construction job sites.

• *UAS Related Factors:* These are the factors that are associated with the aircraft itself and the sensors mounted on it. The weight and velocity are considered as the inherent risk factors associated with UAS operations above construction workers (FAA 2019). In addition, the noise UAS create while in motion could stress the workers out or distract them from the task they are performing, which may put them in serious danger and hamper the quality of project (Namian et al. 2018, Moud et al. 2019). Moreover, UAS that are available on the market varies a lot in terms of sophistication and performance (Plioutsias et al., 2017). Some of them lack various necessary and high-performing technical features, such as sense-and-avoid capability and high-precision navigation, that could lead to system failure and harm people and structures on the ground (Martinez et al., 2021a,b). Also, if not maintained properly, the chances for UAS to fail and pose risks to people and structures on the ground would increase (Petritoli et al., 2018).

• *Environment Related Factors*: Environment related factors have to do with weather and other physical conditions. Poor weather conditions would greatly increase the likelihood of failure in UAS operations. The components of UAS, such as the battery and sensor, are very sensitive to moisture and temperature. Rain or snow as well as extreme temperatures could threaten those components and cause system malfunction or navigation problems (Howard, 2017, Namian et al., 2021). In addition, low temperatures could also affect UAS operators' performance as a result of their hands getting cold or movements being limited due to protective/extra layers of clothing (Aliyari, 2020). Moreover, UAS are vulnerable to high winds as they are lightweight, which may lead to losing control of the aircraft while navigating or landing (Martinez et al., 2021a,b). High illumination is another risk factor that could disrupt the vision of both the operators and the camera that is mounted on the UAS, which could lead to accidents because of disruption in vision (Namian et al. 2021). Clear airspace is another important factor since other flying objects and birds, could strike UAS and cause accidents (FAA 2019).

• *Flight Crew Related Factors*: Flight crew related factors are related to the pilot and the observer(s). Safety during UAS operations is highly dependent on the skills of the pilot even though UAS flights are highly automated. Lack of experience in operating UAS on construction sites could make operators nervous, which may potentially lead to accidents (Xu et al., 2020, Kim and Irizarry, 2019). The safety records of pilots are identified as an important indicator of the safety attitude of the pilot

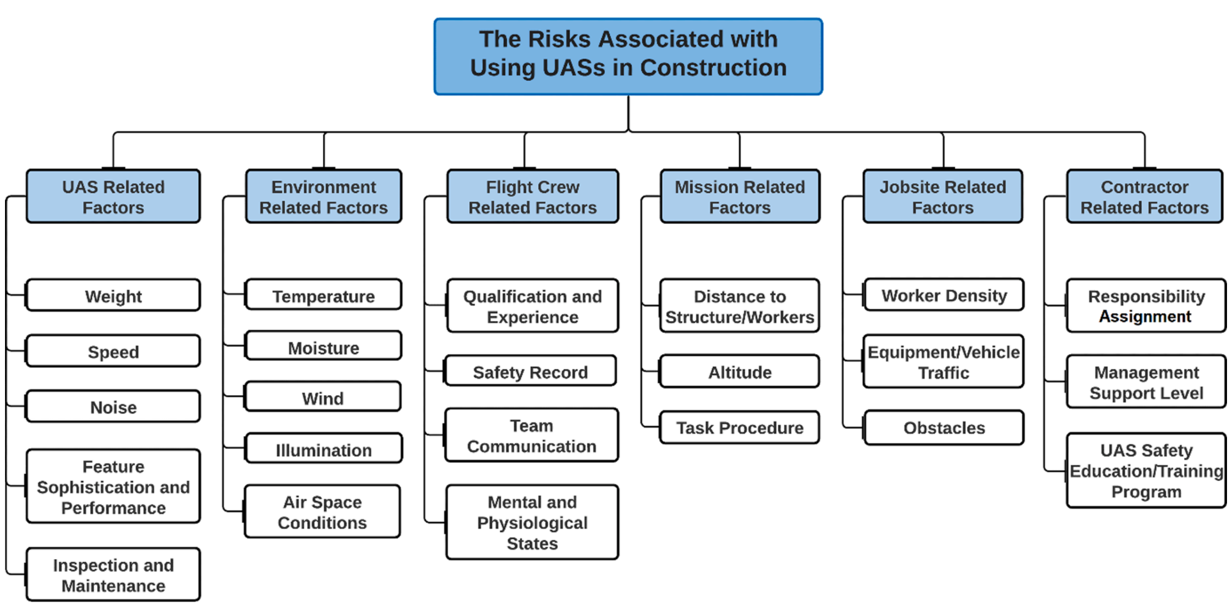


**Fig. 2.** Causal Factors of Safety Risks Associated with Using UAS in Construction.

(Kim and Irizarry, 2019). UAS pilots with unsatisfactory safety records have a higher chance of making mistakes. In addition, inefficient communication between the operator and the observer(s) could prevent the operator from making timely and adequate decisions (Aliyari, 2020). Besides, mental and physiological states such as drowsiness, fatigue, distraction, and stress could affect operators' judgment and behavior, and task performance (Aliyari, 2020).

- *Mission Related Factors*: Mission related factors refer to the requirements related to specific tasks. For instance, the requirement for UAS distance to workers/structures and the operating altitude would be different for different tasks/projects, e.g., progress monitoring vs safety inspections (Kim et al. 2020a). However, there are not any standardized regulations regarding the safe operating distance from workers/property (Gheisari and Esmaeili, 2019). UAS operations close to workers and structures could stress both operators and workers and increase the likelihood of them making mistakes (Moud et al. 2019). UAS falling from higher altitudes could cause a higher level of danger to people and structures on the ground. In addition, not having a step-by-step procedure for specific tasks could cause confusion among the flight crew and may increase the possibility of making mistakes during UAS operations (Kim et al. 2020b). Many studies indicated that non-compliance with FAA regulations, such as unauthorized trespassing, is another vital risk factor that will increase the possibility of fatal consequences (Aliyari 2020, Namian et al. 2021).
- *Jobsite Related Factors*: Jobsite related factors are related to the complexity of the construction job site. For example, UAS failure on a crowded job site would increase the likelihood of worker injuries/fatalities (Kim et al. 2020b). Also, moving equipment on site, such as cranes, could hit the UAS or obstruct UAS operators' point of view (De Melo et al. 2017). For this reason, equipment and vehicle traffic on site are important factors for safe UAS operations on construction job sites. Furthermore, obstacles, such as power lines and trees, could interfere with UAS signals and need to be investigated further to avoid any accidents (Opfer and Shields 2014). The location of the construction project is also recognized as a safety risk factor as UAS failures could cause severe damages if the job site is located in a dense urban area or close to an airport (FAA 2019).
- *Contractor Related Factors*: Contractor related factors include not having clear responsibilities assigned to different individuals (among the flight crew as well as the project personnel) which may decrease the performance of UAS related tasks as a result of no one taking responsibility for specific tasks (Kim et al. 2020b). A low level of support from the project management team could lead to inadequate flight planning and operations, thus increase the chances for mistakes and lead to lower productivity. Insufficient UAS safety education/training programs would lead to workers being uninformed about the risks associated with UAS use on construction sites and unfamiliar with the proactive protective methods to respond to any emergencies (Xu et al. 2020).

### 4.2. Expert qualification

As mentioned previously, the point system used in this study to assess expert qualification was adapted and modified from the study conducted by Hallowell and Gambatese (2010). The weight of each of the criteria used in this point system 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 qualify the experts who participated in this study 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 expert panelist. On the other hand, all the participants from academia satisfied the minimum required scores, and therefore, it was determined that they were all qualified to be included in the Delphi panel. At the end of this validation process, nine experts from academia and ten experts from industry were determined to be qualified for the expert panelist for this study. In terms of the panel size, there is no agreed-upon answer given the different goals and disciplines of studies. Based on a review of sixty-seven construction engineering and management researchers that used the Delphi method, the size of the expert panel ranged from three to ninety-three, and the majority of them are between eight to twenty (Ameyaw et al., 2016). In addition, Hallowell and Gambatese (2010) indicated that the size of an expert panel of eight to sixteen was used in most studies and recommended a minimum size of

**Table 1**
Criteria for Expert Selection and Qualification.

| CriteriaParticipants (Score) | 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 point system used in this table are adapted and modified from Hallow and Gambatese (2010) an expert panel of eight. Considering the possibility of experts seceding from the subsequent rounds of the survey, the number of panelists identified in this study (19 in total) was conservative, practical, and manageable. The results of the qualification process for the 19 panelists are presented in Table 1. Finally, it is worth noting that 12 of the experts (out of 19) are registered as FAA remote pilots.

## 4.3. Results from Delphi rounds

### 4.3.1. Round 1 - identify and verify the causal factors

The primary goal of the first-round survey in the Delphi process was to verify the causal factors of safety risks associated with using UAS on construction sites and identify any factor that was missing from the literature review. The questionnaire was designed to collect the experts' level of agreement with both the overall structure and each of the causal factors identified by the research team (Fig. 3). 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 they identified in addition to those listed in Fig. 3. A detailed description of each factor was provided in the questionnaire.

Overall, out of the 19 responses in total, 17 of the experts (89.5 %) agreed with the categorization of the causal factors of safety risks associated with the use of UAS on construction jobsites and confirmed that the causal factors under each category are comprehensive. Only two of the experts raised concerns about the list and the categorization. One of them indicated that jobsite employees were missing and should be added as a new category given that the workers on-site are usually looking for the UAS when they hear the whir and ignoring other surrounding factors. The researchers carefully addressed this expert's comment by explaining such considerations were included in "noise" and "UAS safety education and training program" factors. The other expert argued that UAS are safe enough, and zero issues were observed during operations in construction as long as a safety check was performed before and after each flight. This opinion indicates that the operators could over-trust the UAS movement, which is the most common human judgment error resulting from (OSHA 2019).

Among all causal factors, it is worth noting that the majority of the experts agreed or strongly agreed that UAS noise can be a new distraction source for construction workers on site. However, two of the experts remained neutral arguing that adding UAS into an already dynamic and noisy 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. In addition, one expert suggested adding "operation license" as a subfactor to the "Flight crew related" category, who pointed out that in some cases UAS are operated by individuals who do not have FAA certificates. 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". The structure of causal factors of safety risks associated with UAS use on construction sites was carefully modified based on the comments from the experts. As part of the second round Delphi survey, this revised structure of causal factors along with the descriptive statistical information of experts' responses was sent back to them for review and reassessment. After this reassessment process, 17 responses (out of 19) were received and none of them change their rating. The statistical information obtained from 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.

### 4.3.2. Round 2 - prioritize the causal factors

Besides enabling experts to reassess their ratings from round 1 based

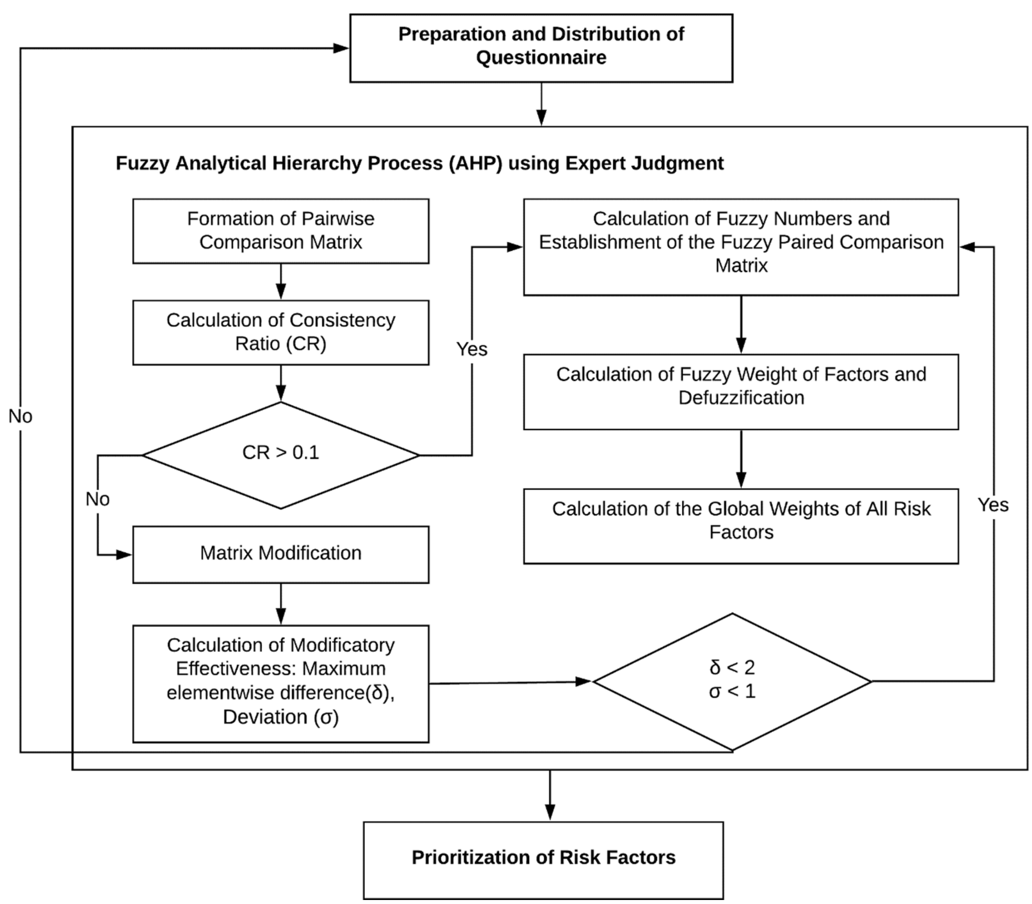


**Fig. 3.** Data Analysis Workflow using FAHP.

**Table 2**
Descriptive Statistics of Level of Agreement on Identified Causal Factors.

| Category | Causal Factors | Median | Average Rating (σ) | Category | Causal Factors | Median | Average Rating (σ) |
|---|---|---|---|---|---|---|---|
| UAS Related Factors | Weight | 4.00 | 4 (0.92) | Environment Related Factors | Temperature | 4.00 | 3.62 (1.24) |
| | Speed | 4.00 | 3.88 (0.98) | | Moisture | 4.00 | 4.25 (0.71) |
| | Nosie | 4.00 | 3.38 (1.45) | | Wind | 5.00 | 4.63 (0.52) |
| | Feature Sophistication and Performance | 4.00 | 3.75 (1.01) | | Illumination | 4.00 | 3.63 (1.1) |
| | Inspection and Maintenance | 4.00 | 3.80 (0.85) | | Air Space Condition | 4.00 | 4.13 (0.64) |
| Mission Related Factors | Distance to Structures/Workers | 4.00 | 4.13 (0.99) | Flight Related Factors | Qualification and Experience | 4.00 | 4.1 (0.62) |
| | Altitude | 4.00 | 3.80 (1.21) | | Safety Record | 4.00 | 3.87 (1.02) |
| | Task Procedure | 4.00 | 4.13 (1.3) | | Team Communication | 4.00 | 3.87 (1.02) |
| Jobsite Related Factors | Worker Density | 4.00 | 3.75 (1.02) | | Mental and Physiological States | 4.00 | 4.13 (0.64) |
| | Equipment/Vehicle Traffic | 4.00 | 3.5 (1.07) | Contractor Related Factors | Responsibility Classification | 4.00 | 4.25 (1.04) |
| | Obstacles | 4.00 | 4.00 (0.76) | | Management Support Level | 4.00 | 3.88 (0.99) |
| | | | | | UAS Safety Education/Training Program | 4.00 | 3.60 (1.3) |

**Note: 1 = Strongly Disagree, 5 = Strongly Agree**

on other experts' opinions, the objective for the second-round survey in the Delphi process was to collect experts' opinions about the relative importance of all verified causal factors (Table 2) based on the risks they pose to the safety of construction workers. Assessing the risk impact is an important part of the decision-making process since it could serve as a basis for managerial decisions in two ways: (1) help recognize the most serious risk(s) so that necessary precautions are taken and the limited resources are allocated in a way to maximize workers' safety in a more efficient manner, and (2) provide 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 risks they pose to construction workers is a difficult task as it is a complex multi-criteria decision-making problem (MCDM) involving multiple interrelated and interdependent factors. This process was even harder for the expert panelists participated in this study given there was no historical data since UAS use in construction is relatively new. Considering that risk assessment is usually subjective and risk analysts in the construction industry prefer using linguistic languages 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 the linguistic languages. In addition, it allowed the conversion of linguistic 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 Fig. 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 provided to experts are adapted from Saaty (1980), which is shown in Table 3. Fig. 3 presents the data analysis workflow implementing FAHP. The results collected from this round were analyzed using FAHP as well and each step of this process is detailed below:

**Table 3**
Linguistic Scale used for Pairwise Comparison.

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

- *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 was 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 $\leq$ 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 back to the experts to ask them if they would reconsider their judgments. This procedure should be repeated until a matrix with satisfied 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 $F = \left[f_{ij}\right]_{m\times m}$, where m is the number of factors that pair-wisely compared in each category.
- *Calculation of Fuzzy Weight of Factors and Defuzzification.* Relative

fuzzy weights ($W$) of factors are calculated as:

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

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

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 Kwiesielewicz (1998) and Kazemi et al. (2015).

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

In this round, the research team received responses from 17 panelists (out of 19). Out of 17 responses, the original CR check was not satisfied (CR > 0.1) for eight of them. So, the matrix modification algorithm (Xu and Wei 1999) was used, and all of the eight modified responses reached a satisfactory modificatory effectiveness. Thus, all 17 responses reached an acceptable level of consistency. The final weights and the rank of the causal factors are presented in Table 4. 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, jobsite, 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 in terms of importance. 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. As stated above, the findings indicated that the contractor related factors are the least important causal factor group. The reason for this may be because contractors typically hire a specialty vendor/subcontractor to perform UAS related tasks. 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 4**
Local Weight, Global Weight, and Rank for Causal Factors.

| 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 |
| | | Nosie | 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 |

#### 4.3.3. *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' opinions about the mitigation methods or safety practices that could be implemented to control each of the verified causal factors, which could potentially expose construction workers to new hazards resulting from UAS use on construction jobsites. 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 decrease the quality of the responses. Therefore, the research team designed the questionnaire including several reasonable control methods that can be used to mitigate 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 provide any other mitigation method with their level of effectiveness. A 3-point scale ranging from 1 to 3 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 could skip any of the mitigation methods if they considered them ineffective and/or undesirable.

Out of the 17 panelists who participated in round 2, 13 of them fully completed the survey and provided responses in this round. With respect to the identification of mitigation methods, a consensus level of 50 % was used to determine whether a mitigation method should be retained. In other words, a mitigation method was retained if it was selected or brought up by more than seven experts. At the end of this process, all 70 mitigation methods to control 23 causal factors provided by the research team 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 added to 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 recommended by eight of the experts to mitigate the risks associated with "Inspection and Maintenance of UAS". The other risk mitigation approach that was suggested by seven of the panelists was "to use a UAS with some level of dust resistance" to mitigate the risks associated with the "wind" factor.

The level of effectiveness was also determined for each of the risk mitigation methods using the median value of experts' feedback. The median value, unlike the mean, is less likely to be influenced by outliers (Hallowell and Gambatese 2010), thus, it was used in this study to determine the level of effectiveness of each mitigation method. 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 if the consensus was achieved. A consensus was considered reached if a standard deviation was less than 1.1. The identified risk mitigation methods with their perceived level of effectiveness are summarized in the Table 5-10 based on different groups of causal risk factors.

## 5. Development of safety assessment model for UAS use in construction

Based on the results obtained from the literature review and the Delphi survey, a practical risk mitigation and effectiveness assessment model for using UAS on 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 causal factor based on the method implemented to mitigate such risk factor, which is defined as follows:

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

where $PI_{ij}$ indicates the performance index of the $j$ th subordinate factors within group $i$ shown in Fig. 2. $N\left(RMI_{ij}\right)_{level_k}$ is the number of risk mitigations with level $k$ effectiveness that are implemented to control factor $ij$. $N\left(RMA_{ij}\right)_{level_k}$ 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 using the following equation:

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

where $LW_i$ is the local weight of the $i$ th factor obtained from the second round of Delphi survey. $LW_{ij}$ 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 con-

**Table 6**
Mitigation Methods with Perceived Effectiveness Level for Environment-related 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 5**
Mitigation Methods with Perceived Effectiveness Level for UAS-related 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>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 |
| Nosie | 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 7**
Mitigation Methods with Perceived Effectiveness Level for Flight Crew-related 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 8**
Mitigation Methods with Perceived Effectiveness Level for Mission-related 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 9**
Mitigation Methods with Perceived Effectiveness Level for Jobsite-related 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)

struction 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 ($PI_{total}$) can be 100 indicating that the construction company has implemented all suggested mitigation methods to control each of the identified causal factors. Given that implementing all of the identified safety practices is not realistic, three safety levels were developed. The three safety levels were identified based on the calculation of $PI_{total}$, which is governed by the three level of effectiveness. In other word, the upper bound of three safety levels was determined as 1/3, 2/3, and 1 of the highest $PI_{total}$ score. The description of each level is provided in Table 11.

## 6. Discussion

### 6.1. Correlation between the causal factors

In this study, the causal factors of OSH risks associated with UAS use in construction were identified and verified by Delphi experts. The FAHP approach was used to determine the level of importance of each causal factor to OSH risks. The assumption made in the FAHP approach is that the factors within one category are independent from the factors within another category (Liu et al., 2014; Ooi et al., 2018). That is, this method is solid if the factors within one category are correlated to some extent. This assumption is valid here since a hierarchical structure was developed in this study, where the six superior categories of causal factors are independent from each other. For example, the “Noise” factor within the

**Table 10**
Mitigation Methods with Perceived Effectiveness Level for Contractor-related 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)

**Table 11**
Criteria Recommended to Assess UAS Safety Level.

| 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 |

category of "UAS-related" factors is not correlated to the "Moisture" factor within the category of "Environment-related" factors, but it might be correlated to the "Speed" factor within the same category as the "Noise" factor. In addition, given the experts were asked to compare factors pairwise based on their level of importance considering the overall OSH risks from using UAS in construction, they actually compared the potential risks contributed from such two factors rather than the factors themselves. In other words, the global weights calculated using FAHP approach would not be affected by the correlation between the factors in each category. Given the abovementioned considerations, the causal factors were not considered correlated in this study. Accordingly, the mitigation methods identified for each causal factor are used to control the potential OSH risks generated by it specifically.

### 6.2. Understanding of the weights and the developed model

To better utilize the developed model, the meaning of the global weights and the details of the developed model should be discussed. In this study, the developed model is expected to provide information regarding the effectiveness of the current safety program and procedures, if available, regarding their ability to control the OSH risks as a result of using UAS in construction. The total value of OSH risks from using UAS for a specific construction project is considered as a sum of the risks that generated by each causal factor $i$, which can be expressed as $risk_{total} = \sum_{i=1}^{n}(risk_i)$, where $n$ is the number of level 2 factors identified and verified in this study. The global weight ($w_i$) for each level 2 causal factor $i$ was calculated to represent the risk portion that this factor contributed to the total value of OSH risks ($risk_{total}$) in a specific construction project, which can be expressed as $risk_i = w_i \times risk_{total}$. To control the risks generated by each causal factor, one or more mitigation methods with different levels of effectiveness can be implemented. $PI_i$ was introduced to reflect the performance index considering the compliance with the mitigation methods identified and verified for the given factor in this study as well as their levels of effectiveness. For example, a 60 % $PI_i$ means the current safety program applied 60 % of the effective mitigation methods to control the risks caused by factor $i$. Accordingly, the remaining risks of factor $i$ becomes $risk_{i\_remaining} = (1 - 60\%) \times w_i \times risk_{total}$. Considering all the causal factors, the remaining risks after applying various mitigation strategies can be calculated as follows $risk_{remaining} = (1 - PI_{total}) \times risk_{total}$. Thus, $PI_{total}$ was introduced to represent the effectiveness of the safety program with respect to reducing the potential safety risks associated with using UAS in a given construction project. Since the historical data for UAS caused occupational injuries/fatalities is limited, risk assessment for using UAS in construction is not an easy job. Instead of quantifying the exact risks of UAS use in construction, the model developed in this study enables to quantify the percentage of the risks that are controlled, considering all the identified mitigation methods in this study are implemented. That is, the calculated $PI_{total}$ can be understood as the effectiveness of the current safety program and procedures for mitigating the OSH risks associated with UAS use.

### 6.3. How to use the developed safety assessment model

There are two main uses of the developed model. First, the developed model can be used as an evaluation tool to assess the safety level of integrating UAS in construction workflows from the perspective of occupational safety and health. Typically, construction organizations have their own safety programs and procedures. Such programs and procedures might not be well suited to control the new safety risks, introduced by UAS use, posed to construction workers, considering UAS use in construction is still in its infancy stage. To this end, the model proposed in this study can help construction organizations to evaluate their current safety procedures and determine how well those procedures can control the risk factors regarding the aircraft, the environment, the flight crew, the mission, the jobsite, and the management. Given the possible different conditions of these six categories of factors as well as the rapid changes on construction sites, this assessment is recommended to be performed before each UAS use on the jobsite. Such assessment is expected to indicate the safety level of the UAS use, identify the current safety procedures that need improvement and ensure safety when using UAS in construction jobsites. Also, the proposed model can be used as a guide by construction companies that are already using or planning to use UAS in their projects. The casual factors, one of the components of the developed model, can provide safety personnel a better understanding of the root causes of the UAS related safety risks in construction. Accordingly, this can help raise awareness in the construction industry about the additional safety risks that may be posed towards construction workers. In addition, the weights assigned to each causal factor would enable decision makers to prioritize the causal factors and allocate the limited resources rationally and efficiently.

## 7. Conclusions and recommendations

The use of UAS in the construction industry is rapidly increasing due to numerous benefits they offer including rapid data collection from hard-to-reach places among others. Although the various benefits of using UAS in construction have been shown in numerous studies, its impact on workers' safety and health have not been studied adequately. In addition, the current regulatory interventions are considered insufficient for using UAS in construction since such high-level guidelines are not specifically designed for the construction industry. Therefore, this study took the first step toward developing industry guidelines for using UAS in construction and proposed a practical model that can be used for assessing the safety level of UAS utilization in the construction industry with a specific focus on workers' occupational safety and health. To develop such a model, a mixed-methods research approach was used. First, a comprehensive review of the literature was performed to identify the safety risks for UAS-assisted construction projects as well as the causal factors of those safety risks and to categorize them in a hierarchical structure. Next, a three-round Delphi survey was administered to identify, verify, and quantify the causal factors and the corresponding mitigation methods by a panel consisting of 13 qualified experts. In the final step, a safety assessment model was developed, by aggregating the results from each Delphi round, to evaluate the safety level of using UAS in construction projects.

The proposed assessment model consists of 23 risk factors and 74 mitigation methods that are identified through the literature review and the Delphi surveys as well as an evaluation procedure to assess the safety level of UAS use in construction projects. The proposed model is expected to enable practitioners working in the construction industry to 1) understand and recognize the risks associated with the use of UAS in construction as well as their causal factors, 2) measure and evaluate the effectiveness of their own safety control programs and procedures for UAS-assisted projects, and 3) adjust and update their own safety control programs using effective mitigation strategies. The proposed model is expected to lay the foundation for subsequent studies in the field of UAS integration in construction workflows to assess the safety level from the perspective of workers' occupational safety and health.

Although the proposed assessment model has the potential to enhance the safety performance of the UAS-assisted construction projects, there are several limitations to this study that can be improved in the future. First, the implementation and validation of the proposed model are beyond the scope of this study. Future research is needed to assess and validate the proposed model in a real construction project. Second, the causal factors identified and verified in this study were derived from a wide range of UAS applications in construction. That is, the weight provided by experts for each causal factor were based on a general consideration of the UAS use in construction. Thus, the proposed model provides a general safety assessment for using UAS in construction projects. It is recommended that future research develops an assessment model for a specific UAS application, such as safety inspection or progress monitoring. Third, the mitigation methods identified in this study were categorized based on their level of effectiveness. It is recommended that future research extends the current model to consider both the level of effectiveness as well as their feasibility to increase the reliability and practicality of the proposed model. Finally, with the improvements in technology, the causal factors and mitigation methods identified in this study may be changed or outdated over time. Thus, it is recommended that future research explores and utilizes simulation tools and various visualization technologies (e.g., virtual reality/augmented reality) to identify effective and practical mitigations and update the proposed model.

## CRediT authorship contribution statement

**Yiye Xu:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Yelda Turkan:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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