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SAFETY-I AND SAFETY-II: CONTRIBUTIONS OF UAS SAFETY MONITORING ON CONSTRUCTION SITES

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ABSTRACT

Unmanned Aerial Systems (UASs) have been incorporated into safety management systems to facilitate hazard identification and propose corrective actions on time, meaning practices related to the Safety-I approach. However, its impacts on understanding and dealing with everyday operations in front of adverse conditions, meaning Safety-II practices, are still unknown. Thus, this study investigates the contribution of safety monitoring using UAS to support Safety-I and Safety-II practices in everyday operations. Two case studies in construction projects were conducted, involving the following steps: (a) proposition of UAS monitoring protocol integrated into safety management routines; (b) field tests to monitor safety performance using UASs; (c) data analysis considering Safety-I, Safety-II and Resilience Engineering. As a main result, resilience mechanisms were identified, such as adaptation in the lifeline safety systems, use of photos and videos to improve workers' awareness, and collaborative work between frontline workers. Regarding the Safety-I approach, most of the identified non-conformities were classified as precarious structures on the construction sites, failures in the Personal Protection Equipment (PPE) use, and safety barriers. The perceived limitations emphasized the difficulty in promoting corrective actions due to the lack of flexibility in the constructive processes, availability of resources timely, and absence of slack.

KEYWORDS

Construction sites, safety management, resilience engineering, and digital technologies.

INTRODUCTION

Safety monitoring in construction sites could be considered a complex task due to the many activities that happen simultaneously and the few safety professionals performing them. This complexity becomes even more prominent without adopting digital technologies to monitor working conditions (Guo et al., 2017). In addition, safety professionals faced some issues in inspection routines that imply the difficulty of timely decision-making, such as the high amount of work required for manual data collection and processing, the lack of standardized safety procedures, and poor communication between teams (Cheng and Teizer, 2013; Lin et al., 2014; Rey et al., 2021).

To improve such aspects, previous studies proposed using digital technologies to identify unsafe conditions, streamline data collection and processing and provide real-time information (Lin et al., 2014; Guo et al., 2017; Awolusi et al., 2018). Among the technologies applied to safety monitoring, the Unmanned Aerial Systems (UAS) must be highlighted due to their ability

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to collect high-resolution visual data, monitor large construction sites, and access hard places in less time and at less cost (Melo et al., 2017). Melo et al. (2017) and Martinez et al. (2020) discuss that the use of the UAS facilitates the visualization of hazards and the inspection of safety regulations on construction sites, especially in situations related to the absence of Fall Protection Systems and inefficient use of Personal Protective Equipment (PPE). Based on the irregular situation identified on-field, safety professionals propose immediate or corrective actions to mitigate or eliminate the risk of accidents visualized by UAS (Melo et al., 2017; Rey et al., 2021).

Despite the potential gains related to the use of UAS for safety monitoring, most studies focus on reactive actions (Melo et al., 2017; Martinez et al., 2020; Kim et al., 2020; Rey et al., 2021) since they aim to prevent something negative from happening, Safety-I approach (Hollnagel, 2014). To cope with this matter, Safety-II emerges as a new way to see and understand safety management. Safety-II believes that to improve safety performance is necessary to look at things done correctly in daily operations rather than just looking at errors and unwanted events (Hollnagel, 2014; Wahl et al., 2020; Martins et al., 2022).

According to Martinez et al. (2020), Rey et al. (2021), and Lima e Costa (2023), the UAS could be used for safety planning, construction site monitoring, and risk assessment. However, none of these studies showed the contribution of UAS safety monitoring to improve everyday operations considering Safety-I and Safety-II perspectives. Therefore, this study aims to investigate the contributions of UAS safety monitoring to support Safety-I and Safety-II practices in daily operations on construction sites.

SAFETY-I, SAFETY-II, AND RESILIENCE ENGINEERING

The Safety-I approach promotes a bimodal view of how work is performed. According to this perspective, operation success occurs because the system works as it should, and people work according to procedures. The failures are usually associated with errors, deviations, and system malfunctions (Hollnagel et al., 2015). This approach does not consider complex socio-technical systems' dynamic and non-linear nature (Wahl et al., 2020). Therefore, it is necessary to adopt other strategies to improve safety performance on construction projects.

In this context, Safety-II seeks to understand how people adjust their actions when they face a critical situation to achieve desirable results (Hollnagel et al., 2015; Wahl et al., 2020). According to the Safety-II perspective, positive and negative effects are possible, which makes it necessary to recognize the risks and opportunities of everyday operations (Hollnagel et al., 2015).

According to Hollnagel (2014), Safety-I and Safety-II perspectives might coexist in the same environment, and the balance between them is essential to move toward a resilient performance. Resilience is the intrinsic ability of an organization to adjust its functioning prior to, during, or following changes and disturbances so that it can maintain required operations, even after an unexpected event or in the presence of continuous stress (Hollnagel, 2014).

Resilience emerges from the performance adjustments carried out by people by themselves or by a group, as characterized by Hollnagel (2018). However, the technical, technological, and organizational factors are also essential to support this adjustment (Heggelund and Wiig, 2019).

Some researchers have been seeking to identify the actions and characteristics that influence performance adjustments, characterized as resilience mechanisms or skills (Hollnagel, 2014; Saurin et al., 2014; Heggelund and Wiig, 2019). The resilience mechanism could be interpreted as actions or strategies to deal with the factors that restrain daily work. Wachs et al. (2016) pointed out some examples of "work restrain," such as the limitations of resources or unavailability (labor, equipment, and materials), incomplete project information, high workload, excessive administrative activities, time limitations, and casual incidents. Regarding performance adjustments, Hollnagel (2014) classified them as actions to maintain and create good working conditions; compensate for something missing, such as replacing materials; and propose solutions to avoid future problems, such as updating procedures.

Wehbe et al. (2016) argued that team discussions about safety conditions, team communication, and collaboration support resilience, even as the efforts to propose actions that prevent an error from recurring. Thus, the lack of resolution to correct the non-compliance compromises resilient performance.

As a practical example, Peñaloza et al. (2017) analyzed frontline workers' behaviors in the precast concrete assembly process and noted some resilience mechanisms, such as team discussions about the set of maneuvers required to reduce risk exposure (compensating); the adoption of strategies to deal with rework (creating conditions); and the practice of avoiding activities that bring a high level of uncertainty (avoiding future problems).

During the evaluation of the safety management system, Peñaloza et al. (2020) emphasized that the compliance indicator and safety checklist, the standardized data collection routines, and the involvement of safety and production professionals in safety conditions assessment and planning could be practices managing complexity. Aiming to incorporate Safety-II practices in construction projects, Martins et al. (2022) proposed a framework based on Safety-I and Safety-II concepts. In this framework, Safety-I refers to work as imagined, and it's established in the form of safety procedures. In contrast, Safety-II relates to work as done, and it's assessed by the monitoring of the constructive processes.

Therefore, despite each approach seeing safety in a specific way, Figure 1 shows they are not mutually exclusive but complementary (Hollnagel, 2014; Wahl et al., 2020; Martins et al., 2022). This means that they must be combined to promote a balance between safety practices and procedures, aiming to increase learning with daily work (Wahl et al., 2020; Martins et al., 2022).

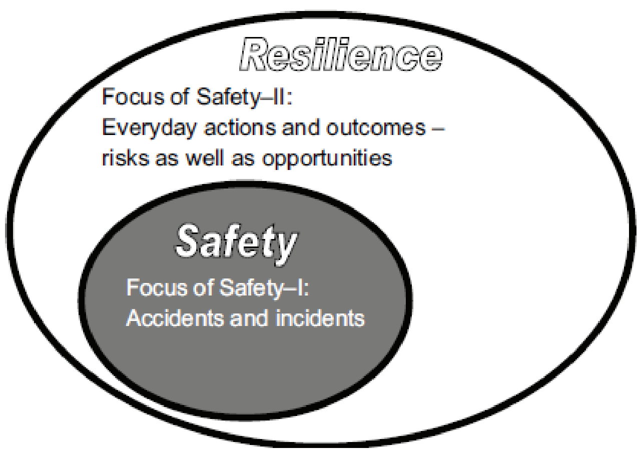

Figure 1: Relationship between Safety–I and Safety–II Source: Hollnagel (2014).

RESEARCH METHOD

This research adopted Case Study as the research strategy, which is a method that emphasizes the real-world context in which phenomena occur (Yin, 2014; Flyvbjerg, 2011). In this study, the phenomenon studied refers to implementing the UAS safety monitoring by adopting Safety-I and Safety-II approaches. The research process was developed according to the following stages: (a) proposition of UAS monitoring protocol integrated into safety management routines; (b) field tests to monitor safety performance using UASs; (c) data analysis considering Safety-I, Safety-II, and Resilience Engineering.

An exploratory case study was developed in Project A, aiming to understand the safety routines through document analysis, interviews, and UAS data collection. Based on this study, a UAS safety monitoring protocol was proposed to be implemented into weekly safety routines to support data collection and analysis (Figure 2). Case studies B and C lasted for 34 weeks and 21 weeks, respectively. During this period, the researcher performed 55 monitoring using UAS technology. Both studies are residential projects for the middle and low-income housing sector. The main construction methods were a continuous flight auger foundation and a cast-in-place concrete wall system. Table 1 describes the primary features of the projects and Flight log data collected in each project.

Table 1: Features of Construction Projects – Case Studies B and C

Case Studies	Project B	Project C
Project features	Land Area: 19,524 m² Total of 380 units Construction time: 16 months Period: Nov/2018 to Oct/2019 34 safety inspections using UAS	Land Area: 16,091m² Total of 300 units Construction time: 14 months Period: Apr/2019 to Oct/2019 21 safety inspections using UAS
Flight Log	Database: 2.210 images Flight time:11 hours and 25 minutes Average flight distance: 1.482 meters	Database: 1.281 images Flight time:6 hours and 19 minutes Average flight distance: 1.340 meters

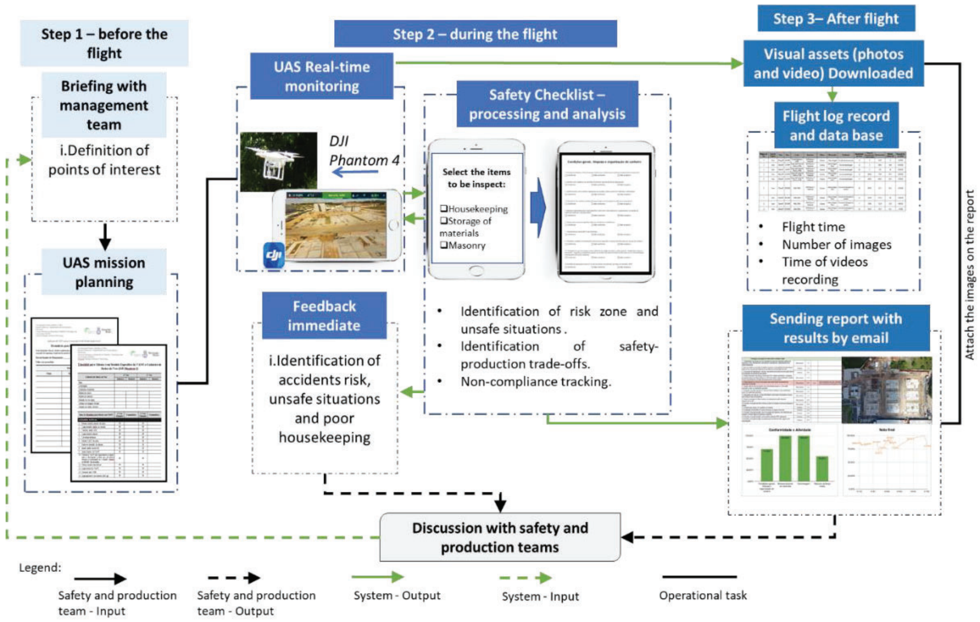

Figure 2: UAS Safety monitoring protocol integrated SMS routines.

During the case studies, the research group automated the safety inspection process, proposing the combination of UAS to monitor safety conditions on-site and a web system to fill out the checklist [OMITTED BY REVIEW]. The UAS safety checklist has 241 items divided into 21 categories (organization and housekeeping, storage of materials, construction site signaling, stairs and ramps, collective protective equipment, and earthwork and foundation). During the monitoring, the pilot controls the drone and gives real-time feedback about the status of each item from the safety checklist for the observer. The observer is responsible to fills out the checklist on the field. In Projects B and C, the safety personnel often participated in the inspections.

The outputs of this phase are the inspection report which contains a safety checklist assessment, the UAS images, and the safety compliance indicator (i.e., the ratio of the sum of compliant items and the sum of items checked). After each inspection, the pilot delivers the report to safety and production teams, including the managers.

The UAS was used to record working conditions, which include non-conformity safety items and informal practices carried out by frontline workers. The inspection report and photos and videos collected using UAS were used in meetings by safety and production professionals to discuss the workplace conditions and production process.

DATA ANALYSIS

Aiming to understand Safety-I practices, it was done a document analysis focusing on operational procedures and a safety checklist, besides the direct observation in safety and production meetings to promote corrective and preventive measures. Two analyses were accomplished based on the UAS safety inspection reports: i) analysis of the safety compliance indicator, identifying the main critical processes and the safety items more recurrent, ii) analysis of non-compliance by constructive process and degree of risk.

From the Safety-II approach, the analysis focused on identifying performance patterns and classifying the system's functional characteristics that contributed to a resilient performance (Wachs et al., 2016; Heggelund and Swiig, 2019). The data collected using UAS were combined with other sources of evidence, such as safety reports, safety meetings, and interviews with safety professionals and civil engineers. A total of nine interviews (a Safety Coordinator, Two Safety Personnel, a Project Manager, a Quality Coordinator, a Production Manager, Two Production Engineers, and a Production Trainee) were conducted to identify the new practices or improvements supported by UAS safety monitoring. The interview data were analyzed using thematic analysis (Braun and Clarke, 2006), allowing for identifying and exploring major themes systematically and flexibly. The thematic analysis considered the following question: *How does the UAS safety monitoring can improve resilience abilities (monitor, respond, anticipate, and learn)?* The codes were extracted by theme and analyzed according to the corresponding mechanisms.

This analysis focuses on two perspectives: i) operational level (i.e., adaptations and actions made by frontline workers to deal with the daily variability); ii) managerial (i.e., decision-making by management teams aiming to improve workplace conditions and avoid non-conformity recurrence). From the operational mechanism, the images and videos collected using UAS were used to recognize adaptation and good practices carried out by frontline workers and production engineers to maintain production workflow. All adaptations were discussed with the safety technician. From the managerial mechanism, the UAS visual assets and the interviews were the primary sources of evidence, and the mechanisms emerged from the thematic analysis.

RESULTS

RESULTS FROM THE SAFETY-I APPROACH

Figures 3 and 4 show the safety performance of Project B and C over time, respectively.

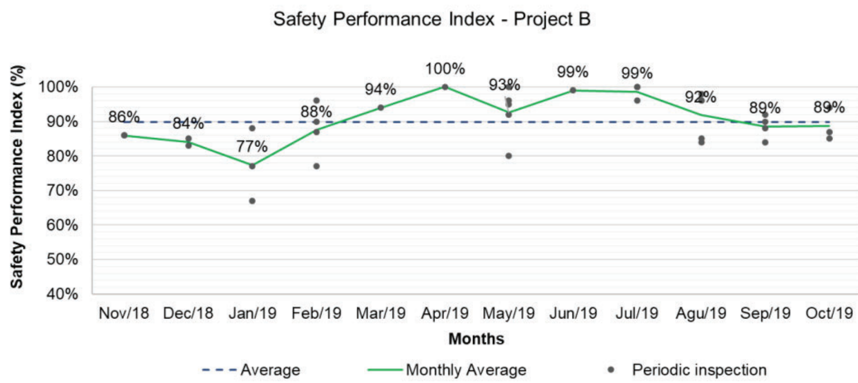

Figure 3: Safety Performance Index of Project B.

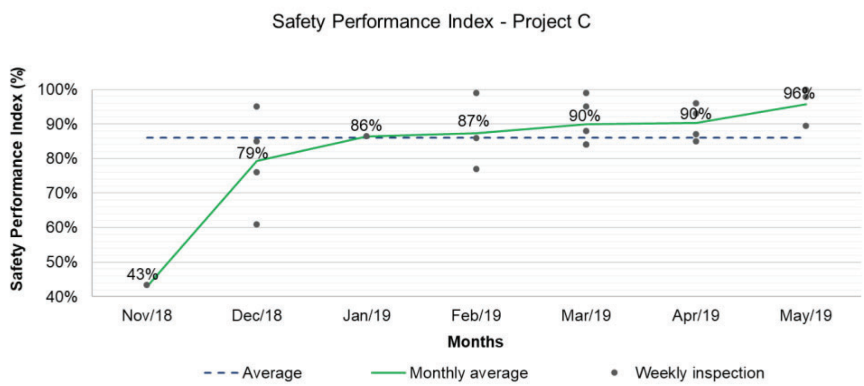

Figure 4: Safety Performance Index of Project C.

In Project B, 1,105 safety items were checked during UAS monitoring, and 102 were classified as non-conformity, corresponding to three notifications per assessment. In Project C, 722 safety items were inspected using UAS, 88 items being non-conformity.

The overall safety performance was 90% in Project B and 86% in Project C. Figure 3 shows that in the first months, the indicator was below the average in both projects, justified due to the lack of safety personnel and the beginning of the site mobilization phase. In Project C (Figure 4), performance improvement is evident over the months, which indicates the team's effort in complying with safety regulations and improving working conditions.

Figure 5 presents the non-conformities by category and by the degree of risk. Regarding Project B, the results indicate that the structural masonry, foundation, cast-in-place concrete wall, and roof had more non-conformities to risk degree 3 (high exposure) than the other processes. Project C demonstrated a similar distribution.

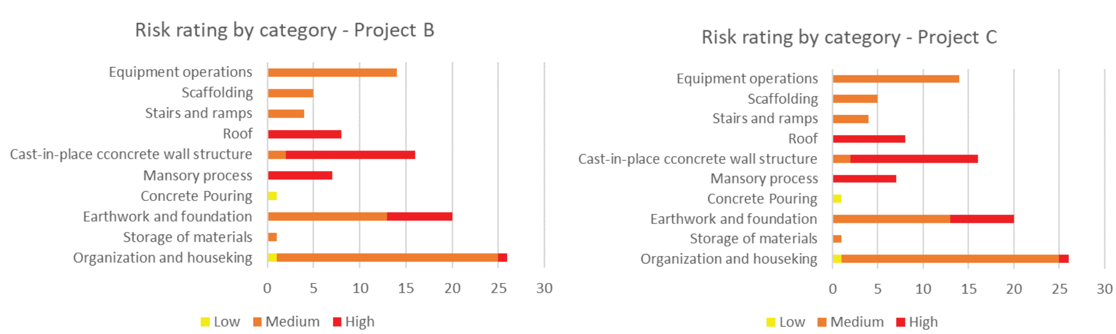

Figure 5: Risk Rating by Category of Projects B and C.

The main non-conformities were: i) waste stored in an inadequate location, ii) lack of signs advertising the risks of the activities, iii) lack of isolation of the cargo handling area, iv) failure in the use of safety belt for working at height, and v) guardrails and safety platforms incomplete or not installed.

In both projects, the number of safety inspections performed increased with the adoption of UAS, contributing to identifying the non-conformities and supporting the corrective measures faster.

RESULTS FROM THE SAFETY-II APPROACH

Table 2 indicates the operational and managerial mechanisms identified in the data analysis. These findings are based on the analysis of visual assets collected using UAS, safety inspection reports, safety and production meetings, and interviews with safety professionals and civil engineers (see the section Data Analysis).

Table 2: Operational and Managerial Mechanisms

Operational Mechanisms	Project	
	B	C
[1] Maintenance of the accesses and internal routes for vehicles and machines to facilitate loading and unloading operations.	✓	✓
[2] Maintenance of the accesses and internal routes for pedestrians, including those not involved in the operations.	✓	✓
[3] Decentralized distribution of materials at the construction site, being them made available at the place of use when necessary.	✓	×
[4] Correct isolation of materials stored in the construction site.	✓	×
[5] Construction of temporary installations (living areas and for storing materials) in regions that do not require repositioning throughout the construction phases.	✓	✓
[6] Marking in the aluminum forms to define the assembly sequence of the parts.	✓	✓
[7] Use wooden structures or metallic guardrails for isolation in excavation areas and work at height areas replacing safety nets.	✓	✓
[8] Adaptation in the lifeline systems connection during guardrail assembly and disassembly.	✓	✓
[9] Use of steel reinforcements as a "barrier" during the guardrail assembly.	✓	✓
[10] Pre-assembly of slab reinforcement and electric installation.	✓	×
[11] Collaborative work between frontline workers during the execution of cast-in-place concrete wall (teams of hydraulics and electric installation, concrete formwork reinforcement, concrete pouring and assembly, and disassembly of collective's protective equipment).	✓	✓
Managerial Mechanisms		
[12] Use of UAS safety inspection report on daily safety dialogue aiming to discuss the main problems, including housekeeping maintenance.	✓	✓
[13] Use of photos and videos to improve awareness about safety and production routines. Ex. Safety training with technicians about risk perception.	✓	✓
[14] Use of the UAS safety inspection report to promote corrective action on time.	✓	✓
[15] Change in the operational procedures of cast-in-place concrete walls based on photos and videos collected by UAS.	✓	✓
[16] Use of UAS inspection report to evaluate the progress of safety conditions throughout the month and compare it with the safety audit outcome.	✓	✓

The operational mechanisms related to the logistics at the construction site [1-5] appear from the analysis of the conforming items (UAS safety inspection report). It was noted in the UAS safety monitoring and discussed in safety meetings that the safety requirements regarding those mechanisms were always correct. So, they were responsible for maintaining and creating good working conditions. The mechanisms [6-10] were identified during the monitoring using UAS. They were classified as adaptations promoted by frontline workers to compensate for the absence of materials, failures in the lifeline system, and production pressure.

Collaborative work [11] emerge as a mechanism that influences both the creation of good work conditions and compensation for something missing. It was observed in the execution of cast-in-place concrete walls that several teams work together in a restricted space. The results showed that workers helped each other in many moments, for example, during the load of the aluminum forms. In addition, when a team worker was absent, the colleagues did their job to avoid delaying production. Everyone on the team knew to assemble and disassemble the forms of all the rooms.

From the managerial perspective, the safety technicians used the feedback from UAS safety monitoring to discuss with workers the main problems identified, including the ones related to housekeeping [12]. The safety technicians used the feedback from UAS safety monitoring to discuss with workers the main problems identified, especially the ones related to housekeeping [11]. In the same way, the safety coordinator used the feedback provided by UAS monitoring in monthly training carried out with company safety technicians [13]. The use of images and videos about the main problems aims to improve risk assessment and prevent future problems.

The safety inspection report delivered after the UAS flight as well as the immediate feedback (Figure 2) were used to promote corrective action on time [14].

The visual assets were used to promote changes in the execution of the services, especially the sequence of assembly and improvements of collective protection equipment [15]. The feedback provided by UAS monitoring was used to evaluate the progress of the working conditions [16], promoting cycles of learning. The item inspected by UAS monitoring were also verified during the safety audit. Despite being considered a redundancy, this overlap was seen as an opportunity to promote corrective and preventive action in a short time since the UAS monitoring was carried out weekly and the audit only once a month.

Discussion in Light Of Safety-I, Safety-II, and RE

The studies about Safety-I look at errors and non-conformities, blaming the worker for the negative outcomes. While, Safety-II understands that adverse effects are inevitable, and several factors contribute to them due to the complexity and non-linear characteristics of the systems. In this perspective, the worker's participation is indispensable to maintaining operations.

Despite the literature on RE being mature, almost two decades, there is a need to clarify Despite the literature on RE being mature, almost two decades, there is a need to clarify how Digital Technologies (DT) could contribute to a resilient performance. The results show that the UAS safety monitoring supports the identification of nonconformities, supporting decision-making on time. Thus, the UAS monitoring helps understand the types of barriers used and their conditions, allowing the manager to know how much the system operates at the performance limits regarding degraded defenses and barriers.

The visual assets allowed the safety personnel to identify the potential risk of each process individually, especially those regarding work-at-height, the excavation process, and machine operation (such as backhoes, trucks, and cranes). Despite the risk assessment being done before the beginning of the execution, in daily routines, continuous monitoring should be made since new risks could appear from failures in the procedures or the intrinsic complexity of the processes.

Thus, when the information provided by UAS monitoring is only used to promote corrective measures and not to understand what is happening, how the system behaves, and how to avoid the occurrence of new non-conformities, we can say that the Safety-I approach prevails. From the moment that the information contributes to increasing the understanding of how the work is done in practice, it clarifies the adaptations made by frontline workers to compensate for the work limitations, avoiding the occurrence of production disruption for any reason, the system goes towards the Safety-II approach (Provan et al., 2020). Consequently, it becomes more resilient.

According to this understanding of Safety-II and RE, the UAS monitoring furnished visual content to support the discussions between safety and production professionals to promote corrective and preventive actions, encouraging decision-making from different perspectives. For example, interruptions in field activities for correcting unsafe situations, layout changing (storage materials), and use of UAS safety inspection report on daily safety dialogue aiming to discuss the main problems, including housekeeping maintenance.

Safety-II also refers to the learning processes built from previous experiences and knowledge (Hollnagel, 2014). This research found that the UAS monitoring captures the inspector/pilot perspective in the field, which could be mistakes and deviations made, or good practices performed daily. Both case studies used images and videos to disseminate good practice and successful adaptation through training and meeting, especially on the cast-in-place concrete wall process.

While Safety-II practices have been noted, the Safety-I view was predominant. In both case studies, the UAS monitoring has provided helpful information about work conditions. However, the main interest of production engineers and managers was visualizing if the construction site was according to the safety norms. On the other hand, when a non-conformity was identified, it wasn't easy to promote action on time to correct it. This delay or difficulty in acting promptly goes beyond the team's ability to know "when" and "how" to respond. The proposition of corrective measures was influenced by organizational factors, such as the team's technical capacity, availability of resources, the lack of slack in production planning, high productivity targets, and inefficiency in the short term.

CONCLUSIONS

This research aimed to identify the contributions of UAS monitoring integrated into safety management routines for developing resilient mechanisms. The results obtained in Projects B and C show that the UAS monitoring combined with other sources of data and management routines have the potential to contribute to the development and enhancement of resilient mechanisms. Since it improves the system's capacity to monitor the working condition and supports decision-making in a timely manner.

The safety monitoring using UAS made visible both non-conformities and the adaptations performed by frontline workers to deal with work restraint and production pressure. Thus, the visual assets and inspection report proved to be a great source of evidence to be incorporated into the management routines, such as production and safety planning meetings, safety training, risk assessment, the study of critical processes, and layout planning.

From the Safety-I perspective is easy to apply the UAS to identify non-conformity and risk situations in an everyday operation, despite the challenges of using new technology. However, regarding Safety-II further studies need to investigate how to incorporate UAS monitoring into the safety routine to support resilience practices. This is the main defiance since the safety and production professionals need to open their main to look at the adaptations carried out by frontline workers as well as learning with daily practice.

As limitations, the difficulties of accepting new technology from the workers were solved through communication in daily safety dialogues about the use of UAS, the potential risks, and its function. The ongoing work was carried out to raise awareness among engineers and technicians about using images and videos and to use visual assets to improve processes instead of observing people. In addition, the safety professionals argued that the UAS monitoring had low interaction with frontline workers, requiring more routines to integrate them into the monitoring and learning process.

For future research, this paper also indicates the need to investigate using UAS visual assets to support risk assessment and automatic recognition using Machine Learning techniques.

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