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The Development of User Requirements as a Framework for the Design and Evaluation of a Fit-for-Purpose Missing Person Locator System for Underground Mines

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Abstract

Entrapments are a huge risk in underground mines. This happens when miners (or any other persons who have entered underground) survive the initial event of an accident, become trapped or lost in unknown and life-threatening locations after evacuation, and remain unaccounted for. At this point, every second counts, and emergency response is highly desired for any chances of saving survivors. The survival chances of the missing persons depend on how quickly they can be located. Rescue teams are often deployed to search for the missing persons underground. However, the rescue teams are forced to search in random and presumed areas of the mine. This is due to the unavailability of information pertaining to the whereabouts of the missing persons. Not only the provision of accurate locations, but various other types of information such as post-accident two-way communication can enhance the survival chances of the missing persons. This information can be provided by a fit-for-purpose missing person locator system. A wide variety of missing person locator systems are already commercially available, some are in testing phases and others in prototype and development phases. This includes tracking, tracing, location detectors and post-accident two-way communication systems. These systems have unique functionalities, capabilities and limitations; making it difficult for mines to select the most effective, applicable and suitable system specific to their mine. In this study, the user requirements for a fit-for-purpose missing person locator system were developed. The purpose of the user requirements was to provide a guideline to facilitate the system selection process. The user requirements can also be used as a tool to measure and evaluate the performance of the selected missing person locator system. The user requirements were also used to predict the success of the selected system under different missing person incident scenarios. The development of the user requirements showed a potential for many other benefits for missing person locator systems.

Keywords Missing persons · Tracking · Locator · User needs · User requirements

1 Introduction

The continued occurrences of accidents and fatalities relating to miners going missing underground have accelerated the need for a fit-for-purpose and reliable missing person locator system. These are incidents whereby miners survived have the initial event of an accident but remained trapped or lost underground. This can be due to reasons such as being trapped behind falls of ground, buried in falls of ground, underground explosions and fires, disorientation, poor visibility, mud rush, water inundation or lost novices and visitors. In the context of this study, a 'missing person' refers to any person (including mine personnel, visitors, inspectors) who have entered underground, became trapped or lost for any reason and remain unaccounted for after evacuation and shaft clearance. In the event of a missing person emergency, search-and-rescue teams are often deployed to search for the missing persons. However, search-and-rescue operations have proven ineffective, slow and dangerous [1, 2]. This can be attributed to the lack of positioning information which can be timeously obtained from a fit-for-purpose and reliable missing person locator system. Various types of missing person locator systems have been developed around the world. A 'missing person locator system' refers to any system that track, trace, locate or detect trapped miners, and enable two-way communication between the rescue teams

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and the missing persons in the form of voice, text or data. The missing person locator system does not necessarily rescue the missing persons, but provides the locations of the missing persons as quickly as possible to help facilitate and guide rescue teams to the missing persons. This can help avoid time wastages by the rescue teams searching for the missing persons in the wrong places. In the absence of a missing person locator system, the rescue teams are forced to search in random areas or presumed locations due to limited or at times total unavailability of information pertaining to the locations of the missing persons. This often results in failed and/or prolonged search-and-rescue operations. Failure to locate the missing persons as quickly as possible has often resulted in the missing persons being killed as a consequence of the lack of life-sustaining necessities such as fresh air, food and water. The trapped persons can also succumb to their injuries sustained during the initial event of the accident if emergency care is not provided as quickly as possible.

In the United States of America, personnel tracking and post-accident communication systems were mandated by the Mine Improvement and New Emergency Response (MINER) Act of 2006 [3]. The aim of this Act was to improve the survival chances of mineworkers and visitors should they become trapped underground after an accident. Eight years after the inception of the MINER Act in 2006; Damiano, Homce and Jacksha [4] provided an update on the progress made on the implementation of communication and tracking systems in the United States of America mines. Their update showed that up to 306 personnel tracking systems and 306 post-accident communication systems were installed by 2014 in the United States of America. Despite the progress made at the time, several authors have suggested that the mining industry was still in need for a fit-for-purpose missing person locator system [5–8]. According to Menold et al. [9], most of the existing communication systems were found to be lacking flexibility, robustness and adaptability in underground environments. This led to extensive research being conducted to improve the existing systems and invent of new technology.

2 Classification of the Available Missing Person Locator System

The idea for underground missing person locator systems have existed since the early 1900s after several authors explored the theory of propagating electromagnetic waves through the earth's crust [10–13]. After several attempts, the first ever successful trapped miner locator system was eventually reported by Wadley [14] in the 1950s. This system could achieve a range of 600 m through the earth at a frequency of 300 kHz. Research in this field continued to evolve with an aim of improving the capabilities of the initial systems. Despite their long existence, these systems were still experiencing challenges underground in the 2000s [15]. This necessitated further research and improvements.

The currently available missing person locator systems are mainly classified into Through-the-Wire (TTW), Through-the-Air (TTA) and Through-the-Earth (TTE) as described in Table 1 and Fig. 1. This is in accordance to the mechanism used to establish communication in the process of locating the missing miners [16–22]. The TTW communication systems were the first to be implemented and used in underground mines after the use of bells and whistles. This included the use of magneto, sound-powered, dial and pager phones in key areas such as crew stations and refuge bays [20]. The underground phones were adopted from surface/outdoor industries and introduced underground to enable wired two-way communication between surface and underground, but were later largely used as backbone. The wired systems evolved from half-duplex and later full-duplex. With TTW communication, signals are transmitted and received along the length of cables such as coaxial, trolleys, leaky feeders, twisted pair and fibre optic, from one point to another [20]. Recent research on the TTW communication systems focused on channel modelling and optimization in underground communication [23]. One of the major disadvantages of these systems is that they are highly susceptible to damage due to accidents such as falls of ground and gas explosions. This resulted in the need to explore wireless communication technologies. The TTA two-way voice, text or data communications, tagging and tracking and the TTE electromagnetic waves and seismic waves communication became a solution to some of the limitations of TTW systems. The TTA communication systems have been successfully used in underground mines to provide real-time positioning systems. The various positioning algorithms, techniques and protocols of the TTA communication systems have been continuously improved, especially in terms of positioning accuracy, precision and bandwidth [24–29]. To minimise the susceptibility of infrastructure to damage, a mesh network configuration in which the node-readers are battery-powered to connect wirelessly has been developed, channel modelling and optimization conducted [30–34]. The TTE communication systems are based on the propagation of electromagnetic and seismic waves through the ground. The TTE electromagnetic wave system is further divided into magnetic induction and electrode-based transmission. For both techniques, various studies have been conducted to optimised factors such as the depth of penetration, choice of frequency, transmission and received power, antenna design, etc. [35–44]. The TTE seismic wave system has not gained much popularity but shows great potential to operate in environments where the primary communication systems have failed [45–50]. Lastly, the TTR signal search locator systems

Table 1 Capabilities and limitations of the available missing person locator systems

System	Functions and capabilities	Limitations
Through-the-Wire (TTW) two-way communication	■ Provides real-time two-way voice communication ■ Clear voice communication due to high data rates ■ Full-duplex communication	■ Missing person must be uninjured to be able to use the system ■ Missing person must be uninjured to be able to reach phone station ■ Communication limited along length of cable ■ Lack redundancy ■ Highly susceptible to damage post-accident
Through-the-Air (TTA) two-way communication	■ Provides real-time two-way voice/text/data communication ■ Portable handset units are carried by workers at all times ■ Full-duplex communication	■ Requires infrastructure (node-readers and data transmission cable) which can be damaged during accidents ■ Some are half-duplex depending on frequency bandwidth
Through-the-Air (TTA) tagging and tracking: passive RFID	■ Provides real-time locations of miners ■ Provides last detected locations of miners ■ Wireless tag-to-reader communication	■ Data transmission to surface infrastructure can be damaged by accidents ■ Tag-to-reader communication can be interrupted by external interferences ■ Line of sight dependent ■ Blind spots can exist
Through-the-Air (TTA) tagging and tracking: active RFID	■ Provides real-time locations of miners ■ Provides last detected locations ■ Increased redundancy with mesh network ■ Wireless tag-to-reader communication ■ Increased read range ■ Adjustable tracking read range	■ Data transmission to surface infrastructure can be damaged by accidents ■ Tag-to-reader (signal propagation interferences) communication can be interrupted ■ Line of sight dependent ■ Blind spots can exist
Through-the-Earth (TTE) seismic waves	■ Provides locations of missing persons through large overburden (up to 300 m deep – field tested) ■ Does not require any major infrastructure to operate ■ Large slabs of rock can also be used by the trapped persons	■ System can only work in relatively shallow mines approximately 300 m ■ Missing person must be able to reach system (pounding) station ■ Missing person is required to provide locations by pounding (therefore must not be injured or dead) ■ Workers must be trained to operate the system and to follow system procedures
Through-the-Earth (TTE) electromagnetic waves	■ Provides locations of missing persons through large overburden (up to 600 m deep – field tested and 1 600 m by design) ■ System does not require any major infrastructure to operate (transceivers and loop antennas) ■ Provides two-way voice, text and data communication through rock	■ System can work only in relatively shallow mines approximately 300 m below ground ■ Missing person must be able to reach transceiver station ■ Missing person is required to provide locations through phone calls or text messaging at the station ■ Normally half-duplex
Through-the-Rock (TTE) signal search	■ The system can locate persons trapped behind and buried in solid or collapsed rock up to 40 m ■ System can locate persons around corners and inside cavities from a distance beyond 40 m ■ System does not require any major infrastructure to operate	■ The system is limited to a distance up to 40 m through rock ■ Rescue teams must be as close as possible to the trapped persons ■ The tags must be in possession of the trapped persons and undamaged

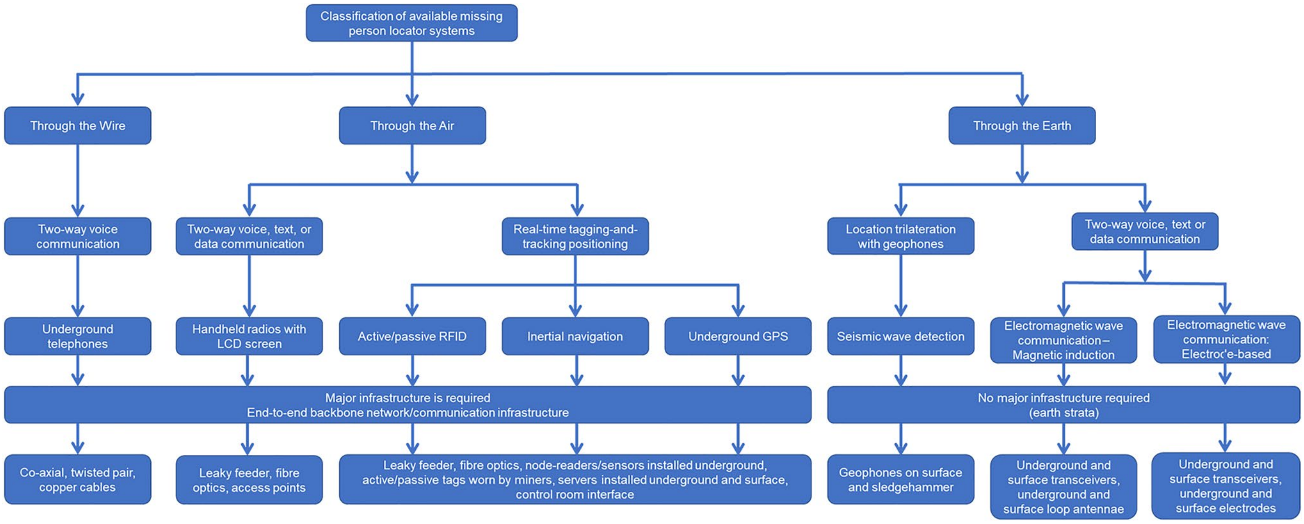


Fig. 1 Classification of the various types/groups of missing person locator systems for underground mines

have been researched and trialled. The TTR system requires the rescue teams to physically search for the trapped persons. Persons trapped between 20 and 60 m behind solid or collapsed ground can be detected and located [51–53]. The TTW and TTA communication systems operate through network or backbone infrastructure. The backbone infrastructure has become an integral part of underground mines with various applications [54, 55].

3 The Need for Specifying User Requirements of a Missing Person Locator System

Given the wide variety of the different types of missing person locator systems described in Table 1 and Fig. 1, selecting the most suitable one can become a serious challenge. This has necessitated the need to develop user requirements to guide and facilitate the process of selecting the most suitable system. The user requirements can be used as a tool to determine if a particular system will be fit-for-purpose under certain conditions. Currently, there are no methodologies or guidelines to bed used in the process of selecting a fit-for-purpose missing person locator system for underground mines. According to Schafrik, Dietrich and Harwood [56], there is currently no uniform method for evaluating the suitability and effectiveness of underground tracking and communication systems. Harwood et al. [57] noted that the modelling and testing of tracking and communications systems have been lagging in underground mining compared to outdoor industries. Due to the lack of these guidelines, mines have often struggled with selecting the most appropriate system specific to their conditions from a wide range of alternatives.

4 User Requirement Formulation Methods

The formulation of user requirements is the first step towards the design and development of any new system. This process should take into consideration the business and technical parameters of the proposed system. The user requirements of a particular system can be collected and formulated using methods such as surveys, interviews, workshops, literature review, group task analysis, focus groups and brainstorming sessions have been used for the collection and specification of user requirements [58–66]. According to the International Organization of Standardization (ISO) report [67], specifying user requirements is an essential process for developing a fit-for-purpose system. The term 'user requirements' refers to the *user-system-environment* interaction. This interaction is required to achieve the intended outcomes as well as the user-related quality requirements such as effectiveness, efficiency and satisfaction. The user requirements are set out based on the needs of the end user and provide the basis of a framework for further specifications, design, prototype and verification. The 'requirements' refer to the condition or capability that must be met by the system and the 'user' refers to the person who interacts with the system in a defined environment. A user-centred design approach has been widely used and focuses mainly on the users and their needs. The user-centred approach takes into consideration the user, system functions, the environment, user feedback, interaction between user and system, and the desired design [68, 69]. The ISO report recommends a Common Industry

Format (CIF) framework for defining the user requirements and is centred around the user needs based on the context of use, specifications, solution and evaluation as illustrated in Fig. 2.

- Context of use—understanding and describing the context of use (describe the user needs, tasks and the environment of use).
- User requirements—specifying the user needs (active involvement of end-user).
- Design—design and develop the solution or prototype then final product.
- Evaluation—verification and validation of the designed solution (design, test and modify).

Other than the mining industry, various other industries have conducted studies to developed user requirements. This includes the cellular, underwater, outdoor and indoor environments, summarised in Table 2. The indoor and outdoor positioning systems have applications in industries such as shopping complexes, military, firefighting and children safety (keeping track of children). Similarly, these systems have been adopted in underground mines. In underground mines, the positioning systems have applications in personnel, assets and machines tracking, robotics, automation, monitoring, survey and mapping. However, unlike in outdoor industries, the underground mine environments are more hostile, dynamic and continuously changing. This necessitated the need to redefine the user requirements of these systems for underground mines.

5 Missing Person Locator System User Requirement Formulation

The accurate and rapid provision of the locations of trapped or lost persons post-accident is one of the most critical requirements of any potential missing person locator system. The user requirements of a fit-for-purpose missing person locator system were developed over a series of steps that increase the validity of the context as demonstrated in Fig. 3. The first step was to establish the context of the user requirements and defined the end user needs. This was conducted through a literature review and a preliminary survey. From the contextualisation of the initial list of the user requirements, a preliminary survey was conducted to validate the initial list of the user requirements. The survey was comprised of industry experts from different mines and different roles or positions. The initial list of the user requirements was refined after conducting the preliminary survey. The survey was seconded by interviews with personnel in management positions at different mines. Thereafter, a workshop

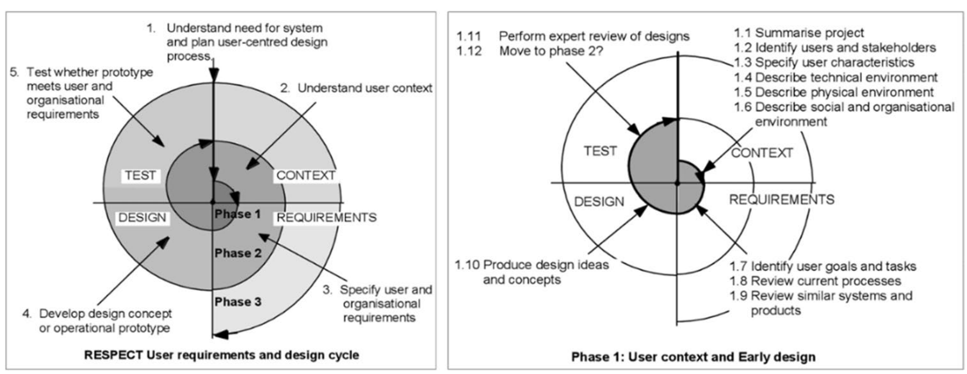


Fig. 2 Developing the user requirements and needs process (adopted from the CIF by the International Organization for Standardization [67])

Table 2 System specification evaluation metrics for different industries

Industry	Cellular and surface	Underwater and outdoor	Indoor and buildings	Indoor and underground mines
System evaluation metrics	Accuracy	Accuracy	Accuracy	Accuracy – predictable, repeatable and relative
	Data rates	Integrity	Precision	Confidence radius
	Coverage	Availability	Complexity	Adequate coverage
	Capacity	Compatibility	Robustness	Low latency
	Robustness	Interoperability	Scalability	Increased availability
	Accessibility	Continuity connectivity	Cost	Low susceptibility to failure
	Lightweight	Clear communication	Reliability	Robustness
Reference	[70]	[71]	[72]	[57]

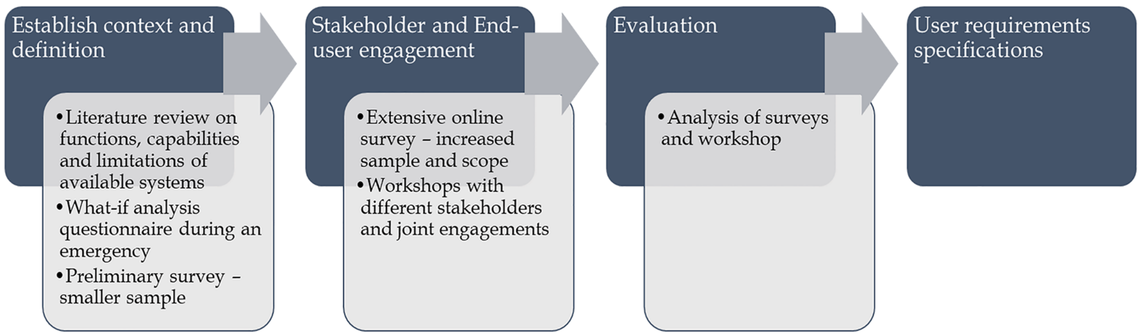


Fig. 3 Methodology used for defining user requirement specifications

was conducted with trade union representatives as part of stakeholder engagement.

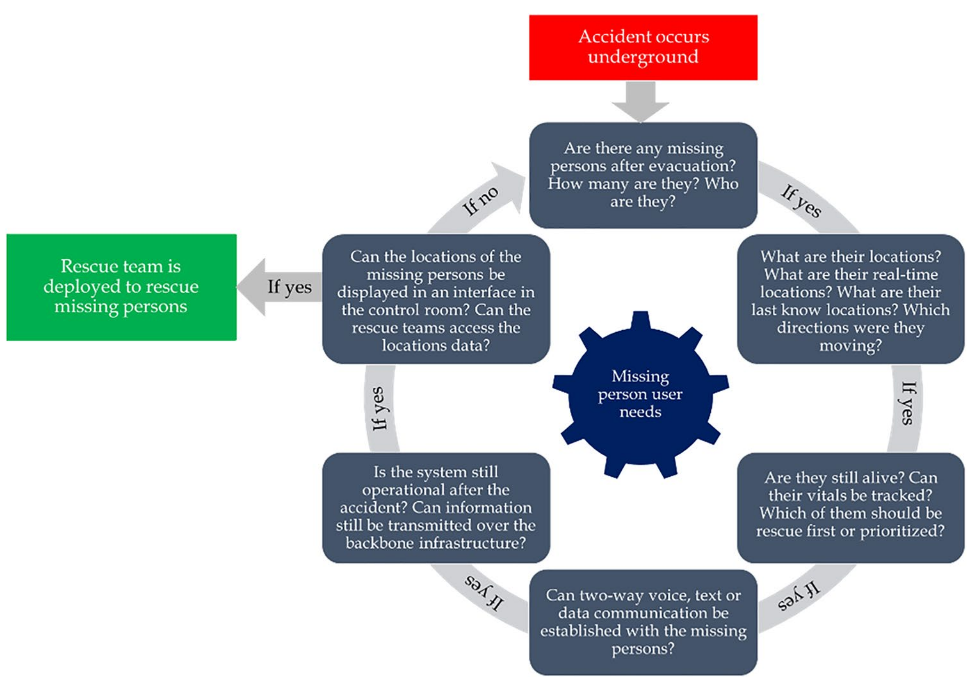
In addition, a what-if analysis was conducted. This was based on a series of continuous and critical questions that may arise during an emergency where miners have become trapped or lost underground. The what-if analysis was used to generate the series of questions that can come up during an emergency. Figure 4 shows the order of the questions asked during the what-if analysis.

The development of the user requirements also took into consideration factors such as the nature of underground accidents, possible number of persons in a mine at any given point in time (i.e. expected to be the highest during shift change), distance between shaft and working area, post-accident conditions, mining depth, number of levels and the scenarios in which miners can possibly go missing. Other studies found that the selection of a system can be influenced by factors such as the type of rock, size of excavations, atmospheric conditions and depth of mining. The development of these user requirements also took into consideration factors such as the technical parameters, functions and capabilities of the available missing person locator systems with respect to mine layout. Literature review findings from relevant industries were also considered. This process should be repeated to ultimately increase the level of confidence of the proposed user requirements [73].

6 Proposed User Requirements of a Missing Person Locator System

The outcomes of the preliminary survey, workshop, literature review and what-if analysis were then consolidated to develop the user requirements of a fit-for-purpose missing

Fig. 4 Critical questions during an accident involving missing persons



person locator system. The descriptions of the proposed user requirement are stipulated in Table 5. The purposes and drawbacks of each of the user requirements are also stipulated. It should be noted that not all the types of missing person locator systems will be able to provide requirement information from the proposed user requirements. These user requirements represent an ideal missing person locator system that will be suitable under any given circumstances. It is not expected that any of the currently available missing person locator systems can satisfy all the user requirements but the more the better. A study is required to evaluate and measure the available missing person locator systems against the proposed user requirements. Thereafter, the learnings from the evaluations can be used to make modifications to improve the current prototypes and other available missing person locator systems. In this study, the user requirements were developed from the literature review, preliminary survey of a smaller sample, informal interviews and workshop with the trade union representatives. Going forward, an extensive and industry wide survey should be conducted to validate and modify the user requirements. More stakeholder engagements will also be conducted developed to accommodate perspectives from all the stakeholders and role-players in the mining industry. Figure 6 demonstrates the systematic application of the user requirements in a typical emergency where miners have become trapped or lost underground. This is based on the actions or steps required to enhance the effectiveness of rescuing the missing miners. This answers the critical questions of an emergency raised in Fig. 5.

7 Evaluation of the Available Missing Person Locator Systems

Evaluating the effectiveness and quality of any system is an essential aspect for predicting its success. The evaluation process should be able to determine if the selected missing person locator system can satisfy the user requirements and to what extent (Table 3). Conducting the evaluations has a number of benefits. Firstly, the outcomes of the evaluation can help challenge manufacturers to design and develop new systems and technologies based on indicated shortcomings from the currently available systems. Secondly, the manufacturers can use the user requirements to modify and improve on their current technological limits and come up with new technologies. According to Mautz [74], user requirements can drive the direction for future research and development; and subsequently lead to new inventions, new designs or even integrate different systems. According to Rantakokko et al. [75], the user requirements of a tracking or localization system should pay attention on positioning accuracy, robustness, accessibility and weight of system components. In the mining industry, Shyu, Rossetti and Pratt [76] suggest that user requirements can be to measure the performances

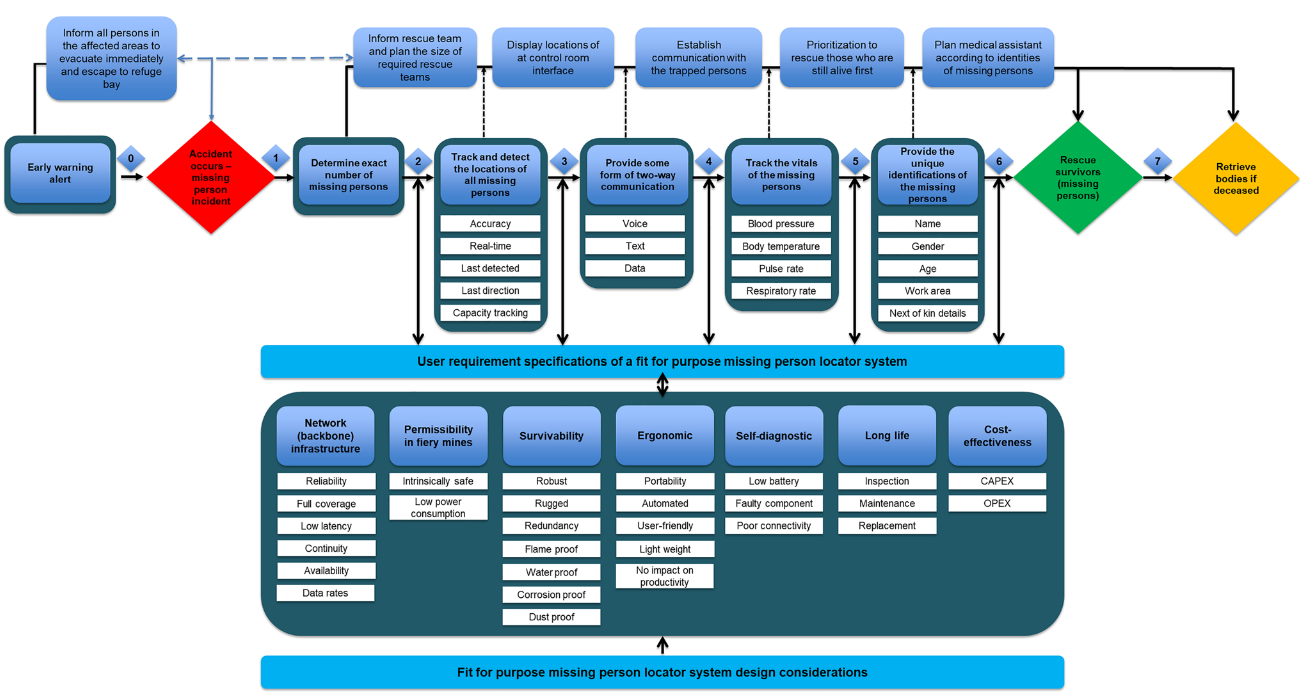


Fig. 5 Application of the proposed user requirement in a situation where miner have become trapped or lost underground after the occurrence of an accident and evacuation

Table 3 Proposed user requirements for a fit for purpose and reliable missing person locator system

User requirement components		Description of the user requirements	Purpose	Potential drawbacks
A. Effectiveness (functional)	A0. Early warning and alert	The system must warn and alert all person underground of a potential accident before it occurs	The persons present underground can escape to the refuge bays and avoid being affected during the accident	The infrastructure and the system must have a high availability and reliability. Waring cannot be received if the system is damaged
	A1. Exact number of missing persons	The system must first determine the exact number of missing persons after an accident and all other persons have been evacuated from underground	The rescue teams can use this information to determine the size of the rescue operation required based on the total number of missing persons	No obvious drawbacks were identified. Clock-in and clock-out systems are already being extensively used in the mining industry with applications in shaft clearance
	A2. Track locations of missing persons from shaft to face: ■ Accuracy (*x*, *y*, *z*) ■ Real-time ■ Capacity ■ Adjustability ■ Last detected locations ■ Travel direction	The system must provide three-dimensional (*x, y, z*), adjustable accuracy of the locations of all missing persons as quickly as possible. If the missing person locator system is damaged and the real-time locations are not available, then system must provide the last known locations and the last direction of travel of the missing persons as a starting point for search	The real-time and accurate locations of the missing persons will enable a timeous emergency response. The system should have the capacity to detect all tags. The range of beacons should be adjustable to define the accuracy of locations according to specific area in the mine. The last known location and last travel direction can be used as a starting point for search and rescue in case of a system failure	The installation of infrastructure such as fibre lines and node-readers in the stopes and gullies can be extremely challenging. The infrastructure and system components such as readers are highly susceptible to damage. The installed infrastructure will require frequent extension with the advancing working faces. The harsh conditions of the stopes must be taken into consideration (e.g. dusty, humid, line of sight) which can affect not only installation but also maintenance and service
	A3. Two-way communication	The system must enable two-way voice, text or data communication between the rescue teams and the missing persons. Two-way communication can also be used in early warning applications and general communication in the mine	Two-way communication can enable an efficient search and rescue operation. The rescue teams can communicate with the missing persons to obtain more information pertaining to their locations and status. This can also allow the missing persons to cooperate with the rescuers	TTA two-way communication infrastructure (e.g. leaky feeder or fibre) is highly susceptible to damage whilst TTE communication do not require any major infrastructure. TTE magnetic induction is difficult to achieve in highly conductive ground with restricted bandwidth and depth of penetration. Furthermore, with two-way communication, the missing persons must be alive and able to communicate their locations and status
	A4. Vitals tracking	The system must track the human vitals of the missing persons to determine which of the missing person are deceased and which are still alive	Mortality indication can enable the rescue team to make a more informed decision to prioritise rescue for the missing persons who are still alive. In this case, there is still a chance to save lives	Vitals tracking requires a more sophisticated device such as a wrist watch. This device may push the cost of the system up especially for conventional mines that employ a large number of people

Table 3 (continued)

User requirement components		Description of the user requirements	Purpose	Potential drawbacks
	A5. Unique identification	The system must provide unique identifications of all the missing persons such as name, gender, age, workplace or section, pre-existing conditions and next of kin details	This information is necessary for planning rescue operations and also for informing families of the missing persons. The rescuers can better prepare and plan medical assistance based on considerations such as gender, age and pre-existing medical conditions	This may not be accepted by workers and trade unions with speculations that this information can be used as a 'stick' by the employer. However, from the workshop it was suggested that this information be kept private until such a need arise
	A6. Location interface	The system must have a user-friendly and smart interface that can consistently, in real-time provide all the necessary information pertaining to any missing persons in case of an emergency	In real-time, the rescuers will know the exact locations of the trapped people. If infrastructure is damaged, the rescuers can use the last detected locations as starting point	No major drawbacks were identified other than the availability of the interface and being able to provide accurate locations and storing the last detected locations of the missing persons in the event that the system is damaged
B. Survivability (non-functional)	B1. Robustness (rugged components) and redundancy	The components of the system and its infrastructure must be robust enough to survive accidents such as falls of ground, explosions and underground fires. The system must also have alternative routes for information conveyance	The survivability aspect will ensure reliability of the system such that it remains operational and available post-accident	To incorporate rugged components and redundancy requires additional cost. This can also increase the gross weight of the system components
C. Availability and reliability of backbone infrastructure (functional)	C1. Network: ■ Full coverage ■ Low latency ■ Good bandwidth ■ Continuity ■ Reliability	The system must have full network coverage in all working and travelling areas including lamp room, shaft and shaft stations, travelling-ways, haulages and cross-cuts, along gullies and working face	The availability of infrastructure enables the tracking of personnel in real-time and storage of tracking data	It was suggested that the infrastructure and its components in fiery mines should be intrinsically safe with low power consumption. Infrastructure installation can be challenging at the stopes and gullies compared to the shaft and haulages
	C2. Accessibility of system by missing persons	The missing persons must have easy access to the system during an emergency	This will allow the system to quickly and easily provide the information pertaining the missing persons	Extensive installation of infrastructure will be required throughout the mine for easy accessibility
	C3. Continuous power supply and backup power	The backbone infrastructure must have reliable power supply – uninterrupted at any given point in time. The system must have a backup power unit	The continuous power supply ensures that the system is available at all times. In case power interruptions, the backup power unit can be used	The power supply infrastructure can be affected during accidents or other power outages. The power supply system and backup power unit must be intrinsically safe to be operated underground
D. Design considerations and ergonomics (non-functional)	D1. User-friendly and automated functions	The system must be as easy as possible to operate by employees. Ideally, the system must detect the locations of missing persons automatically without the need to perform any other task	This will allow the system to pick up the locations of the missing persons even if they are incapacitated, severely injured or deceased post-accident	No major drawbacks on the automation of the tracking system. This may sophisticate the system and thus increasing its costs to purchase and operate

Table 3 (continued)

User requirement components		Description of the user requirements	Purpose	Potential drawbacks
	D2. Privacy and intrusiveness	The system must not allow any person to access the tracking data of employees except in case of an emergency	This is to ensure that the system is only used for its purpose – track and locate missing people. This is to prevent managers from using the tracking data for other purposes such as monitoring absenteeism, lateness, the movement of workers during shift	The tracking data should only be accessed during or after a missing person incident and this can necessitate a data access policy. An employee acceptance criterion for a missing person locator system may be required. It was also suggested that the tracking data is managed by a third party
	D3. Permissibility (intrinsic safety)	The system must be intrinsically safe for use in all types of underground mines especially fiery mines	The missing person locator system must not cause additional safety risks for employees. The system must not create any sparks and have the risk of igniting explosive gases	High power consumption systems with a risk of igniting explosive gases will not be permitted in fiery mines. This will necessitate flame-proofing of the system to comply
	D4. Component portability	The components of the system must be easy to carry by employees (e.g. mounted on hardhat or safety belt)	The missing person locator system must not have a negative impact on the productivity of the employees	No major drawbacks were identified on this point
	D5. Integrate-ability and interoperability	The system must be integrate-able and interoperable with other pre-existing or future systems	The system should be integrated and interoperated with systems such as collision avoidance and monitoring	The potentials systems that can be integrated and interoperated are from different manufacturers and should be enable for this
	D6. Self-diagnostic	The system must be self-diagnostic with functions such as low battery indicator, faulty components indicator or poor connectivity indicator	This is to allow the mine to attend to the faulty components to ensure that the system is fully functional when needed	No major drawbacks were identified on this point
	D7. Cost-effective – OPEX and CAPEX	The system must be of reasonable cost to purchase and implement for both existing and new mines. This includes power, labour, maintenance and expansion costs	This is to ensure that mines can afford the system	If the system is relatively expensive, it may difficult for mines to purchase
	D8. Maintenance strategy	Ease of installation, inspection, extension and maintenance	This will ensure that the system is always in good working order and there are surprises when needed during an emergency	Additional cost may be incurred due to required artisans to conduct inspections and maintenance
	D9. Productivity feature	The system must have a productivity feature. This will be an added benefit for the mines	The productivity feature can benefit the mines financially in terms of the added productivity gains	Incorporating the productivity feature in the system may result in additional costs. This can also limit or affect the capability of the system in its primary function of tracking and locating missing persons

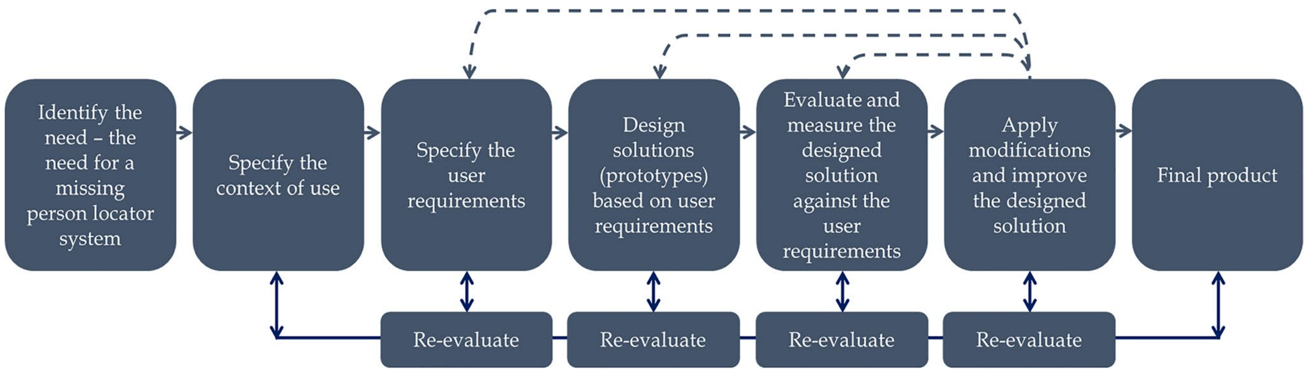


Fig. 6 Improving the user requirements to develop a fit-for-purpose missing person locator system

of underground communication systems. The study focused on the functional and technical requirements as well as their impact during planning and implementation of the systems. A study by Lehnen [77] was conducted to develop technical considerations for an underground mine localization system. The user requirements define the qualities of a system and what it must do, but not necessarily how it should do it. This includes the design and validation of the system before it is developed and implemented [78]. The process of re-evaluating the developed user requirements can be seen in Fig. 6.

The performance of a fit-for-purpose missing person locator system can be described as a measured of how quick the system can provide the locations of all missing persons to help guide rescue teams during an emergency. In Table 4, the available missing person locator systems are evaluated effectiveness, reliability in underground conditions and design considerations. The evaluation provides an indication of which system or systems can satisfy each of the requirements listed. In the evaluation, some of the requirements are answered with a yes or no answer whilst other are a measure of how well each system can perform. From the conducted evaluation, it was evident that none of the available systems could fully or perfectly satisfy all the user requirements. This showed that the different systems were designed for specific purposes and conditions. For example, it can be seen that the TTE communication systems were designed for post-accident conditions but are currently experiencing depth limitations. Although the TTE magnetic inductive communication systems make use of larger antennae which can be as small as 1.2 m in diameter but can be as large as 90 m in diameter [44], they have a lower susceptibility to failure due to not requiring any major installation of infrastructure throughout the mine. The TTE electrode-based system has an even lower susceptibility to failure due to its smaller electrodes. On the other hand, the TTA tagging-and-tracking systems can provide the locations of missing persons at high accuracy and in real-time but have a higher susceptibility to failure due to the required extensive infrastructure. Another interesting finding is that none of the systems provides a vitals-tracking feature. Vitals tracking requires a more sophisticated device such as a wrist watch that can monitor vitals. Such a device has been developed for underground mine emergencies [79, 80]. Another interesting finding is that all the systems are relatively cheaper to operate but have varying purchasing and installation costs.

From the evaluations, system effectiveness and quality of system were seen as the most critical parameters of the user requirements. Effectiveness can be described as the measure of the system to fully perform its intended functions in order to achieve its required goals or objectives [81–84]. Therefore, in this study, the effectiveness of a missing person locator system can be described as the measure of the system to accurately and timeously locate all missing persons underground. Quality of system is defined as a combination of the reliability, availability and survivability of a system [85]. Other studies have also shown a strong link between reliability, availability and survivability [86, 87]. Reliability is concerned with the risks of malfunctioning of systems over time [88]. Therefore, the reliability of a missing person locator system can be described as the measure of the system to continuously perform the intended functions without failure or interruptions. This requires the system to withstand the effects of an accident and remain operational under hostile environments, adverse conditions or changes in surroundings. The availability aspect is a measure of the probability that the system will perform its functions when required or needed [89]. The survivability aspect of a system based on the degree of vulnerability of the system components and its infrastructure during and after an accident [90]. Survivability can also be measured in terms of the susceptibility of the system components and its infrastructure to failure during and/or after an accident. Therefore, the quality of the missing person locator system will be critical in the underground mining environments which are prone to various types of accidents that have the capacity to damage the infrastructure and components of the installed missing person locator system. Any damages on the system person locator system can result in the failure of

Table 4 Evaluating the available systems against the proposed user requirements

User requirement components		TTA communication – underground telephones	TTA communication – hand-held radios or walkie talkie	TTA communication – RF tagging and tracking	TTA communication – underground GPS	TTA communication – inertial navigation	TTE communication – seismic waves detection	TTE communication – electromagnetic waves	TTR Communication – signal search scanners
A. Effectiveness	A0: Early warning alert feature	No	Yes	Yes	Yes	No	No	No	No
	A1: Exact number of missing persons	No	No	Yes	Yes	Yes	No	No	No
	A2: Location accuracy (*x*, *y*, *z*)	Very low	Medium	High	Very high	High	High	Low	Low
	A3: Real-time tracking	No	No	Yes	Yes	Yes	No	No	No
	A4: Storing of last detected locations	No	No	Yes	Yes	Yes	Yes	No	No
	A5: Multiple persons tracking capacity	No	No	Yes	Yes	Yes	No	No	Yes
	A6: Adjustable tracking capability	No	No	Yes	Yes	Yes	No	No	No
	A7: Tracking of last travel direction	No	Yes	Yes	Yes	Yes	No	No	No
	A8: Two-way communication – voice	Yes	Yes	No	No	No	No	Yes	No
	A9: Two-way communication – text	No	Yes	No	No	No	No	Yes	No
	A10: Two-way communication – data	No	Yes	No	No	No	No	Yes	No
	A11: Personnel vitals tracking	No	No	No	No	No	No	No	No
	A12: Unique identification of persons	No	Yes	Yes	Yes	Yes	No	No	No
	A13: Location display interface	No	Yes	Yes	Yes	Yes	No	No	No

Table 4 (continued)

User requirement components		TTA communication – underground telephones	TTA communication – hand-held radios or walkie talkie	TTA communication – RF tagging and tracking	TTA communication – underground GPS	TTA communication – inertial navigation	TTE communication – seismic waves detection	TTE communication – electromagnetic waves	TTR Communication – signal search scanners
B. Quality of system – reliability, availability and survivability of system	B1. Susceptibility to failure post-accident	Low	Low	Low	Low	Low	High	High	High
	B2. Required infrastructure	Major	Major	Major	Major	Major	Minor	Minor	None
	B3. Susceptibility of infrastructure to failure	High	High	High	High	High	Low	Low	Low
	B4. Susceptibility of components to damage	Medium	Medium	Low	Low	Low	Low	Medium	Low
	B5: Redundancy of system	Low	Low	Low	Low	Low	High	High	High
	B6: Network coverage underground	Low	High	High	High	High	Low	Low	Low
	B7: Latency	Low	Low	Low	Low	Low	N/A	Medium	Medium
	B8: Bandwidth	High	High	Medium	Medium	Medium	N/A	Low	Low
	B9: Continuity	High	High	High	High	High	N/A	Low	Low
	B10: Availability	Low	Low	High	High	High	High	Medium	Medium
	B11: Accessibility during emergency	Low	Medium	High	High	High	Low	Low	Low
	B12: Continuous power supply	Yes	Yes	Yes	Yes	Yes	N/A	No	No
	B13: Backup power	No	No	No	No	No	No	Yes	No
	B14: Depth limitation	No	No	No	No	No	Yes	Yes	No

Table 4 (continued)

User requirement components		TTA communication – underground telephones	TTA communication – hand-held radios or walkie talkie	TTA communication – RF tagging and tracking	TTA communication – underground GPS	TTA communication – inertial navigation	TTE communication – seismic waves detection	TTE communication – electromagnetic waves	TTR Communication – signal search scanners
D. Design considerations and ergonomics	D1: User-friendliness and ergonomics	Medium	Medium	High	High	High	Low	Medium	Low
	D2: Automated tracking functions	No	No	Yes	Yes	Yes	No	No	No
	D3: Privacy and intrusiveness	No	No	Yes	Yes	Yes	No	No	No
	D4: Permissibility (intrinsic safety)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	D5: Component portability	Low	High	High	High	High	Low	Low	Medium
	D6: Integrate-ability	Yes	Yes	Yes	Yes	Yes	No	No	No
	D7: Interoperability	Yes	Yes	Yes	Yes	Yes	No	No	No
	D8: Self-diagnostic	No	Yes	Yes	Yes	Yes	No	No	No
	D9: Cost-effective – CAPEX	High	High	High	High	High	Low	Medium	Medium
	D10: Cost-effective – OPEX	Low	Low	Low	Low	Low	Very low	Low	Low
	D11: Maintenance strategy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	D12: Productivity feature inclusion	No	Yes	Yes	Yes	Yes	No	No	No

the system. Effectiveness and quality of the system will therefore ensure that the missing person locator system can achieve its goal and has a chance to remain operational post-accident. The available missing person locator systems were the plotted in an effectiveness-versus-quality of system in Fig. 7. A fit-for-purpose missing person locator system must rank high in both effectiveness and quality of system.

The ranking of the different systems in Fig. 7 was based on the following key findings from the evaluations conducted in Table 4:

The ***TTW communication system (underground stationed telephones)*** provides two-way voice communication in fixed areas such as the crew station but does not provide any electronical tracking or detection functions. The missing persons must be alive and uninjured after an accident to be able reach a telephone station in order to communicate their locations and status. This system was found to be more suitable for survivors who manage to escape to refuge bays provided the system was undamaged. This system is highly susceptible to damages or failures due to its extensive backbone infrastructure requirements. Therefore, this system ranked low on both effectiveness and survivability when used as a means of locating missing persons.

The ***TTA two-way voice communication system (handheld radios)*** operates through an Ethernet or a leaky feeder backbone infrastructure to enable flexible two-way voice and text communication. Like the TTW communication system, this system does not provide any electronic location detection or tracking functions. This system is also susceptible to damage during incidents due to its required infrastructure. The system requires the missing persons to be alive and uninjured to be able to communicate their location. The system can work in situations where the missing persons are unharmed but affected by non-disastrous incidents such as poor visibility or lost novices. Therefore, this system also ranked low on both effectiveness and survivability.

The ***TTA tagging-and-tracking system*** can effectively provide adjustable locations of missing miners in real-time. In case of infrastructure damaged, as a last resort, the system can store and provide the last detected locations. However, this system is highly dependent on network infrastructure such as ethernet or leaky feeder which can be easily damaged during incidents. A wireless mesh network infrastructure configuration has been incorporated to improve survivability. Therefore, this system ranked high on effectiveness in terms of determining the locations of missing persons but ranked low on survivability due to the susceptibility to damage of the required backbone infrastructure during and after an accident.

The ***TTE seismic wave system*** operates wirelessly through the earth's overburden with no major infrastructure required. The locations of the trapped miners can be detected from surface using an array of geophones. This system has an enhanced survivability and a relatively good accuracy but has a depth limitation. However, its biggest disadvantage is the need for the missing persons to remain alive and physically abled in order to locate a station and be in good status to start pounding. Therefore, this system ranks high on survivability but very low of effectiveness.

The ***TTE electromagnetic waves (magnetic inductive or electrode-based)*** system enables two-way voice, text and data transmission through the earth's overburden with no electronic location detection functions. The biggest advantage of this system is the ability to propagate signals through rock wirelessly. Although it makes use of large antennae, this system has a higher chance of surviving an accident and remain operational because it does not require any major backbone infrastructure. However, its biggest disadvantage is the need for the missing persons to locate a station and be able to communicate their loca-

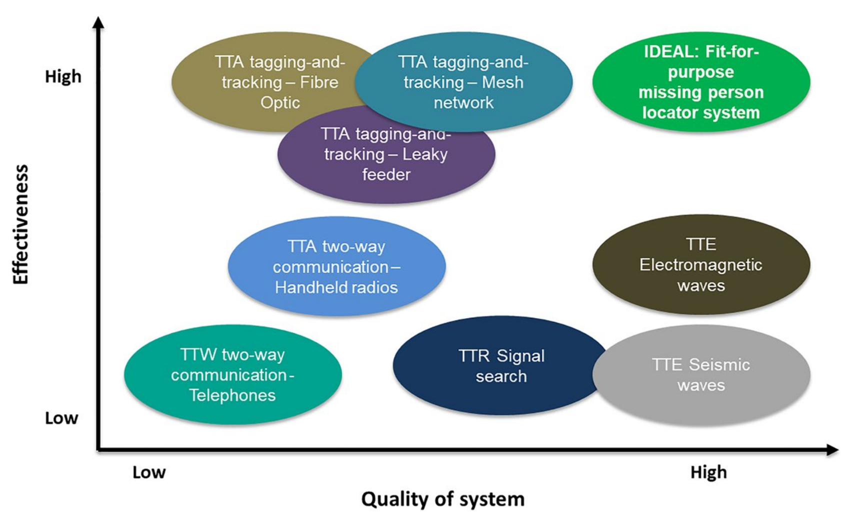


Fig. 7 Ranking of the effectiveness and quality of system for the different missing person locator systems

Table 5 User requirement application in different incidents

User requirement components		Person trapped behind a fall of ground or buried in a fall of ground	Person trapped in poor visibility due to fires and explosions or power outages	Person struck by machine and unnoticed by the driver	Underground lost visitor or novices and unfamiliar with the mine	Person fell and got trapped inside a cavity (e.g. ore-pass or grizzly) and injured	Person swept away and displaced during a water inundation or mud-rush	Person disorientated or unconscious and unnoticed due to heat exhaustion
A. Effectiveness	A0: Early warning alert feature	√	√	√			√	
	A1: Exact number of missing persons	√	√		√	√	√	√
	A2: Location accuracy (*x*, *y*, *z*)	√	√	√	√	√	√	√
	A3: Real-time tracking			√	√	√	√	√
	A4: Storing of last detected locations	√	√	√	√	√	√	√
	A5: Multiple persons tracking capacity	√	√	√	√	√	√	√
	A6: Adjustable tracking capability		√	√	√	√	√	√
	A7: Tracking of last travel direction		√	√	√	√	√	√
	A8: Two-way communication – voice		√		√			
	A9: Two-way communication – text				√			
	A10: Two-way communication – data		√		√			
	A11: Personnel vitals tracking	√	√	√	√	√	√	√
	A12: Unique identification of persons	√	√	√	√	√	√	√
	A13: Location display interface	√	√	√	√	√	√	√

Table 5 (continued)

User requirement components		Person trapped behind a fall of ground or buried in a fall of ground	Person trapped in poor visibility due to fires and explosions or power outages	Person struck by machine and unnoticed by the driver	Underground lost visitor or novices and unfamiliar with the mine	Person fell and got trapped inside a cavity (e.g. ore-pass or grizzly) and injured	Person swept away and displaced during a water inundation or mud-rush	Person disorientated or unconscious and unnoticed due to heat exhaustion
B. Quality of system – survivability, reliability and availability	B1. Probability of system to survive the incident, remain operational and available post-accident?	Low	Low	High	High	High	Low	High

tion and status. Therefore, this system ranks high on survivability but lacks effectiveness.

The ***TTR signal search system*** requires rescue teams to be in close proximity to the missing persons. The missing people can be found by searching for signals emitted by active tags which are worn or carried by miners. The signals emitted by the active tags are detected using signal scanners carried by rescue teams. This system can work well as backup to the proposed system. Therefore, this system ranks high on survivability as it is only deployed after an accident and ranks low on effectiveness as the rescue teams are required to physically search for the missing persons at the scene of the accident.

8 Application of User Requirements in Different Incident Scenarios

The selected fit-for-purpose missing person locator system should be applicable and operable in different types of accidents associated with underground mines. Underground mining environments are known to be associated with various types of accidents that can lead to the entrapment of mine personnel. The selection of a suitable missing person locator system should also consider the type accidents that are mostly associated to their mine. The available missing person locator systems have a varying degree of susceptibility to damage and failure post-accident, depending on the destructive nature of the accident. Table 5 shows the user requirements that must be met by the fit-for-purpose missing person locator system for different incident scenarios that have resulted in entrapments. This was based on the possible after effects of the accident. For example, if the missing persons are injured, they will not be able to walk to a phone station and communicate their locations to surface. Therefore, an automated missing person locator system that does not require any intervention from the missing person would be necessary in this situation.

Furthermore, it was necessary to determine which of the missing persons locator systems can work in the different missing person incident scenarios. This was conducted in Table 6 which indicates the systems that have a chance of working in the different missing person incident scenarios. The TTA communication systems telephones and handheld radios, as well as the TTE communication systems, require significant intervention from the missing persons to operate (i.e. the missing persons to be alive and not severely injured post-accident to be able to reach a phones station or radio and be able to talk). Therefore, these systems become unsuitable in incidents were the missing persons could be seriously injured and unable to walk or talk after accidents such as falls of ground, gas explosions and underground fires. On the other hand, the TTA tagging-and-tracking, underground GPS and inertial navigation systems have electronic or automated

Table 6 Applicability of different systems in different accident scenarios

Accident – missing person scenario underground	TTA communication – underground telephones	TTA communication – handheld radios	TTA communication – RF tagging-and-tracking	TTA communication – underground GPS	TTA communication – inertial navigation	TTE communication – seismic signalling	TTE communication – electromagnetic waves	TTR communication – signal search
Person trapped behind a fall of ground	No	No	Possibly	Possibly	Possibly	No	No	Yes
Person buried in rubble a fall of ground	No	No	Possibly	Possibly	Possibly	No	No	Yes
Person trapped in poor visibility due to fires and explosions	No	Yes	Yes	Yes	Yes	No	Possibly	Possibly
Person struck by machine and unnoticed	No	Possibly	Yes	Yes	Yes	No	No	Possibly
Person trapped in poor visibility due to power outage	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Lost visitor or novices and unfamiliar with the mine	Possibly	Possibly	Yes	Yes	Yes	No	Possibly	Possibly
Person trapped inside a cavity (e.g. ore-pass) and injured	No	Possibly	Yes	Yes	Yes	No	No	Yes
Person swept and displaced by water inundation	No	No	Yes	Yes	Yes	Possibly	Possibly	Possibly
Person disorientated or unconscious and unnoticed	No	No	Yes	Yes	Yes	No	No	Possibly

positioning functions (i.e. do not require intervention from the missing persons). Therefore, these systems can locate missing persons if they are injured, dead or unconscious. Lastly, the TTR signal scanning system requires the deployment of a rescue teams to search for the missing persons in very close proximity to the scene of the accident and detectable range of the active tags carried or worn by the missing persons.

9 Conclusion

There are different types of missing person locator systems that can be used for tracking and locating missing persons in underground mines. The missing persons can be trapped or lost underground due to various reasons associated with the initial event of an accident. A fit-for-purpose missing person locator system can play a critical role in guiding rescue teams to the missing persons as quickly as possible an ultimately save the lives of survivors. Selecting the most suitable and fit-for-purpose system can be a challenge given the wide variety of available missing persons locator systems specific to their mine. This study developed user requirements of a fit-for-purpose missing person locator system. The proposed user requirements can provide the necessary information as much as possible to enable rescue teams to locate missing persons as quickly as possible and ultimately save lives. These user requirements can be used for a number of purposes such as in the process of selecting the most suitable and applicable system from a number of options, evaluating the effectiveness and quality of a particular missing person locator system, to improve on current systems and to make recommendations for future systems. The user requirements can also be used for determining if a particular missing person locator system will be fit-for-purpose. The user requirements were further used to evaluate the applicability of the available missing person locator systems in various accident-scenarios. The evaluations conducted suggest that the available missing person locator systems can be suitable for specific conditions.

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Declarations

Conflict of Interest The authors declare no competing interests.

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