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Algorithm for quantitative analysis of close call events and personalized feedback in construction safety

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ABSTRACT

In many of the developed countries about 15–25% of all fatal construction workplace accidents relate to a too close proximity of pedestrian workers to construction equipment or hazardous materials. Extracting knowledge from data on near hits (aka. close calls) might warrant better understanding on the root causes that lead to such incidents and eliminate them early in the risk mitigation process. While a close call is a subtle event where workers are in close proximity to a hazard, its frequency depends–among other factors–on poor site layout, a worker's willingness to take risks, limited safety education, and pure coincidence. For these reasons, pioneering organizations have recognized the potential of gathering and analyzing leading indicator data on close calls. However, mostly manual approaches are infrequently performed, subjective due to situational assessment, imprecise in level of detail, and importantly, reactive or inconsistent in effective or timely follow-ups by management. While existing predictive analytics research targets change at strategic levels in the hierarchy of organizations, personalized feedback to strengthen an individual worker's hazard recognition and avoidance skill set is yet missing. This study tackles the bottom of Heinrich's safety pyramid by providing an in-depth quantitative analysis of close calls. Modern positioning technology records trajectory data, whereas computational algorithms automatically generate previously unavailable details to close call events. The derived information is embedded in simplified geometric information models that users on a construction site can retrieve, easily understand, and adapt in existing preventative hazard recognition and control processes. Results from scientific and field experiments demonstrate that the developed system works successfully under the constraints of currently available positioning technology.

1. Introduction

Better understanding the root causes that lead to an accident is important to protect construction personnel from similar mishaps in the future. Unfortunately, most of the current accident investigation methods focus on supplying valuable information after the fact, once a person has been injured or killed. Accident investigation reports, as explained in [1], are often (purposely) brief and only a few pages long [2]. Fatality assessment and control evaluation (FACE) reports are one example of a practiced method of an investigation [3]. They typically contain factual information, for example: a description of what happened, the actual results of the event, the persons involved, the equipment or material involved, the activities preceding and during the event, the date, time and place of the event, any emergency actions taken, some pictures of the event situation, and the immediate remedial actions taken. They may also include additional information: risk classification, determination of potential consequences, cause analysis, direct causes, basic causes, management system factors, and importantly, remedial actions which include the assignment of responsibilities for adequate follow-ups.

The professional who conducts the written investigation usually enters the reporting process in three ways: (a) designs the report forms and keeps them current for the organization, (b) analyzes the data for trends and implications, and (c) measures of the quality of the report (typically with a manual scoring sheet to enable continuous improvement of the reporting and follow-up processes). Conducted in such a manner, the professional can promote thorough investigations and quality reports which enable full control by management later.

While the contributions of this study do not substitute any of the existing investigation approaches that are in place, it tackles the topic more pro-actively. In the ideal case, the proposed method will support existing processes with new information to close calls that has not been

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available before. As [4] has previously outlined, construction safety has to happen at the right-time. Thanks to emerging technology, detailed information on close calls can be recorded and analyzed near real-time. The generated information then can be used for predictive analysis and even immediate mitigation.

This paper first reviews the existing research body on close calls in construction. It explains the proposed algorithm for quantitative analysis of close call events in construction safety. Scientific verification through simulation and validation using real field experiments follow. The results demonstrate the functionality of the developed algorithm and software user interfaces. A discussion and an outlook for future research conclude the paper.

2. Background

A vast body of knowledge exists on close calls within the construction industry and outside of it. This already existing evidence in the published literature is not repeated, instead this review focuses on a comparison of manual and automated data collection methods that are suitable for close call measurements.

2.1. Close calls

Several researches in construction describe a close call as an event that almost resulted in an accident. Too close proximity between a pedestrian worker and a known hazard is one of such events. However, there is no research that provides a scientific definition of the exact characteristics of a close call [5]. According to [6], a close call can be part of a sequence of events that result in anywhere from minor to major accidents. Therefore, close calls should be recorded and followed-up with a close call reporting program. Such programs, in an ideal case, measure safety performance and reduce the probability of accidents. However, the success of close call reporting crucially depends on the participation of persons to report near-misses, which can lead to inconsistent or false results [7]. Due to the often complex contractual organization of projects, construction companies often face difficulties in implementing effective close call reporting and analysis programs.

2.2. History on reporting and analyzing close calls

Heinrich's safety pyramid (aka. the accident triangle) provides an early example (from the 1930s) for separating close calls (called therein *near misses*) from actual accidents. Interestingly to note, the original data to generate the safety pyramid came from a manual analysis of 75,000 injury and illness reports [8]. Visualization of the difference between accidents (e.g., fatalities or injuries) and incidents (e.g. at-risk behavior and close calls) in a graph strengthened the argument made by Heinrich for the higher occurrence of close calls relative to the number of fatal accidents or injuries.

Fast forward and decades later, the results from a survey by [9] suggest that employees from companies with high health and safety ratings perceive their own safety, zero harm, and continuous improvement in health and safety as very important. In the same study, construction hazard identification, including close call reporting, ranked 10th out of 38 topics which shows the general acceptance of such a system. [10,11] then discussed the strengths and weaknesses for a qualitative (matrix) and quantitative (index) near-miss management system. They focused on how close call reporting and filtering could be implemented to minimize both missed near-miss reports and unnecessary reports. Their design consists of four separate phases: Event identification and reporting, event assessment, prevention measure application and follow-up actions. Among other noteworthy research that followed, [12], for example, established a database consisting of feature vectors (values that represent information on an incident) for close calls, filled with data from common written incident-reports, viewing close calls as events which lead to an accident.

Today, under often self-motivated initiatives for establishing leading indicators for safety, pioneering owner and contractor organizations highly encourage the (voluntary) reporting and analysis of close calls by everyone involved in a project. Databases with restricted access exist where close calls are entered manually or via guided user interfaces (GUI) on mobile devices. Such recent examples from modern construction sites demonstrate the advancements that have been made for reporting and investigating incidents. In brief, the reasons for this change can be summarized twofold: (a) driving organizational change in safety culture by rethinking existing and establishing new processes and (b) taking advantage of sophisticated technologies to record and analyze real data. Our work therefore focuses on low-severity, high frequency injuries. It does not necessarily translate to high-impact, low-frequency events.

2.3. Related examples using technology

The most closely related previous study was performed by [13]. It describes a method called Proximity Hazard Indicator (PHI). PHI successfully detects spatial-temporal (proximity) conflicts between workers and construction equipment using real-time location sensing (RTLS). Other researchers, for example [14] used a real-time location and a virtual construction simulation system to test the performance on safety behavior. [15,16] also demonstrated the application of virtual reality (VR) to detect the proximity of pedestrian workers to heavy construction equipment. Several more research groups identified that fusing real data (construction site layout and building geometry from Building Information Modeling (BIM) and trajectories of workers and equipment from RTLS) would make their VR-scenarios more realistic.

[17] developed a tracking system of near-miss accidents on construction sites to aid in the research of accident prevention on construction sites. The proposed system in the study used Zigbee radio frequency identification (RFID) to identify resources and store specific information, e.g., the last time ladders were inspected, location and environmental information such as brightness, noise, or weather. Though this method allows the detection of more subtle and complex accident precursors, it focuses little on human-machine interaction.

[18] first integrated Ultra-wideband (UWB), a wireless location tracking technology, in the practical training workflow of union ironworkers. They collected data for post-reasoning lagging safety and productivity indicators. One suggestion of their work is to improve the workers' education and training performance by personalizing feedback. The authors of the study envision using near real-time analysis of actual training data. They also conclude that any technology assisting in the data collection tasks must be wisely selected. UWB, for example, requires a rather large investment and set-up of sensing infrastructure. UWB, though preferred over other remote sensing approaches for location tracking, might still be limited by its signal strength (limiting its range in occluded/indoor spaces).

[19] introduced CHASTE (Construction Hazard Assessment with Spatial and Temporal Exposure) which assigns estimated risk levels to specific tasks to compute risk-levels of scenarios. It requires employees to manually evaluate the risk level of specific construction tasks, leading to potential errors or inconsistency. The dynamic construction environment provides a further challenge. New hazards might appear if the construction plans change. To resolve this issue, [20–22] and [23] presented examples for utilizing construction safety knowledge to improve Job Hazard Analysis (JHA).

[24,25] pursued an alternative method of detecting hazards for outdoor work environments. In their respective works, Global Navigation Satellite System (GNSS) data loggers record the resources' location (work crews and equipment, respectively) and visualized the associated close call risks using heatmaps. Safe work station planning based on real-time resource location tracking and site layout geometry data becomes possible. Both studies refer to [26] who performed an in-depth

evaluation on commercially-available GNSS data loggers.

2.4. Remaining problems

Practiced close call reporting and analysis rely on manual data gathering efforts. Using only manual reports as a source of information has several disadvantages. Some of the issues presented in the following help explain the problem:

1. *Size of the problem*: The number of reported close calls is probably smaller than the true number (i.e., personnel may not report close calls fearing retaliation or a drop in productivity).
2. *Standardization*: Accident investigation reports vary by country and are kept general to inform the entire organization and sometimes even the industry. An open-access benchmark which is based on high quality (anonymized), near real-time data and available to every construction site or personnel is missing presently.
3. *Data availability and processing*: Processes depending on manual data lack the necessary level of detail (i.e., unlike the airline industry for the past decades or unmanned autonomous vehicles just recently, trajectories of construction equipment are often neither recorded nor analyzed).
4. *Collaborative planning*: Though BIM offers the construction industry a method to plan, build, and operate infrastructure or buildings, standardized tools for construction safety (and health), site layout or work station planning are missing (i.e., most projects perform modeling efforts with BIM manually at low or moderate detail and only on an as-needed basis).
5. *Safety culture change for labor and management*: Since close call reports may include sensitive information to an incident [27], person(s) reporting them might impact labor-management (i.e., workforce vs. supervisor, management) relations and organizational fairness.

3. Existing and proposed close call reporting, analysis and personalized feedback process

Using manual approaches only to gather information about close calls is not practicable as these can be subtle and frequent events. The current assessment might also vary depending on the observer. Since human-machine interactions are one of the more serious problems in the construction industry [28], this study specifically focuses on the continuous position logging of the involved resources in a close call for a more detailed investigating of, for example, human-equipment and human-hazardous material incidents. It proposes change to the traditional close call reporting and follow-up process (see Fig. 1).

Close calls, as introduced earlier, are typically reported when a human witnesses or participates in an event which compromises or threatens to compromise the health or safety of a person or the environment. If necessary, a person may conduct first efforts to prevent an accident or a further incident. The person notifies their supervisor or safety coordinator on site directly or using a close call reporting application on a mobile device (i.e., if permitted on site: smartphones or tablets). Some organizations offer close-call reporting through a neutral third party service to remove sensitive information. At least some general information about the event is shared once the case reaches the corresponding safety professional within an organization (a knowledgeable person). Afterwards, a problem-solving peer-review team consisting of workforce (who are trained in operational skills), safety professionals (who are trained in root-cause analysis), and management (who are trained in continuous-process improvement) will heighten the awareness for the seriousness of the case within their own organization. Various means exist to learn more about the risks and how to mitigate them, for example, calling for dedicated close call review meetings, department safety meetings, one-on-ones with workforce or supervisors, or involving a neutral third party. The team, while protecting employees from blame [29], finally recommends corrective actions. At this point, well-working close call reporting processes in practice (should) ensure timely feedback to the person(s) who reported the incident in the first place.

The proposed close call reporting and analysis, and personalized feedback process takes advantage of remote sensing and information modeling to automatically record the circumstances that lead to close calls. By attaching a RTLS device on every *resource* (pedestrian workers, equipment, and material that was a-priori declared hazardous), their then available trajectory data will be analyzed in BIM to locate close calls (step 1 in Fig. 2) and interfere further valuable information that led to the close call (step 2). Once analyzed, the data generated therefore provides an elevated level of detail of information that has not been available so far (step 3). This way, measurement and evaluation of close calls during the actual construction phase becomes an active leading indicator which can result in a quicker (perhaps immediate) improvement of the safety performance [30]. The statistical analysis currently ends on assessing the close calls of a particular work environment (simulated or actual construction site), but a future research vision is to extend the close call data analysis to the levels of an organization or industry (step 4). This would lead to benchmarking close call metrics for many construction sites or an entire industry. Once such data becomes available, peer-to-peer pressure outperforming competitors may lead to further reduction of the number of close calls, ultimately leading to higher safety performance of the industry. A corresponding workflow for fusing all data types and data post processing generates descriptive analytics on each close call event.

The *proposed methods* used in the new workflow are explained next in more detail. It is followed by a detailed investigation into the theoretical verification of the proposed methods using first a *simulated data set in a fictional construction setting* and thereafter (after ensuring the methods work successfully) several *realistic data sets for experimental validation on live construction sites*. As a note, the initial selection of simulated over realistic data permitted the verification of the proposed method under ideal (repeatable) conditions. In the simulated setting, a fictional building information model and trajectory information was assumed for the artificial pedestrian workers' and equipment travel paths.

4. Definitions and methods

4.1. Construction resource data

Construction resources are physical objects and spaces that are required to finish a construction process. In this research, the term

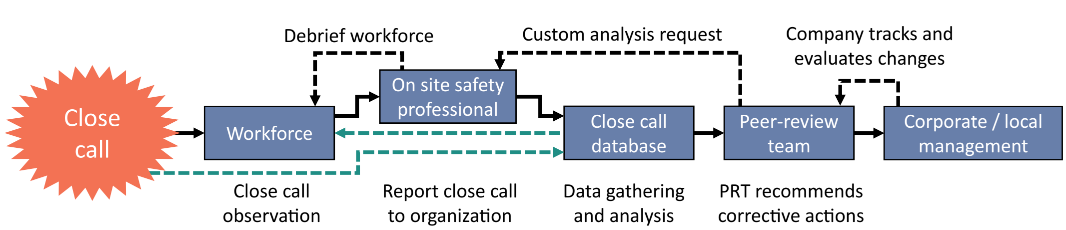


Fig. 1. Close call reporting, analysis, and personalized feedback process.

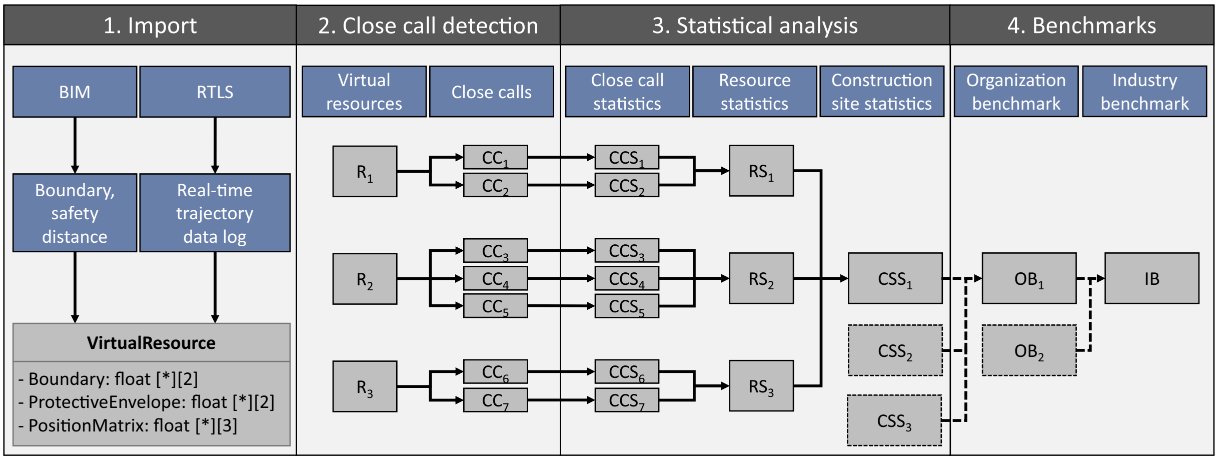


Fig. 2. Proposed workflow for data processing algorithm (dashed lines are part of a future predictive close call data benchmarking).

construction resource refers to (a) the pedestrian workforce, (b) construction equipment, and (c) objects or structures of temporal or final state. The number of any of these resources in the scene under investigation can be one or many. They can also be static or dynamic in nature. Pedestrian workers as well as equipment are moving frequently, while temporary objects, such as scaffolds or hazardous materials like gas bottles, are mostly static and stay in one position. Other examples of static or as-built structures which can be hazardous are unprotected edges in elevator shafts or leading edges in high-rises.

As needed later in the *experimental field validation*, actual geometric data of the as-built conditions of the work environment were recorded using terrestrial laser scanners and unmanned aerial vehicles (UAV) [32]. The point cloud information was georeferenced and imported as simplified boundary objects in building information models [21]. The resource trajectory data in the outdoor work environments was recorded using remote sensing technology.

Construction resource data is defined as a term to summarize *boundary data* from building information modeling and *trajectory data* from trajectory logging files. Microsoft EXCEL-files served as the initial medium to transfer this information, since construction personnel is familiar with this software package. The data for each resource is contained in a separate file.

Ultra-wideband (UWB) [31] and Global Navigation Satellite System (GNSS) [25] offered two suitable options to record the trajectory data in real-time. It was important to consider that deployment of any of RTLS in the field highly depends on the work environment that is under proposed investigation. Business and technological factors, such as return on investment (ROI), signal propagation, size of measurement errors, hardware form factors, power consumption, ease of installation and maintenance, and many more factors must be and were considered as well [31]. However, they are not the main focus of this study.

4.2. Protective envelopes and boundary data representing resources

To automatically detect and analyze close call events between *resources*, additional descriptive information for each individual resource involved in a *close call event* is necessary. For example, its precise position and boundary information define a *protective envelope*. For the reason of simplicity, all data presented in this study is kept to two-dimensions (2D, plan view). As a result, the protective envelopes come in shapes of circles or polygons (Fig. 3). The number of the involved resources as well their parameters, i.e. the size of the protective envelope called the *safety distance*, are set in advance based on the previous research findings by [31]. Trajectory information and building information model complement this chosen approach.

Boundary data represents a simplified version of the true shape of a resource in 2D space, typically derived from a building information model. While a straight wall object, for example, is represented as a rectangle of the same length and width in 2D, workforce and equipment are more simplified. The width of the shoulder of an adult is approximately 0.6 m [31]. The value is rounded up to 1 m, which leads to representing the shape of a pedestrian worker as a circle. Much slower speeds than equipment, for example, and rapid changes in direction suit this representation of a worker well. In contrast, in most application scenarios the simplified shape of a piece of equipment is a bounding box. A bounding box [33] encompasses all of its inner attachments. More complex objects are represented as a freeform using polygons. As explained earlier, boundary data contains a *safety distance* which extends the object boundary and creates a *protective envelope*.

4.3. Protective envelopes

Unless specified otherwise by a user upfront, every resource boundary is surrounded by its own protective envelope (see Fig. 3). While the protective envelope is used to detect too close proximity events between resources, the size of its safety distance and its shape are based on the following assumptions:

- *Pedestrian workforce*: A circle with a radius of 1.5 m is selected. This value is based on the average distance a human walks in 1 s, reacts, and comes to a complete stop [31].
- *Construction equipment*: A protective envelope for equipment must be wisely chosen considering several of its operating parameters. These include, but are not limited to: operating speed, angle of operation, and articulation. Even external factors, such as ground conditions, might be included into calculating a machine's breaking distance. While [34] has shown that multiple hazard zones for equipment are advisable to avoid a hit, generally a fixed value decided by a user is added around the equipment's known bounding box.
- *Temporary object*: The size of a protective envelope for temporary objects (e.g., safe storage of gas bottle) is determined according to rules and regulations set by governments and local authorities [35]. The resulting shape is a resized version of the existing boundary.
- *As-built structure*: Many structures, once they are erected and remain on site, might also require protection. Guardrails, for example, preventing workforce or equipment from falling to lower levels typically have protective envelopes associated to them. Their safe installation is also regulated by official regulations or company best practices [35].

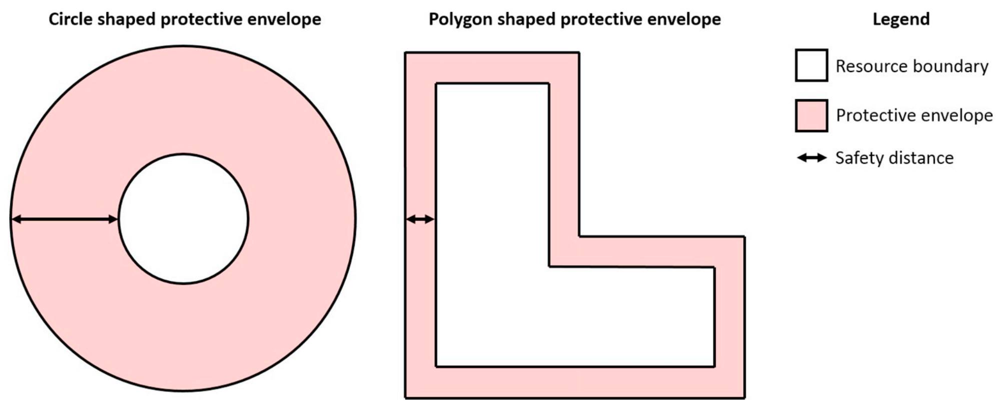


Fig. 3. Examples of two protective envelopes (plan view).

4.4. Trajectory data

Trajectory or position logging devices frequently store a resource's relative position and the current time, namely timestamps, inside a log-file [25,26]. The logging frequency and additional logging information like battery status both depend on the type of device. In this research, a frequency of one event per second (1 Hz) is assumed to simplify the following calculations. When a log file is imported, its information is trimmed to a uniform trajectory matrix,

$$T(R)=\begin{pmatrix} x_{start} & y_{start} & t_{start}\\ x_{start+1} & y_{start+1} & t_{start+1}\\ \vdots & \vdots & \vdots\\ x_{end-1} & y_{end-1} & t_{end-1}\\ x_{end} & y_{end} & t_{end}\end{pmatrix}, \tag{1}$$

where t_{start}, t_{end} refer to the first and last logged timestamps and x and y to the location of the device. This matrix is referred to as *trajectory data*. To help with further definitions, a function which returns the position of *resource R* for a specific *timestamp t* is defined as:

$$P(R,t)=\begin{cases}(x_t,y_t), & \text{if } t\in\{t_{start},t_{start+1},\dots,t_{end}\};\ x_t,\ y_t,\ t,\ t_{start},\ t_{end}\in T(R)\\ \text{undefined}, & \text{otherwise}\end{cases}. \tag{2}$$

4.5. Close call event

Currently, there exists no common definition for close calls [5,6]. A *close call*, as defined in this research, is a proximity event between one or several pedestrian workers and a hazard, leading to an endangerment of the workers. Also, a close call as it relates to a too close proximity event between two resources A and B is defined as an overlap of their protective envelopes at positions $P(A,t)$ and $P(B,t)$. When using trajectory data, there are two possible approaches towards categorizing close call events: (a) to categorize every proximity event as a separate close call or (b) to combine consecutive occurring proximity events to a single close call. The latter is the more sensible choice for this study.

4.6. Close call event buffering

For each proximity event, a proximity event buffer is created to store information for later processing. This information includes timestamp a [yy:dd:hh:mm:ss], position [m], velocity [m/s], and orientation [°]. Information on the distance [m] and facing direction [°] towards the other resource is also stored. In the example shown in Fig. 4, a piece of equipment has been traversing too close to a gas bottle.

4.7. Close call analysis

For two resources A and B, a close call detection algorithm (1) analyses their trajectories and (2) checks for each *timestamp* $t\in T(A)$, $T(B)$ if their protective envelopes overlap. If an overlap is found, a new close call gets created and a proximity event buffer is assigned to it. Every consecutive proximity creates a new event buffer which is added to the same close call. If no further overlap is detected, the close call is completed and the next proximity will create a new close call. Inside a completed close call, three event buffers will be marked for later processing:

- *Entry event*: First assigned event buffer.
- *Exit event*: Last assigned event buffer.
- *Closest event*: Event buffer where the distance between both resources is the smallest.

Additionally, the buffer events from the entry event to the closest distance event are summarized to the *entry path* and likewise the events from the closest distance event to the exit event are summarized to the *exit path*. As the trajectory data only consists of coordinates and timestamps, *velocity*, *facing direction*, *distance*, and *orientation* must be calculated separately.

4.8. Velocity

The close call algorithm has to compute a distinct velocity for each event buffer using only the resources' position data. As the trajectory logging frequency is assumed to be 1 Hz, the *velocity v* of a resource for *timestamp* t_i is numerically equal to the 2D-Euclidean distance between $P(A,t_{i-1})$ and $P(A,t_i)$,

$$v(A,t_i)=\begin{cases}0, & t_i=t_{\text{start}}\\ Euclid(P(A,t_{i-1}),P(A,\ t_i)), & t_{start}<t_i\le t_{end}\\ undefined, & otherwise\end{cases}. \tag{3}$$

4.9. Facing direction

The *direction d* towards which workers or vehicles are facing at a timestamp t_i is expressed as a normalized 2D-vector on the *x*-*y*-plane. Similar to the calculations for velocity, this vector can also be computed by using two position vectors. To be consistent, the direction will be calculated using $P(A,t_i)$ and $P(A,t_{i-1})$. Let *norm* be a function that returns the normalized version of a vector. Then the facing direction of a dynamic resource at *timestamp* t_i is defined as

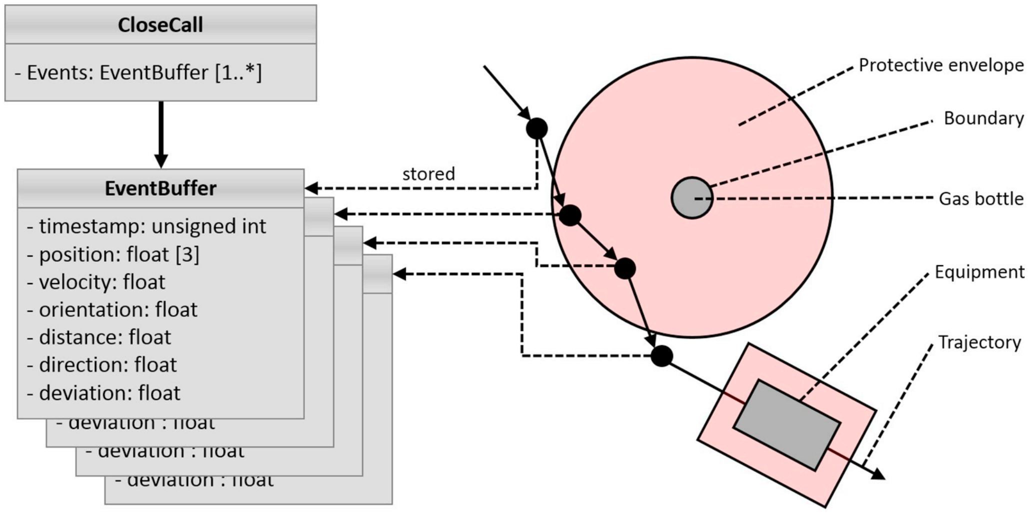


Fig. 4. EventBuffer class diagram.

$$d(A, t_i) = \begin{cases} \|P(A, t_i) - P(A, t_{i-1})\|, & t_{\text{start}} < t \le t_{\text{end}} \\ d(A, t_{start+1})), & t = t_{\text{start}} \\ undefined, & else \end{cases} \quad (4)$$

4.10. Distance

For a *timestamp* t_i the distance between two resources is defined as the closest distance between their boundaries (see Fig. 5). The vector spanning this distance is described as the *boundary distance vector.* As these calculations are based on simple geometric operations, they are not discussed in greater detail.

4.11. Orientation

The orientation value for an event buffer quantifies the position of the hazard relative to the facing direction of the resource. For this purpose, the resources' *facing direction vector* as well as the *boundary distance vector* will be utilized to compute an angle from 0° to 360°. The angle expresses by how many degrees a worker has to turn to the right to face the hazard directly (see Fig. 5).

5. Algorithm for automated close call data processing

5.1. Trajectory analysis

After storing all proximity event buffers, the close call analysis algorithm post-processes each close call to extract additional information that is later applied in data or statistical analysis:

- *Duration*: The duration of the close call event in seconds. Under the assumption, that the logging frequency equals 1 Hz, the number of event buffers is equal to the duration.
- *Entry duration*: The time interval between entry event and closest event (including the closest event).
- *Exit duration*: Duration between closest event and exit event (excluding the closest event)
- *Hazard weights*: Values which indicate the severity of a close call. This includes a separate weight for the orientation, velocity, distance, deviation, and duration.

Additionally, the *deviation* from an optimal direct path (see Fig. 6) is calculated. This direct path is assumed to be a path that leads directly from the entry position over the closest position to the exit position. It is calculated using the same number of steps as the real trajectory. The direct path positions are calculated by using a linear spacing algorithm between the entry position and closest position and between the closest

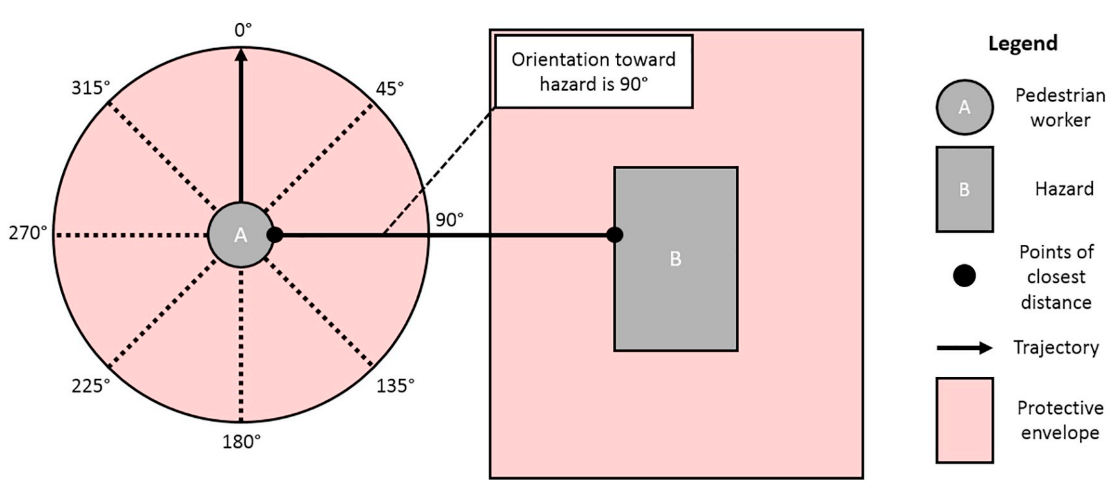


Fig. 5. Orientation.

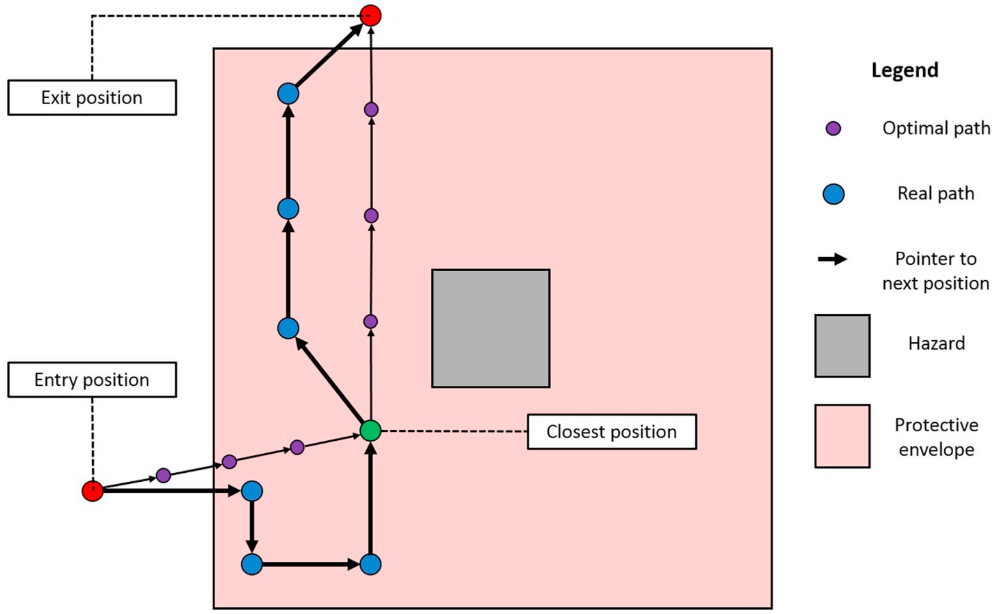


Fig. 6. Real path and direct path.

position and exit position, respectively. In the following, the ratio between length of real path and length of direct path is described as the deviation of the close call. This value indicates how much the worker or vehicle has strayed from the shortest optimal path during the close call event.

5.2. Radar plot

For each close call a radar plot is computed showing the weight values for velocity, duration, deviation, distance, and orientation. These weights, as explained next, visualize the severity of the different aspects that contributed to the close call event. The higher the value points in the radar plot, the more the aspect contributed to the endangerment of the resource. Velocity and length during the close call event (see Fig. 7) give a user a brief overview of a resource's safety performance. As suggested by [25] personalized feedback or other change (i.e., selection of other equipment or type, modification to site layout plans) can be issued and future performance monitored until the issue is resolved.

5.3. Hazard weights

The following introduces the formulas to calculate the weights (velocity, duration, deviation, distance, and orientation) (Fig. 8). While the original values for the weights can be based on historical data records, they may be adjusted over time or with the experience of close

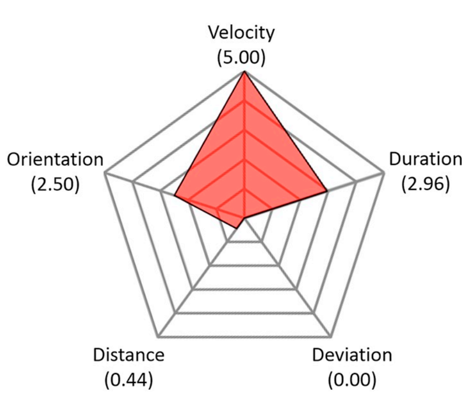


Fig. 7. Radar plot indicating factors leading to close calls.

calls. $Weight_{max}$ refers to a maximum weight.

5.4. Velocity weight

The velocity weight for a close call is calculated by using the velocity weight function (Fig. 8), with the average velocity of the close call as an input. In addition to W_{max} the course of this function depends on the parameter v_{max} which represents the maximum velocity a vehicle or pedestrian worker is allowed to have. [36] points out that there is no common definition for safe velocities to operate construction equipment. The speed limits on construction sites depend on numerous factors like the type of equipment or the ground surface conditions [37]. In the following sections, Vel_{max} is assumed to be 1 m/s (or 3.6 km/h).

It is assumed that a velocity of 0 is always the safest and therefore the weight is set to 0 for all parameters of W_{max} and v_{max}. Furthermore, moving with a velocity equal to the speed limit v_{max} is weighted with $\frac{W_{max}}{2}$. Since the risk of severe injuries increases exponentially, the weight function also increases exponentially as a function of velocity. Moving with a speed of 150% of the allowable speed limit (or even faster) is rated with W_{max}. In brief, these conditions lead to three specific points,

$$P_0 = (0, 0),$$
$$P_1 = \left(v_{\max}\ ,\ \frac{W_{\max}}{2}\right),$$
$$P_2 = (1.5\ v_{\max}\ , W_{\max})$$

on the velocity weight function which is of the form $f(x) = ax^2 + bx + c$ for $x \in [0, 1.5\ v_{max}]$. Inserting these points into this function creates a linear system of equations which can be written as a matrix equation

$$\begin{pmatrix} 1 & 0 & 0 \\ 1 & Vel_{\max} & Vel_{\max}^2 \\ 1 & (1.5\ Vel_{\max}) & (1.5\ Vel_{\max})^2 \end{pmatrix} \begin{pmatrix} c \\ b \\ a \end{pmatrix} = \begin{pmatrix} 0 \\ 0.5\ Weight_{\max} \\ Weight_{\max} \end{pmatrix} \tag{5}$$

and solved using the MATLAB matrix division operation.

5.5. Duration weight

The *duration weight Du* could be determined by using the duration of the close call alone. However, this might lead to a correlation between

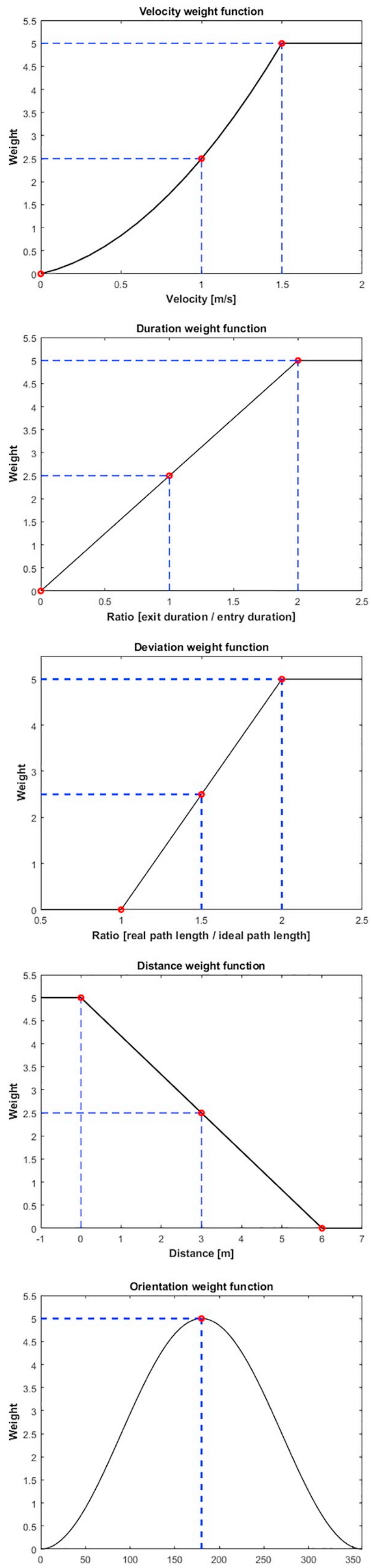


Fig. 8. Weight functions.

the size of a hazard envelope and the duration weight, as the risk of being longer inside a hazard increases with its size. Given that one of the research aims is to quantify aspects that help to analyze pedestrian workers' behavior, it is more sensible to examine the ratio between entry duration and exit duration. This value could indicate if the worker noticed the hazard or if the worker took action accordingly to leave the dangerous area soon after sensing it. Combined with other values, for example the exit velocity, one can draw more conclusions about the incident.

The weight function (Fig. 8) is composed of a linear function for ratios from 0 to $R_{\max}$and a constant function with a value of $W_{\max}$ for all ratios above $R_{\max}$. In the event of the entry duration being equal to the exit duration, the weight function returns half of $W_{\max}$.

Fig. 8 displays the duration weight function for $R_{\max} = 2$ so that it returns $W_{\max}$once the entry duration is at least half as long as the exit duration. Let the ratio for the duration weight function be defined as

$$R = \frac{exitDuration}{entryDuration} \tag{6}$$

Then the weight function for duration is defined as

$$Du(R) = \begin{cases} \dfrac{W_{\max}\ \ R}{R_{\max}}, & 0 \le R \le R_{\max} \\ W_{\max},\ R \ge R_{\max} & \end{cases} \tag{7}$$

5.6. Deviation weight

The ratio between the length of a real path and a shortest path (Fig. 8) is described as the *deviation De* of a close call event. Since the ideal path of a close call event leads directly through three positions of the real path (namely: entry, closest, and exist points), the real path length is always greater than or equal than the ideal path length. Therefore, the ratio between these values is 1, if both lengths are equal. In this case the worker walked the ideal path and the deviation weight is set to 0. A$Weight_{\max}$is assigned if the actual walked path is twice as long as the ideal path length. Let $Path_r$ be the real path length and $Path_s$ be the shortest path length. Then the deviation weight function can be defined as

$$De(Path_r, Path_s) = \begin{cases} \left(\left(\dfrac{Path_r}{Path_s} - 1\right) W_{\max};\ 1 \le \left(\dfrac{Path_r}{Path_s}\right) \le 2\right. \\ W_{\max};\ Path_r \ge 2Path_s \\ undefined;\ Path_r < Path_s \end{cases} \tag{8}$$

5.7. Distance weight

For the computation of the *distance weight Di* of a close call event, the resources' individual safe distances as well as the closest distances are required. There are three major cases to distinguish for the distance between two resources (see Fig. 9):

Case 1. The distance is equal to the sum of both safe distances or greater. This is assumed to be the best case and a weight of 0 is assigned.

Case 2. The distance is equal or smaller than 0 (which is the case if the resource models overlap). This would be the worst case and is evaluated with Weight$_{max}$.

Case 3. The distance lies between the two cases mentioned above. In this case the assigned weight is between 0 and W$_{max}$.

Let D_A and D_B be the assigned safe distances for resource A and resource B with $D_A \le D_B$, let d be the input distance and D_{sum} be the sum of D_A and D_B. The distance weight function is partially defined as a linear function for distances between 0 and D_{sum}, composed with a constant function of $W_{\max}$for all distances that are smaller than 0 and another constant function of 0 for all distances greater than D_{sum}. The slope of the linear function is equal to $-\frac{W_{\max}}{D_{sum}}$. In summary, the weight function can be written as

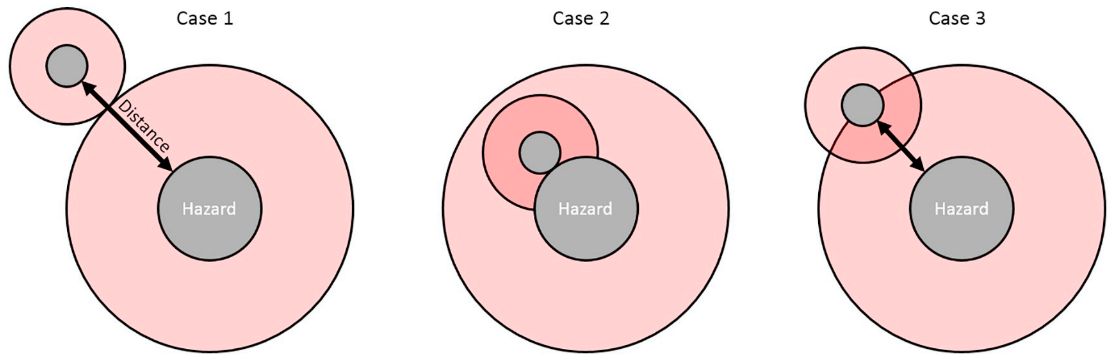


Fig. 9. Three cases for the distance between two resources.

$$Di(d, D_{sum}) = \begin{cases} W_{\max};\ d \le 0 \\ -\dfrac{W_{\max}}{D_{sum}} d + W_{\max};\ 0 < d < D_{sum} \\ 0;\ d \ge D_{sum} \end{cases} \tag{9}$$

As an example, Fig. 8 displays the distance weight function for safe distances of $D_A = 1$ m and $D_B = 5$ m, where the value for d ranges from -1 to 7 m.

5.8. Orientation weight

Computed orientations, as shown earlier, range from 0 to 360°. Using the average orientation over all buffer events is not feasible as potential left-side and right-side orientations would cancel each other out (average of 90° and 270° is 180°). Therefore, the *orientation weight* W_{orient} depends on three values:

- O_{entry}: Orientation at entry event buffer.
- O_{exit}: Orientation at exit event buffer.
- $O_{closest}$: Orientation at closest position event buffer.

Separate orientation weight values for each of these three values are calculated. Evaluating the orientation is then a matter of perspective. Weighting hazards appearing from the front (around 0°) can help to find inattentive workers, while hazard behind a worker can pose a dangerous threat even to very cautious workers. Therefore, unless other methods are used to track whether a human has recognized a hazard or not, the evaluation of orientation may depend on a users' personal preference. In the presented scenario, hazards appearing from behind will be evaluated as more dangerous.

The resulting function is based on a sine function, which is translated upwards on the y-axis by 1, then translated vertically to the left on the x-axis by $\frac{3\pi}{2}$, then stretched horizontally by a factor of $\frac{180}{\pi}$ and then stretched vertically by a factor of $\frac{Weight_{max}}{2}$. To make sure that the absolute orientation weight is not greater than $Weight_{\max}$ the weights for closest orientation, entry orientation and exit orientation are averaged. If the function for a single orientation weight is

$$w(o) = \left(\sin\left(\frac{o\ \pi}{180} + \frac{3\pi}{4}\right) + 1\right)\frac{W_{\max}}{2}, \tag{10}$$

then the overall weight is averaged as

$$W_{orient}(O_{entry}, O_{exit}, O_{closest}) = \frac{w(O_{closest}) + w(O_{entry}) + w(O_{exit})}{3}. \tag{11}$$

There is also the possibility to rate both hazards from behind and from the front with high weights. However, this would cause the values to lose their informative value since the weight would be the same for incautious workers which do not recognize a hazard as well as for workers which could not see the hazard from behind. In brief, a user may configure the tool based on their personal preferences.

5.9. Visualization

The computational analysis of the gathered and fused data starts with the examination of all single event buffers. From there, it abstracts and combines these information into more general statistics (Fig. 2). As the level of detail drops with this generalization, the GUI is split into three layers whereof each is displayed on a separate window:

- *GUI level 1 (construction site level)*: This window displays: the construction site layout on a map, general construction site statistics and an overview to all construction resources, separated by type. A heatmap, if selected by the user, shows the location of close calls.
- *GUI level 2 (resource level)*: This window focuses on one specific resource, selected by the user on level 1. Subsequently, the total number of level 2 windows is equal to the number of resources that exist on the entire construction site. While the GUI on level2 is similar to level 1, a map displays only the resource's trajectory, its boundary and protective envelope, as well as its own close call events. Additional results (e.g., detailed analysis including statistics and radar plot) on all close call events the resource was involved in are also included in this window.
- *GUI level 3 (close call event level)*: This window displays the finest level of detail for an individual close call event.

5.10. Explanation for GUI level 1

The GUI level 1 window (see Fig. 10) contains the general close call performance information for a construction site. It covers statistical data as well as a brief overview on all resources being present at the construction site and involved in close calls. This GUI might be used by management to derive a quick performance overview on close calls for one construction site.

Since this GUI window is the first one that opens in the current close call analysis, a user may configure the processing parameters using an interactive legend (in subpart 1 of Fig. 10). Results that are illustrated in the other subparts of the figure (titled 4.–6.) change accordingly. The interactive legend also enables the user to hide and show the boundaries of objects that are present on site. The user can enable or disable the visualization of the corresponding protective envelopes, identification numbers (IDs), and trajectories (colorized by resource) on a construction site layout map. The latter is built in advance from a regularly updated site layout plan using BIM [23,38].

In subpart 2, the interactive legend panel allows changes to the grid size of the close call heatmap. The construction site layout window (see subpart 4) displays the heatmap for the resources workforce and equipment separately. Inside the processing configuration panel (subpart 3) are three editable fields to influence the computational data analysis (e.g., the timestamp to begin the analysis). Then a user selects the minimum duration of a close call event. It defines how long a close call has to be to be included in the analysis. Close calls that only last for

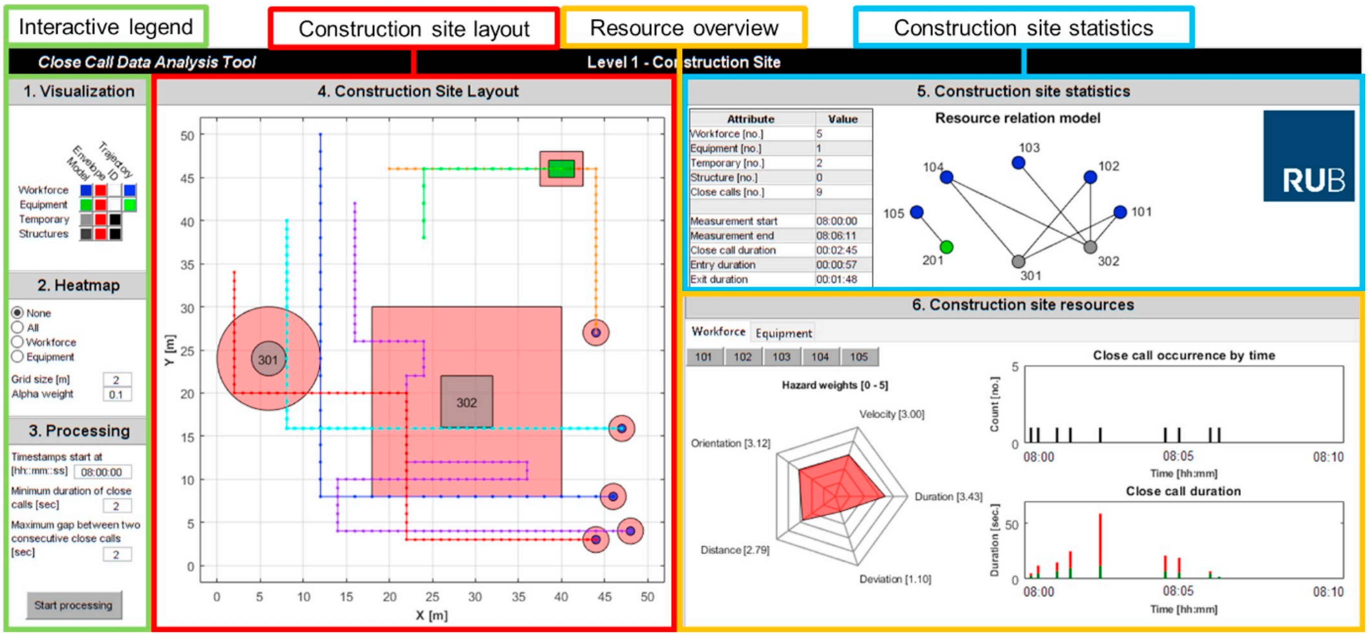


Fig. 10. GUI level 1 – construction site.

1 s might frequently be found in the results, but may not provide valuable information. In fact, in situations when equipment frequently passes by pedestrian workers, many of these might be interpreted erroneous or irrelevant. On the other hand, allowing a user to define a gap value (the maximum time between two consecutive close call events) adds or limits the granularity in the close call analysis.

The GUI level 1 further consists of a tab for construction site statistics (see subpart 5). It gives an overview of the analysis to all close call events that happened at this construction site. The resource relation model visualizes those resources that are most often involved in close calls. The example shown illustrates close calls that involve workforce (1xx) with equipment (2xx) or hazardous objects (3xx). No close call between equipment and hazardous objects was observed in the artificially generated data set.

A radar plot in subpart 6 of the figure shows the calculated weights for velocity, duration, deviation, distance, and orientation for all workers. In this example, 4 out of 5 weights pose a flag and may require the safety management to act upon. Additionally, two plots for occurrences of close calls by time and duration of the close call events give a brief overview of the observed time interval. The red bars on the duration plot represent the exit duration and the green bars show the entry duration of the close calls. Clicking one of the individual tabs for the resources links to the next GUI levels.

5.11. Explanation for GUI level 2

The GUI level 2 window (see Fig. 11) presents a detailed view on a single resource. This includes general close call information for this resource. Subparts 1–4 of GUI level 2 display results to the resource in form of a table with general information, a radar plot for the recorded hazard weights, and plots for timestamp, duration, and velocity. In addition, a pie chart denotes the absolute number of relative orientations of the resource towards the hazards once the close calls occurred. The green pieces represent the front-, the red pieces the rear- and the yellow-pieces the side-facing directions of the resource involved in a close call.

A map, shown in subpart 6, can be configured according to a user's preferences via an interactive legend (subpart 5) and allows to display the trajectory, resource models, protective envelope, or display an individual heatmap for the resource (here: a pedestrian worker). A click on the '101–302' button opens the GUI level 3 window for this particular close call.

5.12. Explanation for GUI level 3

The GUI level 3 window (see Fig. 12) presents the user with information at the highest level of detail to a particular close call event. Information in this window might be used in accident analysis or training scenarios. A map visualizes the data of each event buffer including position, orientation, direction, distance, and deviation. An interactive legend (subpart 1 of GUI level 3) allows the user to hide or show specific information and replay every second of the close call. The statistic panels respond to the selected event buffer and shows the statistics from the entry event to the currently viewed event buffer. A separate legend provides the user with the ability to show or hide individual graphs. The last panel shows the accumulated and current orientations of the worker towards the hazard.

6. Verification of method

As mentioned earlier, a first test of the developed method occurred in a simulated construction scenario. Close calls among few resources were artificially generated. The close calls were analyzed and details for each resource were discovered, for example: the course of close calls, individual resource- and hazard-statistics, a heatmap as well as comprehensive construction site safety statistics. All generated information is displayed on a layered Guided User Interface (GUI) (implemented in MATLAB®) which permits a user to assess the newly generated construction safety information from multiple view points and levels of detail. The GUI was designed based on industry expert input in a way to find intuitive answers to typical safety-performance-related questions:

- Which are the areas where close calls occur frequently?
- Which workers or pieces of equipment are involved in a close call and are there any particular differences in the safety performance among them?
- How does a worker react on entering a hazard zone, when might the worker recognize to be at risk, and how will the worker react upon detecting it?
- Which ways exist to leverage the newly generated information for

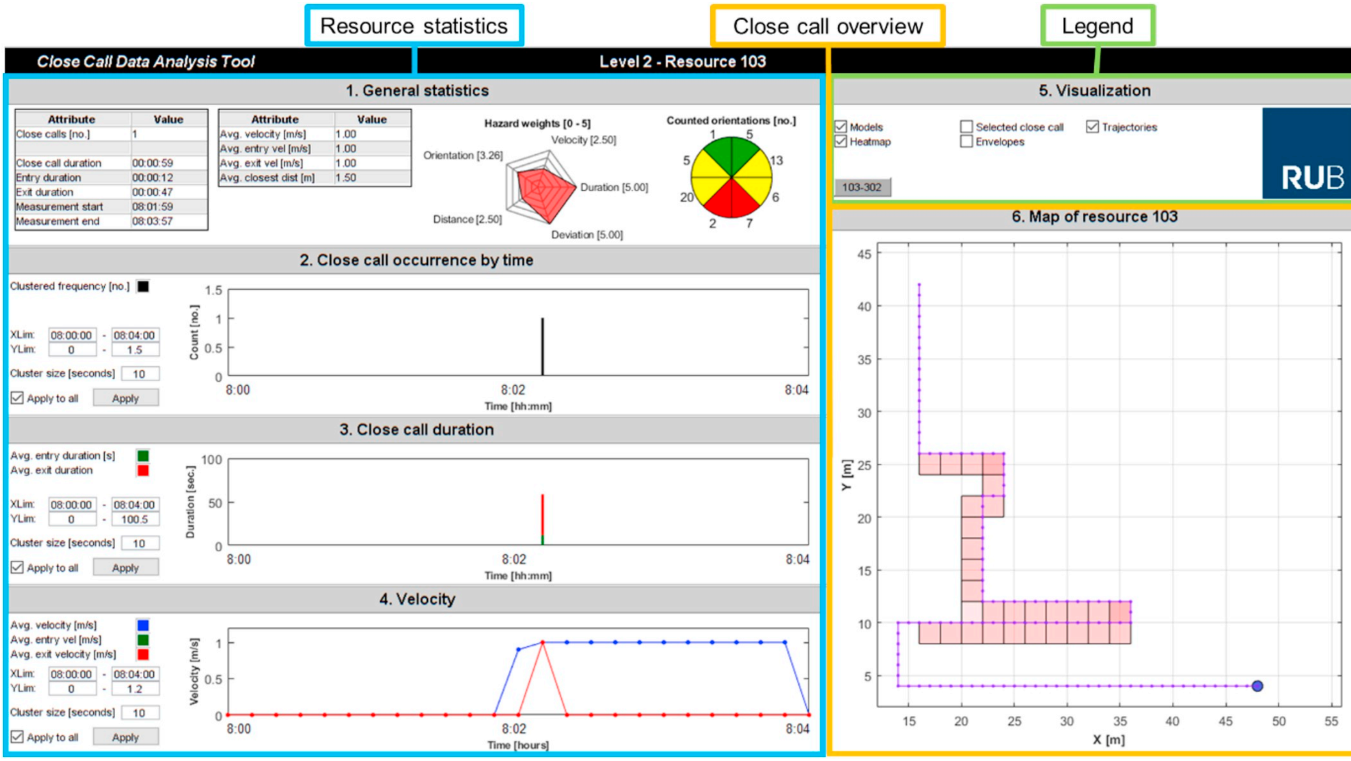


Fig. 11. GUI level 2 – individual resource.

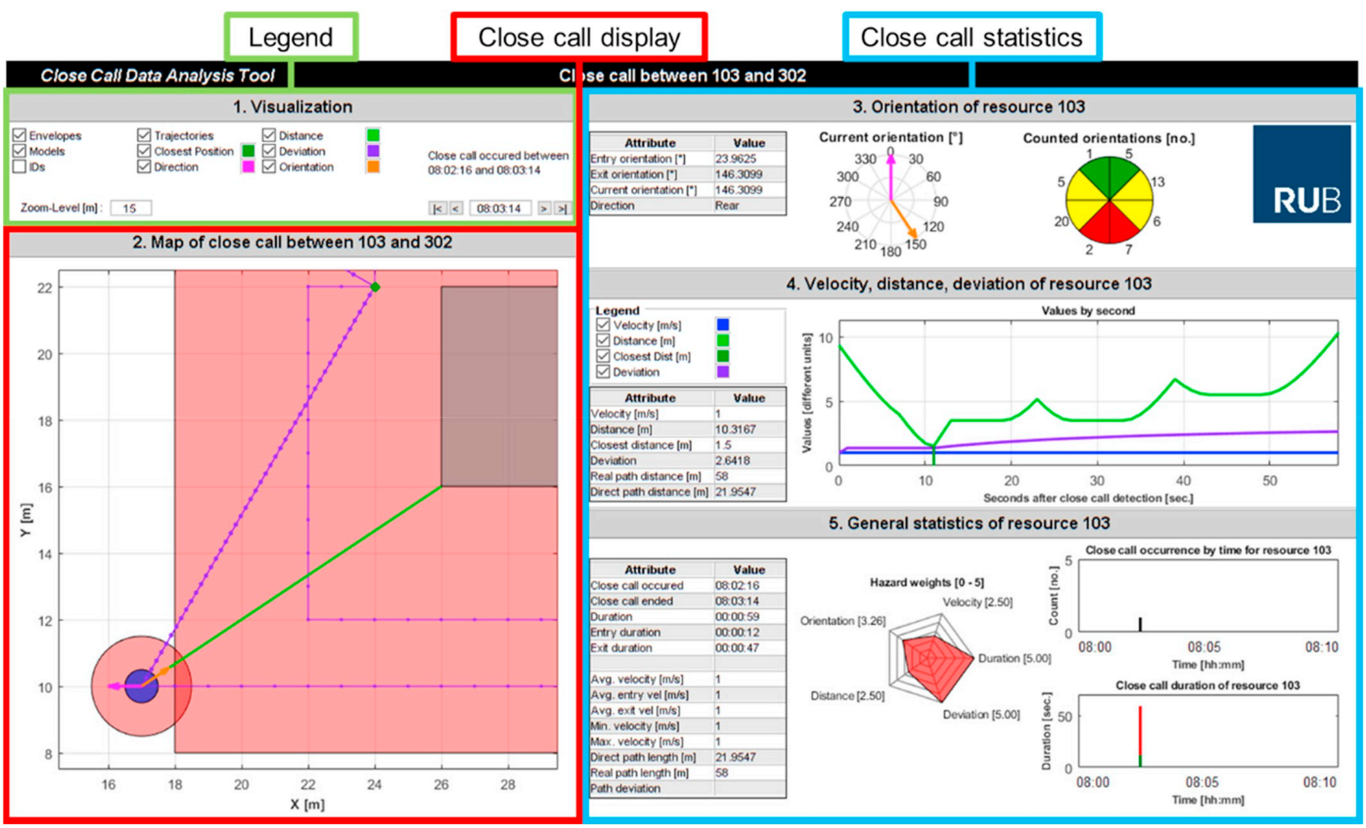


Fig. 12. GUI level 3 – single close call.

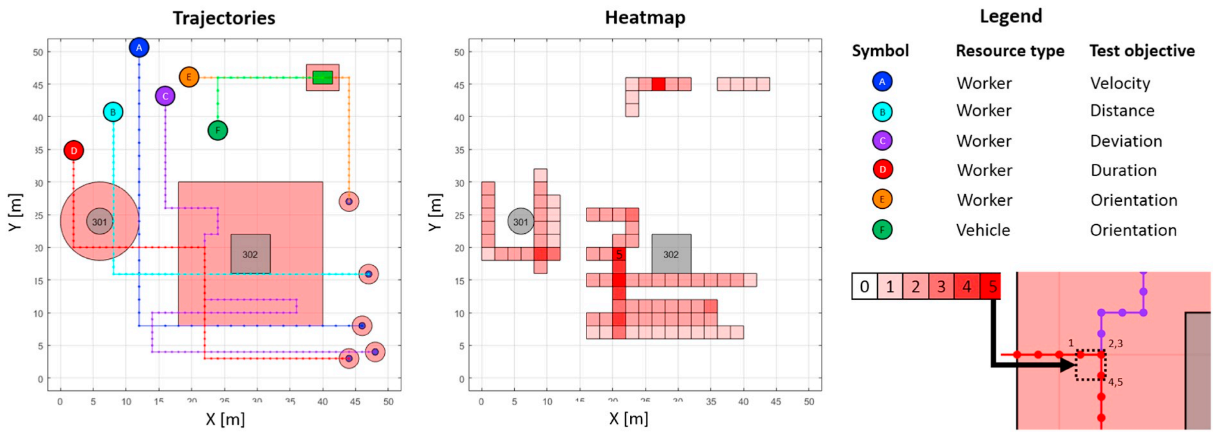


Fig. 13. Verification of close call analysis algorithm using an artificial construction scenario.

continuous safety performance improvement, e.g. in safety education and training?

The artificially generated data set (called scenario) is based on known trajectories (straight lines) where the ground truth is known and evidence available is used to verify the close call analysis algorithm. This scenario included five workers that traverse a construction site in a continuous manner, facing two temporary static hazards and one dynamic vehicle. Each worker simulates a behavior which addresses one of the different hazard weights. To raise the orientation weight value for a worker, for example, the vehicle creates a close call in a workers' blind space. All trajectories are straight lines. This permits simplicity in the verifying process of the algorithm. A heatmap displayed in the GUI further allows the evaluator to spot the close calls.

Some more specifics to the scenario: one pedestrian worker (A) traversed the site at a speed of 2 m/s (at a maximum allowable speed limit of 1 m/s). A second pedestrian worker (B) was a too short distance towards the hazards (301 and 302). A third pedestrian worker (C) simulated a behavior which should result in a high deviation weight. The duration weight was tested by pedestrian worker (D). Pedestrian worker (E) was confronted with a traversing vehicle (F) to verify the orientation weight function. The heatmap functionality was verified by comparing the trajectories with the hazard locations on the map (see Fig. 13).

The weight radar plots for all resources are displayed in Table 1. Resources A, B and D showed expected results that verify the functionality of the velocity, distance, and duration weights. In contrast to the other resources, C shows two raised weights for deviation and duration (numbers in bold). As the deviation value quantifies the straying of the worker from an ideal path and the duration value increases with a longer exit duration, a raised deviation weight might tend to be accompanied by a raised duration weight. In contrary, the radar plot of resource D shows a sole raised duration weight. Therefore, a mutual correlation between these values can be excluded. Resource E shows two raised weight values as well. This can be explained as: (a) vehicle and pedestrian worker do not have a large safety distance and (b) the vehicle stopped right behind the worker with a distance of close to zero meters. In theory, each one of the recorded close call events should be followed up. However, a user in a realistic scenario may need to set preferences on the more severe close calls. According to the initial findings in a simulated test environment, weight values of approximately 4 or higher would require such much more detailed follow-ups.

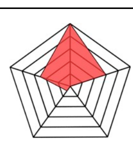
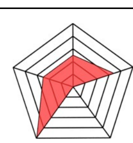
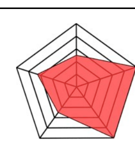
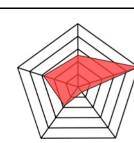
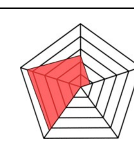
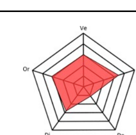
7. Results to validation

To validate the close call data analysis algorithm, datasets from two construction sites were analyzed. The following sections cover the pedestrian workers' individual performances and the overall construction site safety performance. Discussions including future work follow.

7.1. Experiment 1: building construction site

A dataset was gathered on a real building construction site where several pedestrian workers were present at an elevated work level. A restricted workspace was located inside the work area. Although the protective guardrails around the leading edges met the required safety standards, the present supervisor estimated it as insufficient (asking his and subcontracted personnel "to stay away from the edges"). One of his particular concerns was the arrival of a new subcontractor. Their new work crew for tying rebar yet had to familiarize themselves with the work environment (including work at height). Therefore, the close call analysis algorithm aimed at analyzing the trajectories of three of the subcontracted workers for potential close calls near the leading edge and/or unauthorized entry into the restricted work space.

Table 1
Weight radar plots and values for every resource and average team performance (simulated data).

Category	Resource					Team
	A	B	C	D	E	
Radar Plot						
Velocity	**5,00**	2,50	2,50	2,50	2,50	3,00
Duration	2,96	3,42	**5,00**	**5,00**	0,78	3,43
Deviation	0,00	0,00	**5,00**	0,51	0,00	1,10
Distance	0,44	**4,93**	2,50	1,84	**4,26**	2,79
Orientation	2,50	2,50	3,26	2,86	**4,46**	3,12

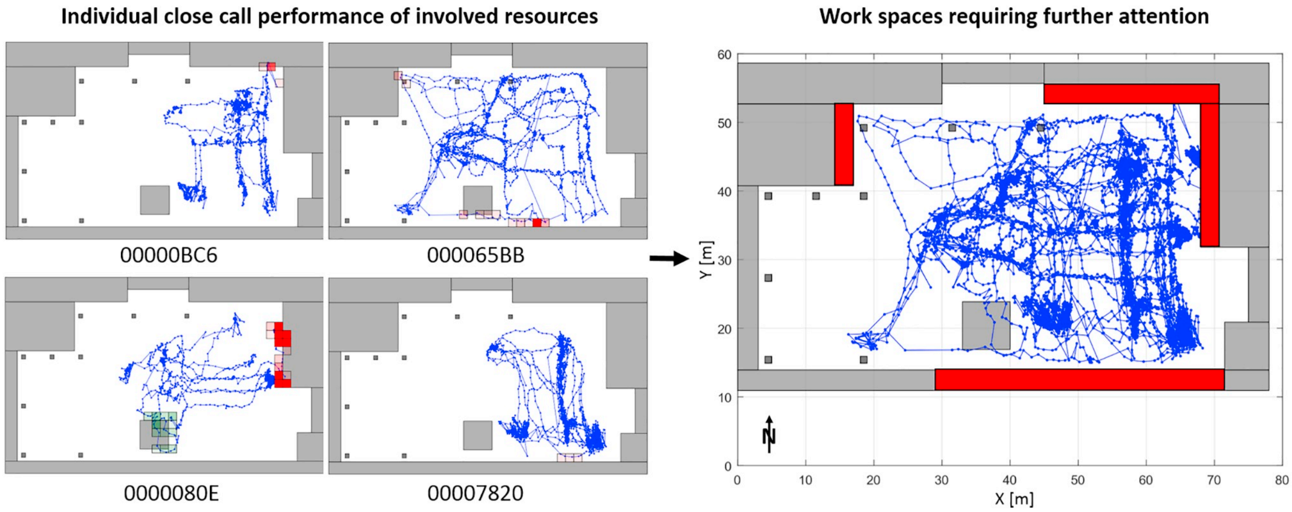
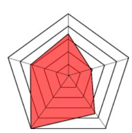
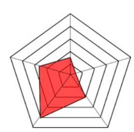
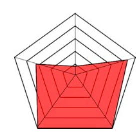
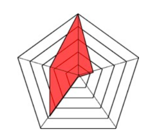
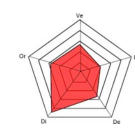


Fig. 14. Heatmaps identify close calls in a BIM-based site layout (extracted for each resource and construction sites from GUI levels 2 and 1, respectively in the order of appearance from left to right).

Table 2
Weight radar plots and values for every resource and average team performance (experiment 1).

Category Tag ID	Resource				Team
	00000BC6	000065BB	0000080E	00007820	
Radar Plot					
Velocity (Ve)	3.40	1.52	0.83	**5.00**	2.69
Duration (Du)	1.90	0.47	**4.36**	1.25	2.00
Deviation (De)	3.57	2.01	**4.98**	0.00	2.64
Distance (Di)	**5.00**	**4.07**	**4.98**	3.78	**4.46**
Orientation (Or)	3.13	2.62	3.23	2.34	2.83

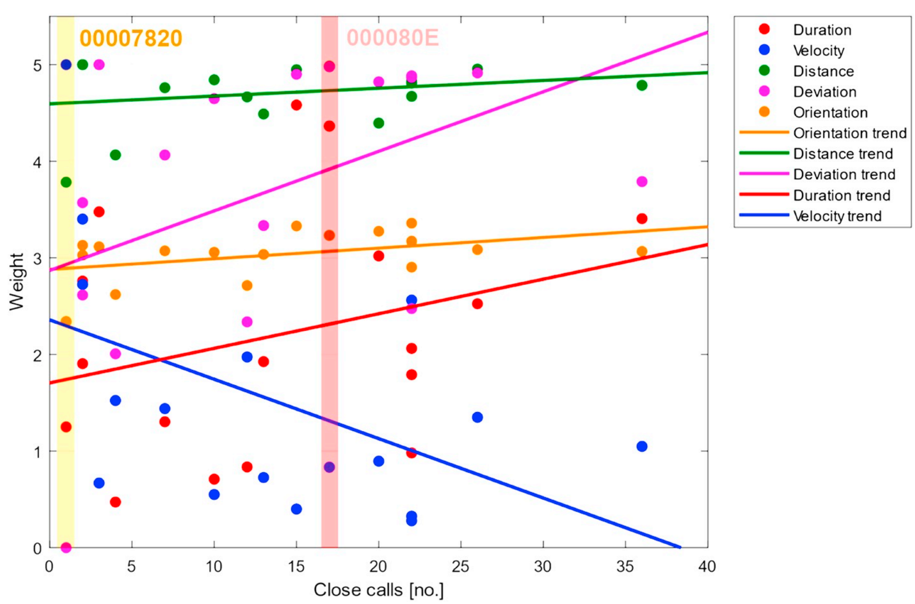


Fig. 15. Close call performance by work team member.

As shown in Fig. 14 (see the grey areas in plan view) the restricted space and the leading edges were modelled as individual objects using BIM. UWB served as the sensing technology for recording the trajectories of the personnel. UWB allowed to allocate a specific ID to every worker. The information in Fig. 14 displays the individual trajectories (in blue color) and, by applying the developed close call algorithm, the resulting heatmap (in a range of red colors) for every worker. The images indicate several close calls, mostly towards the southern and

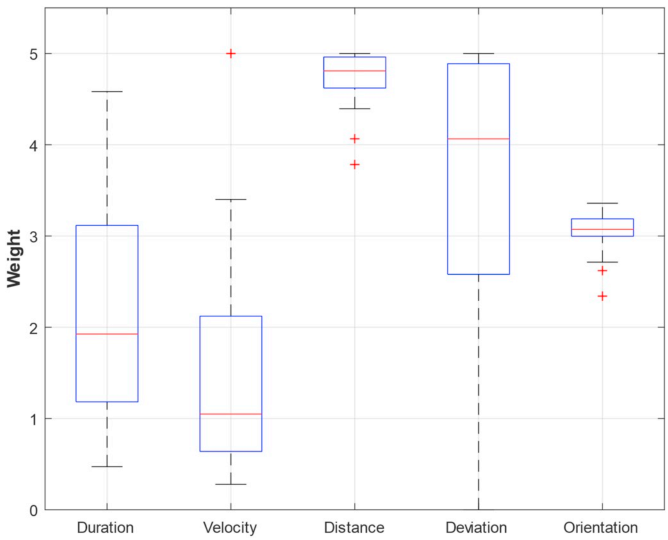


Fig. 16. Box plots with 95% confidence intervals: close call criteria by weight.

eastern sides of the work environment. Interestingly to note are the green tiles, also visualized in Fig. 14. They indicate that a person (tag ID: 0000080E) entered the material storage area. Since it was the material manager there was no real violation. Worker 000065BB once passed by the restricted work space. As shown, the use of sensing technology, data analysis, and visualization offers also the option of positive feedback.

The analysis of several of the generated hazard weight radar plots for the pedestrian workers give further insights into the observed close calls. Table 2 displays the individual workers' hazard weight radar plots and the team's performance. The worker with the ID: 00000 BC6 shows higher hazard weights than most other workers. Several weight values for worker 0000080E were very high (in bold). Although the data visualization indicates only two other close calls nearby, they must have been serious close calls (medium speeds, but very close to the leading edges).

Additional insights can be retrieved from reviewing the team's close call performance. Fig. 15 displays the number of close calls by each worker over the weights. Trend lines are also shown. Worker ID 00007820 had one and worker ID 000080E had 17 close calls. While the one worker (00007820) traversed close (Di = 3.78, note: lowest distance to the hazard of all workers) to a leading edge at high velocity

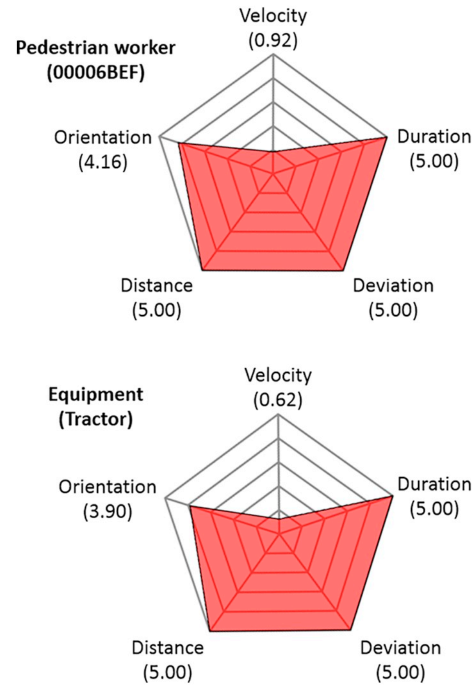


Fig. 18. Hazard weight radar plots.

(Ve = 5, note: highest of all workers) on a straight trajectory (De = 0, note: lowest of all workers), the other worker (0000080E) had numerous more close calls, most of which happened at low velocities and for extended periods of time. Confronting the workers with the data in an exit interview, answers for such behavior were sought: one worker responded with “[I] have been on the direct path to a work station” and the other worker replied “[I was] constantly aware of the danger of tying rebar in a confined area near the leading edge”.

Further investigation can be taken by looking at a box plot. A future research objective will be to investigate outliers in more detail (Fig. 16). The analysis of the experimental data indicates that a too close distance of pedestrian workers to a hazard is a major concern. While worker ID 00007820 had only one close call, he clearly traversed at very high speed. This might ask further questions: What pedestrian velocities are permitted and at what point in time should control measures come into effect? As practiced by industry leaders, in such a case when workers are observed running on construction sites, the worker would be

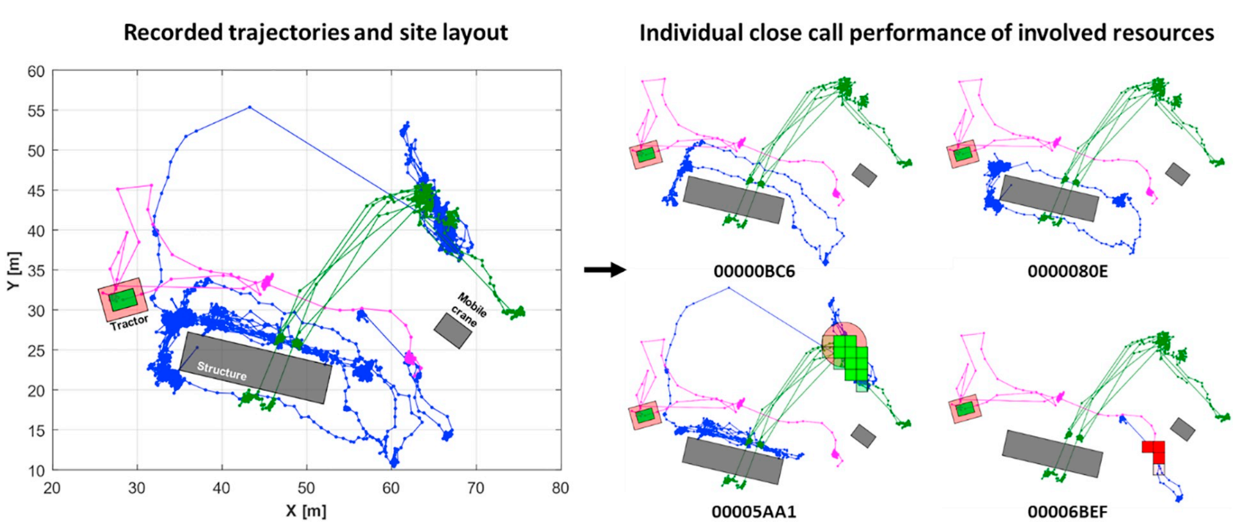


Fig. 17. Close call heatmap visualization (note: structures are grey, equipment movement are pink and green, and trajectories to pedestrian workers are blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

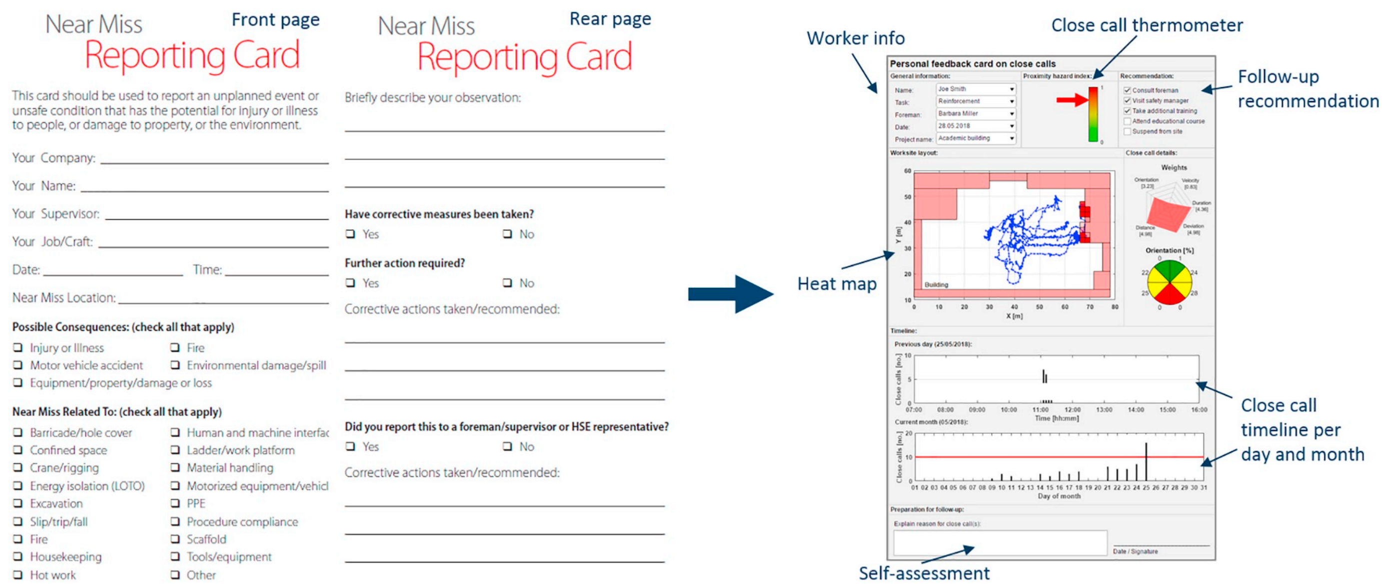


Fig. 19. Conceptual transformation of manual close call reporting into digital reporting and feedback cards.

instructed first, then pulled temporarily from work and provided with additional instructions before being able to return to work. Repetitive poor performance, though, may put a worker's employment at risk.

Since most workers fear such strict retaliation, programs can be developed that heighten workers' morale. As a consequence, the responsible safety personnel on site could be advised to inspect the leading edges that are marked in red in Fig. 14. Showing an illustration like Fig. 14 (object locations with close calls are highlighted in red) could even be shown to the workforce in Job Hazard Analysis (JHA) or toolbox talks ahead of every task execution. While providing active feedback with realistic data from the same construction site has the potential to strengthen workers' risk awareness quickly, future research has yet to validate this assumption.

7.2. Experiment 2: infrastructure construction site

A second realistic trial of the close call analysis algorithm utilized data from a large infrastructure construction site. In a confined work space (an excavated pit) 4 pedestrian workers, 1 tractor, and 1 mobile crane operated conjointly. While the original data analysis was performed by Cheng et al. [31], the objective of this evaluation was to find close calls between the pedestrian workers and the moving construction equipment (or parts of it, for example its attached load). The potential hazard of a pedestrian worker being pinned by the rotating body of the mobile crane was not analyzed, because its outriggers were safely guarded. Similar to the first experiment, the results show the individual trajectories, heatmaps (see Fig. 17), and hazard weight radar plots (see Fig. 18).

The pedestrian workers (different from the first experiment) with ID: 00000 BC6 and ID: 0000080E were not involved in a close call. Worker with ID: 00005AA1 came several times very close to or under the swinging loads performed by the mobile crane. As [39,40] already noted on the same data set, the worker was authorized to work near the operating crane (detach or attach loads to the crane hock). Therefore, the tiles are marked green.

The trajectory of the pedestrian worker with ID: 00006BEF, however, collided with the path of the tractor that delivered material into the pit. The tractor's and the pedestrian worker's hazard weight radar plots (Fig. 18) show nearly matching values for 5 of the observed values. Although these close calls were discovered, they were not severe as both resources moved with very low velocities ($\leq$ 1 m/s). One could argue that the pedestrian worker operated as a temporary flagman, guiding the vehicle into a confined space inside the excavated pit.

7.3. Reporting and feedback cards

The data generated in this research might be used to give safety professionals the required facts to take corrective actions that protect the human workforce. While multi-lingual manual reporting cards for close calls may still exist in the future, they have–as outlined before–-shortcomings in practice (e.g., incentives, collection, and feedback cycle). A successful transformation to digital recording and feedback is possible and yet has to be investigated in the future in much more detail. A conceptual digital feedback card would, for example, need to be tested for simplicity and acceptance by the workforce (Fig. 19). While intrinsically safe mobile devices are required for industrial construction applications, recording and analysis via Internet-of-Things solutions like [41] exist to reduce the time needed in the feedback cycle. The foreman would then have new information in toolbox meetings available for use in safety awareness training.

8. Limitations, discussion, and conclusion

This study presented an algorithm for the quantitative analysis of close call events in construction. A process of collecting trajectory data as a valuable construction resource was introduced and a graphical user interface was presented that provides safety personnel with automatically generated safety information on close calls. The proposed algorithm was successfully verified first in a simulated and later in field realistic work environments.

Although the developed method provides useful information on both artificial and real trajectories that cause close calls, the performed calculations are based on several assumptions. They rely in particular on the performance of RTLS. While many type of sensors provide RTLS data (i.e. computer vision, wireless), existing measurement errors may not qualify these (yet) for commercial application in the harsh construction environment. Though [31] demonstrated that errors with UWB can be below 1 m for each positional data log, RTLS technology must also withstand ethical concerns of tracking workforce and be effective in acquisition, use, and maintenance. The latter issue could be solved by targeting worthwhile business applications at the same time, e.g. logistics for indoor work environments. However, most of the existing RTLS still faces major hurdles and demand new sophisticated solutions to operate successfully in such complex work environments.

On a similar note, the developed algorithm considers trajectory-related information only. Although it tackles a complex question, when are workers safe/unsafe based upon their location and the situation, it uses fixed safety distances. Their current size relies on empiric findings. Though all of these assumptions made still add new functionality to existing close call management processes, additional research is necessary. For example, the presented hazard weight calculations are based on simplified values. Field-based observations are likely necessary to complement the definition of terms and calibrate the weights accordingly. This then may solve whether a close call was a true close call. Options to expand the dataset for such purpose exist. For example, data fusion including new data points from proximity alert sensors that are able to automatically record close calls between pedestrian workers and heavy construction equipment [42–45] could serve future research agendas well. To enhance personal awareness of every worker, a port to safe test bed environments within mixed reality environments would enhance more realistic education and training scenarios, providing users with much needed personalized feedback [46].

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