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Procedia Computer Science 232 (2024) 274–283

Procedia Computer Science

www.elsevier.com/locate/procedia

5th International Conference on Industry 4.0 and Smart Manufacturing

Electronic performance monitoring framework to quantify unhealthy and unsafe on-site behaviours

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Abstract

Health and Safety (H&S) should be a significant concern in construction projects. The quantification of the work injury accidents started with work A. W. Heinrich (1931), passing per Frank E. Bird Jr. (1969) to a study by ConocoPhillips Marine (2003). These theories, also known as the Accident triangle, Heinrich's triangle, or Bird's triangle, are a base for industrial accident prevention applied in practice by the Dupont STOPTM methodology. Over this methodology, the number of unhealthy and unsafe behaviours is classified and accounted for to diagnose the potential workers' recordable injuries, lost workdays, and fatalities. The At-risk behaviours and the Near Misses are the most challenging safety measurement approach as they depend on the human-observation notes usually conducted in a safety audit. Electronic Performance Monitoring (EPM) concerns the use of innovative hardware and software to assess on-site safety and productivity. The electronic monitoring of construction workers can contribute to evaluating unsafe behaviours. At-risk behaviours could be measured based on location, trajectory, and motions. Also, with the monitoring of the equipment and vehicles, it is possible to measure Near Misses. The Information Technologies integration allows for collecting information about Recordable Injuries, Lost workdays, and Fatalities. This work discusses and presents a framework connecting EPM deployment to data acquisition of unhealthy and unsafe on-site behaviours. The contributions in the theoretical and practical fields concern the opportunities of using new technological assumptions to increase data acquisition and improve the accuracy and effectiveness of quantitative safety analysis.

Keywords: Accident Triangle; Worker 4.0; H&S; Behaviour-Based Safety; Construction 4.0

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10.1016/j.procs.2024.01.027

1. Introduction

Health and Safety (H&S) is primarily relevant in construction projects. Innovative approaches concerning the 4.0 industry vision based on IoT and the 5.0 human-centred-based concern should be reflected in H&S initiatives. Conceptual new techniques and tools focusing on applying Electronic Performance Monitoring (EPM) on construction workers may lead to a Worker 4.0 perspective [1]. In the Construction Industry, workforce behaviour is a significant vector of accidents [2]. The accident triangle approach is a solid and tested statistical model to summarise and predict injuries and accidents [2]–[11]. The Behaviour-Based Safety (BBS) approach is prone to prevent accident injuries and manage occupational risks [2]. Finally, a conceptual framework connecting EPM approaches to accident ratio analyses may empower on-site developments to increase data collection and the reliability of BBS implementations.

The European Agency for Safety and Health at Work (EU-OSHA) has intensified research on innovative topics for the safety and health of workers [12]–[16]. EU-OSHA highlighted the use and challenges of electronic monitoring at workplaces, emphasising technologies and OSH (Occupational safety and health) improvement measures [12], [13]. Also, OSHA research discussed Artificial Intelligence decision-making implications, risks, and opportunities for workers' management [14], [15]. The digitalisation of workplaces will empower data acquisition and impact working conditions, increasing opportunities for actions targeting workforce wellbeing [16]. However, OSHA's reports do not step into any practical and quantitative method integrating electronic monitoring tools, techniques, and H&S implementations. With emphasis, it is necessary to investigate the use of digital technologies to support H&S quantitative assessment, such as the Accident Triangle theory. Also, construction industry H&S personification is needed. There are many aspects of the craft workforce and the construction site characteristics to be analysed over the EPM deployment [17].

The Construction 4.0 on-site developments can improve H&S [18]. On-site activities monitoring based on images is investigated for multiple H&S analyses, such as workers' behaviours recognition, PPE (personal protective equipment) correct use, and collision avoidance [19]. Electronic monitoring of the position of construction workers, machines and equipment may identify site logistic problems and human hazard behaviours. Multiple wearable sensors can be attached to PPEs or dressed up on workers to monitor motions, posture and fatigue [11], [20], [21]. At the same time, electronic devices can collect data and deliver safety alerts to the workforce: the data post-analysis and immediate correction of hazard behaviour and situations are a solid base to improve H&S.

First, in this work, a scoping review is done to diagnose the current research concerning H&S, Accident Triangle theory and EPM. Based on that review and the additional background of the authors in a narrative review, a conceptual framework connecting H&S, Accident Triangle theory and EPM is delivered. Finally, the conceptual framework is discussed over the EPM's possible deployment assumptions target acting into the BBS (Behaviour-Based Safety approach) by monitoring the ConocoPhillips Marine (2003) triangle base regarding Near Misses and At-risk Behaviour to prevent workforce injuries.

2. Method

A scoping review was conducted to map the existing research in H&S, EPM, and the Accident Triangle approach to identify overlaps between them. A series of keywords and combinations were developed, and the searches were carried out on the multidisciplinary scientific databases Scopus and Web of Science (WoS) see results in Table 1.

Table 1. Keywords combination and results.

Keywords	SCOPUS	WoS
"accident triangle” OR "Heinrich's triangle" OR "Bird's triangle"	19	12
"at-risk behaviours” AND “near misses"	3	0
construction AND on*site AND safety AND health AND management	29	33
construction AND on*site AND safety AND health AND management AND "electronic performance monitoring"	0	0
construction AND on*site AND safety AND health AND management AND "electronic monitoring"	0	0
construction AND on*site AND safety AND health AND management AND "electronic"	0	0

Over the investigation, 96 documents were identified; after a first analysis based on title, source, and abstract, 31 records remain, and finally, through rigorous scrutiny, 25 complaint documents were selected to be reviewed. Additionally, relevant OSHA reports and known literature concerning electronic monitoring at construction sites were incorporated to support the conceptual analysis to deploy EPM over the Accident Triangle targeting H&S's behaviour-based approach implementations.

3. Literature review

The selected content (25 documents) concerns journal papers (15), conference papers (9), and book sections (1) published between 2019 and 2022. There are five literature reviews. General assumptions are made by seven publications, mostly connected to accident data analysis over different countries. Three works focus on the O&G (Oil and Gas) industry, one on Mines Facilities, and fifteen are regarding the Construction Industry.

The Accident Triangle approach is presented in fourteen works, and the At-risk behaviours (ARB) & Near misses (NM) assessments are discussed in eleven documents. In the construction industry, the accident triangle approach has only three related documents (Small residential construction projects, Underground engineering activities, and Cement industry), two more connected to off-site activities. In this sense, it is possible to highlight the gap in quantifying behaviour-based safety assessment in the Construction Industry.

ConocoPhillips Marine (2003) based on the previous works of A. W. Heinrich (1931) and Frank E. Bird Jr. (1969) highlighted the potential of at-risk behaviours identification to predict damages and fatalities, as illustrated in Figure 1; it is estimated that 300,000 at-risk behaviours materialised, which may infer multiple injuries and lost workdays, and worse, determining one fatality [2]. Based on workforce behaviours observation, it is possible to acquire data (to fulfil the triangle rates) and, at the same time, solve H&S on-site issues and educate workers. However, unreported, unsuitable behaviours or near misses occurrences may mislead the data analysis and give rise to unwanted events plaguing workers [10], [22]. The ConocoPhillips Marine (2003) framework indubitable segments injuries severity into recordable injuries (less than serious), accidents with loss of workdays (serious injuries), and fatalities (ultimate records). A BBS approach targeting the control and action over the triangle base, on the near misses and at-risk behaviours, is relevant to prevent workforce accidents.

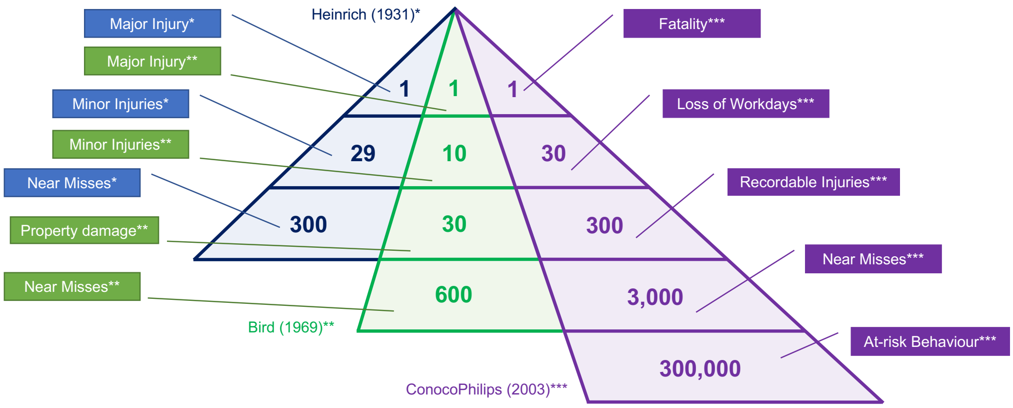

Fig. 1. Accident Triangle theory evolution.

All tables should be numbered with Arabic numerals. Every table should have a caption. Headings should be placed above tables, left justified. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

The Electronic Performance Monitoring approach is found in nine studies. Discarding the literature reviews (five of them), just four works tested EPM for H&S purposes. Laboratory simulations and tests were conducted to electronically monitor the static balance of craftworkers targeting proactive fall safety management using a Wearable

Inertial Measurement Unit (WIMU) and a Smartphone [20]. Also, over laboratory experimentations, an on-body vast sensor, with ECG, respiration, and temperature sensors, was tested to evaluate the fatigue led by physical exertion [23]. An on-site feasibility study was conducted using smartwatches and collecting craftworkers' feedback, envisaging an integrated fatigue measurement system [21].

The only work that combined EPM and the Accident Triangle theory concerned an O&G spectrum [11]. A Predictive Personal Protective Equipment (P-PPE) was developed and tested in the laboratory using EEG and biometrics sensors to acquire heart rate, stress response, temperature, body position and location [11]. Over the discussions, the authors stated that "this PPPE Initiative offers a method that would provide a means to measure leading indicators and also add another base level to the Henrich triangle… …known as predictive opportunities" (page 14) [11]. However, they mislead the theory of Henrich and the Birds improvements, mixing the quantification and assessment of the two references. Most relevant, there is no level concerning “predictive opportunities" in the work of A. W. Heinrich (1931). Somehow, they also mixed some ConocoPhillips Marine concepts; when added to the top of the triangle, they presented the "Fatality" description, as Henrich and Birds set the idea of "Major injury". Based on that, the lack of knowledge of the Accident Triangle theories for the assumptions made leads to some misleading results. However, they presented the top-down approach followed described [11], which has a similar aim to this paper: Fatality (1); Serious accidents (2); Minor accidents (300); Near misses (600); Predictive Opportunities: every second (86 400/day), every minute (1 440/day). Finally, a detailed analysis of the twenty-five documents is summarised in Table 2.

Table 2. Content review analysis.

Title	Year	Sector / field of application	On-site assumptions	Accident triangle	At-risk Behaviours or Near Misses assessment	Electronic Monitoring approach	Outcomes summary
Near-Miss Incident Management of Underground Engineering Safety Risk [3]	2009	Underground engineering activities	Framework for data analysis	Yes	Yes	No	"Identification of a near miss; Causal Analysis; Identification of Solutions to prevent recurrence"
Managing Safety to Achieve Operating Excellence [24]	2009	O&G operations	ExxonMobil's Safety excellence program	No	Yes	No	ExxonMobil's safety program focusses on a "personal commitment by every worker"
The Heinrich Accident Triangle Too Simplistic. A Model For HSE Management in the 21st Century? [4]	2010	O&G operations	On-site data analysis	Yes	Yes	No	"Encourage all employees to participate in risk-identification reporting"
Heinrich and beyond [25]	2011	General	OSHAs recordable cases analysis, lost workday cases, and fatalities	Yes	No	No	New levels and estimations "Lost Workday Cases; OSHA Recordable Cases; First Aid Cases; and No-Injury Accidents."
Use of attitude congruence to identify safety interventions for small residential builders [5]	2011	Small residential construction projects	On-site observation to explore safety problems and/or risky behaviours	Yes	Yes	No	DuPont STOP focusing "worker carelessness and unsafe behaviours… "observing workers and identifying their at-risk or ‘unsafe’ actions and taking immediate action to correct it"
Improving operational discipline to prevent loss of containment incidents [6]	2011	General	Industrial use case	Yes	Yes	No	"Focusing on improving operational discipline can help reduce both the number and severity of loss of containment incidents"
Stepping Out of the	2012	O&G	Upstream & Gas	Yes	Yes	No	"if we simply focus on the bottom

Triangle and into the Field [7]		operations	incidents data				of the triangle, we will continue to miss the potential causes and solutions to severe events"
Cultural Drift and the Occlusion of Electrical Safety [8]	2014	General	Electrical-injury-related	Yes	Yes	No	"the severity of electrical injury in terms of emotional and physical damage, as well as medical cost to employers, is significantly higher"
Exploring the relationship between major hazard, fatal and non-fatal accidents through outcomes and causes [9]	2015	General	Netherlands accidents data	Yes	Yes	No	" the hazard is a link between occupational and process safety and between fatal and nonfatal occupational accidents"
Assessing and Preventing Serious Incidents with Behavioral Science: Enhancing Heinrich's Triangle for the 21st Century [10]	2017	General	USA accidents data	Yes	Yes	No	"The behavior-based safety ... includes identifying critical behaviors and hazards, incorporating judicious leadership choices, and developing action plans addressing engineering and systems issues"
Enhancing Safety Culture in Cement Industry Using Behavior-Based Safety Technique [2]	2018	Cement industry	Implementation reports of behavior-based safety	Yes	Yes	No	"Behavior-Based Safety technique was used to achieve higher standard of safety along with recommendation for control measures"
BIM-enabled health & safety analysis of cross laminated timber onsite assembly process [26]	2018	Cross Laminated Timber construction	Construction safety simulation using BIM	No	No	No (BIM simulation)	The work "utilizes BIM with discrete event simulation to develop a decision support model that assist designers and project management teams to evaluate the potential H&S hazards"
Adding the Predictive P into Personal Protective Equipment [11]	2018	General	Laboratory simulations and tests	Yes	Yes	Yes (EEG, and biometrics (heart rate, stress response, temperature, body position and location) measured by sensors in PPE	"The PPPE Initiative offers a method that would provide a means to measure leading indicators and also add another base level to the Henrich triangle known as predictive opportunities. Being a real time predictive monitoring and correcting system there is a chance on missing out potentially on: Predictive Opportunities: every second (86 400/day), every minute (1 440/day) in an 8-hour shift. In a 12-hour shift."
Prediction accident triangle in maintenance of underground mine facilities using Poisson distribution analysis [22]	2018	Maintenance of underground mine facilities	Indonesia accidents data	Yes	No	No	"One of the fundamental underlying principles of accident triangle is that major accident cannot occur without a foundation of less severe incidents"
Workplace accidents and self-organized criticality [27]	2018	General	USA accidents data	Yes	No	No	"The results herein give scientific support to Heinrich's postulate of a common origin for workplace accidents since the accident statistics"
Development of a tool to monitor static balance of construction workers for proactive fall safety management [20]	2018	Construction industry	Laboratory simulations and tests	No	No	Yes (Wearable Inertial Measurement Unit, WIMU and a Smartphone)	"The developed tool will have a great potential to enhance proactive identification of the workers with a higher risk of falls so that proper balance training can be provided"
Sand casting safety assessment for foundry enterprises: fault tree analysis, Heinrich accident triangle, HAZOP–LOPA, bow tie model [28]	2018	Sand casting operations	Chinese accidents data	Yes	No	No	"The paper proposed a composite sand-casting safety assessment approach based on fault tree analysis, Heinrich accident triangle, HAZOP –LOPA and bow tie model components"
Physical exertion modeling for construction tasks	2020	Construction industry	Laboratory simulations and	No	No	Yes (on-body vast sensors,	"This preliminary study explored the use of multiple physiological

using combined cardiorespiratory and thermoregulatory measures [23]			tests			with ECG, respiration and temperature sensors)	measures (cardiorespiratory and thermoregulatory) to model physical exertion during manual material handling tasks"
A critical review of vision-based occupational health and safety monitoring of construction site workers [19]	2020	Construction industry	Literature review	No	No	Yes (Vision-based)	"the applications of computer vision technology in the health and safety supervision of workers on the construction site were divided into: (1) workers themselves (2) workers interaction with the site"
Computer vision technologies for safety science and management in construction: A critical review and future research directions [29]	2021	Construction industry	Literature review	No	No	Yes (Vision-based)	"It categorizes computer vision studies in the construction industry based on a three-level development framework: 1 Detection, recognition, and tracking, 2 Assessment, and 3 Prediction"
Deep Learning-Based Applications for Safety Management in the AEC Industry: A Review [30]	2021	Construction industry	Literature review	No	No	Yes (Deep Learning-Based data processing)	"Review of all individual articles that investigate the effectiveness of using DL in the SHM (structural health monitoring) and JSM (jobsite safety management) industry to date"
The application of technologies in enhancing safety and health management (SHM) in the construction industry in Sarawak [31]	2022	Construction industry	Literature review and survey	No	No	Yes (multiple technologies: Camera, Mobiles, UAV, BIM, Wearables, RFID, Qrcodes, LiDAR, AI, VR, AR, etc.)	"The results revealed that there are only 2 technologies (camera network system and mobile devices on site) are being categorized as very important technologies whereas another 2 technologies (UAV and BIM) are being categorized as important technologies"
Organizational factors and specific risks on construction sites [32]	2022	Construction industry	Empirical test of two theoretical models	No	No	No	"The results can help construction firms obtain earlier information about which organizational elements can affect future safety conditions on site, improve those elements for preventing risks, and consequently, avoid accidents before they occur"
Improving Health and Safety (H&S) on South African Construction Projects with Industry 4.0 [18]	2022	Construction industry	Literature review and survey	No	No	Yes (multiple technologies: UAV, BIM, Robots and Sensors)	"monitoring H&S hazards onsite is difficult; design-originated and onsite hazards are often experienced onsite; fatalities, injuries, illnesses, and worker fatigue often occur; drone technology has the potential to improve H&S monitoring in construction; building information modelling (BIM) has the potential to reduce design-originated hazards, and virtual reality (VR) has the potential to improve H&S training"
Development of an integrated fatigue measurement system for construction workers: a feasibility study [21]	2022	Construction industry	Use and feedback from construction workers in the field	No	No	Yes (Smartwatches)	"The developed system shows potential for monitoring fatigue based on the real-time collection of relevant data. By expanding this integrated system through further research and onsite application, the health and safety of construction workers can be improved"

4. Accident triangle approach empowered by EPM

Based on the literature review, first, it was possible to overview the Accident Triangle theory and opt-in to follow the ConocoPhillips Marine concept. As presented in Figure 2, the top triangle levels regard the simple record of injuries, loss of workdays, and fatalities, and that data can be collected directly from companies' systems and databases; however, the near misses and at-risk behaviours levels demand humans auto-recordable methods and field inspections observations, prone to be empowered by EPM. The central concept is to use EPM to acquire data and, simultaneously, allow the development of features to act to prevent the recurrence of these same deviations. Still, the EPM tools and techniques meant to collect data on-site should have the same principle of human observation, which means each event of unhealthy or unsafe behaviours detected is accounted as one deviation.

ConocoPhillips Marine (2003) preconised that the identification of at-risk behaviours and their correlation with accidents could support organisations to reduce H&S occurrences [6]. The DuPont STOP programme is established over behaviour-based safety methodology focusing on identifying and correcting workforce unhealthy and unsafe behaviours [5]. The Near Misses are known as "almost accidents", "near hit", or "close calls", which means a slight moment of failure that almost incur an accident [3]. Mostly near misses are correlated to at-risk behaviours. The at-risk behaviours are strictly connected to the on-site environment (spaces, paths, underground, work at height, etc.), and workers' behaviours concern that environment and the safety control measurements. Also, unhealthy and unsafe human behaviours include bypassing safety barriers, dealing improperly with machinery, or eliminating mandatory safety routines to accelerate production [2].

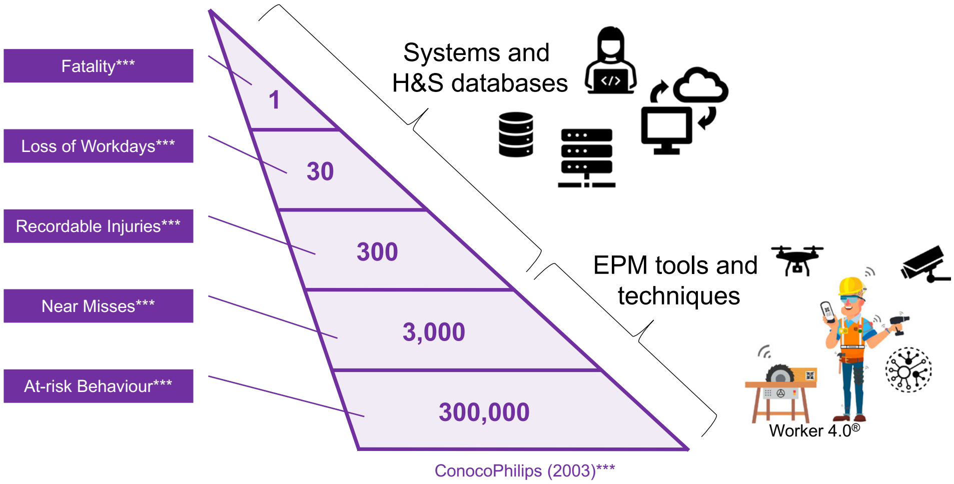

Fig. 2. Using Digital Systems to fulfil the Accident Triangle.

Specific features of the workforce, the machines, and the environment should be monitored to classify some behaviours as unhealthy or unsafe. Based on the literature review and authors' experience with EPM and H&S, it is possible to infer the features more prone to be monitored by some specific electronic device targeting to detect an at-risk behaviour or near misses. Figure 3 summarises the EPM tools and techniques best fitted to acquire H&S on-site data. Aiming to fill in the triangle base and identify at-risk behaviours, more attention is meant to monitor the workforce interaction with the on-site ambience. Taking it into account, it is necessary to map the work environment, covering continually: the pathways, working at height and underground, and overseeing the machines and equipment traffic and their interaction with the workers. The vision-based technologies are prone to map the work environment continually. In a more static on-site ambience, the geolocation of the workstations and elements can be made by the BIM models correlated with the workforce's live status.

Concerning the workforce and their interaction with the on-site constraints to monitor unsafe behaviours, it is primary to acquire the precise location (less than a meter in the three-axis) to evaluate the bypass of safety barriers and the proximity with machines and equipment (e.g. positioning below a load movement), besides the vision-based techniques (e.g., 360 cameras, Drones, CCTV, 3D scan), sensor-based devices can gauge three-axis position to monitor the location. Most precise technologies using UWB (ultra-wideband) at IMUs (inertial measurement units) or other devices can deliver high accuracy (centimetres). At the same time, Wearables, Smartphones, RFID, and GPS, also can gauge real-time location. Also, image analyses or sensor monitoring can assess the proper use of PPEs (personal protection equipment). Finally, based on body motions, the type of tools the workers are manipulating can be evaluated, and the correct task process can be overseeded.

Similar tools and techniques are meant to be applied to evaluate Near Misses occurrences. However, the focus is on monitoring the workforce conditions facing on-site constraints, such as a worker carrying materials slippering on a wet floor and almost falling. The body motion and acceleration can be measured by wearable devices (e.g., smartwatches, smart bands, IMUs), and the near misses' situations can be inferred. Also, the recognition of near misses' occurrences can be classified over images. Finally, EEG (electroencephalogram), ECG (electrocardiogram), and PPG (photoplethysmography) sensors technologies can monitor brain activity and heart rate to connect to other features to assess instants of almost accidents.

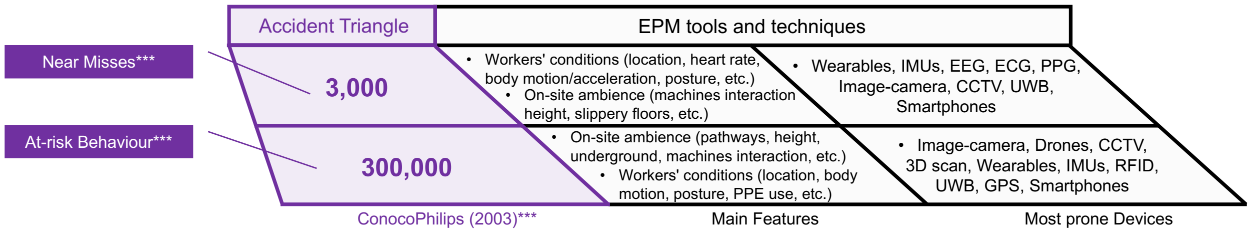

Fig. 3. EPM to acquire data on-site.

Equipment monitoring using RTLS (Real-Time Locating System) such as RFID, UWB and GPS for safety alerts based on a safety zone perimeter can mitigate accidents between workers and equipment [33]. Regarding safety and health, it is crucial to know the location of employees to avoid access to restricted and risky areas and to manage emergency evacuation events [33]–[35]. In addition, workers are in constant movement, which, together with the movement of equipment, leads to multiple risk zones. In this sense, several studies aim to monitor equipment trajectory, mainly those for handling loads and workers, to analyse this intersection between the risk zones arising from the equipment and the occupation of workers [36], [37]. Safety risk events recorded in virtual reality enable assessments of these events from different viewing angles, expanding the ability to assess the risks of tasks, as well as allowing the use of these "real scenes" in worker training [36], [38]. Another example is using RFID readers with wireless communication strategically implemented in the access to the floors of vertical building construction, providing the opportunity to read passive RFID tags contained in the helmets of workers, materials, and transport elevators [39]. Studies to automatically control the use of Personal Protective Equipment, PPE, by workers in construction are relevant to safety [40]. Through reader gates, the passive RFIDs contained in the equipment to be monitored, such as helmets and boots, are read where a graphical interface panel indicates whether the worker is wearing the appropriate PPE to allow entry to a given work area. work. The automated methodology controls the maintenance management of PPE, holds the use, and visually educationally informs workers about the individual safety requirements of each service front [40].

Using smartphones, it was developed and tested systematically with a focus on work safety to register unsafe situations [41]. Specific software based on a filming plan allows the delimitation of risk zones, which, upon identifying a worker's occupation in this space, begins the collection of photos to record the dangerous situation [41]. Using drones to inspect on-site operations can avoid human exposure to the risk of accidents. An experiment with drones in two buildings to evaluate safety items made it possible to assess that out of a preliminary list of things to be checked, only 8% and 27% of each inspected work could not be visualised by drones [42]. A method through movement capture by the VICON 3D system aims to identify unsafe behaviour, evaluating the body movement of workers [43]. Simulations of real risk situations determined an accuracy of 88% in identifying workers' positioning [43]. The Kinect motion capture system also focuses on identifying unsafe behaviours on the part of workers and can obtain an accuracy of 81.44 %, according to studies [44]. The Kinect system calculates three positions of the body's joints with one or two depth sensors and is primarily suitable for indoor use as it presents sunlight interference [44].

5. Conclusions

Based on the literature review, first, it was possible to overview the Accident Triangle theory and opt-in to follow the ConocoPhillips Marine concept. As presented in Figure 2, the top triangle levels regard the simple record of injuries, loss of workdays, and fatalities, and that data can be collected directly from companies' systems and databases; however, the near misses and at-risk behaviours levels demand humans auto-recordable methods and field inspections observations, prone to be empowered by EPM.

The central concept is to use EPM to acquire data and, simultaneously, allow the development of features to act to prevent the recurrence of these same deviations. Still, the EPM tools and techniques meant to collect data on-site should have the same principle of human observation, which means each event of unhealthy or unsafe behaviours detected is accounted as one deviation. In this sense, the amount of At-risk Behaviour (300,000) and Near Misses (3,000) can be electronically summarised. This can improve data collection and accuracy. Most relevant data from the quantification can be connected, for example, to information regarding the exact location of the event and some physical features of the workforce. That can enrich the H&S analysis empowering improvement actions to reduce top accident levels such as recordable injuries, loss of workdays and fatalities. Collecting more information features concerning the site and human conditions can bring more awareness of the characteristics of the accidents' risks.

Finally, further research directions should target deploying software and hardware solutions to collect and classify H&S occurrences over the triangle accidents spectrum. It is relevant to investigate the cost-benefit of each solution. For example, wearable solutions will demand more device units than filming approaches; however, wearables can collect more personal features information. Also, algorithms deployment must avoid recrimination bias and must be GDPR compliant.

Acknowledgements

Base Funding of the CONSTRUCT—Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC): UIDB/04708/2020.

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