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A Computational Model for Simulating the Performance of UAS-Based Construction Safety Inspection through a System Approach

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Abstract: Recent studies have been focusing on unmanned aircraft systems (UASs) to inspect safety issues in the construction industry. A UAS can monitor a broad range in real time and identify unsafe situations and objects at the jobsite. The related studies mostly focus on technological development, and there are few studies investigating potential performance that can be obtained by implementing UASs in the construction domain. Hence, the main objective of this research is to evaluate the potential of UAS-based construction safety inspection. To achieve the goal, this study developed a system dynamic (SD) model, and scenario analysis was conducted. When compared to the existing methods, the use of a UAS resulted in improved safety inspection performance, reduced possibility of incidents, reduced worker fatigue, and reduced amount of delayed work. The results of this research verified that UAS-based safety inspections can be more effective than existing methods. The results of this study can contribute to the understanding of UAS-based construction safety inspection technologies and the potential of the technology.

Keywords: unmanned aircraft system (UAS); construction safety; safety inspection; system dynamics; drone

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Citation: Jeong, K.; Yu, C.; Lee, D.; Kim, S. A Computational Model for Simulating the Performance of UAS-Based Construction Safety Inspection through a System Approach. *Drones* **2023**, *7*, 696. https://doi.org/10.3390/drones7120696

Academic Editor: Higinio González Jorge

Received: 8 November 2023
Revised: 4 December 2023
Accepted: 6 December 2023
Published: 7 December 2023

1. Introduction

Worldwide, the number of incidents that occur in construction industries accounts for a large portion of the entire industry. According to the U.S. Bureau of Labor Statistics (BLS), 4764 laborers suffered fatal injuries in the industry as a whole, and among them the number of deaths in the construction industry was 1000 (21.2%), which represented the greatest proportion [1]. In Korea, according to the Korea Occupational Safety & Health Agency (KOHSA), 2080 laborers died in all industries in 2021, and among them 551 (26.49%) were in the construction industry, thereby accounting for the highest rate [2]. Also, according to the Construction & Economy Research Institute of Korea (CERIK), the rate of fatalities in the construction industry among OECD countries, such as Switzerland, Türkiye, Israel, and Japan, is growing [3]. Since the construction industry is more labor-intensive compared to other industries, the accidents of laborers can have adverse effects on the performance of construction projects [4,5]. For example, when incidents occur, the construction period and construction costs can increase due to legal sanctions and actions [6]. Furthermore, from the perspective of companies, it can have a negative impact on the company's image, bidding activities, etc. [4,6]. That is why safety management and accident prevention are crucial in the construction industry.

Accidents on construction sites are related to various factors such as the number of site managers, site layout, and equipment [7]. Safety managers need to establish manage a comprehensive safety management process considering these factors [8]. Additionally, safety managers should continuously and extensively monitor the site and provide real-time information on unsafe situations to workers and managers [7,8]. However, in practice, it is difficult to establish a safety management process considering all factors, and implementing it as planned is a challenging task. Moreover, it is impractical for a small number of managers to personally identify and provide real-time information on all unsafe situations within the site [8]. This leads to inefficient work for safety managers who, while extensively inspecting the site, end up consuming more time and resources.

Thus, to prevent construction accidents, studies are being conducted on utilizing information and communication technology (ICT), such as the unmanned aircraft system (UAS), building information modeling (BIM), virtual reality (VR), augmented reality (AR), and robots [9–13]. In particular, research on the real-time monitoring of large areas at sites based on UAS technologies is actively being carried out [14–17]. A UAS can collect various types of visual data using sensors, cameras, etc., and can identify unsafe situations for the objects it detects [18]. For safety monitoring research using UASs, studies were conducted on proposing concepts for UAS-based safety monitoring [19,20] and on identifying procedures and requirements of UAS applications [21,22]. In addition, a UAS and game engines were integrated to develop a deep-learning-based safety management system that automatically recognizes objects, such as workers and heavy equipment, of construction sites [23]. In addition, studies on airport runway inspection using UASs and studies on deep-learning-based image processing to improve the quality of images acquired using UASs were conducted [24–27].

Meanwhile, few studies have evaluated the potential performance of UAS-based safety monitoring technologies. The UAS can be viewed as an independent system that converges ICT, and it can naturally be judged to have a positive impact on enhancing the productivity, safety, and efficiency of the construction industry. But compared to other industry groups, the construction industry has more labor-intensive characteristics, and the application of Fourth Industrial Revolution technologies and digitalization are progressing slowly [28]. Therefore, analytical research on the effectiveness of technologies, usability evaluations, and expected effects in the UAS-based safety management technology development research sector is needed. For this, it is necessary to deduce the factors related to the application of UAS-based safety management technologies and identify the complicated relationships between factors. System dynamics is a computer-based numerical analysis model that can identify the reactions, rules, and relationships of factors according to the passage of time and can help explain the above relationships [29]. Therefore, this study will use system dynamics to deduce the potential performance of UAS-based safety monitoring technologies and conduct associated performance evaluation research. To achieve this, we reviewed literature related to UAS-based construction safety management and identified factors influencing safety inspections. Subsequently, we modeled a causal loop diagram representing the interrelationships between the identified factors and developed a stock–flow diagram to simulate UAS-based safety inspections. Finally, based on the defined scenario, we proceed with simulations and analyze the results.

2. Literature Review

2.1. Construction Safety Inspection

Currently, safety management of construction sites is being conducted following a method by which the manager directly inspects all sites according to the relevant regulations of the relevant country [23]. For example, in America, the U.S. Occupational Safety and Health Administration (OSHA) prescribes the qualifications, responsibilities, and other guidelines for managers through the field safety and health management system (SHMS) [30]. Korea also prescribes the safety management work of relevant personnel, such as the client, designer, and builder, through the construction safety management work manual prescribed by the Ministry of Land, Infrastructure and Transport (MOLIT) [31]. Likewise, government agencies provide general guidelines for safety management and legal responsibilities according to the relevant laws, and they serve as the basis for safety management at construction sites. However, safety management guidelines cannot be implemented completely with just the current safety management methods. This is because as the behavioral characteristics of workers, the scope of the jobsite, the number of personnel, and other parameters change continuously, the manager cannot make quantitative evaluations based on different criteria every time [24]. Furthermore, while the safety control methods conducted directly by the safety manager can improve the safety awareness of workers, they have limitations in protecting workers from all physical risks that exist at the site.

Accordingly, technological development research using UASs, BIM, and AR/VR has recently been conducted for safety management in construction sites. BIM research primarily focuses on strengthening on-site communication, detecting construction risk, and establishing safety plans [32]. AR/VR research has mainly focused on technical characteristics, application domains, safety enhancement mechanisms, and safety evaluation. UAS research includes on-site filming, provision of real-time data using drones, and image processing to improve image quality [10]. However, research related to UASs primarily emphasizes technology development, and there are few research achievements of potential performance that can be demonstrated when applying the UAS at construction sites. Once the UAS is implemented at construction sites, the on-site manager is in charge of its operation and management, so prior discussions and predictions on relevant issues and potential performance must be carried out. Thus, in addition to research on technological development, studies on the management and operation of the technologies are also required.

2.2. UAS for Construction Safety Inspection

The term UAS refers to a platform that includes unmanned aerial vehicles (UAVs), commonly called drones, as well as communication sensors and a ground control station including a human flight crew [33,34]. Using the UAS, a wide area can be filmed in real time, and communication sensors can be used to provide real-time data [24,35,36]. The safety manager of the construction site detects safety risks at the site and takes corrective actions but cannot perform real-time monitoring simultaneously on sites with extensive areas [37,38]. In addition, there are limitations related to the number of safety managers at a site. Therefore, studies on using UASs for construction site safety management have recently been conducted.

Among them, Kim [23] developed technology for worker safety monitoring based on game engines that integrated a UAS and deep-learning-based object recognition technologies. The developed framework is composed of game-engine-based digital ITCPs, images filmed by the UAS, and an automatic object detection algorithm. With this system, it is possible to visualize the state of the site and the location of the worker and equipment. Based on this, items that violate safety rules can be automatically identified. Meanwhile, Kim [14] developed an image processing method for measuring the actual distance between objects from 2D images collected using the UAS, and the computed error was less than 0.9 mm. The proposed method detects collision risks in advance at the site to make preemptive safety management possible. Similarly, Bang [27] developed an image processing method, involving correcting distortions and image filtering, for UAS aerial images and created high-resolution maps of a construction site. Using the proposed method, the on-site manager can more easily identify the construction site situation based on high-quality image data. As shown above, most studies using UASs focus on real-time extensive capturing of sites through UASs, along with research on image processing technology development to enhance the reliability and accuracy of video and photo data. But there are few studies that analyze the relationship between key factors and factors to promote activation of the technology to use UASs for construction safety monitoring.

2.3. System Dynamics for Construction

System dynamics is a methodology developed by Jay Forrester, and it is used as a tool for modeling the system thought process [29]. This method can clearly identify the reactions and rules of variables through the passage of time. Hence, it has been widely used in various fields, such as engineering, medicine, business management, and politics [29]. Also, the system dynamic can be used in the construction sector to explain the complicated interrelationships between factors affecting the system performance in the construction project.

Jiang [39] reviewed construction safety management as a single system and used system dynamics to evaluate the impact of unsafe behavior of workers on the system. The system-dynamic-based causation of unsafe behavior (SD−CUB) model can be applied to provide safety management solutions for various construction sites, which can then be used to determine the safety management strategy. Kim [40] analyzed the impact of the deficiency of skilled workers on construction business management using system dynamics. For this, the causes and results of insufficient skilled workers were deduced, and multiple scenarios were set up to identify the trends between impact factors. Through the above process, complexities were simplified, and the trends between factors that impact issues, such as labor wages and construction schedules, were objectified. Zoghi [41] used system dynamics to analyze the economics of BIM-based construction waste and management (CWM). For this, the economic factor (cost, profit) was deduced in the relationship of BIM and Construction and Demolition (C&D) waste relations, and it was quantified to conduct various scenario analyses. They concluded that the costs of BIM-based CWM could be reduced by up to 57%.

As explained above, system dynamics are being used to simplify the difficult and complex issues in the construction sector and to objectify the trends between factors. Furthermore, research is being conducted to analyze multiple scenarios based on quantified factors. In the field of construction safety management, there are various complex factors to consider, such as site layout, equipment, and the number of managers. Additionally, when applying UAS technology, it is essential to analyze the interrelationships between these factors and UAS technology by considering them comprehensively. Therefore, in this study, we analyzed interrelationships among various factors using system dynamics and evaluated the potential performance of a UAS-based safety inspection system.

3. Research Methodology

The purpose of this study is to utilize system dynamics to deduce the potential performance of a UAS-based construction safety inspection system and to conduct a performance analysis on this. A system dynamic is used to analyze the mutual relationship of different factors in a complex system [29]. As an example of the contents of this research, it is possible to analyze the difference of safety inspections and difference in fatigue of managers, etc., according to the frequency of using the UAS.

To evaluate the potential performance of UAS-based construction safety management technologies, the study was divided into four stages, as shown in Figure 1. First, a literature review related to UAS-based construction safety inspection technologies was conducted. And then, various factors influencing safety inspections were identified. In this study, these factors were identified based on their comparability between the conventional safety management approach and the UAS-based safety management approach. These factors include the frequency of using UAVs, safety inspection, worker fatigue, accidents, the amount of delayed work, and various other factors. Afterward, in the system dynamic modeling stage, the interrelations between the identified factors were modeled, and a stock–flow diagram was drafted to simulate the UAS-based construction safety inspection. Lastly, the scenarios set in this study were simulated, and the results of each scenario were analyzed.

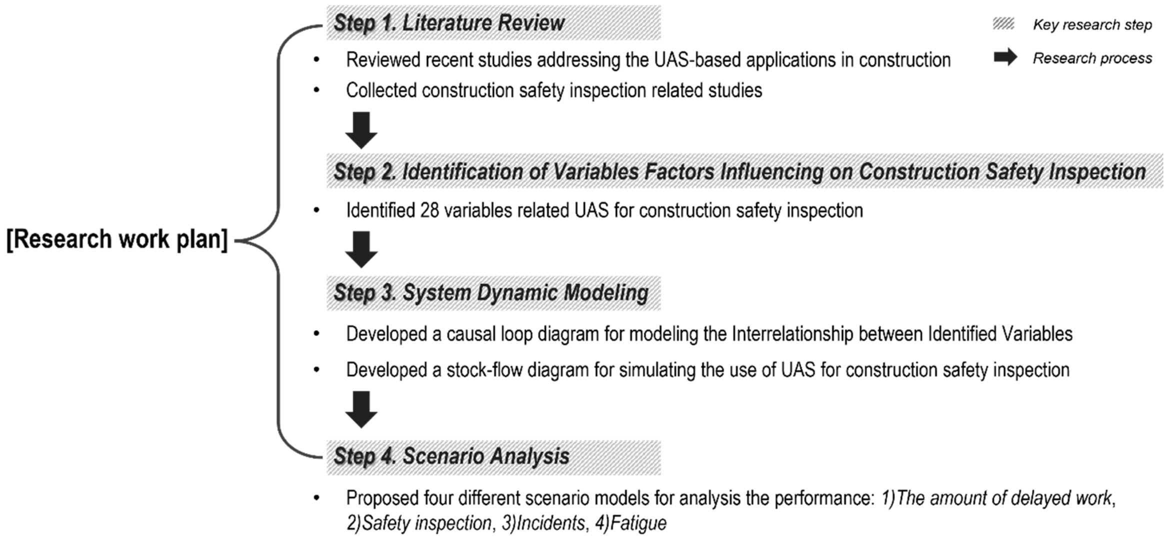

Figure 1. Overall research plan.

4. System Dynamic Modeling

4.1. Identification of Model Variables

Twenty-eight factors were identified through the preceding research analysis in this study. For example, "Accumulated delayed time" is defined by the difference of the accumulated delay time from the start of the project and the compensated time from work in the previous month [20]. The impact of UAS-based safety management on the construction project period can be checked through the "accumulated delayed time". For other identification factors, there is "detecting invisible hazardous situations", which are defined as visible or invisible risk areas that are difficult to detect [39]. Using the "detecting invisible hazardous situations" factor, the technological differences and relationships of the existing safety management method and UAS-based safety management can be checked. In addition, factors for evaluating the potential performance of UAS-based safety management, such as "fatigue", and "frequency of using UAVs for safety inspection", were identified and verified. Table 1 shows the factors and definitions related to UAS construction safety inspections.

Table 1. Identification of variables related to UASs for construction safety inspection.

Variable	Definition	Reference
Accumulated delayed time	The time difference between all delays occurring since the project started and the delay due to the work pressure in the previous month.	Kim et al., 2016 [20]
Communication	Interaction between project engineers and labor during the construction activities.	Zoghi et al., 2020 [41]
Corrective actions	Activities to correct hazardous situations potentially resulting in accidents.	Jiang et al., 2014 [39]
Detecting invisible hazardous situations	Areas where hazards and risks are invisible or difficult to inspect.	Jiang et al., 2014 [39]
Detecting visible hazardous situation	Intentional or unintentional methods to detect hazards within a construction site.	Jiang et al., 2014 [39]
Exchanging real-time information	Information and data exchange between the safety inspection system and the project managers.	Kim et al., 2016 [20]
Fatigue	Workers' physical and mental fatigue.	Rodrigues et al., 2017 [42]

Table 1. *Cont.*

Variable	Definition	Reference
Fixing non-compliance and hazards	Identifying hazards and fixing risks during safety inspection.	Jiang et al., 2014 [39]
Frequency of using UAVs for safety inspection	Frequency of using a UAV system to identify hazards at construction sites and improve work environments.	Rodrigues et al., 2017 [42]
Hazardous situations	Site conditions that may put workers at risk.	Jiang et al., 2014 [39]
Learning and training	Systematic learning and routine safety training among workers.	Jiang et al., 2014 [39]
Maximum monthly work capacity	The maximum amount of work that one laborer performs in a specific job in a month.	Rodrigues et al., 2017 [42]
Monitoring hard-to-access areas	Refers to inspection areas that are difficult to access.	Rodrigues et al., 2017 [42]
Postponing inspection service	Refers to delay of safety inspection and measurement.	Jiang et al., 2014 [39]
Potential hazardous situations	Hazardous situations and behavior of workers that may cause accidents at the jobsite.	Kim et al., 2016 [20]
Rate of extra work	Amount of a worker's extra work to accelerate project.	Rodrigues et al., 2017 [42]
Reporting	Refers to the percentage of anomalies groups reported in construction projects.	Misra et al., 2005 [43]
Safety inspection	Refers to a series of processes carried out to identify hazards within a construction site.	Kim et al., 2016 [20]
Safety regulations at jobsite	Safety instructions and plans that laborers must follow to prevent accidents.	Rodrigues et al., 2017 [42]
Speed of measurements	Refers to the speed of carrying out instructions and reacting to potential hazards and incidents.	Rodrigues et al., 2017 [42]
Subjective norms	A type of behavior that puts social pressure on others to behave in certain way.	Ham et al., 2015 [44]
Taking a rest	One day to release work stress.	Rodrigues et al., 2017 [42]
The amount of delayed work	Cumulative delay since the beginning of the project.	Kim et al., 2016 [20]
Time wasted for documentation process	Refers to the time needed to organize and classify safety inspection documents.	Kim et al., 2016 [20]
Violation	Workers do not follow the safety rules and compliance.	Jiang et al., 2014 [39]
Workflow	This refers to a pattern that is repeated at a construction site.	Jiang et al., 2014 [39]
Workers negligent	Some workers who work in inconspicuous locations use safety equipment carelessly.	Rodrigues et al., 2017 [42]
Workers' safety awareness	This refers to the technical and psychological state of workers that keeps them cautious of potential hazards within a construction site.	Jiang et al., 2014 [39]

4.2. Causal Loop Diagram

Through feedback loop R1, which includes the various potential of UASs, the dynamic effects on safety inspections in the construction project are shown (see Figure 2). With the key variables of the subloops and the increasing frequency of use of UASs, the range of different potential increases or decreases.

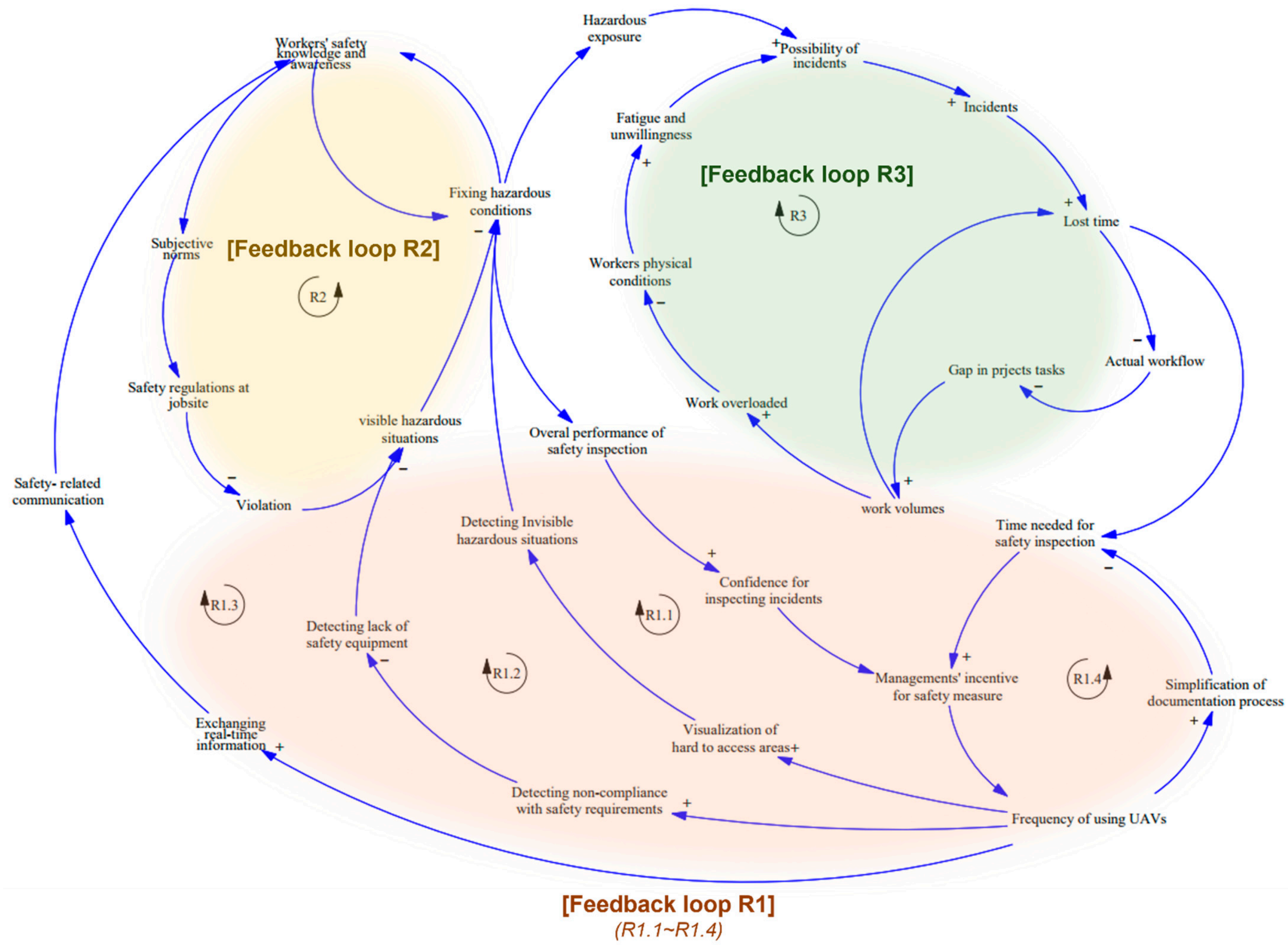

Figure 2. Causal loop diagram of UAS-based construction safety inspection.

Feedback loop R1.1 shows how UAV systems enhance visibility in hard-to-access areas at jobsites and assist managers in detecting potentially hazardous situations, subsequently reducing the possibility of potential incidents. A successful accident investigation encourages managers to conduct more effective safety inspections.

Feedback loop R1.2 shows that as the frequency of UAV use increases, non-compliance of safety regulations can be better identified. A better understanding of the inconsistencies within the construction process can help identify and solve potential hazards that are visible and accessible (via a similar process to R1.1). Additionally, another benefit of using UAVs is improved communication regarding safety inspections between contractors and workers through real-time information exchange.

Feedback loop R1.3 shows that simplification of information exchange in the safety control process can improve safety knowledge and safety awareness of workers. Therefore, simplifying information exchange can make it easier for workers to identify potential hazards (via a similar process to R1.1)

Feedback loop R1.4 shows that the increased frequency of use of UAVs can reduce the time wasted in preparing and organizing construction reports. Reduced paperwork time gives managers enough time to conduct safety inspection on construction site.

Feedback loop R2 shows that the level of safety awareness increases due to communication and training between participants, thereby creating subjective norms among participants. These norms help ensure workers comply with site's safety rules and reduce potential hazards on construction sites.

Feedback loop R3 shows the interrelationship between "time loss" and "probability of accidents". Accidents that occur during the construction period are caused by interruption and time loss. The interruption of construction causes huge pressure on the physical condition of the workers and imposes a significant workload on them. This situation causes "fatigue" and "unwillingness" among workers. Additionally, "fatigue" and "unwillingness" increase the possibility of an accident.

4.3. Stock–Flow Diagram

The causal relationship model drafted in the "4.2. Causal Loop Diagram" must be converted to a mathematical model for simulation. The mutual relationship of all factors, initial values, and factors must be formulated and digitized for this, and a stock–flow diagram must be drafted to enable model simulation.

Therefore, in this study, each factor was formulated and digitized first, as shown in Table 2. "Frequency of using UAVs for safety inspection" was digitized as (0, 1, 2, 3, 4) to identify changes in other factors, and this represents the number of times UAVs are used per month. Among the factors that change with the number of times UAVs are used, "incidents", "safety inspection", "the amount of delayed work", and "fatigue" are the most important for evaluating the potential performance of UAS-based safety management technologies, and formulated equations for the above factors were collected and compensated for based on the existing literature. Next, a stock–flow diagrams was developed based on quantified factors, as shown in Figure 3. Figure 3 includes quantified relationships among various factors, illustrating the sequential process of factors in UAS-based safety management. Additionally, based on this, it is possible to understand UAS-based safety management impact factors such as amount of delayed work, workers fatigue, safety inspection, and incidents.

Table 2. Mathematical equations of identified parameters.

Variables	Equations
Exchanging real-time information	IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 4, 8, IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 3, 6, IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 2, 4, IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 1, 2, 1))))
Accumulated delayed time (t)	Accumulated delayed time (t $-$ dt) + Adding time passed $\times$ dt
Adding time passed	Postponing inspection service
Changing workers' condition	Work pressure
Communication	"Exchanging real-time information" $\times$ 0.1
Corrective actions (t)	Corrective actions (t $-$ dt) + "Fixing non-compliance and hazards" $\times$ dt
Detecting invisible hazardous situations	Monitoring hard-to-access areas
Detecting visible hazardous situation	(100-Workers negligent)/2
"Exchanging real-time information"	IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 4, 8, IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 3, 6, IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 2, 4, IF THEN ELSE (Frequency of using UAVs for safety inspection $\geq$ 1, 2, 1))))

Table 2. *Cont.*

Variables	Equations
Fatigue	DELAY1(MAX (Workers' physical condition, 5), 2)
"Fixing non-compliance and hazards"	(Detecting visible hazardous situation + Detecting invisible hazardous situations)/2 × 0.01 × Potential hazardous situations × Speed of measurements
Frequency of using UAVs for safety inspection	0, 1, 2, 3, 4
Gap in projects	INTEGER (Lost time) + 0.1
Hazardous situations	90 − 0.9 × Corrective actions
Incidents	MAX (0.1, INTEGER (Possibility of incidents/10))
Learning and training	IF THEN ELSE (Communication ≥ 0.8, "Fixing non-compliance and hazards" × 0.8, IF THEN ELSE (Communication ≥ 0.6, "Fixing non-compliance and hazards" × 0.7, IF THEN ELSE (Communication ≥ 0.4, "Fixing non-compliance and hazards" × 0.6, IF THEN ELSE (Communication ≥ 0.2, "Fixing non-compliance and hazards" × 0.5, "Fixing non-compliance and hazards" × 0.4))))
Lost time	RANDOM UNIFORM (0, Incidents, 0)
Maximum monthly work capacity	2 + 2 × ABS(SIN(Time))
Monitoring hard-to-access areas	IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 4, 96, IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 3, 75, IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 2, 60, IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 1, 45, 30))))
Possibility of incidents	Hazardous situations
Postponing inspection service	INTEGER (The amount of delayed wok)
Potential hazardous situations (t)	Potential hazardous situations (t − dt) − Fixing non-compliance and hazards × dt
Rate of extra work	Work pressure
Reporting	RANDOM UNIFORM (0, 2, 0) + Exchanging real-time information
Safety inspection	DELAY1(Corrective actions, 0.1 × Accumulated delayed time)
Safety regulations at jobsite (t)	Safety regulations at jobsite (t − dt) + Subjective norms × dt
Speed of measurements	1/Time wasted for documentation process
Subjective norms	Workers' safety awareness × 0.01
Taking a rest	1
The amount of delayed wok (t)	The amount of delayed wok (t − dt) + workflow × dt-Rate of extra work × dt
Time wasted for documentation process	IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 4, 4, IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 3, 7, IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 2, 10, IF THEN ELSE (Frequency of using UAVs for safety inspection ≥ 1, 13, 16))))
Violation	((10-Reporting) + ((100-Safety regulations at jobsite) × 0.1))/2
Workflow	Gap in projects
Work pressure	MIN (Maximum monthly work capacity, The amount of delayed wok-Maximum monthly work capacity)

Table 2. *Cont.*

Variables	Equations
Workers negligent	(Fatigue + 3 × Violation)/2
Workers' physical condition (t)	Workers' physical condition (t − dt) + Changing workers' condition × dt − Taking a rest × dt
Workers' safety awareness (t)	Workers' safety awareness (t − dt) + Learning and training × dt

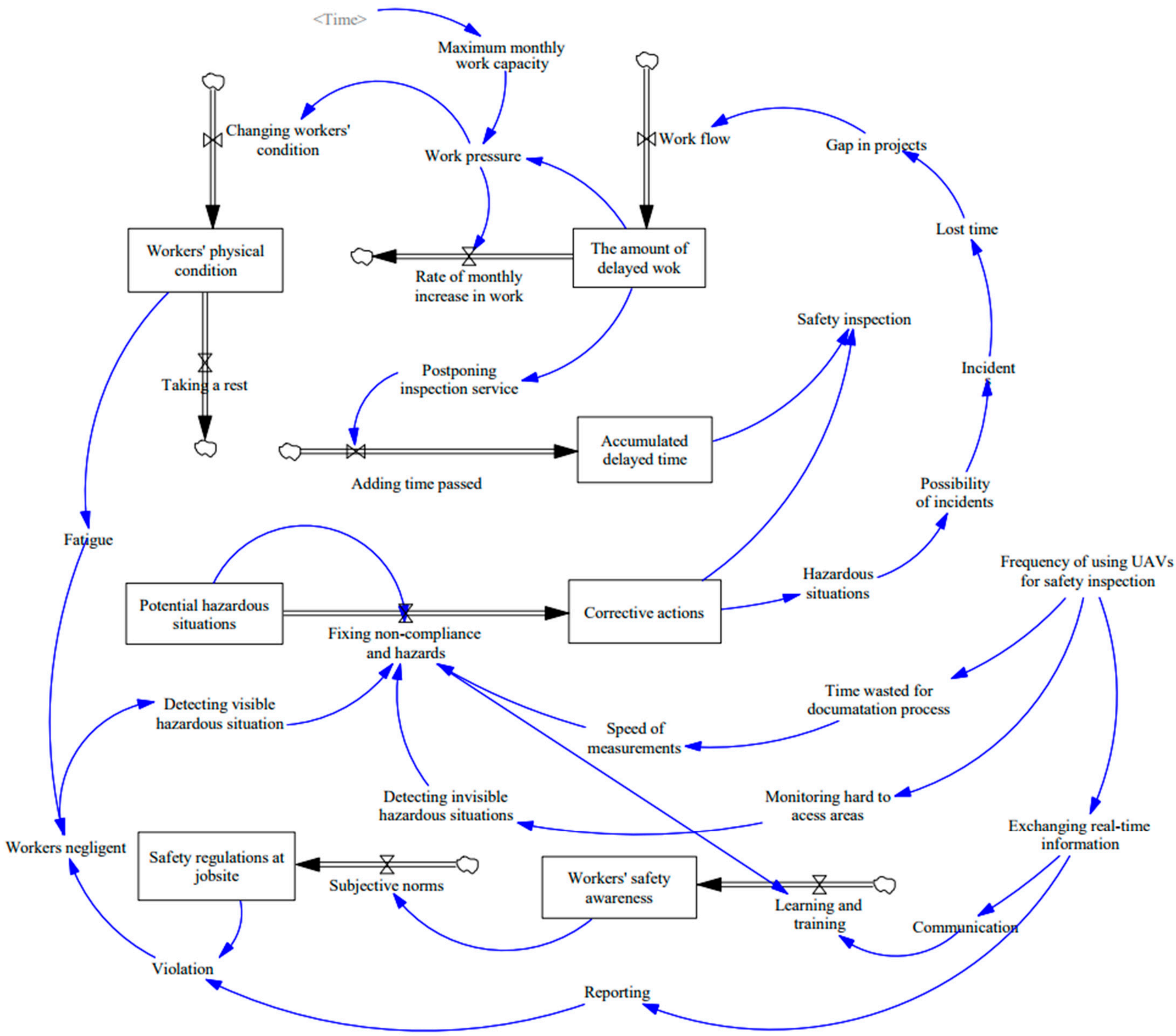

Figure 3. Stock–flow diagram of UAS-based construction safety inspection.

4.4. Model Validation

In this study, pilot tests were conducted using the changing ratio of corrective actions of the manager as an example according to the number of mistakes by the worker, to test the accuracy and sensitivity of the SD model. The change value of worker mistakes was set as (0, 20, 40, 60, and 80) to test a total of five times. The results showed that with the increased number of mistakes by the worker, the ratio of corrective actions by the manager also increased. The results of this test are natural and common in construction sites and consistent with the results of past studies (see Figure 4). Thus, it was presumed that the behavior of the developed model was feasible, and the developed model was used to perform four different scenario analyses.

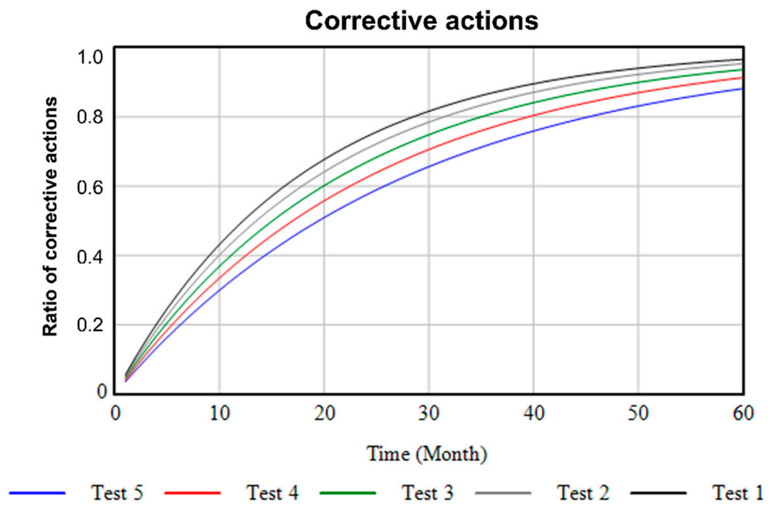

Figure 4. An example of model testing (corrective actions), with different numbers of "workers negligent"; test 1: number of "workers negligent" = 0; test 2: number of "workers negligent" = 20; test 3: number of "workers negligent" = 40; test 4: number of "workers negligent" = 60; test 5: number of "workers negligent" = 80.

5. Scenario Analysis

As shown in Figure 5, with the increase in frequency of using UAVs the safety inspection performance is improved dramatically. However, after a certain period, there was little change in the rate of safety inspection performance. This suggests that while the frequency of using UAVs leads to a dramatic increase in safety inspection execution, there is a limit to the extent to which the performance rate continues to rise over time. Next, Figure 6 shows the variation in the ratio of incident reduction based on the frequency of using UAVs. The most important point in evaluating the rate of reducing incidents is the time and slope of its reduction, which shows the difference between preventive measures and reactive measures. The sooner the potential for accidents is identified and reduced, the lower the probability of accidents. By identifying and reducing the number of potential incidents in the project, the work gap is also reduced. Next, Figure 7 shows the variation in the ratio of worker's fatigue based on the frequency of using UAVs. As shown in Figure 7, the ratio of worker's fatigue decreases with an increase in the use of UAVs. However, the rate of changing fatigue remains constant and even increases, indicating that the work pressure is still imposed on workers. Next, Figure 8 exhibits the influence of the frequency of using the UAVs on the amount of work delay. Based on the scenario analysis, it shows that more frequent use of UAVs for construction safety inspection can decrease the rate of the delay at the construction jobsite.

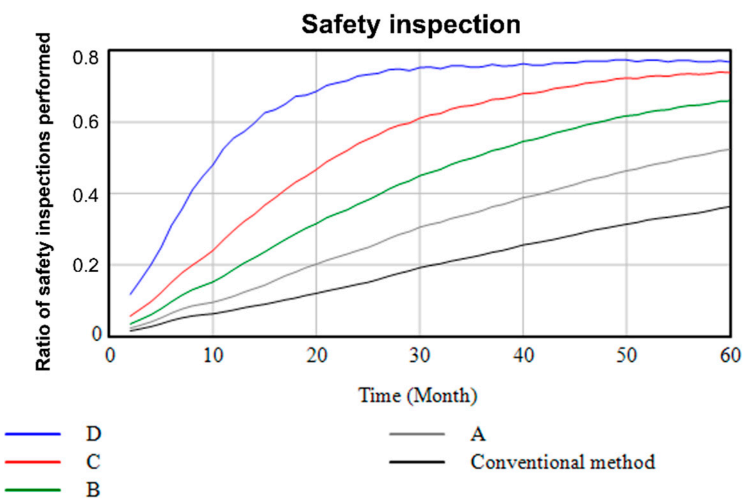

Figure 5. UAV-based safety inspection with different frequency of UAV use; A: once a month; B: twice a month; C: three times a month; D: four times a month.

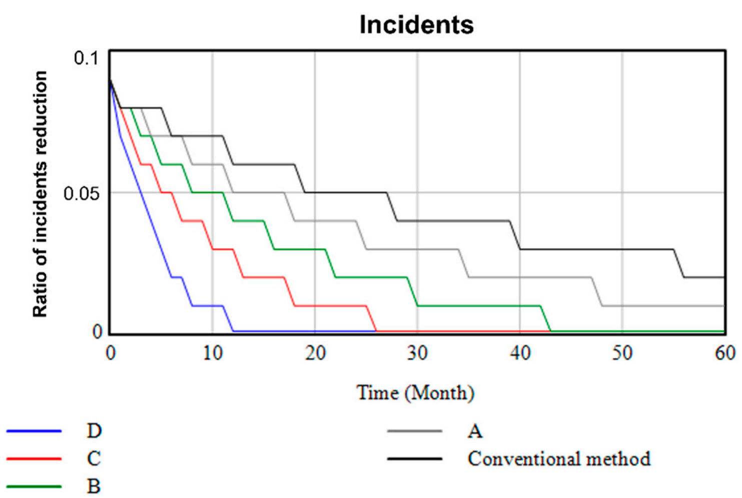

Figure 6. Rate of decreasing incidents with different frequency of UAV use; A: once a month; B: twice a month; C: three times a month; D: four times a month.

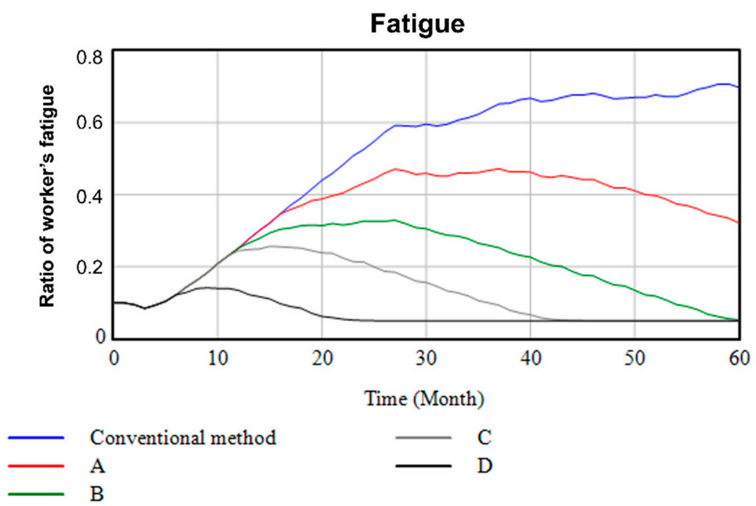

Figure 7. Changes in workers' feelings of fatigue with different frequency of UAV use; A: once a month; B: twice a month; C: three times a month; D: four times a month.

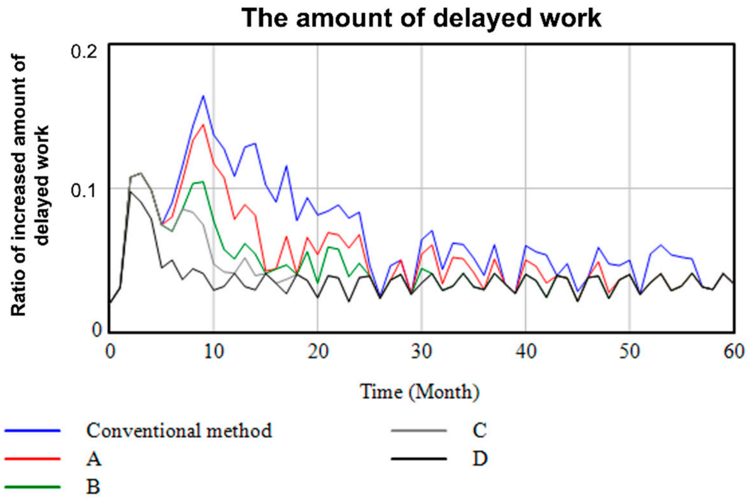

Figure 8. The amount of delayed work with different frequency of UAV use; A: once a month; B: twice a month; C: three times a month; D: four times a month.

6. Discussion and Conclusions

In this study, an SD model was developed to evaluate the potential performance of UAS-based safety inspection technologies, and scenario analysis was conducted.

First, 28 factors were identified through the preceding research analysis, and each one was defined. The 28 factors are related to safety inspections and were identified to evaluate the performance of UAS-based safety inspection. Second, a causal loop diagram was developed by analyzing the interrelations between the identified factors. Third, the interrelations of all factors, initial values, and factors were formulated and digitized to develop a stock–flow diagram to simulate the causal loop diagram. Lastly, scenario analysis was conducted for four cases (safety inspection, incidents, fatigue, and amount of delayed work), and the results of analysis were as follows.

In the case of the "safety inspection" scenario in Figure 5, it was found that the performance of safety inspections increased greatly according to the frequency of using the UAS. However, after a certain period, there was little change in the rate of safety inspection performance. This means that, although the frequency of UAV usage results in a dramatic increase in safety inspection execution, there is a limit to extent the performance rate continues to rise over time. Furthermore, while the rate of safety inspection performance has dramatically increased, further research should be conducted to ensure that this dramatic performance is manifested as quickly as possible. Next, for the "incidents" scenario in Figure 6, it was found that when UAS usage frequency increased, the incident decrease rate dropped, and, in particular, it was found that the potential for early incidents greatly decreased. However, since even a single incident is unacceptable, UAS-based safety inspection technology must be developed to minimize the probability of any incidents to zero. Next, For the "fatigue" scenario in Figure 7, it was found that when the frequency of using the UAS increased, worker fatigue dropped significantly. But it was also found that after a certain period of time, worker fatigue no longer dropped. This is judged to be the fatigue that workers normally feel when performing safety inspection work. However, even the basic level of fatigue perceived by workers can lead to negligence and potential safety incidents. Therefore, there is a need to establish a safety management system that includes real-time tracking and management of the worker's fatigue. Lastly, for "the amount of delayed work" scenario in Figure 8, it was found that when the frequency of using the UAS increased, early on, the amount of delayed work decreased greatly. But, as time passed, it was found that the amount of delayed work did not make much of a difference when compared with the "conventional method". This is deemed to be because toward the end of the construction project, the frame construction, window and door construction, etc., that have higher risk of accidents, are already completed, and finishing processes with lower risk are being carried out, thus having little difference in the amount of delayed work. Thus, even with an increased frequency of UAV usage, it can be observed that the amount of work delay does not decrease entirely. However, work delays can impose job pressure on both managers and workers, potentially leading to fatigue. Moreover, these factors may increase the likelihood of safety incidents. Therefore, efforts to minimize work delays will be necessary.

As detailed above, this study showed through the four scenarios in which UAS-based safety inspection can be more effective than conventional methods. However, there are challenges in generalizing the results of this study as follows.

First, practical factors must be considered for conducting UAS-based safety inspections. For example, factors such as the type of UAS, battery capacity, flight duration, recharge time, and sensor type need to be considered. Additionally, simulations based on real or virtual construction sites should be performed. In other words, experimental validation is deemed essential. Second, the appropriateness of the interrelations between factors shown in the causal loop diagram and stock–flow diagram must be reviewed through surveys for field safety managers. Based on this, the SD model needs to be revised, and more scenarios should be established and analyzed to present more objective results. Lastly, as mentioned in the introduction, in addition to recent research on UAS-based construction safety inspections, integration with various ICT (AR/VR, BIM, etc.) can also be considered. Therefore, there is a need for research evaluating the potential performance of construction safety management technologies that integrate UASs with other technologies.

The results of this study make a significant contribution to the understanding of UAS-based construction safety inspection and the potential of the technology.

Author Contributions: Conceptualization, S.K.; methodology, S.K. and K.J.; Literature review and analysis, K.J., C.Y. and D.L.; writing—original draft preparation, K.J.; writing—review and editing, S.K.; project administration, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021R1F1A1064109). Also, this research was supported by the research fund of Hanbat National University in 2021 (No. 202103310001).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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