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Qualitative and Quantitative Risk Analysis of Unmanned Aerial Vehicle Flights on Construction Job Sites: A Case Study

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Abstract **- Unmanned Aerial Vehicles (UAVs) have been extensively used on construction job sites in the last ten years. UAVs applications span from progress monitoring and site monitoring to structural health inspection and construction safety. While different applications of UAVs on job sites have been extensively researched, the risks and hazards of flying UAVs on construction job sites have never been quantitatively or qualitatively measured. Around the world, the general aviation industry developed sophisticated methods to evaluate risks of UAV flights over general population. However, in construction domain, discussions over risks of UAV flights is nonexistent. This is particularly interesting as the construction industry constantly maintains one of the highest rates of fatalities and injuries, among all other industries, in the world. Currently, UAVs are used in various construction activities regularly without proper risk assessment schemes or safety plans. Neither construction project managers nor construction safety officers have action plans in place for UAV safe use. This paper presents the first known quantitative and qualitative analyses of UAV flight risks in construction job sites. A quantitative model is presented and tested for UAV flight risk assessment, using the Monte Carlo Simulation technique. A case study tested the proposed model on an actual construction job site. The model proposed in this paper can be used by construction safety officers and construction project managers to take safety into account when planning UAV flights over job sites. This paper further argues that using models and methods introduced in this paper can make UAV flights in any environment safer and more reliable.**

Keywords- Risk Assessment; Unmanned Aerial Vehicle; UAV; Monte Carlo Simulation; UAV flight risk

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, have been used in the construction industry for over ten years [1]–[4]. The versatility that UAVs provide enables construction managers, project managers, safety professionals, superintendents and other project team members to capture different types of data, mainly visual data, from locations that might not easily be accessible due to variety of reasons including, but not limited to, high hazards or elevations. UAVs are commercially available, which makes them favorable tools that can be used in even small size construction projects. Relatively low-cost of purchase and operation of new generation UAVs along with the various capabilities that UAVs offer, including high resolution visual imaging, thermal imaging, Radio Frequency IDentification (RFID), laser scanning and other sensing technologies, have played a crucial role in UAVs proliferation in construction research and practice. UAVs are being used on most construction job sites in the United States (U.S.) on daily basis. UAVs have been used for variety of purposes including construction progress monitoring [5], [6], overall site monitoring [6], structural health inspection [8]–[12], surveying job sites and building 3 Dimensional (3D) models [13], infrastructure asset management [14]–[17], urban monitoring [18], material tracking [19], sustainable energy production management [20], and construction safety [21]. In the last ten years, UAV uses and applications in construction have grown exponentially but the risks arise from integrating UAVs into construction job sites, as a new construction equipment, are hardly explored.

In overall, risks associated with UAV flights over general population can be divided into the following two categories:

1- Direct Hazards: Hazards and risks associated with direct impact of UAV-involved accidents; such as falling of a UAV, falling of debris from a collision accident involving a UAV and other elevated objects, other UAVs or other flying objects [22], [23]; and
2- Indirect Hazards: Secondary hazards and risks associated with UAV-involved incidents including hazards associated with the invasion of personal space [24], [24], diverting the attention of workers due to the UAVs' sound and motion (thereby increasing their cognitive load while performing their tasks [26]–[28], and invasion of a workers' personal space [29].

Construction is one of the deadliest industries in the U.S. Unfortunately, the highest rates of fatalities and injuries usually belong to the construction industry. This asks for immediate action from the construction industry to prevent fatality and/or injury on job sites as soon as possible. In the U.S. alone in 2015 and 2016, more than 900 cases of fatalities are reported in the construction domain. In 2015 around 4,836 job related fatalities occurred in the U.S.; out of these 4,836, almost 20% occurred in construction. In construction, falls, slips and trips are the most common cause of fatal incidents, with 364 cases. Transportation incidents were the second highest cause (with 226 cases) and contact with objects came third (with 159 cases) [30]. Many of these incidents are equipment-involved. These statistics show the crucial role that construction equipment plays in safety incidents that happen on construction job sites. It also reminds construction professionals that there is an immediate need for better monitoring job site safety conditions and the extent that safety rules, regulations and procedures on job sites are being followed. It is fatefully important to have the safety of construction equipment in check at all time in order to avoid any accident. It is not difficult to provide a safe environment of use for traditional construction equipment such as excavators, loaders, and cranes as they are thoroughly regulated due to prolong use on construction job sites. However, regulating safe use of more innovative types of construction, equipment such as UAVs, is a critical job; as there are not many, if any, rules and regulation concerning the safe use of newly introduced equipment to construction job sites. In case of UAVs, there is no specific rule regarding safe use in construction environments. Only rules and regulations that are concerned with safe use of UAVs are the Federal Aviation Administration (FAA) general rules that govern the safe UAV flights in public, and over general population. The lack of a comprehensive qualitative and quantitative methodology for risk assessment of UAVs operations on construction sites coupled with a rapid increase in their use pose a new safety threat that requires attention. This paper investigates the risks associated with UAV flights on construction job sites. It further aims at evaluating quantitative and qualitative UAV flights risks on construction job sites by proposing quantitative and qualitative approaches that can measure risks associated with UAV flights over construction job sites under certain circumstances. This paper proposes the first ever known model to quantify UAV flight risks on construction job sites. A case study is presented in later sections, which shows the applicability of the proposed risk model. In this case study, risks of UAV flights over construction job site of an under-construction building at the University of Florida is quantitatively and qualitatively measured to demonstrate the proposed model applicability and significance. An earlier version of this paper [1] presented in Eighth International Conference on Advanced Communications and Computation (INFOCOMP 2018) in Barcelona. This paper presents a more in depth discussion on the topic and is an extended version of the conference papers.

II. RULES AND REGULATIONS GOVERNING UAV FLIGHTS IN THE UNITED STATES

The FAA oversees the U.S. civil aviation for the Department of Transportation. Small Unmanned Aerial Systems (UAS) (a broader category for UAVs) definition concerns UAS weight. The small UAS means an unmanned aircraft with a take-off weight of less than 55 lbs., including everything that is on board or otherwise attached to the aircraft. The FAA published the regulations Part 107 for small UAS operation as the following [31][32]:

(1) Limitations for Flight speed, altitude, and space of small UAS. The ground speed of small UAS may not exceed 100 miles per hour. The flying height of small UAS cannot exceed 400 feet above the ground unless the UAS is flown within a 400-foot radius of a structure and does not exceed 400 feet above the structure's immediate uppermost limit. In addition, the minimum flight visibility of small UAS must be no less than 3 miles from the control station. The minimum vertical distance of the UAS from clouds must be no less than 500 feet below the clouds and the minimum horizontal distance from the clouds must be no less than 2,000 feet (Section 107.51);

(2) Operation of a small UAS is prohibited during the night. In addition, the small UAS cannot be used during periods of civil twilight unless the small unmanned aircraft has lighted anti-collision lighting visible for at least 3 statute miles (Section 107.29);

(3) With a vision that is unaided by any device other than corrective lenses (including contact lenses), the remote pilot in command, the visual observer, and flight control operators must be able to see all flight operations of the small UAS (Section 107.31);

(4) A small UAS cannot be flown above a person unless the person: (a) is directly involved in the operation of the small UAS; or (b) is inside a covered structure or a stationary vehicle which can provide reasonable protection against a falling of the small UAS. (Section 107.39)

(5) A person cannot operate or act as a remote pilot in command or visual observer in the operation of multi-UAS at the same time. (Section 107.35)

(6) No person is allowed to operate a small UAS on a moving aircraft, on a moving land or water-borne vehicle unless the operation requires the small UAS to fly over a sparsely populated area and is not transporting another person's property for compensation or hire. (Section 107.25)

(7) Operation near aircraft and right-of-way rules: Each small UAS must yield the right of way to all aircraft, airborne vehicles, and launch and reentry vehicles. Yielding the right of way means that the small UAS must give way to the aircraft or vehicle and may not pass over, under, or ahead of it unless well clear. [Section 107.37 (a)] In addition, no one may operate a small UAS approaching another aircraft to avoid the risk of collision. [Section 107.37 (b)]

(8) Prohibition of Dangerous Work. No person may (a) operate a small UAS with carelessness or recklessness to endanger the life or property of another; or (b) allow to drop objects from small UASs in a manner that may cause undue harm to persons or property on the ground. Small UASs cannot carry dangerous substances. (Section 107.25)

(9) Operation near airports: Small UASs must not interfere with the normal operation (take-off and landing) of any airport, helicopter airport, or seaplane base. (Section 107.25)

(10) Small UASs may not be flown in prohibited or restricted zones unless the person manipulating the UAS has the permission issued by the controlling agency. (Section 107.45)

This research made the following assumptions based on the most critical aspects of the FAA regulations for small UAS: (1) the construction site mentioned in the case study is not located within a five mile radius of any airport; (2) the operations of the UAV used in the research are following all FAA regulation; (3) the UAV is flown within the vision line-of-sight of the remote pilot in command, the operator, and the visual observer; (4) the specifications of UAV in this research comply with FAA regulation, and more importantly (5) UAV were not flown over any person for safety consideration. These assumptions are specifically highlighted in the qualitative risk analysis that is provided in the discussion and conclusion sections.

III. RISKS OF UAV FLIGHTS

A. *Quantitative Risks of UAV Flights*

Quantifying risks of UAV flights over construction job sites is the main step in decision making process of UAV safety on job sites. By quantifying the risks of UAVs, superintendents, construction project manager, construction safety managers, insurance companies and other decision makers can have a clear view of the risks associated with UAV flights under certain circumstances. A quantifiable risks analysis of UAV flights will give insurance companies a better insight into the value, extent and severity of risks associated with UAV flights on construction job sites. It also helps the decision makers to make rational, informed and scientific decisions on the issue of UAV safety on job sites. In risk management, risk is assumed to be the product of probability of occurrence and impact (Eq. (1)).

$$\text{Risk} = \text{Probability of occurrence} * \text{Impact} \qquad (1)$$

In order to develop a model for UAV flight risks on job sites, first step is to define *Probability of occurrence* and *Impact*. This paper uses some of the risk models that have been extensively used in the general aviation industry (1) as the bases for developing a risk model that fits UAV flight risks on construction job sites, and (2) to quantify the probability of occurrence and impact. In general aviation industry Clothier and Walker [23], proposed a model that defines and measures the ground fatality expectations of flights. The model measures and enumerates the risk of expected ground fatalities based on the chances that a UAV flight might fail and/or due to falling debris of a UAV involved incident. It is worth noting that this model only quantifies the direct risks of falling UAVs, and/or debris. This model does not consider the indirect risks associated with UAV flights.

Some of the indirect risks that are not considered in this model but could have a crucial impact on safety are: (1) threatening workers' personal space, (2) threatening privacy of workers, (3) potential distraction of workers due to UAV on-board lights and (4) potential distraction of workers due to UAVs noise and motion.

Clothier and Walker [23] proposed the ground fatality expectation model of UAV flights as below:

$$SO = MR * \varphi * AL \qquad (2)$$

In this model SO is the Safety Objective in terms of the number of fatalities per flight hours. The φ refers to the population density of the area under flight path of the UAV. This area is the exact area under UAV flight path in which UAV can maneuver. The AL (sometimes shown as A_L) is called the lethal area. The lethal area refers to the circular area around the UAV which is measured by using a diameter of maximum length of UAV diameter plus a (safety) buffer. Lethal area is believed to be the area of direct impact in case of a falling UAV. As demonstrated in Eq. (2), the bigger this lethal area, the larger would be the ground fatality impacts due to a flight failure or accidents. MR is referred to the mishap rate. Mishap rate is calculated using the formula in Eq. (3).

$$MR = SFR + MC\mathit{Debris} + \text{Other} \qquad (3)$$

In this formula, SFR is referred to System Failure Rate, which is measured per (million) flight hour(s). The MC*Debris* refers to the quantity of debris from a possible midair collision per flight hour. While MC*Debris* is a factor that is hard to measure, it is possible to assume a probability or an estimate this factor. It is also possible to assume that there will be no injuries and/or fatalities due to debris. In this paper MC*Debris* is assumed to be zero as estimating *MCdebris* in construction context is not possible due to lack of data. The last factor is *Other*. This factor refers to the other types of hazards that might result in fatality risks. Like MC*Debris*, for this factor, it is possible to assume a probability, an estimate or no value at all. Sometimes lack of data could result in avoiding the use of MC*Debris* and *Others*.

B. *Qualitative Risks of UAV Flights*

As discussed in Section II, FAA established a series of general rules and regulations for UAV flights in the national air space. Out of all FAA rules, two rules and regulations are specifically very significant for the construction industry. These two are as follow: (1) never fly a UAV out of the pilot's line of sight and (2) never fly a UAV over a populated area. The implementation of these two would mean that it is not legal for construction managers to (1) allow a UAV flight over general population close to the construction job sites, (2) allow a UAV flight over construction personnel working on job sites and (3) allow a UAV flight over and close to construction machinery and equipment on job sites. It is vital for construction project managers, superintendents and construction safety managers to guarantee the safety of construction personnel working on site. When it comes to UAV flights, the three qualitative measures outlined above have to be strictly enforced in order to avoid any violation of FAA rules and regulations and make job sites safer. As it is outlined in Section II, the rest of the rules outlined by FAA are assumed to be enforced by the project team. Some of them such as distance from airports are to be checked on a case by case basis by the project team in order to assure the safety of UAV flights on job sites.

Based on these specific regulations, authors developed a qualitative safety map for UAV flights over the job site that has been used as a case study in this research and is presented in the analysis and discussion sections.

IV. MONTE CARLO SIMULATION AS A RISK ASSESSMENT METHOD

Monte Carlo simulation (MCS) is named for the well-known gambling capital of Monaco and is essentially a random number generator technique [33]. As MCS generates a large quantity of sample paths of outcomes for prevalent features analysis, it is widely used for risk analysis, risk quantification, sensitivity analysis, and prediction [34]. With the rapid advancement of computing technology, computers become competent of modeling reality and assisting in decision making by taking account of randomness and uncertainties via exploring various scenarios. Through calculating the values of the modeled scenarios, a more reliable decision can be made through use of MCS [33].

With great ease, MCS has been widely adopted by scholars and practitioners in a broad spectrum of disciplines to solve thorny and sophisticated problems [33]. The most famous application was probably by Enrico Fermi, a Nobel Laurent in physics in 1930, to study the properties of the newly discovered neuron. MCS was also a core technique for the Manhattan Project in 1950s [33][34]. Its application was then expended to engineering, research and development, business, and finance [33]. Thompson et al. [35] employed MCS in a public health risk assessment research to account for uncertainties. Burmaster and Anderson [36] proposed 14 principles of good practice in conducting and evaluating MCS-based risk assessments for hazardous waste sites. Stroeve et al. [37] substantiated the feasibility of using MCS for air traffic safety assessment. Au et al. [38] proposed an upgraded MCS with an ability to accommodate rare failure events commonly seen in engineering for compartment fire safety. To copy with the high transaction costs and financial risks for renewable energy technologies, Arnold and Yildiz [39] introduced MCS for risk analysis through representing the lifecycle of a renewable energy technology investment project. Their research uncovered tremendous advantages concerning content and methodology over the traditional NPV estimation or sensitivity analysis. Arunraj et al. [40] combined fuzzy set theory with MCS for industrial safety risk assessment, which was used to a benzene extraction unit (BEU) of a chemical plant.

MCS also comes into the radar of scholars in the construction community and has gained great popularity. MCS has typically been used in conjunction with other techniques in construction management related research. Rausch et al. [41] applied MCS in off-site construction to mitigate rework risks through tolerance analysis. To deal with data scarcity and uncertainty, Kwon et al. [42] incorporated MCS into Case-based reasoning to estimate cost compensation in construction noise disputes. Kim and Lee [43] employed MCS with a genetic algorithm in the last step of their prediction model development for the engineering maturity effect on oversea megaprojects.

MCS is a favorable tool for UAV related studies. To ensure low altitude safety, Chen et al. [44] used MCS to evaluated the effectiveness and robustness of a proposed UVA and bird targets tracking and recognition model using surveillance radar data. Similarly Lu et al. [45] utilized MCS to validate an approach proposed to improve the performance of direction arrival estimation of UVAs for low signal-to-noise ratios. Dabiri et al. [46] verified the reliability of a channel modeling and parameter optimization system for UAV-based free space communication using multi-rotor UAVs.

As UAVs are increasingly prevalent on construction projects, this phenomenon poses a series of safety related risks to the construction workers and properties on job sites due to obstacles, operational mistakes, and inclement weather. Plioutsias et al. [47] discovered that small UAVs were typically neglected for hazard analysis among researchers and practitioners and identified 20 hazardous types. Izadi Moud et al. [48] presented a quantitative tool for UAV flying risk assessment on construction jobsites in combination with qualitative analysis by considering FAA rules and regulations on safety specifications of UAVs. Izadi Moud et al. [48] applied the previously developed risk quantification model to a real-world case based on malfunction rate of UAVs, population density of the area covered by UAVs flight routes. Izadi Moud et al. [49] further studied the indirect risks of UAVs operations on construction sites, in which MCS was employed in measuring the proximity between UAVs and construction workers.

On construction job sites, small UAVs require safety consideration due to uncertain operational conditions, such as their weak structural shape that may cause instability and failure in windy weather, their potential for operational errors, as well as their high maneuverability and potential for mechanical failures. Plioutsias et al. [47] published a research paper that concludes current commercial UAVs are very far from being able to meet safety requirements. To simulate collision and other hazards between one or multiple UAVs operating on construction sites and their bordering area, use of MCS method offers flexibility and accuracy in simulation. This method is playing an important role in modeling uncertainties, such as the movement of different kinds of object on a construction site and environmental factors, such as wind [50]-[53].

V. ANALYSIS OF THE CASE STUDY

This section presents Analysis of Quantifying Risks of UAV Flights and Analysis of Quantifying Risks of UAV Flights.

A. Analysis of Quantifying Risks of UAV Flights

In this section, MCS is used to assess the risk of flying UAVs over construction job sites, which is referred to as the Safety Objective (SO) as described by Eq. (2). Mishap Rate (MR), the Lethal Area (AL) and the density of population (φ) are needed to find the SO in each area. MR is the variable with the least empirical data as there is not much information recorded on the MR of UAVs. In this analysis, it is assumed that the UAV lifetime, or the duration over which possibilities of crash exist, is normally distributed, with a range between 100 hours and 10,000 hours, a mean of 5,050 hours, and standard deviation of 1,650 hours. MR is referred to as the rate of failed UAV flights in a given lifetime for a UAV. In this case, the normal productive life of a UAV is estimated to be in this range. As a result, MR is calculated as one crash in a UAV's lifetime: 1 / (lifetime of UAV in flight hours).

AL is the area that has the potential for lethal impact from the UAV or debris if a UAV crashes. Typically, it is calculated by using the longest dimension of a UAV. In this case, considering the fact that most of the UAVs flying over construction job sites are commercially available, it is presumed that AL can assume a value between 0.3 m and 1.8 m. Thus, an even distribution across a diameter with a minimum of 0.3 m and maximum of 1.8 m is used in the simulation. The density (φ) represents the number of personnel on the site divided by the area of the location that a UAV flies over. In this study, it is assumed that only construction workers are present at the job site. Due to a lack of empirical data, it is estimated that the number of construction personnel on the job site varies between 2 and 14 with a normal distribution (a mean of 8, a standard deviation of 2). The density is calculated for Area 1 to Area 4 by dividing the sampled number of construction workers for each zone by its area. The area of each location that a UAV can fly over is calculated and shown in Figures 1 and 2. The area surrounding the job site is divided into Area 1 through Area 4 using the logic of FAA regulations regarding safe UAV flights, which prohibits UAV flights over head of people, in this case construction personnel sidewalks and pathways. Thus, considering the pathways that construction personnel routinely commute between workstations and the job site, four separate areas are drawn as separate areas that UAVs can fly over. Due to these regulations, UAVs cannot fly from one of these areas to another because they need to fly over a construction personnel pathway, which is prohibited by FAA regulations.

Figure 3 depicts the resulting distribution for density (φ) for area 1. The representative population density distribution for area one is a normal distribution with mean of 0.001061765 and standard deviation of 0.000262214.

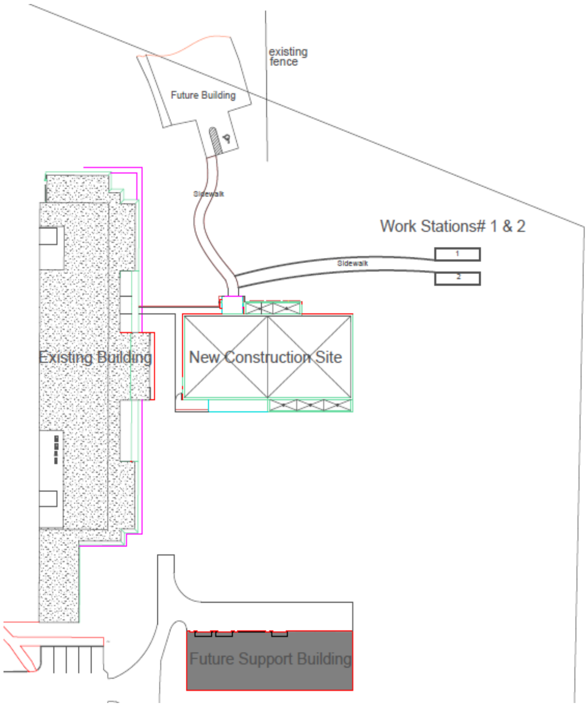

Figure 1. General layout of the construction site.

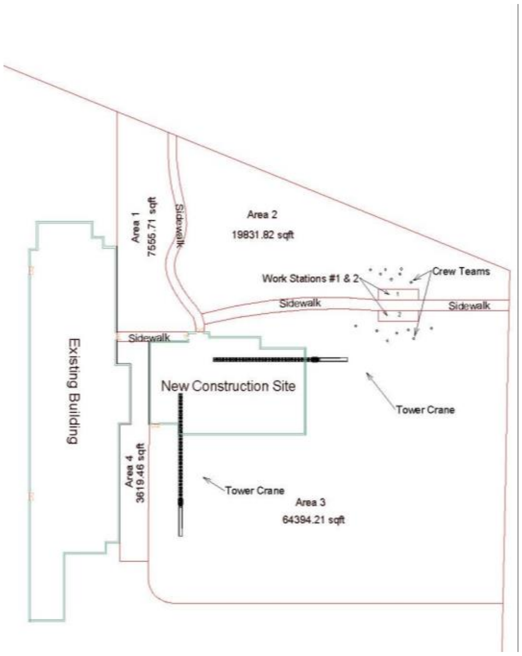

Figure 2. simplified layout for analysis.

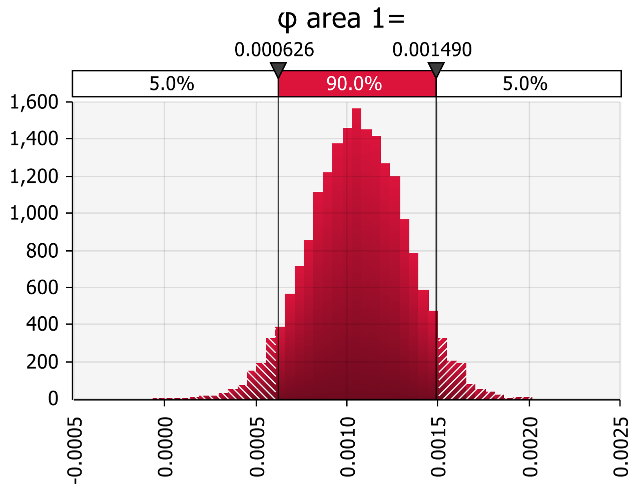

Figure 3. Resulting φ distribution for area 1.

Figure 4 depicts the resulting distribution for density (φ) for area 2. The representative population density distribution for area two is a normal distribution with mean of 0.000402085 and standard deviation of 0.000102536. Figure 5 depicts the resulting distribution for density (φ) of area 3. The representative population density distribution for area three is a normal distribution with mean of 0.000124368 and standard deviation of 3.07317E-05. Figure 6 shows the resulting distribution for density (φ) of area 4. The representative population density distribution for area four is a normal distribution with mean of 0.002208846 and standard deviation of 0.000551396. It can be seen that the density distribution for the area 4 has a denser distribution representative.

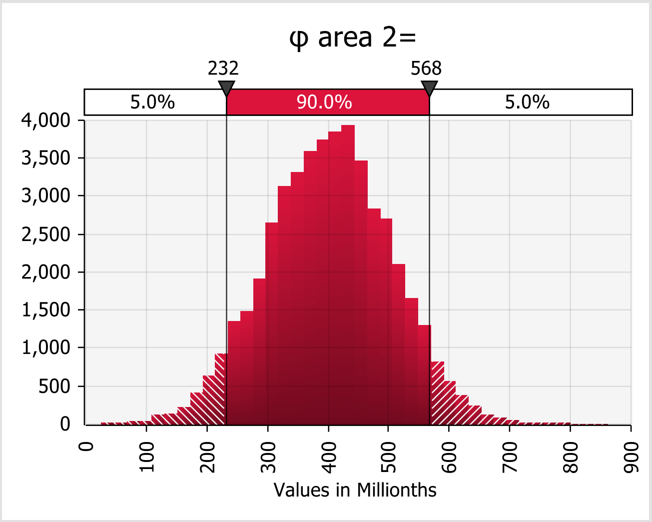

Figure 4. Resulting φ distribution for area 2.

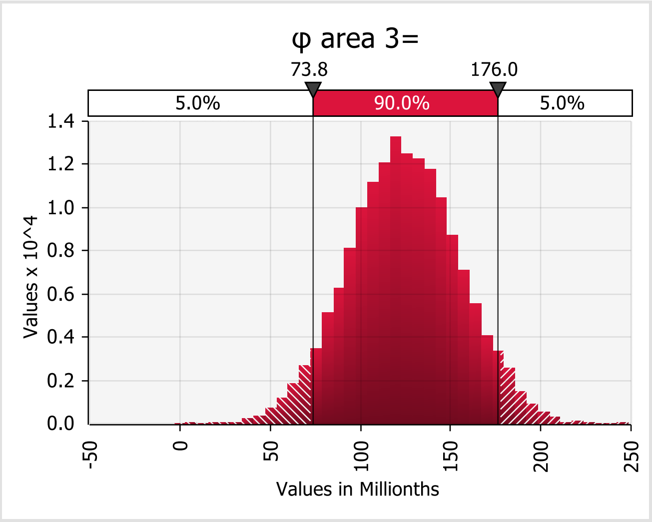

Figure 5. Resulting φ distribution for area 2.

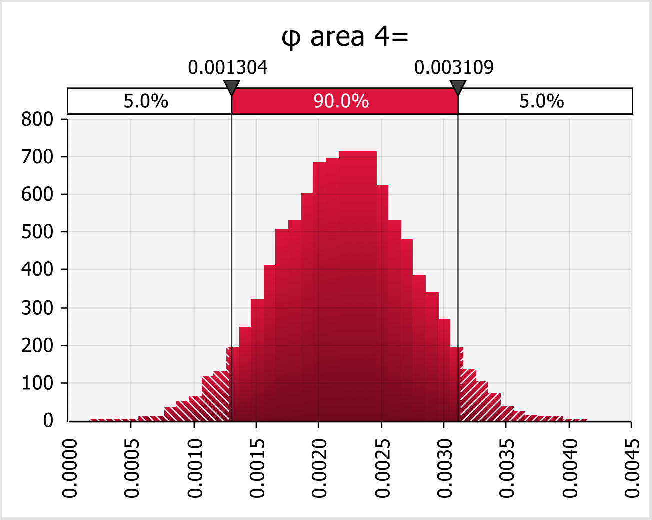

Figure 6. Resulting φ distribution for area 2.

A MCS of Eq. (2), using the aforementioned factors, was run using the Palisade @Risk 7.5. The number of simulation iterations was controlled for convergence of the mean, standard deviation, and 90% percentile simulated values of the SO results of each area. The simulation was run until it reached convergence with 95% confidence and 5% tolerance. The convergence was checked every 600 iterations. The simulation reached convergence at 102,000 iterations. The results of the Monte Carlo simulation are summarized as follows:

- Area 1 (Figures 7 and 8):
    - Mean: 2.53521E-07
    - Mode: 2.64621E-08
    - Median: 1.7822E-07
    - Standard deviation: 6.22557E-07
- Area 2 (Figures 9 and 10):
    - Mean: 9.57806E-08
    - Mode: 9.05201E-09
    - Median: 6.7361E-08

    - Standard deviation: 1.968E-07
- Area 3 (Figures 11 and 12):
    - Mean: 2.94819E-08
    - Mode: 2.86018E-09
    - Median: 2.07374E-08
    - Standard deviation: 6.47009E-08
- Area 4 (Figures 13 and 14):
    - Mean: 5.21982E-07
    - Mode: 4.10386E-08
    - Median: 3.73742E-07
    - Standard deviation: 9.33199E-07

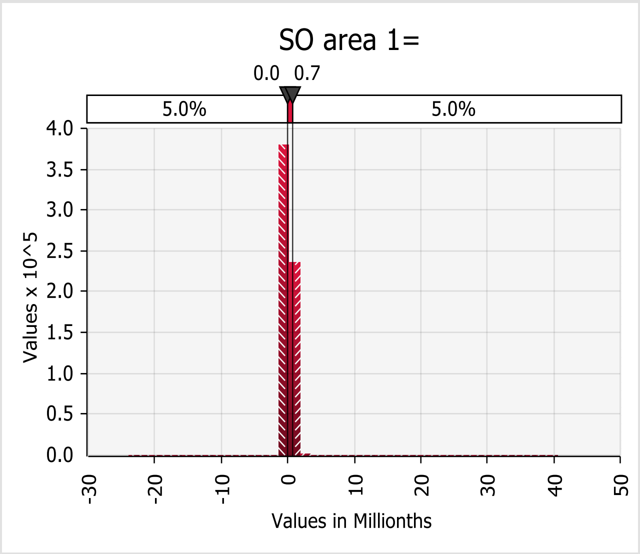

Figure 7. SO result of area 1 from simulation.

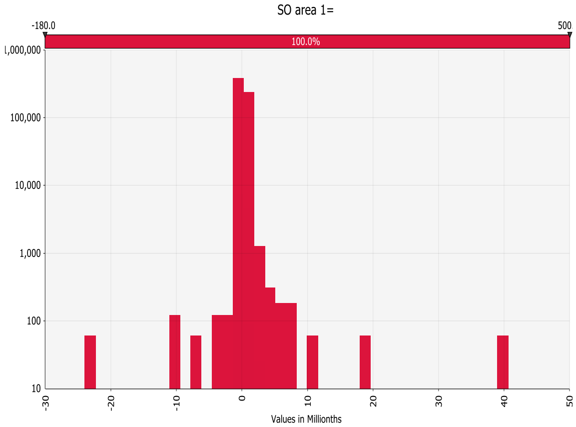

Figure 8. Zoomed in SO result of area 1 from simulation.

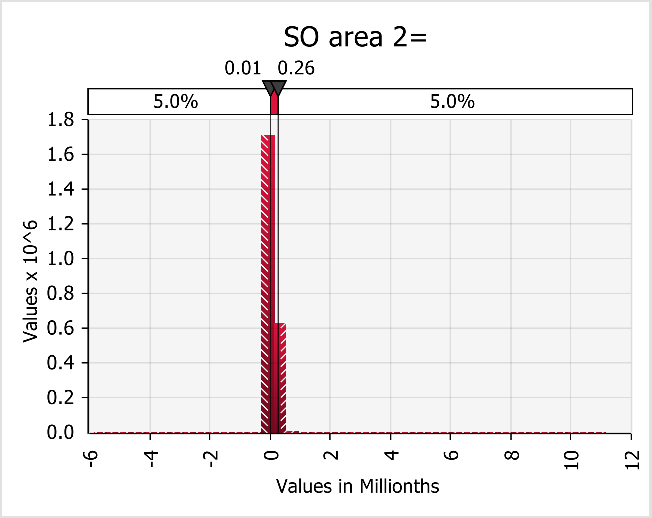

Figure 9. SO result of area 2 from simulation.

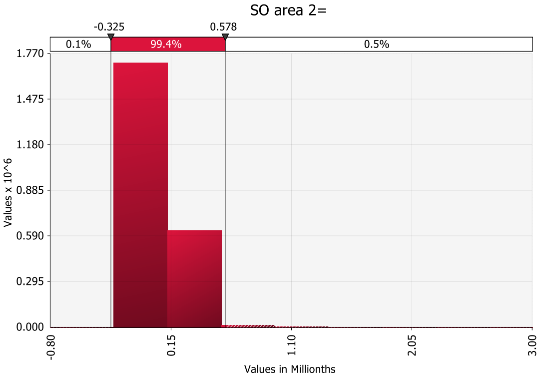

Figure 10. Zoomed in SO result of area 2 from simulation.

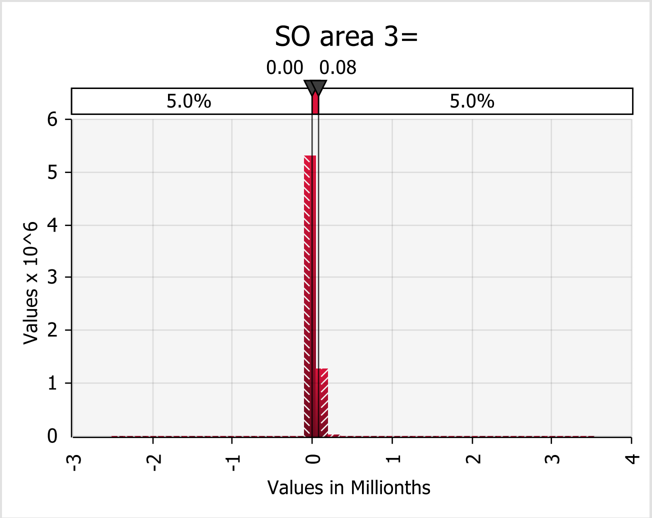

Figure 11. SO result of area 3 from simulation.

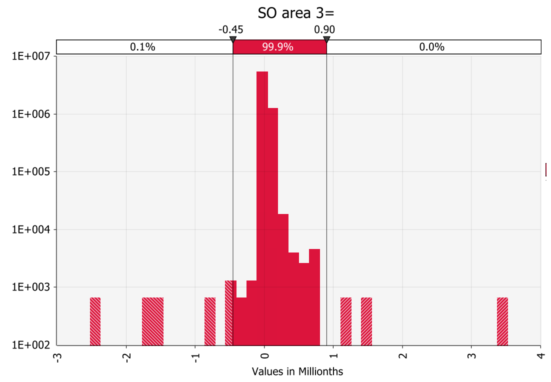

Figure 12. Zoomed in SO result of area 3 from simulation.

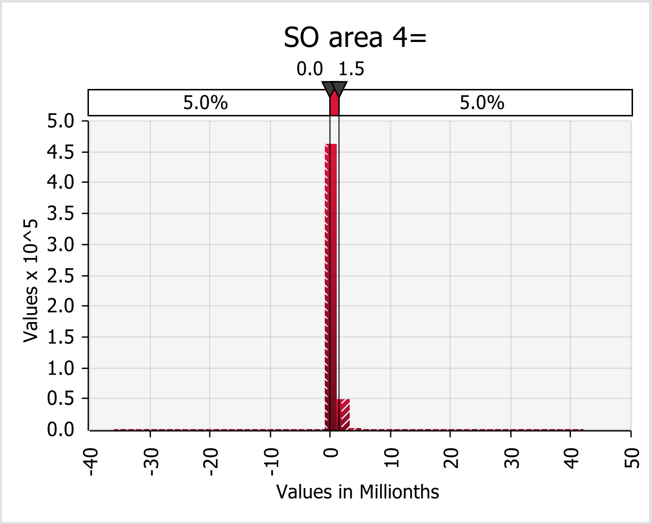

Figure 13. SO result of area 4 from simulation.

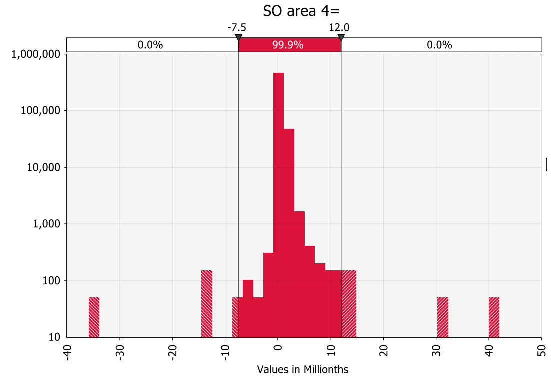

Figure 14. Zoomed in SO result of area 4 from simulation.

Figures 15-18 depict the inputs' impacts on the corrosponding SO output means. It is evident that AL had the most significant impact, followed by the MR and the least impactfull variable is the number of workers in the area. However, it should be noted that this conculusion is based on the assumptions of this study and it should evaluated on a case by case basis.

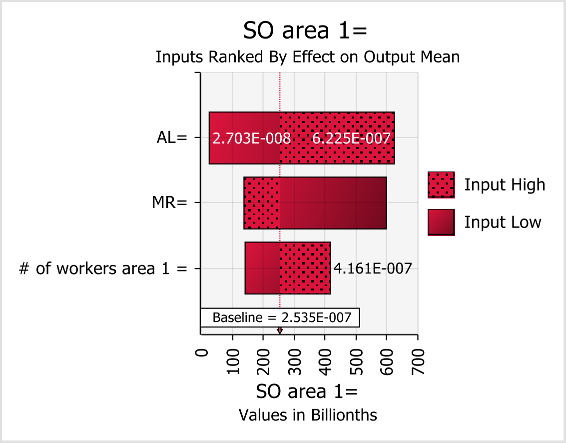

Figure 15. Inputs effect on SO area 1 mean.

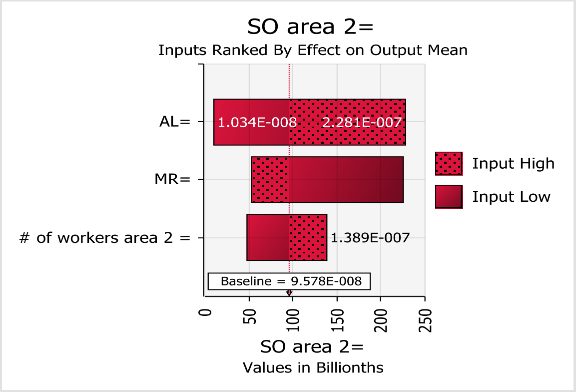

Figure 16. Inputs effect on SO area 2 mean.

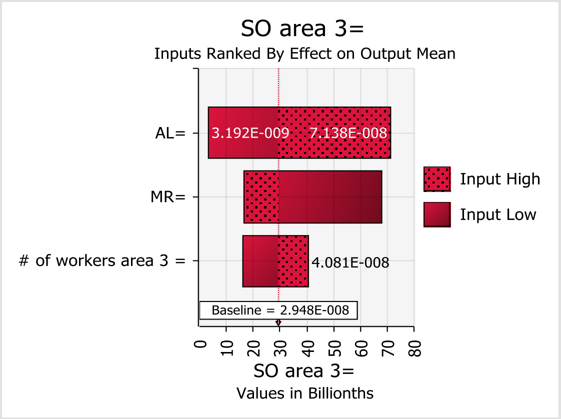

Figure 17. Inputs effect on SO area 3 mean.

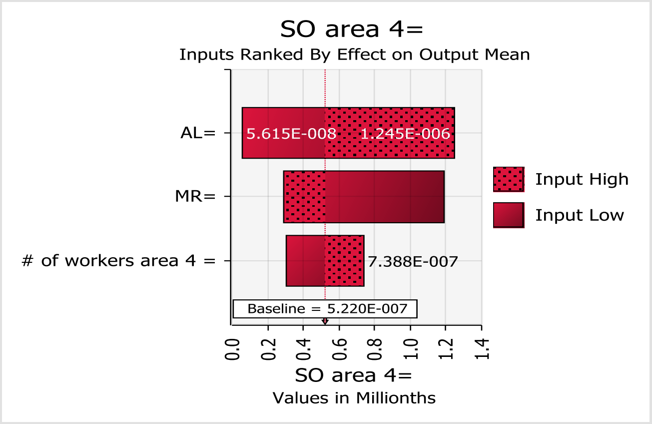

Figure 18. Inputs effect on SO area 4 mean.

Figure 19 shows the changes in the output mean of the SO area based on the variation on of the inputs. It can be seen that the AL and MR have the same imapct on the SO while the number of workers in the area has the opposite effect.

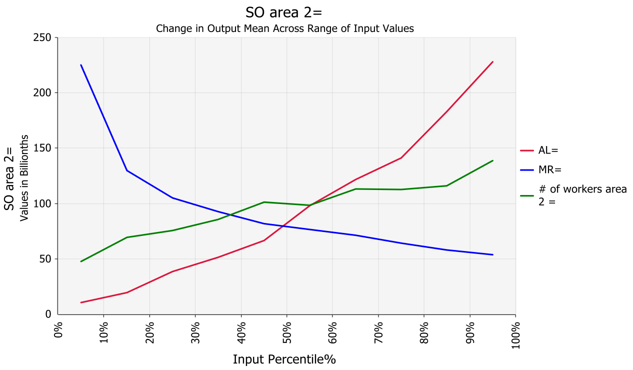

Figure 19. Change in output mean of SO in area 2 depending on variations in the inputs.

B. *Analysis of Qualitative Risks of UAV Flights*

As extensively discussed in Section II, the FAA governs UAVs flights in U.S. National Air Space. Some of the rules and regulations that FAA posed on UAVs flights prohibit UAV flights over general population or simply over people's heads. Using this logic, in Figure 1, there is a need to restrict UAV flights to only areas that are considered safe based on FAA rules and regulations. Consequently, in Figures 2 and 20, the job site is divided into four standalone areas; each safe for UAV flights considering these areas do not contain workers' pathways. These areas are contained between shared workers' pathways or walkways. In order to qualitatively measure the safety of UAV flights in this case study, a qualitative assessment of UAV flights risks, using FAA rules and regulations, is developed. Some of the principles that are used are as follow:

- UAV no-fly zone areas are shown in red. These are the areas that are absolutely forbidden for UAVs to fly over/on due to federal rules. The no-fly zones are considered to be airspace above people's heads.
- The area immediately adjacent to the red areas are shown in orange as it is risky to fly close to a no-fly zone.
- Any existing construction equipment is shown in orange. It is risky to fly over, on or adjacent to this moving construction equipment.
- In this example, there are two tower cranes which, by nature, are constantly moving in three dimensions. It is risky to fly on or close to these tower cranes.

By taking into account of all the above-mentioned facts, a color-coded safety map in Figure 20 illustrates the safety risks of UAV flights based on the qualitative facts. In this figure, green indicates safe flight zones. Red indicates no-fly zones and orange indicates risky flight zones. As shown in Figure 20, all areas of this job sites are considered safe, shows in green, except the areas that are on the direct workers' pathways, which are shown in red as an indicator of absolute no-fly zones, and areas close to red zones or close to construction equipment including two giant tower cranes shown in east and south sides of the under-construction building in Figure 20. It is recommended that UAV flights in orange areas be in discretions of the construction project teams. Construction project teams are advised to make decisions on the safety of UAV flights over orange areas by considering all facts and on a case by case basis.

VI. DISCUSSION AND CONCLUSION

This paper presents qualitative and quantitative risk analyses of UAVs flights over construction job site environments. It is the first known study discussing risks of UAVs flights over construction job sites using a Monte Carlo Simulation as a well-known quantitative analysis and also a qualitative analysis based on FAA rules and regulations. The qualitative method proposed in this research uses UAV lethal area, failure rate, also referred to as Mishap Rate, and population density as the main factors to quantify the direct risks associated with UAV flights. The model is tested in a case study; an under-construction building at the University of Florida's campus. Monte Carlo Simulation is used as the computation technique to run the simulation of the proposed model using the case study characteristics as inputs. Different probabilities are given for personnel on job site, UAV size, which is used for finding the lethal area, and mishap rates. The results show that the safety objectives, expressed in terms of fatalities per million flight hours, vary in Areas 1 through 4. Areas 1 and 4 have the highest median of safety objectives by 1.7822E-07 and 3.73742E-07, respectively. These numbers mean the expected fatalities for a UAV flight over these areas are 1.78 per ten million flight hours for Area 1 and 3.73 per ten million flight hours for Area 4. Based on Clothier and Walker [23], the general aviation industry fatality rate is restricted to one fatal incident in one million flight hours. While it is not truly

Figure 20. A color-coded map showing the qualitative risks of flying UAVs in a construction job site, where green represents the minimum risk, orange represents the medium risk and red represents high risk or no-fly zones.

accurate to propagate the fatality rate of the general aviation industry to the UAV industry, authors use the general aviation industry as a reference to compare the risks due to the lack of data on qualitative risks of UAV flights.

By comparing the simulation results to the general aviation industry fatality restriction rate, which is one fatality in a million flight hours, it appears that in the case study analyzed in this paper, most areas have lower than normal fatality risks of flights. It is worth noting that ultimately is up to construction managers or safety officer to utilize these findings and decide on the appropriateness of UAV flights on this construction site.

The FAA rules and regulations prohibit UAVs to fly over peoples' heads, over or close to airports and set specific guidelines regarding UAVs operations. By combining FAA rules and guidelines and safety needs of UAV flights in construction environments, such as higher risk of UAV collision in proximity of tower cranes, a qualitative color-coded safety map is generated that shows the relatively safer areas for UAV flights, using green, compare to medium UAV flight risks areas, with orange color, and no-fly zones, or the highest risks of UAV flights zones with red.

The presented qualitative and quantitative analyses help construction project managers, construction safety managers, site superintendents and insurance companies to make informed decisions, based on actual data, regarding the safety of UAV flights using specific temporal and spatial data. These models will also enable different stakeholders to detect, explore and address the risks of UAV flights in construction job site environments, which will help the construction industry to better manage the safety of UAV flights.

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