Development of a new smart evacuation modelling technique for underground mines using Mathematical Programming

By

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ABSTRACT

Current evacuation plans for underground mines are inefficient and outdated. Simulations have proven that smart evacuation can significantly increase the efficiency of escape times in case of an emergency. In a smart evacuation, miners are given real time instructions on a smart device (such as a smart-watch) about their route to a safe haven if an emergency occurs. In order to make smart evacuation possible, an optimization model is needed that determines the most efficient route to safety. Currently, shortest path algorithms, such as Dijkstra's algorithm, Floyd-Warshall's algorithm, or ant colony optimization are used for solving the optimization models. These algorithms, however, are computationally inefficient (Dijkstra and Floyd-Warshall) or may not provide the optimal solution (ant colony optimization). In this thesis, a mathematical programming method will be used to calculate the most efficient escape plan.

Mathematical programming translates the goal of finding the most efficient escape solution to an optimization problem. The goal of this optimization problem is to minimize the total distance travelled by all individuals that are underground in case of an emergency. This is done by setting an objective function, which sums up all the distances travelled by the miners, and a set of constraints, which are used to localize the miners and safe havens. The ensuing problem statement is solved using the network simplex algorithm. This principle was used to calculate escape solutions in four different scenarios: with or without blocked pathways and with or without correcting the distances for the stamina of the individual miner.

Four different types of results were generated: the division of miners among the safe havens, the total distance travelled by all individuals taking part in the evacuation, the path of an individual miner (called Miner X), and the running times of the different scenarios. It was found that blocked paths can have a large impact on the division of miners among safe havens and can significantly increase the total distance travelled. Using stamina categories increases the path length of Miner X (who has a high stamina) and also the running times of the algorithm.

It can be concluded that the algorithm works for all four scenarios. As including blocked paths does not give a time penalty, but will locate trapped miners and send their colleagues on safer escape routes, using this feature has no downsides. The usefulness of adding stamina categories to the algorithm can be debated. The running time of the algorithm increases, while the solutions for realistic numbers of miners do not change. Furthermore, there are philosophical and social questions about the ethics of using these types of categories.

DEDICATION

For my father, mother, brother and sister.

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First and foremost, I would like to thank my father, mother, brother, and sister, who helped me through the exciting, wonderful, terrifying, and stressful period of writing this thesis. My father and brother, who have a good base in programming, were always helpful if I got stuck. I cannot count the times I was lost for a solution, where I got a push in the right direction from them, simply by introducing a new line of sight or by technical support in my code. My mother also helped with this. Whenever I was stressed or out of ideas, she asked me to explain to her what I was doing. This often helped me clear my head, and enabled me to continue working. Also, she came up with the idea of using stamina categories instead of using individual stamina for the miners, which meant I could write a far more efficient algorithm. My sister always offered her encouragement and advice whenever I needed it.

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CHAPTER 1 : INTRODUCTION

1.1 Motivation

Current strategies for mine evacuation are blind and outdated technologies that only require people to run to the predefined locations such as escape ways or refugee chambers during emergencies. In many cases, these predefined routes may pass through danger zones and are definitely not the best choice for dispatching people (Brenkley, Bennett, & Jones, 1999). The most common methodology in underground mining for evacuation starts with releasing stench gas as the evacuation command (Conti, 2005). Upon smelling the stinky gas, miners leave their workplace and start moving towards pre-defined locations. This is a quite blind methodology because; (i) it takes a relatively long time for the air current to reach the people underground (Conti & Yewen, 1997), (ii) Not all people may be familiar with the lay-out of the mine, which may lead to confusion when trying to find the route to a safe haven, (iii) some of the pre-defined escape paths may cross the danger zones (like fires) and miners may approach the danger instead of running away from it, (iv) people may get confused while navigating when the visibility decreases, which could lead to them making decisions while panicking. A smart evacuation technology seems to be needed for the optimized evacuation of underground miners through simulation-based destination determination, accurate localization, and real-time navigation. It should make a correct decision about destinations that individual miners need to reach and navigate the people until they get to a safe haven, as well as sending a real-time report to the disaster manager about the location of all personnel. Additionally, if smartwatches are used, they can record highly valuable data from the performance of the miners during evacuation drills, which can be used for improving the existing evacuation strategies and serve in planning for risk management.

1.2 Research Methodology

The final goal of this thesis is to provide a fast and efficient escape algorithm that can calculate the shortest and safest path of egress in case of an emergency in the underground network of openings in a mine. The algorithm should cater to the specific needs of each individual in the mine. For instance, if twenty miners are at location A, but the refugee chamber at location B can only harbour fifteen people, five miners will get a different route of escape, to prevent overcrowding of the safe haven. In order to set the full scope, the research question is formulated as:

Can mathematical programming be used to write a smart evacuation algorithm for an underground mine?

This question will be answered by looking at the following sub-questions:

- Can an individual path for each miner be determined?
- Can miners that are trapped during an emergency be localized?
- Can the physical condition of a miner be taken into account when determining his escape route?
- What is the computational efficiency of the smart evacuation algorithm?

In order to answer these questions, firstly a literature study on the background of evacuations will be done. Topics that will be touched upon include the types of scenarios in which an evacuation may be ordered, how people react in an emergency situation, what the current methods for mine evacuation are and how miners can be localized underground. The literature research is followed by a chapter on the background of mathematical programming. After this, the method, which consists of two algorithms for mine evacuation (with the second containing categories for the stamina of miners) will be introduced. For the results, four different scenarios will be looked at. For these scenarios, in five different situations, the final outcomes and timings will be discussed and compared. The thesis will end with a conclusion, discussion, and recommendations for future research.

1.3 Case Study

The mine that will serve as the test case for the evacuation algorithms to be presented in this thesis will be a gold mine, which is located in north-central Nevada, USA (Rai, Howell, Weatherwax, Sandbak, & Kallu, 2015). The mine used to be owned for 61.5 percent by the Barrick Gold Corporation (which will from now on be referred to as Barrick) and for 38.5 percent by the Newmont Corporation (Newmont) (Bolin, Fiddes, Olcott, & Yopps, 2020). It is now part of Nevada Gold Mines Joint Venture. The operation consisted of two underground and one surface mine. The algorithm will provide means of escape for one of the underground mines. The mine used in the test case produces 2,700 tonnes of high-grade refractory gold ore per day (Bolin et al., 2020). As of the 31^{st} of December 2019, it has 16 Mega tonnes of proven reserves with an average grade of 11.56 grams per tonne, which leads to 5.9 million ounces of gold in total. In addition to this, there is a probable reserve of 12 Mega tonnes that, at an average grade of 10.28 grams per tonne, could lead to the production of another 3.9 million ounces of gold.

Two shafts provide access to the mine (Bolin et al., 2020; Rai et al., 2015). The First Shaft has a diameter of 6.1 meters and serves as the ventilation outtake. Furthermore, it can serve as a secondary means of egress in case of an emergency. The Second Shaft has a diameter of 7.3 meters, is the ventilation intake, and serves as the primary entrance and exit to the mine. Underground, an extensive system of ramps can be found, which connect the shafts to the deposits. These ramps run for a considerable distance. A third shaft is currently in the planning, to shorten the distance between the entrance, exit, and the deposits.

The ground at the mine is generally soft; the Rock Mass Rating is below 20 (Bolin et al., 2020). This means that, in general, the ground conditions in the mine are poor. The mining method is underhand drift and fill, which is a method that is used often in these types of conditions. Underhand drift and fill is similar to the underhand cut and fill method (Harz, 2014). This method is mainly used in steeply dipping, vein-type ore bodies. The method is expensive but comes with low ore loss and dilution.

In general, the mining sequence in underhand cut and fill mining is upwards (Harz, 2014). Part of the orebody is removed in slices, in a horizontal direction. After the slice has been removed, the void is backfilled. In the this specific underground mine, cemented rock fill is used as a backfill material (Bolin et al., 2020). This is a material that is made above ground in a special plant, and consists of crushed rock, cement powder and fly ash. After it is produced, it is transported underground, where it is deposited tightly to the back and walls of the removed stope.

The difference between drift and fill and cut and fill is that the orebody in drift and fill operations is wider (Harz, 2014; Hustrulid & Bullock, 2001). This means that while working in the horizontal direction, not the entire width of the orebody is mined. Instead drifts are constructed adjacent to each other. One drift is backfilled before mining of the next drift commences. To loosen the ore, both drill and blast and rock cutting methods are used (Bolin et al., 2020).

1.4 Scope

As mentioned in the research methodology, the final goal of this thesis is to build a smart evacuation algorithm for an underground gold mine using mathematical programming. Mine evacuations can be very complex operations, and not every factor that comes into play will be taken into account. In order to give the reader an understanding of which factors are and which aren't considered, a brief description of the scope will be given in this sub-chapter.

As explained in the previous sub-chapter, the goal of mathematical programming is to (in this case) minimize the total distance travelled by all the miners underground during an evacuation. It is therefore important to have a realistic view of the length of the underground pathways. Also, it is important to know which pathways connect to one another. Furthermore, the slope of the pathways is also important (as going uphill requires more energy than downhill). Therefore, pathways going uphill should be given more weight in the objective function. Considering these factors, a network of nodes and pathways (also called arcs) can be made, which serves as the skeleton for the rest of the algorithm.

An evacuation needs only be called if miners are present in underground. Therefore, miners need to be placed in the network described before. As no data on the location of workstations or other important places is available, the miners were placed into the network at random. This, however, had to be done realistically. Miners should not only be located on the nodes of the network, or halfway along the arcs. Therefore, it was made sure the localization was truly pseudo-random, and could have occurred at any point in the network.

Another gap in the data is the precise location of safe havens, and their capacities. Therefore, these locations were chosen at random as well. However, the location of these safe havens was kept equal in all simulations, as, in a normal mining situation, these places do not constantly move over time. The capacity of the refugee chambers was estimated to be thirty miners, while the shafts were set at infinite capacity.

Another thing that was chosen at random is the location of the underground fires. In a normal situation, the presence of fires and smoke is perceived by sensors (or nearby miners). Fires and smoke may spread rapidly, which may lead to changing routes of egress. The model presented here, however, is static. The fires are at set locations, and do not spread. The routes created by the algorithm, then, should be seen as a solution for a specific moment in time. However, by re-running the algorithm with new information from the sensors, the routes of egress can be updated. The solutions, then, are static, but the algorithm can be used dynamically.

CHAPTER 2 : MINE EVACUATION

In this chapter, a literature review will be done on the background of evacuations of underground mines. Topics that will be researched are the causes that trigger an evacuation, management of evacuations, evacuation methods, algorithms used in smart evacuation and the localization of miners that are underground.

2.1 Triggering the Evacuation of an Underground Mine

The company 'Coresafety' is specialised in mine safety. In a 2015 report, they defined what can go wrong in an underground mine and what the proper emergency response is in each case. For each category, there are three levels of seriousness. In this sub-chapter, the situations which require an evacuation of the mine will be looked at. The type of emergency will be described in detail, and the relevance for the mine used in the test case will be evaluated. The following emergencies will require an evacuation of the mine (Coresafety, 2015):

- Fires
- Explosive Fires
- Premature Blast / Explosion
- Impoundment / Slope / Fall of Ground Failures
- Leaks, Spills or Releases
- Severe Weather Conditions / Natural Disasters
- Labour / Civil Disturbances or Distraught Person
- Bomb Threats

2.1.1 Fires

In the period from 2008 to 2018, a total of nine miners died because of fire in metal and non-metal mines in the USA (Casey, 2019). Of the 61 fires in underground metal/non-metal mines in the USA in the period 1991 to 2000, 10 percent were categorized as electrical, 5 percent was due to friction, 46 percent initiated in mobile equipment, 2 percent was due to spontaneous combustion, 16 percent because of cutting and welding and 21 percent due to other causes (Conti, 2001b).

The threat caused by an underground mine fire is not solely the heat and the flames (Adjiski, Mirakovski, Despodov, & Mijalkovski, 2015). Other things that may be harmful are smoke, toxic products of combustion, and poor visibility. All these factors make the evacuation of an underground mine more complicated than in other types of emergencies (such as, for instance, bomb threats). More details about the evacuation process in case of a fire will be given in chapter 2.3.

In case of a mine fire, not only the evacuation is important, but also the response to the incident (which can prevent fatalities) (Conti, 2001b). Although not every element of such an event can be planned, it is important to have an emergency plan. This plan must contain, amongst other things, communication protocols, responsibilities of personnel and in- and outside sources of support. All parties involved should be familiar with the emergency plan, and emergency drills should be undertaken each six months. Human response is further specified in chapter 2.2.1.

According to Conti (2001), the emergency response to fires can be divided into three stages. The first responders are the miners working on location when the fire occurs. These miners may have limited experience and knowledge on firefighting, but it is important they act immediately, as a fire may spread fast. Miners, then, should be properly instructed in how to handle in case of a fire, for instance by training on how to use a fire extinguisher. If two or more miners encounter a fire, one will try and extinguish it and the other will communicate the circumstances to the relevant parties. If a miner discovers a fire by himself, he first tries to extinguish it before calling the surface to report the incident. The second responders to an underground mine fire are the fire brigades. These consist of specially trained and equipped miners. A fire brigade should be on call during each shift that is worked in the mine. In the third stage, sustained responders, also called mine rescue teams, try and rescue people who get trapped in the mine during the fire (or other types of incidents).

2.1.2 Explosive Fires

Between 1880 and 1981, around five-hundred major gas and dust explosions occurred in mines in the United States (Nagy, 1981). Most of these explosions, however, were in coal mines, which, because of the presence of coal dust, have a more prominent source of ignition. Nevertheless, the amount of fatalities because of explosions in metal and non-metal mine exceeds one hundred. Exact numbers are not known, as prior to 1966 it was not mandatory to report these incidents to the authorities. Explosions in these types of mines may be caused by methane, sulphide dust, sulphur dioxide, and gilsonite dust. Ignition may be caused by shorted electrical wires and unshielded flames (smoking).

2.1.3 Premature Blast / Explosion

As mentioned, there are three levels with regards to a premature blast according to Coresafety (2015). In the lowest level, no damage or injury occurs. In the intermediate level, there is sufficient damage to the mine to temporarily disrupt the operations, but no serious injury or property damage occurs. In the highest level serious damage to the mine or injuries have occurred. If premature blasting has taken place, the employee involved shall notify his supervisor and provide him with all known details. Equipment not involved in the accident shall be removed from the area, after which the area shall be secured for investigation. The supervisor will notify the health and safety department, which will start an investigation as soon as possible. The results of this investigation will be reported to the Site Manager. If necessary, corrective action will take place. Out of all injuries coming from blasting related incidents, 11.4 percent is due to premature blasting (Bajpayee, Verakis, & Lobb, 2005).

2.1.4 Impoundment / Slope / Fall of Ground Failures

The lowest level of these type of failures cause no injuries or damage to equipment and limited disruption of the mining operation. The case will generally concern small scale bench/ground failure or an impoundment leak (Coresafety, 2015). In the medium level, no serious injuries occur, but there is significant damage to property and a disruption of the operation. In this case, there is a larger scale bench/ground failure or impoundment leak. At the highest level, the failure occurs on a large scale, and there is a lot of property and equipment damage, together with injuries.

Slope failures, which can best be described as the unanticipated movement of ground, may occur in both open pit and underground mines (Girard & McHugh, 2000). Between 1995 and 2000, 33 miners lost their lives because of these types of failures. In order to avoid these incidents, safe geotechnical designs, secondary supports, and monitoring systems are important. These monitoring systems can be used to evacuate the mine before a slope failure occurs. In case a failure does occur, all personnel needs to be removed from the area and be accounted for (Coresafety, 2015). Relevant parties need to be informed as soon as possible. After this, no one will be allowed into the area, unless they are part of the response team.

Failure of an impoundment can lead to a gigantic release of energy, which may do great damage to people, structures, and equipment (Darling, 2011). If a failure occurs, the effects will be large and serious. To avoid this, the safety factors of embankments, dams, and dikes need to be high relative to other structures. Moreover, the structures will have to be monitored regularly. If a failure does occur, the site manager, mine manager, process manager, and environmental manager need to be informed immediately (Coresafety, 2015). Furthermore, the relevant governmental institutes need to be informed by the mine managers. If chemicals are spilled, the appropriate response procedures must be followed.

Ground fall is a significant contributor to injuries and fatalities in underground mines (Pappas & Prosser, 2003). In the period between 1983 and 1999, a total of 16 fatalities and 140 lost time injuries occurred in American underground stone mines. Ground falls cause more injuries than any other type of incident. Of all incidents, most happened during scaling. Other situations in which ground fall occurred include the handling of explosives, roof bolting, and drilling. If a worker in the mine notices ground fall, he should report this to his supervisor, who will inspect the area and close it off if necessary (Coresafety, 2015). Harm from incidents can be minimized by using the proper safety equipment and providing mining personnel with appropriate training about activities where ground fall may occur.

2.1.5 Leaks, Spills, and Releases

Coresafety (2015) divides up leaks, spills, and releases into three levels of seriousness. The lowest level contains spills of chemicals used for printing or office cleaning. These types of spills can usually be cleaned up by mine personnel, with equipment available onsite. The intermediate level spills contain harmful materials, have a quantity of over 10 gallons, and have the possibility of release into a waterway. The spill, however, can also be cleaned up by materials available at the mine site. Finally, the highest level entails spills that may cause immediate harm to persons or the environment. Toxic material will end up in local waterways in this scenario. Clean-up and containment cannot be done with materials available on site. Regardless of the level of seriousness, a spill report must be completed for every spill occurring in the operation.

Materials that might cause damage when leaked, spilled, or released include hydrochloric acid, ammonia, propane/natural gas, and diesel/gasoline (Coresafety, 2015). In case of a spill of hydrochloric acid, clean-up personnel shall wear full protective clothing, dilute the spill and possible vapours with water. Furthermore, contaminated materials shall be removed to the leach heap area, and spilled solutions shall be returned to the processing circuit. In case of an ammonia spill, emergency services shall be contacted, and everyone not necessary in the clean-up shall be kept away from the spill. If propane or natural gas is released into part of the mine, this area shall be immediately evacuated. Furthermore, all possible ignition sources shall be removed from the spill area. The source of the gas spill shall be shut down, and the area will be ventilated. If fumes are present, they shall be dispersed with water. If diesel or gasoline are spilled, sources of ignition will be removed, the fuel supply will be cut-off and absorbent pads shall be used to clean up the spill.

Another important chemical that is used in gold mining is cyanide (Hilson & Monhemius, 2006). The chemical is not categorized as a toxin, but, nevertheless, can be a deadly poison in high concentrations and have a large impact on a range of ecological species. In high quantities, cyanide can be lethal to both human beings and animals. Symptoms of cyanide poisoning in humans include irregular heartbeat, convulsions, chest pains, and vomiting. An important risk that comes with the use of cyanide is that it leaks into the environment from the tailings pond or from other areas where the chemical is kept. This can have adverse effects on local communities and wildlife.

2.1.6 Severe Weather Conditions / Natural Disasters

Examples of severe weather conditions include high winds, extreme precipitation (including heavy snow), and lightning (Coresafety, 2015). Natural disasters include earth movements, floods, and earthquakes. As floods and earthquakes may have very serious consequences for the operation, they will be treated in separate subchapters. The three emergency levels for severe weather are as follows. The lowest level concerns weather events that cause no damages or injuries and give limited disruption to the operations. The intermediate level includes incidents that cause material damages, disrupt the operations, but not cause serious injuries. The highest level includes damages, injuries, and disruption of the operation. In case of severe weather or natural disasters, the shift manager should notify the department head or site manager, and lead his team to safety.

2.1.7 Floods

Flooding of underground mines, or inundations, may have several causes or reasons (Vutukuri & Singh, 1995). According to Vutukuri and Singh (1995), there are three categories: Event Controlled Inundation, Accidental Inundation, and Spontaneous Inundation. As mine closure is not dealt with in this thesis, event controlled inundation will not be treated any further. Spontaneous Inundation, or inrushes, are associated with karst aquifers. Limestone is also not dealt with in this thesis, therefore this topic will also not be elaborated on anymore. Accidental inundations can be triggered in different situations. Vutukuri and Singh give the following main reasons:

- Contact with surface water (pond, river, canal or stream)
- Contact with surface unconsolidated deposits (glacial or organic)
- Strata water entering working
- Clearing of old shafts
- Contact with abandoned old workings
- Failure of an underground dam, seal or leakage of a borehole

If a flood occurs, appropriate action should be taken. If the water is deeper than one foot (or unknown) or flowing very fast, it should not be crossed and discretion should be used (Coresafety, 2015). When in a vehicle, four-wheel drive should be engaged and the brakes should be tested. If a vehicle stalls in the stream, help should be called.

2.1.8 Earthquakes

In general, underground openings suffer less from earthquake damage than structures on the surface (Sharma & Judd, 1991). Sharma and Judd (1991) did a data analysis of 192 reports on 85 earthquakes and looked at six categories to see how underground structures are damaged during these events. These categories are the extent of damage, overburden, predominant rock type, geographic location, magnitude and epicentral distance of the earthquake. From their analysis they reached the following conclusions:

- Damage decreases with increasing overburden depth
- Peak ground acceleration, which depends on magnitude and distance to the epicentre of the earthquake, can be related to the amount of damage
- Underground structures in colluvium suffer more damage than openings in a competent rock

To give an idea of how much damage to underground openings is done during earthquakes in relation to structures on the ground: in the 192 reports analysed by Sharma and Judd, 94 cases of underground damage were reported, compared to thousands of structures on the ground.

Coresafety (2015) gives the following three levels of seriousness in case of an earthquake. At the lowest level, the earthquake is noticeable to most people on the surface, but no damage or injuries occur. At the intermediate level, everyone notices the earthquake. Injuries and damage occur, and the operation is disrupted. At the highest level, people are severely impacted by the earthquake. Extensive damage, injuries, and sometimes fatalities may occur. Operations are deeply impacted or possibly shut down.

2.1.9 Labour / Civil Disturbances or Distraught Person

Again, Coresafety divides the seriousness of labour, civil, or distraught person disturbances up into three categories (Coresafety, 2015). At the lowest level, the threat is non-violent, the mining operations are not disturbed, only minor criminal acts take place, and the publicity can be kept to a minimum. In this case, evacuation of the mine is not necessary. At the intermediate level, threats or acts of violence have been made, a group of demonstrators consists of fifty to one-hundred persons and publicity on the event is likely. Finally, at the highest level, the situation is quite violent, demonstration groups are larger than one-hundred persons, publicity will be significant and the operations will be disturbed. In the latter two cases, the mine will have to be evacuated.

Out of the thirty largest strikes in the history of the USA, three were organized among miners (Frohlich & Harrington, 2020). Moreover, the largest strike in the country's history was the 'United Mine Workers of America Strike' in 1946. A total of 400,000 workers were on strike for over eight months. However, as mentioned, the strike took place in 1946, which raises the question of whether strikes of this magnitude could occur in the present day. The most recent large mining strike in Frohlich and Harrington's article took place in 1993. However, evidence of smaller strikes in the USA, as recent as 2019, has been found (Sainato, 2019). It can be concluded, then, that the chance of a strike is not only present but could turn out to be quite a large ordeal.

Evidence of anti-mining protests in Nevada has been found (Associated-Press, 2014; Spillman, 2020). However, the information did not contain indications for a large outbreak of anger towards mining companies in this part of the USA. The risk of civil disturbances, then, can be categorized as low to medium, and evacuation because of such an event is unlikely.

2.1.10 Bomb Threats

Bomb threats can be also divided up into three levels of seriousness. At the lowest level, the threat is not really specific (Coresafety, 2015). Details such as the type of bomb, time of detonation, and ransom demand are not specified. On this level, no evacuation or localisation of the bomb is needed. With the intermediate level, these specifics are named in the threat, but the real danger is assessed to be low. In this case, the mine needs to be evacuated, but no search for the bomb will be conducted. Finally, at the highest level, all the specifics are included with the threat and it is categorized as credible. In this case, the mine needs to be evacuated and a search for the bomb needs to be conducted.

Could bomb threats be an issue at the mine that serves as the test case? In 2018, in the United States, a total of 1,627 bomb threats were made (USBDC, 2018). In the same period, 289 actual bombings took place. Furthermore, 426 fake bombs were planted. Literature does not provide specific numbers on how many threats and actual bombings took place in Nevada, or at mining companies in the same year. However, if one digs deeper into the numbers provided by the United States Bomb Data Centre (USBDC), one finds that less than ten of the bombings have taken place in Nevada. Furthermore, of 7,305 explosive recoveries (explosives that were found and made inoperable), only 15 were done at mining companies. All things considered, it is not very likely that the mine will have to be evacuated because of a bomb threat, but it is a possibility, and protocols should be in place in case it happens.

2.2 Management of Evacuation in Underground Mines

2.2.1 General Human Reactions in an Emergency

In an emergency (more specifically during a fire) where an evacuation is called, people generally tend to react within a fixed pattern (Kuligowski & Gwynne, 2010). Kuligowski and Gwynne (2010) describe the following five behavioural facts:

1. People's first instinct is to feel safe in their environment.
2. People will engage in information seeking actions, especially when cues are ambiguous and/or inconsistent.
3. People act rationally and altruistically during (*building*) fires.
4. People are likely to engage in preparation activities before beginning their evacuation response.
5. Once they begin the evacuation movement, people tend to move to the familiar.

What do these facts mean? Fact one relates to the fact that in any type of emergency, people's initial reaction is believing that they are safe (Kuligowski & Gwynne, 2010). This phenomenon is known as the normalcy bias. If the information provided on the emergency is inconsistent or ambiguous, this bias may persevere. According to the second fact, if the information provision remains this way, people will start collecting information by themselves. They will form groups, discuss the event unrolling, and start looking for clues on what is going on in their environment. Once the evacuation gets going, people will not tend to panic, but help others and make rational decisions (as described in the third fact). However, before they start evacuating (according to the fourth fact), people will, for instance, gather their belongings and put their coats on. Finally, as explained by the fifth fact, people will take routes they know towards exits they are familiar with.

The research done by Kuligowski and Gwynne was mainly focused on evacuating buildings during a fire. Although there are some parallels (which is the reason why a brief description of their work was given), evacuating a mine is a different business (Kowalski-Trakofler, Vaught, Brnich, & Jansky, 2010). The first reactions during the evacuation of an underground mine are extensively described by Kowalski-Trakofler et al. (2010). A visualization of their version of emergency response is given in Figure 1. The steps in this figure will be described in more detail.

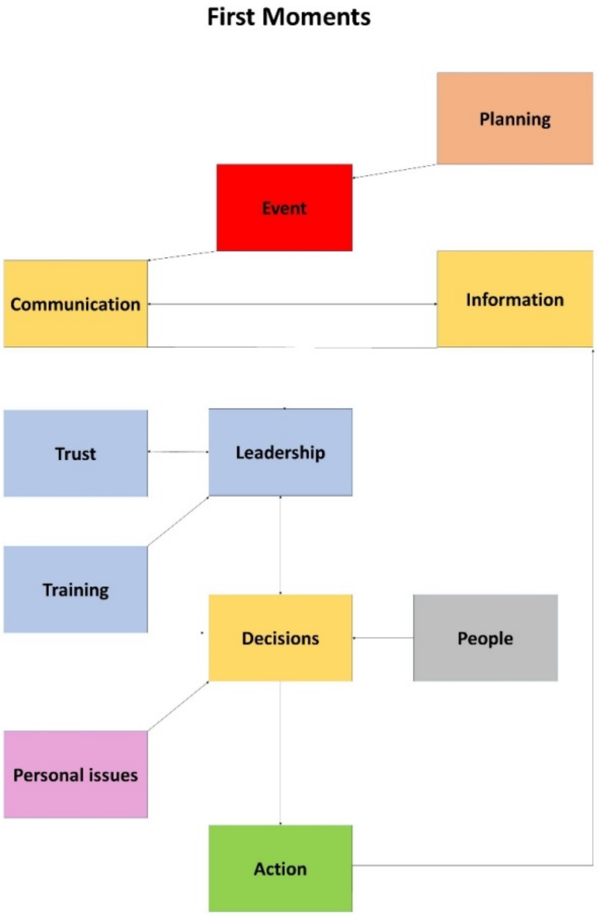

Figure 1: : Framework of First Moments in Mine Emergency Escape (Kowalski-Trakofler et al., 2010)

2.2.2 *Planning for an Evacuation*

In the United States, having an emergency response plan for a mining operation is regulated on a federal level (Kowalski-Trakofler et al., 2010). Although some companies see this response plan as a set of written regulations that can be pulled off the shelf when necessary, it should be seen as a dynamic continual process. The most important aspect of an emergency response plan is preparedness. A lot of research has been done on this topic, and several theories exist on how to be best prepared for an emergency. However, in general, one can distinguish three types of knowledge that are important for miners in the case of an evacuation. Firstly, there is technical knowledge, which means that miners should have the know-how on how to operate emergency equipment, such as 'Self Contained Self Rescuers' (SCSR's), lifelines, and refugee chambers. Secondly, there is mine specific knowledge, which is knowledge on the mine layout and the emergency response plan. Finally, conceptual knowledge entails the ability to think during an emergency and to adapt to changing circumstances.

Miners, when interviewed about emergency planning, indicate the following points as being important (Kowalski-Trakofler et al., 2010) (p. 13-14):

- A plan will help to manage the emergency.
- The miner should know the emergency plans thoroughly.
- Everyone should be trained on the response plan.
- Flexibility is important: the plan should be revisited if the situation changes.
- Being prepared for emergencies should be a priority.

2.2.3 Communication and Information

In order to be able to communicate, the communicator needs information (Kowalski-Trakofler et al., 2010). Therefore, the initial response to an incident is dependent on this information and how it is communicated. The 'National Institute for Occupational Health and Safety' (NIOSH) has developed an emergency triangle, which consists of three pieces of initial information, and three pieces of secondary information. The primary information covers who, where, and what. The secondary information contains the miners (people involved), event, and response. Whether an individual believes the information that is presented to him depends on credibility and content. Credibility makes for quicker response, while content can improve the initial reaction. If the information is incredible or has ambiguous content, people will likely interpret their situation as non-threatening (as also explained by Kuligowski and Gwynne).

Workers also agree that the right information and how it is communicated is crucial for the initial response to a mine emergency. In general, the information which falls within the emergency triangle is considered most important. Furthermore, the source of the information is of importance in how miners interpret what they hear. This, often, comes down to whether a miner trusts the source of the information. Furthermore, there is an altruistic component (which was described before): miners and rescuers tend to take more risks if other people are involved. Finally, there is a time component. Initial information may not be enough to make a good decision on what to do. Therefore, it can be recommended to ‘make haste slowly’.

2.2.4 Training

Training, which may come in many different forms, is considered a crucial part of the emergency response planning process (Kowalski-Trakofler et al., 2010). Training allows for the procedures in place to be tested. Furthermore, it gives responders a chance to come together and bond. Training should go further than rote learning and passive teaching methods. Simulated emergencies and reliance on self-rescue should be the cornerstone of training programmes. Especially self-rescue is important; studies have shown that chance of survival is higher if miners have a self-escape strategy. If the focus lies on rescue teams, the survival rate drops. Besides this, miners should know where to assemble in case of an emergency. If assembling takes too long, miners could be exposed to additional risks. Miner themselves urge training should not only cover emergency response, but also decision making in case of an emergency. Furthermore, they urge for hands-on training (for instance in how to use a fire extinguisher). For coal miners, initial training of 48 hours is required, followed by 8-hour refresher each year and monthly fire drills (Cole, Vaught, Wiehagen, Haley, & Brnich, 1998). This type of training, however, may not give miners the tools they need when making decisions in an emergency situation (as will be described in the next sub-chapter).

2.2.5 Decision Making

According to Kowalski-Trakofler et al. (2010), decision making in an emergency relies on the quality of the information that is received and the technical communication system in place. As one decision will lead to (and affect) other decisions, the process can be seen as iterative. Furthermore, the experience level of the miner in question is important in his decision-making process. Also, in an emergency situation, there are often multiple decision-makers. It is important, however, to make the decisions in an emergency quickly as the event unfolds. There simply is no time to consider every possibility. This requires template style thinking, for which experienced decision-makers are needed.

Twelve identifiable factors, divided up into five categories, can have an influence on decision making. These are:

- Situational
    - Circumstances
- Organizational
    - Roles
    - Objectives
- Cognitive
    - Information
    - Communication
    - Knowledge
- Autonomic
    - Training
    - Instinct
- Psychological
    - Stress
    - Fatigue
    - Adrenaline
    - Fear

Some of these factors are considered more important than others. Circumstances, for instance, have a big influence on the decision making process. These circumstances can range from straightforward to chaotic, and are influenced by things such as the type of incident and the amount of people involved. Besides this, the roles people play in an emergency are important. If people are calm and confident, they tend to make better decisions. Finally, information plays an important role. As described before, things like source, certainty, and accuracy have a big influence on whether the right decisions are being made.

Decision making in mine emergencies has been described more in-depth by Cole et al. (1998). In a mine emergency, there is often no obvious best solution to problems. Information might be incomplete or faulty. Each choice may have pros and cons and, when made, be irreversible. Furthermore, even the most experienced mine rescue professionals may make the wrong decisions. Decisions that were right in the past needn't be right in the future. Also, miners are taught to react according to pre-set rules in case of an emergency. However, these rules may be impossible to follow in real-life cases. For instance, trapped miners might not make it to assembly points. If the rule is to evacuate only if every worker is accounted for, this may lead to unworkable or even dangerous situations. Training, then, does not always give the right tools for decision making.

2.2.6 Personal Issues

There are many personal issues that may influence one's response to a mine emergency (Kowalski-Trakofler et al., 2010). Physiological and emotional state are important factors in how miners react. Furthermore, people tend to take more risks to help one another if they have personal or professional bonds (which links to the altruism discussed before). Also, rescue teams and other responders have to cope with personal issues, as in an emergency they will work long shifts with heavy duties. Besides this, mine emergencies may have a traumatising effect on the people involved. Finally, fear may influence one's behaviour, which can cause workers to freeze or otherwise react irrationally.

2.2.7 Other Aspects

Behaviour during an emergency depends on whether miners understand the situation, know their respective roles, understand the procedures in place and perform the necessary actions efficiently (Mallett, Vaught, & Brnich Jr, 1993). Basically, this sequence of behaviours depends on three pillars: interpretation, preparation, and action. Proper interpretation of a warning message depends on five characteristics. Firstly, the message should have a certain level of specificity, secondly, it must have historical validity, thirdly it must be clear who is in danger and to what extent, fourthly, it should be rapidly verifiable and fifthly it should contain cues for further action. The most important issue regarding preparation is the understanding of one's tasks during an emergency. Well trained people switch more easily to their specific role. Furthermore, if well trained, miners will better recognize colleagues with authority in an emergency. Finally, in order to take appropriate action, the credibility and content of the message are important. Again, people's first reaction in an emergency tends to be disbelieve. If the situation is communicated well, it is more likely people will react in better ways.

2.3 Current Evacuation Methods

2.3.1 Conventional Evacuation Methods.

Conventional methods can be divided up into passive and active guidance systems (Brenkley et al., 1999). Passive systems can best be described as localization in terms of objects. These can be objects belonging to the operation, such as machines and conveyor belts, or objects that are specifically present for evacuation, such as signage and lifelines. Active guidance systems give the evacuees visible and audible signals about the direction in which they should head. These types of systems are usually electronic. Different passive and active guidance methods will now be described, giving both their advantages and disadvantages.

One passive method is hanging signs with directions towards the nearest exit or refugee chamber on intersections in the network of mining pathways (Brenkley et al., 1999; Chasko, Conti, Lazzara, & Wiehagen, 2005). This method is cheap and effective in conditions where the sight is clear. However, when the sight is limited, for instance, because of smoke, it is harder to see the signs and therefore harder to find the route of egress. This lack of visibility gets even worse if the signs are not cleansed regularly, and get covered in mining dust or other pollutants.

Another passive method of indicating escape ways are, as mentioned, lifelines. These lifelines begin at the outermost workstations in the mine and lead to the exits (Conti, 2001a). They can therefore be several kilometres long. The lifeline is usually installed at a height of about two metres, although this height can be less when the roof is low. In order to give a sensible cue of the direction of egress, conical shapes are installed on the line (an example is given in Figure 2). One has to move in the thickening direction of the cone. This way, it is not only clear for the evacuee in which direction to head, but he also does not have to take his hand off the line when passing one of the cones.

Figure 2: Lifeline with cones indicating direction of egress (Conti, 2001a).

Over to the active escape aid systems. Brenkley et al. (1999) describe an ‘Egress Beacon System’ designed by IMC. This system gives both visual and audible cues about the route to safety in case of an emergency. The beacons in this system have a red and green LED facing in opposite directions. In an evacuation scenario, the egress route is marked by the green lights, while in the opposite direction (away from safety), red lights are visible. The system is visualised in Figure 3.

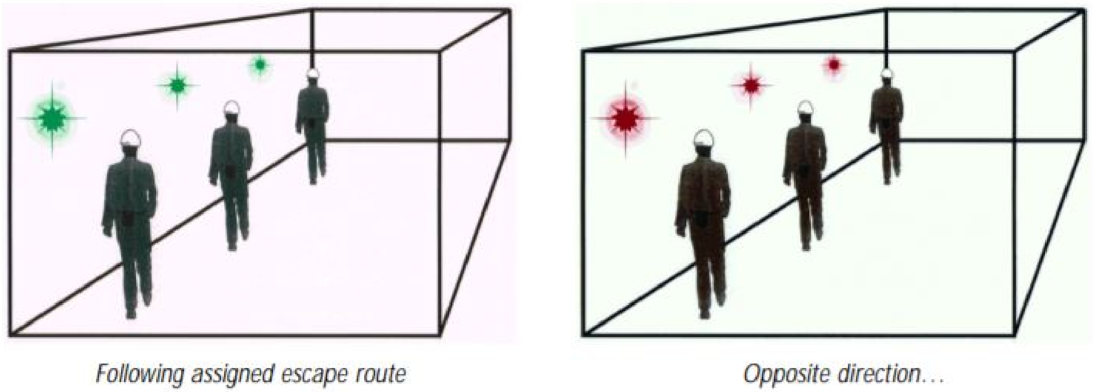

Figure 3: IMC Egress Beacon System (Brenkley et al., 1999).

The LEDs used in this system have a relatively high rate of optical penetration in case of low visibility conditions. However, in cases of very thick smoke, or for workers with severe red-green colour-blindness, the visual cues may not be sufficient. In order to augment the system, audible signals are given to the people escaping the mine. The pitch of the sound leads the evacuees in the right direction. The beacons in the system are connected to a power line. In case of a power failure, they contain batteries to keep them functioning. Moreover, they can function independently, so the failure of one of the beacons does not mean the others are affected.

Laser pointers can also be used as an active means of evacuation (Conti, 2001a). Lasers have an even higher penetration rate through smoke than LEDs. The beams coming from the lasers can, like LED's, be green and red in colour. Furthermore, they are cheap, light, and easy to use. Conti (2001a) states that lasers in combination with lifelines are very reliable means of evacuation.

Finally, high-intensity strobe lights can be used as a means to indicate the route of egress in case of a mine emergency (Chasko et al., 2005). They are battery-powered, and can be used for at least seven hours. They can be activated, in case of an emergency, by a through-the-earth signal. Several colours were tested, and again green gave the highest rate of penetration through the smoke. Practice evacuations using strobe lights have proved to be successful, even when miners had to abandon the lifelines they were holding.

2.3.2 Smart Evacuation

It has been proven, in a virtual reality environment, that smart evacuation, is faster than conventional methods (Gaab, 2019). What is smart evacuation? According to Gaab (2019), smart evacuation systems are ‘real-time evacuation guidance systems that are adaptable to changing conditions such as location and spreading of fire and resulting safest and fastest exit routes’ (p. 23). These types of systems use real-time localisation of the miners. This localisation will be further explained in chapter 2.5. Also, the locations of things such as fires or cave-ins can be monitored by these systems. Using this information, the system can calculate the fastest and safest route of egress in case of an emergency. This route can be sent to smart-devices carried by the miners or to other escape route indicators in the mine. In the following chapter, the different types of algorithms used by smart evacuation systems will be looked at and their advantages and disadvantages shall be discussed.

2.4 Algorithms

For this thesis, mathematical programming is used to find optimal evacuation routes. There are, however, other algorithms that can be used. The most significant methods will be described in this chapter.

2.4.1 Dijkstra’s Algorithm

Dijkstra’s algorithm is a commonly used method to calculate the most efficient path of egress in smart evacuation systems (Hong, Li, Wu, & Xu, 2018; Hughes, 1990). The algorithm has two different methods in which it can be used, depending on the type of network for which a path needs to be calculated (Dijkstra, 1959). The first of these types is a tree, which is a network in which there is only one possible path between two nodes. As this is not the case in underground mines, the method to calculate the shortest paths in trees is omitted and only the method to determine the paths in a more complicated network will be described.

In order to explain Dijkstra’s algorithm, firstly the conceptual setting needs to be explained. Dijkstra describes a network as a collection of nodes, which are connected by edges (Dijkstra, 1959) (another word for edges is arcs, these words can be used interchangeably). Each of these edges has a certain weight assigned to it, which can be seen as the distance between the two nodes it connects. The objective is to find the shortest path between two nodes (which, for the sake of the argument, shall be called P and Q). Dijkstra states that if a third node (called R) lies on the route between P and Q, then the shortest path between P and R is part of the shortest route between P and Q. By breaking the route up into a series of shortest paths between intermediate nodes, one can eventually find the shortest path between the begin and end node.

How is this done? Firstly, the nodes in the network need to be divided up into three categories (Dijkstra, 1959). The first category contains nodes for which the shortest distance from the starting node (node P) is known. The second set contains the nodes from which the next node that will be added to the first category will be determined. Also, there is a third category, which contains the remaining nodes. Besides this, the edges that connect the nodes are also divided into three categories. The first category are the edges that connect the nodes that lie on the shortest path between P and Q. The second category contains the edges that might be transferred to category one. The final category contains all other edges. When one starts solving the problem, all nodes and edges belong to the third category. As a first step, node P is transferred to the first category. Now, repeatedly two steps have to be performed. In the first step, one needs to consider all edges that connect the last node that was transferred to the first category with the nodes in the last two categories. One has to see if these connections lead to a shorter path to these nodes than was previously discovered. If this is not the case, this edge is rejected and will remain in the last category. If an edge is found to give a shorter route between node P and R, both the edge and node R go to the second category. In the second step for each node in the second category, the shortest route to node P is determined. The node with the shortest distance is transferred to the first category, just like the corresponding edges. One then goes back to the first step until node Q is transferred to the first category and the shortest route is found.

Dijkstra's algorithm is one of the oldest and most popular algorithms for calculating a shortest path (Dramski, 2012; Fan & Shi, 2010). It is, however computationally inefficient (with a running time of $O(n^3)$ (Bari, 2018)) and cannot take into account negative edges in the network. A lot of research has been done into making the algorithm more efficient, which has led to methods related to Dijkstra's, each with their own advantages and disadvantages.

2.4.2 Floyd-Warshall Algorithm

Another method that can be used to compute the shortest path is the Floyd-Warshall algorithm (Hougardy, 2010). According to Hougardy (2010), it is widely used and relatively simple. Just like Dijkstra's algorithm, Floyd-Warshall's method works on a network of nodes that are connected by edges (again, it will be assumed one is not dealing with tree networks). The worst-case runtime of the algorithm is $O(n^3)$. If used correctly, the method will always return the shortest route between all nodes in a network. However, it does not work in networks where some of the edges have negative values. As this is not the case in an underground mine, these types of networks will not be dealt with in this thesis.

How does the Floyd-Warshall method work? In order to understand the algorithm, one needs to comprehend the following equation (Bari, 2018):

$$A^k[i,j] = \min(A^{k-1}[i,j], A^{k-1}[i,k] + A^{k-1}[k,j]) \qquad [1]$$

In order to understand this equation, one has to start at the very beginning, when $k = 0$. In this stage, one has to make a $n*n$ matrix (where n is the number of nodes in the network). In this matrix, one depicts the lengths of the paths between the different nodes. If nodes have no path between them, one indicates this with the symbol for infinity (∞). The distance from nodes to themselves will always be zero.

Once the matrix at $k = 0$ (which, from now on, will be called A^0) has been made, it is time to move to the matrix at stage $k = 1$ (A^1) (Bari, 2018). In this stage, one will check if a route between node i and j is shorter if one passes node 1 on the way. If this route is indeed shorter, one will replace the value at location A[*i,j*] with the value of the newly found route. If traveling past node 1 takes longer than the current length at A[*i,j*], one keeps the existing value in the matrix. One continues to check for all *n* nodes to see if routing past node *i* gives a more efficient route. If this is done, one has the full matrix A^1. Now one moves to value $k = 2$, and goes to see if routing past node *2* is more efficient. These steps have to be repeated until one has finished step $k = n$, and completed the matrix A^n. If the method is properly executed, this matrix should give the shortest routes between all *n* nodes.

2.4.3 Ant Colony Optimization

Another method for finding an efficient route of egress in case of a mine emergency is ‘Ant Colony Optimization’ (ACO) (Guangwei & Dandan, 2013). ACO is inspired by foraging ants (Mirjalili, 2018b). Ants are blind, and therefore, initially, seek food at random. However, they do leave a trail of pheromones while they are on their way. Once they have found food they follow the pheromone trail back to their anthill, leaving new pheromones, making the trail stronger. The crux of the matter is that ants are more likely to follow the stronger pheromone trails. As, over time, the shorter routes to food will have more deposited pheromones on them, more ants will use the more efficient routes. Note however that the most efficient route found isn’t necessarily the optimal route. Especially if only small amounts of ants have gone out, the solution might be sub-optimal.

How can ACO be used as an algorithm to find the shortest path? There are several formulas used to define an ACO network, but the most important one is as follows (Mirjalili, 2018a):

$$P_{i,j} = \frac{(\tau_{i,j})^{\alpha} * (\eta_{i,j})^{\beta}}{\sum((\tau_{i,j})^{\alpha} * (\eta_{i,j})^{\beta})} \qquad [2]$$

Where:

- $P_{i,j}$ is the chance an ant uses an edge that connects node *i* to node *j*.
- $\tau_{i,j}$ is the amount of pheromone on the edge that connects nodes *i* and *j*.
- $\eta_{i,j}$ is the inverse of the length of the edge between nodes *i* and *j*.
- α and β are parameters used by operators to add specific weights for either pheromone trails or edge lengths.

In ACO simulations, a number of ‘ants’ is send out to find their way, through the network of mining tunnels, to a safe haven. From there, they return to where they came from, where they ‘die’. After this first step, an initial amount of pheromone is deposited. In some cases, evaporation takes place, in which some part of the pheromone that is present in the network is removed. After this, the process of going out, depositing pheromone, and evaporation is repeated for a certain amount of times. The shorter routes will, over time, have more pheromone deposited on them, which makes it more likely that ants will choose this specific trail. After the simulation has ended, one ends up with a probability distribution, where each route is assigned a likelihood that an ant would take this route. The routes with the higher probabilities will be more efficient, and can therefore be used for evacuation.

ACO has a number of advantages and disadvantages (Abdmouleh, Gastli, Ben-Brahim, Haouari, & Al-Emadi, 2017). According to Abdmouleh et al. (p. 274) the advantages are:

- Multiple routes can be investigated in one simulation (more than one ant can be sent out at once).
- A fast route of egress can be found relatively fast.
- It is easy to adapt to changes in the network, such as new drifts in the mine.
- The solution will converge to the optimal solution.

Disadvantages are:

- Possibly a different probability distribution after each iteration
- Theoretical analysis may be difficult.
- Dependant sequences of random decisions.
- The route is found more by experimental than theoretical research.
- The time it takes for convergence to be reached is uncertain.

2.5 Localization of People in an Underground Mine

In order for smart evacuation methods to work, the position of the workers in the mine needs to be (constantly) monitored. For open-pit operations, this can be done using the ‘Global Positioning System’ (GPS) (Huang, Zhu, & Lu, 2010). However, the satellite signals that are needed to localize workers or machinery do not penetrate (deep) into the ground. Therefore, an alternative system is needed to track the locations of miners that are underground. Several of these systems exist and include Radio Frequency Identification (RFID), Bluetooth, Wi-Fi, and Wireless Sensor Networks (WSN). In this chapter, each of the technologies behind these methods will be described.

2.5.1 RFID

RFID systems work by making a connection between what are called tags and readers (Radinovic & Kim, 2008; Rusu, Hayes, & Marshall, 2011). This connection is made by electromagnetic waves (also called radio waves). Tags can be worn by miners or be attached to vehicles, and contain information about the wearer. The tags consist of an integrated circuit, an antenna, a connection between the circuit and the antenna, and a substrate. The information about the wearer of the tag is stored on the integrated circuit. Through the antenna, this information is communicated with the readers, which on their turn are connected to a computer that processes the information. The tag can be powered by a battery (active systems) or by radio waves (passive systems). However, in order to be powered by radio waves, one needs to be close to the reader. For real-time localization of miners, active systems are used.

As mentioned, the localization of the miner is determined by the communication between the tag and the reader (Radinovic & Kim, 2008). One method for calculating the position is through difference in time of arrival. For this method, contact between the tag and at least three readers is required. The time difference between the arrivals of radio waves at the different readers is used to triangulate the location of the wearer of the tag. Another method is the received signal strength indicator (RSSI). This method uses the strength of the radio signal to determine the location of the tag. Finally, the time-of-flight method measures what time it takes a tag to respond to the signal from a reader.

2.5.2 Wi-Fi

The location of a miner can also be determined by using a wireless local area network (WLAN) (the specific name is 802.11b) (Radinovic & Kim, 2008). This type of localization also uses the RSSI principle (Mohapatra et al., 2020). Miners can carry a smart device that is connectable to the internet. The closer the miner is to a wireless access point, the stronger the connection is with the smart device. An advantage of this method is that the smart device can, at the same time, be used for smart evacuation.

2.5.3 Bluetooth

Bluetooth uses a signal similar to the one that is used for Wi-Fi (Radinovic & Kim, 2008). However, while Wi-Fi sticks to one channel, Bluetooth can use several channels. This makes it useful in circumstances where there is a lot of ‘background noise’ on the transmission frequencies. Other advantages of Bluetooth systems are that they offer good signal detection, are relatively cheap to deploy, and that it is easy to develop apps for the systems that Bluetooth is run on (Baek, Choi, Lee, Suh, & Lee, 2017). Moreover, Bluetooth devices can communicate with one another. This means smart devices can indicate whether there are colleagues near your position during an evacuation.

2.5.4 WSN

WSN give the possibility of a localization method that is not yet discussed in this chapter: fingerprinting. Fingerprinting is based on the RSSI principle: the signal strength between a miner and sensors in the mine is measured (Chehri, Fortier, & Tardif, 2009; Yiu, Dashti, Claussen, & Perez-Cruz, 2017). However, in the case of fingerprinting, the location of the miner is not determined by triangulation. Instead, a map of sensor patterns is used. This map is made before the operation is started. The values that are read from the sensors are compared to patterns corresponding to known locations of miners or vehicles in the mine. These known patterns are stored on a computer. Once the operation is started, the values of the sensors are constantly compared to the patterns on the computer. By finding the pattern that is most similar to the readings of the sensors, one can get an idea of the location of a miner or other objects. An advantage of this system is that the sensors can not only measure the location of miners but also parameters like temperature and air quality. A disadvantage is that only a limited number of patterns are stored: not every scenario has its own fingerprint. Furthermore, this type of localisation does not take the identity of a vehicle or miner into account. An example of a WSN is a Zigbee system, which has proven to be applicable in underground mines (Huang et al., 2010).

2.5.5 Image-Assisted Person Location

A final localization method that will be mentioned here is Image-Assisted Person location (IPL). This system assumes miners wear a lamp on their helmets when they work in the mine (Niu, Yang, & Yin, 2018). By giving each of the lights emitted from these lamps a unique shape (for instance triangles or circles) a miner can be identified by the looking at the specific pattern of this light. The lights are read by special cameras, which communicate this with a computer at the base station. This system can determine the location of miners with relative accuracy.

2.6 Synthesis

In this chapter, it has become apparent that there are many reasons why a mine may be evacuated. Furthermore, there is a significant probability that a worker will have to evacuate the mine she works in at some point in her career. Therefore, it is important that a miner is well prepared for an evacuation. Traditional methods are outdated and may not give workers the safest and most efficient route of egress. With smart evacuation, this problem can be solved. For smart evacuation to be efficient, the location of miners needs to be monitored digitally. Several methods for doing this exist. Furthermore, there are several algorithms that can be used for smart evacuation, they do however lack efficiency or do not necessarily give the optimal route of egress. What is needed, then, is a method for smart evacuation that runs efficiently and determines the optimal route for each individual miner. An attempt at this will be presented in the next chapters.

CHAPTER 3 : MATHEMATICAL MODELING OF EVACUATION

3.1 Mathematical Programming and the Minimum-Cost Network Flow Problem

The task of finding the optimal evacuation routes for each specific miner during an emergency in an underground mine can be modelled as a ‘Minimum-Cost Network Flow Problem’ (MCNFP), which, on its turn, can be solved using mathematical programming. This section explains the problem statement and the approaches for solving it.

Mathematical programming can be used to solve optimization problems (Winston & Goldberg, 2004). In their book ‘Operations Research: applications and algorithms’ (2004) Winston and Goldberg describe a mathematical programming problem as follows (p. 53):

- It is attempted to maximize (or minimize) a linear function of decision variables. The function that is to be maximized or minimized is called the objective function.
- The values of the decision variables must satisfy a set of constraints. Each constraint must be a linear equation or linear equality.
- A sign restriction is associated with each variable. For any variable x_i, the sign restriction specifies that x_i must be either nonnegative ($x_i \geq 0$) or unrestricted in sign (urs).

The divisibility assumption is an important characteristic of mathematical programming. This assumption states that each variable x_i is allowed to take fractional values. This, of course, is not the case in mine evacuation scenarios (one cannot split miners into fractions). Therefore, a special type of mathematical programming, called integer programming, where the optimal integer solution is determined, will be used for all optimization problems in this thesis.

The mathematical programming representation of an MCNFP, as described by Winston and Golberg (2004), is stated below.

$$min \sum_{all\ arcs} c_{ij} * x_{ij} \qquad [3]$$

$$s.t. \sum_{j} x_{ij} - \sum_{k} x_{ki} = b_i \qquad [4]$$

$$L_{ij} \leq x_{ij} \leq U_{ij} \qquad [5]$$

Where

- x_{ij} is the number of units of flow sent from node i to node j trough arc (i, j).
- c_{ij} is the cost of transporting one unit of flow from node i to node j via arc (i, j).
- b_i is the net supply (outflow minus inflow) at node i.
- L_{ij} is the lower bound on flow through arc (i, j).
- U_{ij} is the upper bound on flow through arc (i, j).

In the objective function (equation 3) the length of the arc between two nodes, c_{ij}, is multiplied by the number of miners, x_{ij}, that take this route when they are heading for the exit. The total distance that miners need to travel altogether is minimized. It should be noted that, c_{ij} is not only based on the distance between nodes (Adjiski et al., 2015). Influences like the slope angle of the path, the temperature and quality of the air can be incorporated in this parameter, as to not only to calculate the shortest route, but also one that is safe and efficient. In this thesis, only slope angle, closed pathways and the stamina of the miners are considered.

Constraints (as given in equation 4) describe the difference between the flows that lead towards a node (x_{ij}), and the flows that go away from it (x_{ki}). By setting parameter b_i to a certain value, locations where miners are located at the time of an emergency and the nodes where they can find a safe haven can be simulated. For instance, if a worker is present at node 1, b_1 can be set to one. This way, a worker is introduced in the network of nodes and arcs. If a refugee chamber at node 2 can house ten people, b_2 should be set to more or equal than minus ten. This way, when a miner reaches a safe haven, he ‘disappears’ from the system. Keeping b_i zero at nodes where nothing is happening, makes sure that all miners arriving at this node will have to leave as well. This way, miners have to keep passing ‘empty’ nodes until they find a safe haven.

Equation 5 defines the capacity constraints for the arcs. This can avoid the arcs becoming overly crowded. In this thesis, however, no capacity for the arcs is used, assuming the fact that mining access roads are wide enough for the passing of a large number of people.

The programming to solve the problem of getting mine workers from their workstations to a safe haven will be done using the Python language. Special note needs to be made of the GUROBI library that solves the minimization problems using the network simplex algorithm.

3.2 Steps of the Algorithm

Four scenarios are tested in this thesis. In the first scenario, the arcs for all miners have the same weight, and none are inaccessible (for instance due to fire or smoke). In the second scenario some of the arcs are inaccessible. This is done to show that the algorithm can calculate alternative routes if necessary and that trapped miners can be localized. In the third scenario the miners are divided up into stamina categories. The arcs for people with lower stamina have higher weights than for those with higher stamina. This way, people with less stamina should, if necessary and applicable, be sent to safe havens closer by. This third scenario does also not take into account inaccessible pathways. The fourth scenario does take into account closed pathways and stamina, for the reasons given previously.

In order to test the scenarios, two codes are needed. The first is programmed to have equal arc-weights for all miners, while in the second code the arc-weights are adjusted according to the stamina categories which are assigned to the miners. Section 3.2.1, describes the common basis of the codes. The specific code for the equal weights scenario is given in section 3.2.2, while the code for the adjusted weights is given in section 3.2.3. The interested reader can find the Python codes for both algorithms on GitHub. The URL's linking to the codes are given in the appendix.

3.2.1 Basic Steps

Figure 4 depicts a flowchart with the basic steps that are taken in the base part of the code. Each of these steps will be described in more detail.

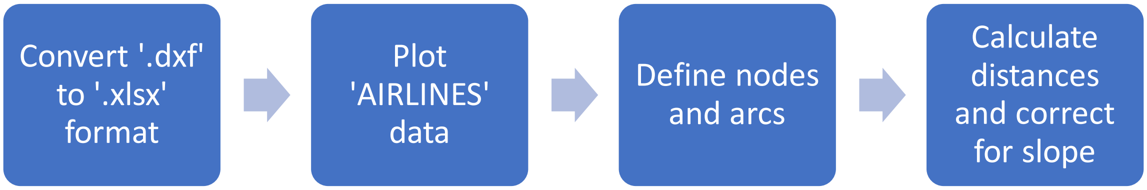

Figure 4: Flowchart Basic Steps

The data concerning the dimensions of the mine used for the case study was delivered in an AutoCAD file (with a '.dxf' format). In a separate programming file, the AutoCAD file was loaded to the Python environment. Subsequently, the data was loaded into an Excel file ('.xlsx' format), which will serve as the source of data for the main programming file. Converting the data to the excel format made it easier to comprehend and manipulate the data.

A visual inspection of the file revealed that it contains three categories of data: 'AIRDATA', '2DARROW' and 'AIRLINES'. The first category contains points in space, while the latter two are line strings, with a beginning and an end node. It was found that the 'AIRDATA' and '2DARROW' are used merely for ventilation purposes, while the 'AIRLINES' dataset contained the drifts making up the mine used for the case study. Therefore, all further use and manipulation of data is done solely on the 'AIRLINES' category.

A 3D plot of the data is given in Figure 5, Figure 6, and Figure 7. These plots were compared to another plot made using the AutoCAD file. It was found that one unit of distance in the AutoCAD is equal to one meter. Therefore, the distances that will be calculated in a later stage will not be modified to another scale. This way, it is ensured that the evacuation simulations that will be run are done in a realistic model.

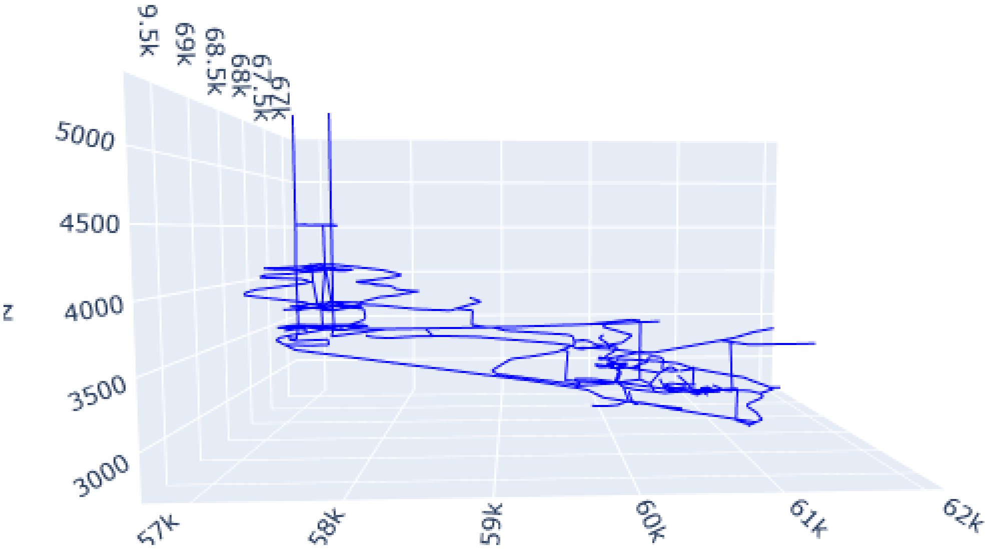

Figure 5: Side view of 'AIRLINES' network

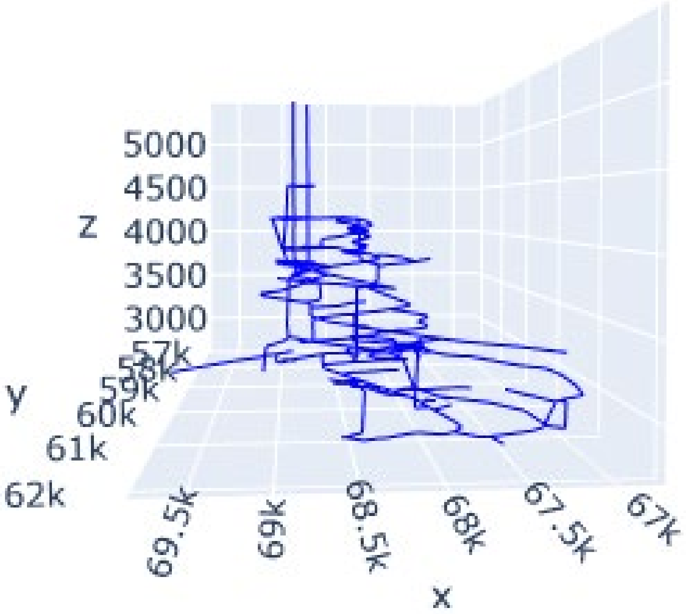

Figure 6: Front view of 'AIRLINES' network

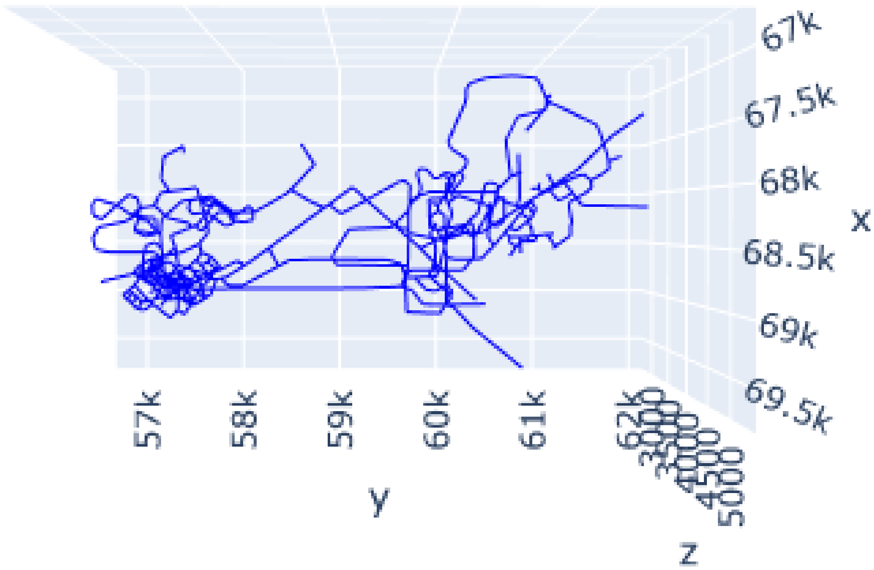

Figure 7: Top view of 'AIRLINES' network

The next step is to build a model in which simulations can be run. It must be noted that although line strings have been drawn, they have not been quantified yet. The only information that is known at this point are the start and end coordinates of each arc. The first step that had to be taken, then, was to identify each individual node in the network. This is done using the 'define_nodes' function. This function first runs through all coordinates of the starting nodes of the line strings. If a combination of coordinates has not occurred, it is added to a list. After this is done a sweep is made through the tail nodes, to see if any original nodes can be found here. These are also added to the list. In total, 453 nodes were found using this function.

The next step is to find which nodes are combined to form arcs. This is done using the 'define_edges' function. Firstly, the nodes that were found before are stored into a Pandas data frame. Secondly, the coordinates of each begin and end node of the arcs in the 'AIRLINES' data are compared to their position in the data frame. This way a list can be made with the relative position of the node pairs. For instance, node zero is connected to node six. This will appear as [0, 6] in the list of arcs. In total there are 522 arcs. Also, the pairs are reversed, as it is assumed miners can travel in both directions on each arc. This way, both directions of a pathway can be used during the evacuation simulations.

The next steps calculate the distance between the connected nodes, the slope of the particular path and a correction to the distance for this slope. These calculations are done using the Euclidian method. The slope angle of each path is calculated using the tangent. Adjiski et al. (2015) have devised a formula that makes a correction to the Euclidian distance, as to give paths that go more steeply upwards more weight. The correction factor is calculated using the following equation:

$$k_{gi} = \frac{m * g * v_0 * sin\theta_i}{P_0} + cos\theta_i \qquad [6]$$

Where:

- k_{gi} is the correction factor.
- m is the mass of the miner (taken to be eighty kilogrammes on average)
- g the gravitational constant (9.81 m/s^2)
- v_0 is the average walking speed (taken to be 1.35 meters per second (Cronkleton, 2019)).
- θ_i is the slope angle of the path in degrees.
- P_0 is the human's walking power (taken to be 200 Watts).

The correction factor is only used for slopes that rise upwards. Slopes going downwards are kept at their original length. The correction for the slope is linked to a maximum angle (taken to be 80 degrees). This is done to prevent the weights for the shafts, which go steeply upwards, becoming erratic. Together, the three functions named in this paragraph are used to calculate the distances between the nodes that will be used in the optimization model, which are saved as a list under the name ‘final distances’. The piece of code where this list is generated concludes the common part of the two algorithms used for this thesis. The remaining code for both algorithms will be explained in separate sub-chapters.

3.2.2 Algorithm 1: Common Stamina, Common Distances

In a true mining situation, the localization of mining personnel underground can be done using Bluetooth beacons (Jung & Choi, 2017), or using one of the other systems described in chapter 2.5. Actual application of this type of data is, however, not within the scope of this thesis. Therefore, a manner had to be found to simulate placing workers in the model of the mine. Furthermore, their position had to be detailed: they should not only be located on the nodes or always be placed halfway through the arcs. To solve this problem, firstly the user of the code must define the number of workers in the mine. After this, a random arc in the network is selected for each of the miners. Then, the location along the arc is simulated by choosing a value between zero and one, which is stored in a separate list. To complete this step, two more actions have to be taken. Firstly, a temporary arc has to be created between the location of the miner and the two adjacent nodes. This way, an escape in either direction can be facilitated. Secondly, the exact location of the miner has to be calculated and a temporary node has to be created at this location. These are needed for plotting and optimization purposes.

Normally, conditions in an underground mine, such as temperature and air quality, are measured by sensors and monitored by computers. Again, this is not within the scope of this thesis. This means another simulation, for these types of circumstances, has to be done. To simulate a mine fire, an arbitrary number can be selected by the user (which will serve as the number of fires). For each fire in the mine, a random arc is selected. Subsequently, this arc (both directions) is removed from the network that was built earlier. This way, the arc can’t be used by miners to escape. This can lead to two situations: the miner has to take an alternate route or the miner gets trapped (trapped miners will be handled more elaborately later on). Now that the pathways that are inaccessible are removed from the model, the temporary arcs can be added to the list containing the arcs (pathways) and weights (distances). This is done at this stage, to avoid temporary arcs being chosen as the location of a fire.

At this point, the data is organised in a way that an optimisation model can be started to build. The model is set under the name ‘m’. Firstly, the variables x_{ij} have to be defined. This is done by taking all combinations of nodes (the arcs) and adding them into a Python dictionary. After this, a GUROBI function that registers them as variables is used. Now that the variables are set, an objective function can be made. This is done by multiplying all variables x_{ij} by their respective weights c_{ij}, summing them up, and using the GUROBI function that sets this combination as a minimization problem; the objective function (which is the same as applying equation 3). After this, the model ‘m’ is updated, to have the computer process all actions that have been taken up till now. Also, the objective function can be printed, so it can be given a visual inspection.

Now that the objective function is set, it is time to add the constraints to the model (as depicted in equation 4). In order to do this, firstly, a list of zeroes with the length of the number of nodes (both permanent and temporary) is made. Subsequently, in this list, for each node the variables (arcs) that lead towards this specific node are added and the variables that lead away from the node are subtracted. This leads to a list were all variables x_{ij} are linked to the relevant nodes. The next step is to set the safe havens in the network. Again, as the actual locations of the safe havens are out of scope for this thesis, these nodes were chosen at random by the author (but kept the same for all simulations). In the list ‘refugee’ the nodes where the safe havens are located and their respective capacity are given. A capacity of zero indicates a shaft which, for simplicity purposes, does not have a limit on the number of miners it can handle. Finally, the constraints are added to the model using the GUROBI software. The temporary nodes, where miners are spawned, are given a value of equal to one, the refugee chambers a value more or equal than the negative value of their capacity, and the shafts a value of zero or less (as explained, this is to make miners disappear from the system once they have reached safety). All other nodes are set equal to zero, as the incoming should be equal to the outgoing number of miners.

After another update, the model is now ready to be optimized. This can lead to two situations: the computer finds the model either feasible (in which case the most efficient routes of egress are calculated), or infeasible (in which case the optimization is stalled, and for none of the miners an escape route is calculated). For the sake of the argument, we will assume the model is infeasible, as the next lines of code deal with this type of situation (in the chapter on the results, both feasible and infeasible situations will be treated).

As said, it is now assumed that after an optimization attempt the model comes back infeasible. This means that at least one miner cannot reach safety without passing a fire hazard. Two things need to happen at this point: the trapped miners need to be located and their colleagues, that are not trapped, need to get directions to a safe haven. Firstly, the first problem will be dealt with. As long as miners are trapped, the model will have the status of infeasible. GUROBI has a function that deals with infeasibility. This function relaxes the model: it finds the constraints that cannot be met and filters these out. As the constraints are linked to the (temporary) nodes, it is quite simple to find where the miners are trapped. One simply takes the temporary nodes that are linked to infeasible constraints, as these will be the locations where the miners are trapped. After the model is re-optimized, it indicates the trap nodes, and calculates a way out for the other miners.

At this point, the computer has calculated the most efficient routes of egress and the nodes where miners are trapped. The next job is to find the location of the trapped miners. As explained, the constraints that are infeasible are linked to the temporary nodes (which is where miners are initially located). Therefore, one simply has to find the infeasible constraints that are linked to temporary nodes. From this, the location of the miner, including the drift he is located, can be determined. This information is printed out, to give the emergency response team a clear indication where the trapped miners are located. Also, a plot is made where the exact location of the trapped miners is given as a red dot. Examples of this are given in Figure 8, Figure 9, and Figure 10.

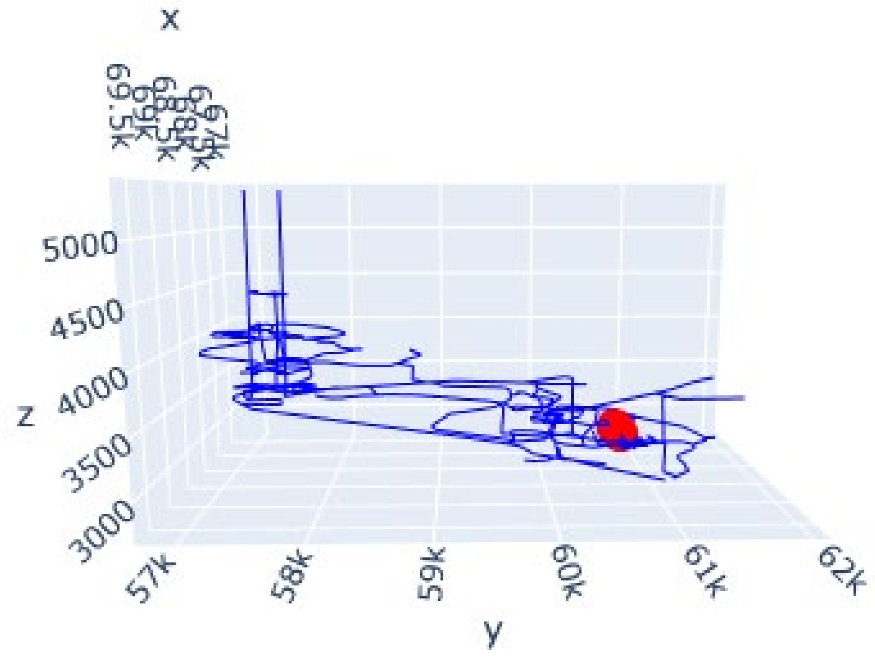

Figure 8: Side view of location trapped miners

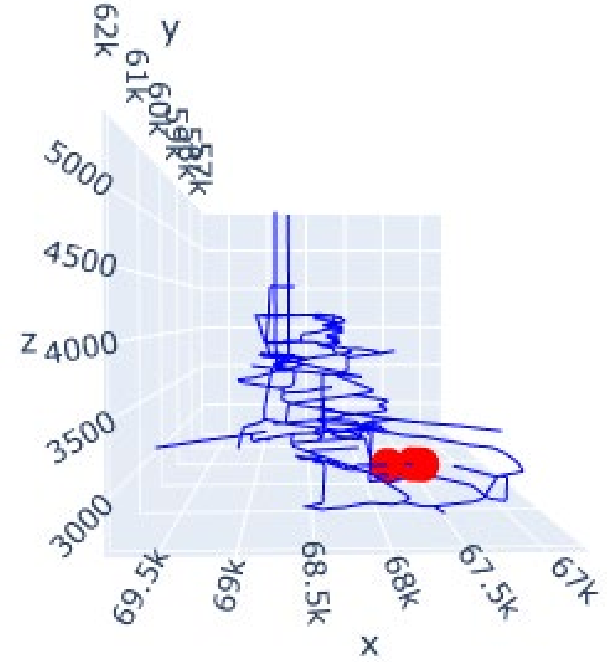

Figure 9: Front view of location trapped miners

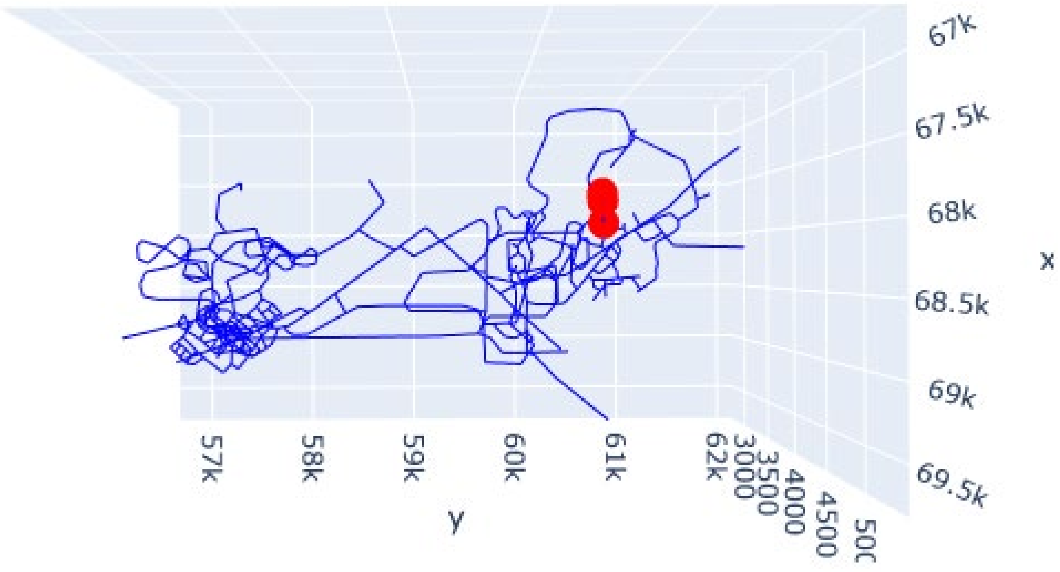

Figure 10: Top view of location trapped miners

Now that the trapped miners have been taken care of, it is time to process the results for the miners that can escape. The results as given by GUROBI are processed and put into a list. As only the nodes that have been passed (and how often they have been passed) are of interest, all nodes that yield a value of zero are filtered out. After this, it is important to find the exit route (from node to node) for each individual miner. This is done by starting at the temporary nodes (which, again, is where the miners are initially located), and looking at the next node that will be visited. By doing this repeatedly, the sequence of nodes that need to be visited by a miner can be determined. This process is repeated for each individual miner (except the ones that are trapped). The routes are sorted and then stored in a list. The route for each individual miner can be printed separately, as to make inspection simpler. Also, the individual data for each miner can be used to make a plot of the escape route of the miner in question. The initial location of the miner is indicated as a red dot. The pathways he needs to cross are indicated by red lines. An example is given in Figure 11, Figure 12 and Figure 13.

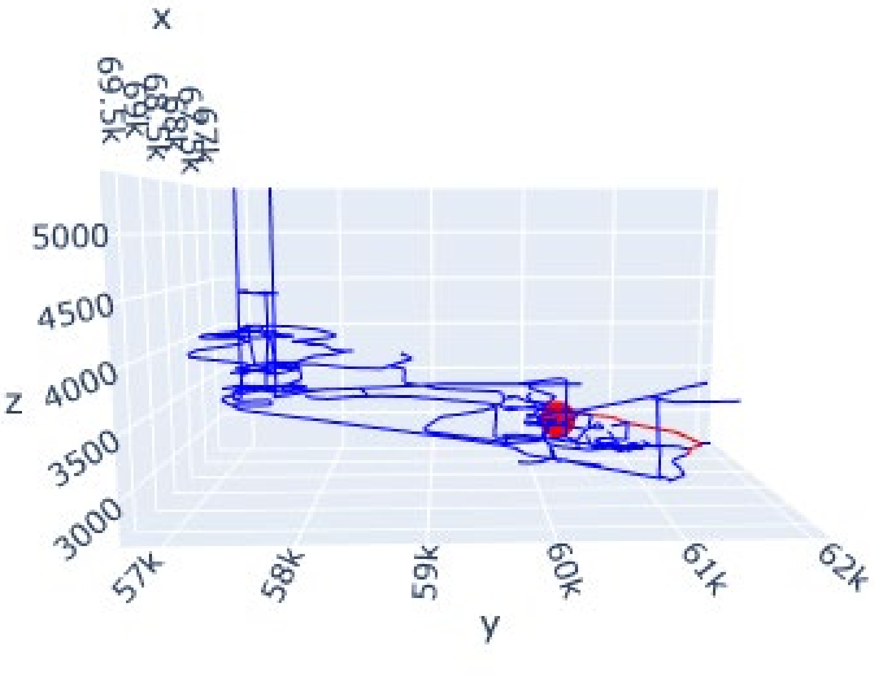

Figure 11: Side view escape route.

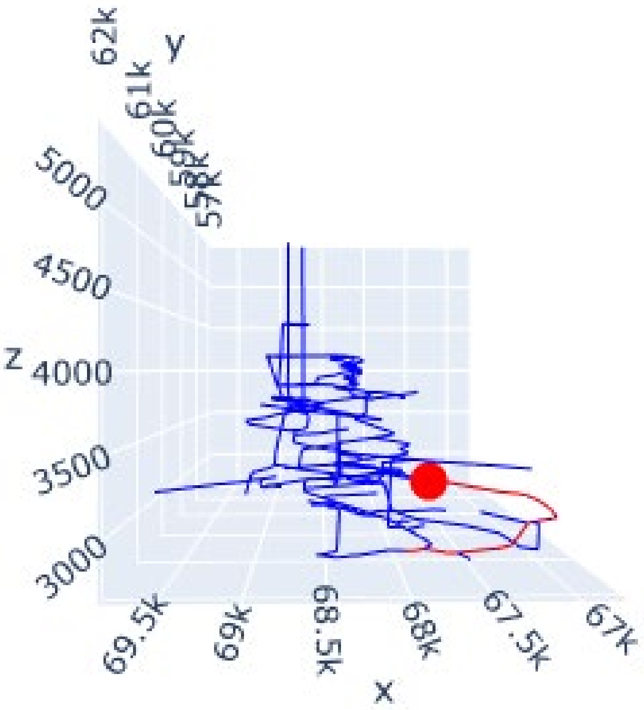

Figure 12: Front view escape route.

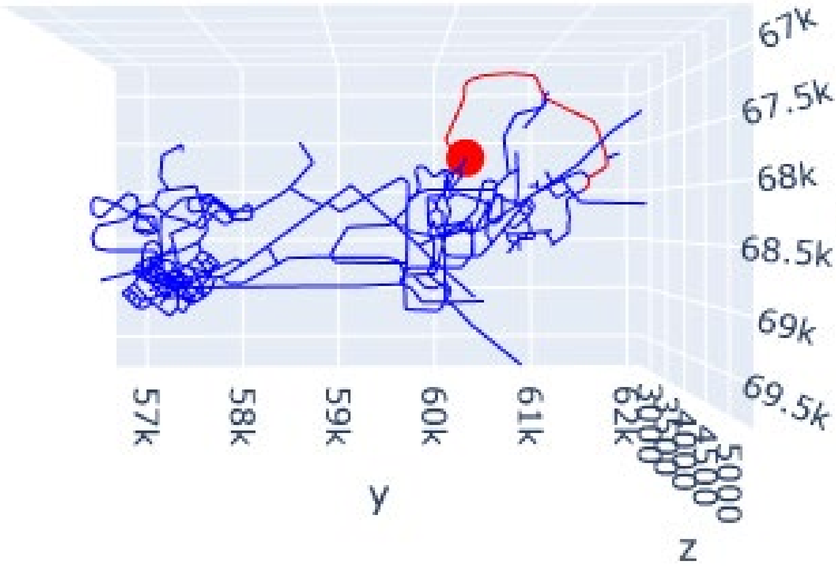

Figure 13: Top view escape route.

3.2.3 Algorithm 2: Distances Corrected for Stamina

In this sub-chapter the approach where the stamina of the miners is taken into account will be explained. The explanation starts after loading the data into the python environment, as was described in chapter 3.2.1. Firstly, five different stamina categories are created. Miners can have stamina with a factor of 0.8, 0.9, 1.0, 1.1 or 1.2. A stamina of 0.8 (or 80 percent) means the stamina of the miner is low, while a stamina of 1.2 (or 120 percent) means the miner is in very good shape. The stamina values will be used to correct the distances that the miners have to travel, which will be explained later in this chapter.

As explained in the previous section, the number of miners and their location in the mine are randomly generated. However, one extra piece of data is added to each miner: their stamina category. As mentioned earlier, there are five different categories. Therefore, each miner is given a (random) number between zero and four. A zero indicates a miner is in the lowest stamina category, while a four indicates the highest category. After this, temporary edges and nodes are created (just as was done in algorithm 1).

The creation of fires and the addition of the temporary edges to the list of final distances is done in exactly the same way as in algorithm 1. However, in this algorithm an extra piece of code is added to correct the distances in this list for the different stamina categories. For each drift, five spin-offs are created, where the corrected distances are stored. For instance, if a drift is 100 meters long, for people in stamina category 0 the distance is corrected to 125 meters (which is $\frac{100}{0.8}$). On the other end of the spectrum, for people in stamina category 4, the distance is corrected to 83,3 meters (which is $\frac{100}{1.2}$). This way, the route is artificially made longer for people with low stamina. This should, in the minimizing of the objective function, lead to them getting routes that are shorter. For each drift, the five spin-offs are stored in a new list.

Again, an optimization model is created. However, the number of pathways (the variables) is five times higher, as each distance is corrected five times. The variables and their weights (distances) are added to a objective function (which, again, is to be minimized). As explained, the idea behind the different stamina categories is that miners in a lower category are send to the closer evacuation nodes. As the weights for lower categories are larger, the minimization function will tend to let the miners with lower stamina pass less nodes. For the higher categories it is the other way around: as their weights are lower it will cost them less effort to travel larger distances, which will lead to the minimization function to send them an escape node further away. This, however, is only done if the capacity of safe havens is limited (if the capacity is sufficient, all miners will be send to the escape node closest by). For instance, if two miners are both 100 metres away from a refugee chamber (which is almost at capacity), the algorithm will send the miner with the lower stamina to this location, while the miner with higher stamina will be send to a safe haven farther away.

After the objective function is set, the constraints need to be defined. This is more complicated than in algorithm 1. Firstly, it is important that miners only take the spin-off path that is linked to their stamina category. Therefore, the individual spin-off paths towards the escape nodes are each set to the specific capacity of the refugee chamber or shaft. Besides this, the sum of all spin-off paths is set at the same capacities, as the total amount of miners in a refugee chamber must not exceed its capacity. After setting the limit for the escape nodes, all other permanent nodes are set to zero, as their only purpose is for miners to pass.

Similar to algorithm 1, the constraints for the temporary nodes where the miners are located need to be set to one. However, again, they can only use the spin-off path connected to their stamina category. Therefore, the paths that are linked to other categories need to be set to zero. For this purpose, the list of stamina classes created earlier is used. Miners are only spawned at their specific spin-off constraint. This also ensures they only take the path designated for their stamina category. This is important, as it will pollute the final results if the paths for the different categories get mixed up.

Again, an optimization attempt is made. Similarly to before, if the model is infeasible, it is relaxed. However, it is not as easy to find the location of the trapped miners as previously. This is because of the different spin-off paths, which leads to the relaxation becoming more complicated. In order to find the location of the trapped miners, a list is made of the start nodes for each route that is calculated after relaxation of the model. This list is compared to a list with all temporary nodes in it. The temporary nodes that are not present in the first list are trap nodes. These trap nodes can be plotted, which yields to a similar result as in Figure 8, Figure 9, and Figure 10.

Now that the trapped miners have again been taken care of, their colleagues need to get their directions outside. This is, again, more complicated than in algorithm 1. The problem is that when looping through the results, the spin-off routes can get mixed up. For instance, a miner in category 1 and category 2 both need to go from node 0 to node 6. If the loop were to only look at the departure and destination nodes, the algorithm could have the miner in category 1 take the route for someone in category 2. Therefore, the results need to be sorted by category.

After the results have been ordered by stamina category, they need to be sorted so they represent the route for each individual miner. This is somewhat more complicated as compared to algorithm 1, but the goal (printing and plotting the results) is the same. The plots of the escape routes are the same as the example given in Figure 11, Figure 12 and Figure 13.

3.2.4 Timing of results

One final note about the timing of the algorithms needs to be made. The clock that times the creation of a solution by the Python code is started just before the definition of the nodes and arcs. This is done as underground mines, usually, expand over time. In case of an emergency, one wants to have the most up-to-date version of the underground network. Therefore, the definition of nodes and arcs can be seen as an integral part of the time it takes to come to a solution. However, one could argue that the nodes and arcs are already loaded into the system when an evacuation is called. In that case, the clock could be started when the objective function and constraints are defined. This will decrease the reported running times. Both options have pros and cons. That said, when reading about the timing results, one should realize what steps of the code are included and why.

CHAPTER 4 : RESULTS AND ANALYSIS

In this chapter an overview of the results will be presented. As mentioned, four different scenarios are tested:

- Scenario 1: An evacuation where all paths are available, where all miners have the same stamina.
- Scenario 2: An evacuation where some paths are blocked (for instance by a fire), where all miners have the same stamina.
- Scenario 3: An evacuation where all paths are available, where the miners are divided up into stamina categories.
- Scenario 4: An evacuation where some paths are blocked (for instance by a fire), where the miners are divided up into stamina categories.

For each scenario, five situations will be tested, with the fires and miners being located differently (at random) in each situation. Each situation will be tested with 1, 5, 10, 50, 100, 200, 500, and 1000 miners. In total, this will give 160 different simulations. The situations (i.e. the location of the miners and fires) are equal in each scenario. The locations of the safe havens are kept the same in each scenario and situation.

Different results will be presented and reviewed. Firstly, the safe havens where the miners are sent to and the total distance travelled will be looked at. The network has three refugee chambers (located at node 120, 150 and 300) which each have a capacity of 30 people. The shafts are located at node 200 and 250. Next, the total distance travelled by all miners present will be analysed. After this, the results for a specific miner (who comes from the same situation in each scenario, and will be called Miner X) will be reviewed. Finally, an analysis of the running times will be done. After each separate scenario has been dealt with, they will be compared to one another.

4.1 Scenario 1

As described, in the case of scenario 1, all drifts in the mine can be used as escape routes. The lengths of the drifts are not corrected for the individual stamina of the miners.

4.1.1 Division Among Safe Havens

In Table 1 till Table 5 one can find the division of miners among the different safe havens in the mine for the different situations.

Table 1: Defined destinations for Scenario 1, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	3	8	18	29	30	30
Chamber 150	0	0	0	3	6	16	30	30
Chamber 300	0	0	0	3	8	21	30	30
Shaft 200	0	2	4	24	45	96	248	497
Shaft 250	1	2	3	12	23	38	162	413
Total	1	5	10	50	100	200	500	1000

Table 2: Defined destinations for Scenario 1, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	4	12	28	30	30
Chamber 150	0	0	1	3	12	26	30	30
Chamber 300	0	2	3	7	10	16	30	30
Shaft 200	1	2	5	22	38	73	216	457
Shaft 250	0	1	1	14	28	57	194	453
Total	1	5	10	50	100	200	500	1000

Table 3:Defined destinations for Scenario 1, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	2	3	10	22	30	30	30
Chamber 150	0	0	0	4	11	30	30	30
Chamber 300	0	0	0	2	5	16	30	30
Shaft 200	0	0	4	22	42	85	223	482
Shaft 250	1	3	3	12	20	39	187	428
Total	1	5	10	50	100	200	500	1000

Table 4: Defined destinations for Scenario 1, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	9	13	28	30	30
Chamber 150	0	0	0	1	7	21	30	30
Chamber 300	0	0	1	4	11	16	30	30
Shaft 200	1	4	5	19	42	88	224	486
Shaft 250	0	1	4	17	27	47	186	424
Total	1	5	10	50	100	200	500	1000

Table 5: Defined destinations for Scenario 1, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	5	15	26	30	30
Chamber 150	0	0	0	7	15	29	30	30
Chamber 300	1	1	2	7	9	13	30	30
Shaft 200	0	3	7	22	44	84	242	506
Shaft 250	0	1	1	9	17	48	168	404
Total	1	5	10	50	100	200	500	1000

As can be seen, up until two-hundred miners the division differs between each situation. From five-hundred miners and up, the refugee chambers are filled to capacity. This means that more and more miners are sent to the shafts (as it is assumed these do not have a limit on the number of miners they can handle). This leads to convergence: the results for the higher number of miners are more similar. That said, as the real location and capacity of the safe havens were not provided for this research, it is hard draw real conclusions from this. One could cautiously say that, in this mine lay-out, up till two-hundred miners can reach the safest haven closest to them. Above this, the refugee chambers clog up. This could lead to miners having to head to shafts, while a refugee chamber is closer by.

4.1.2 Distance Travelled

Figure 14 is a graph that represents the total distance travelled by all miners when they evacuate. As can be seen, there is some difference for the simulations with the lower number of miners. However, as the number of miners increases, the results converge and become more or less equal. This is because for lower amounts of miners there is less regression to the mean. For instance, in two different situations where one miner is present, the first miner might have to travel 1500 metres, while the second has to travel 500 metres. This difference is immediately visible in a logarithmic plot. That said, as the number of miners increases, there are more miners that have either short, intermediate or long paths. This leads to the values averaging out, which is visible as convergence in Figure 14.

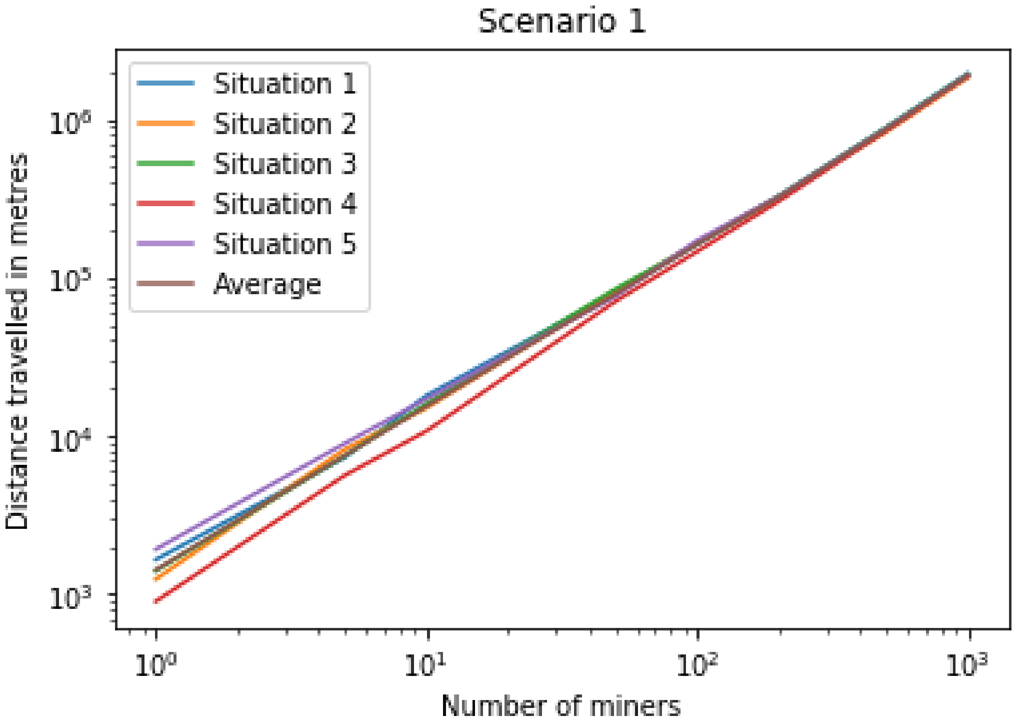

Figure 14: Total distances travelled for scenario 1

4.1.3 Miner X

Miner X comes from the second situation. His paths are determined in the case where five-hundred miners are present. His route, for this scenario, is given in Figure 15, Figure 16, and Figure 17. On this escape path, Miner X travels a total distance of 2502.7 metres. His final destination is the refugee chamber at node 150.

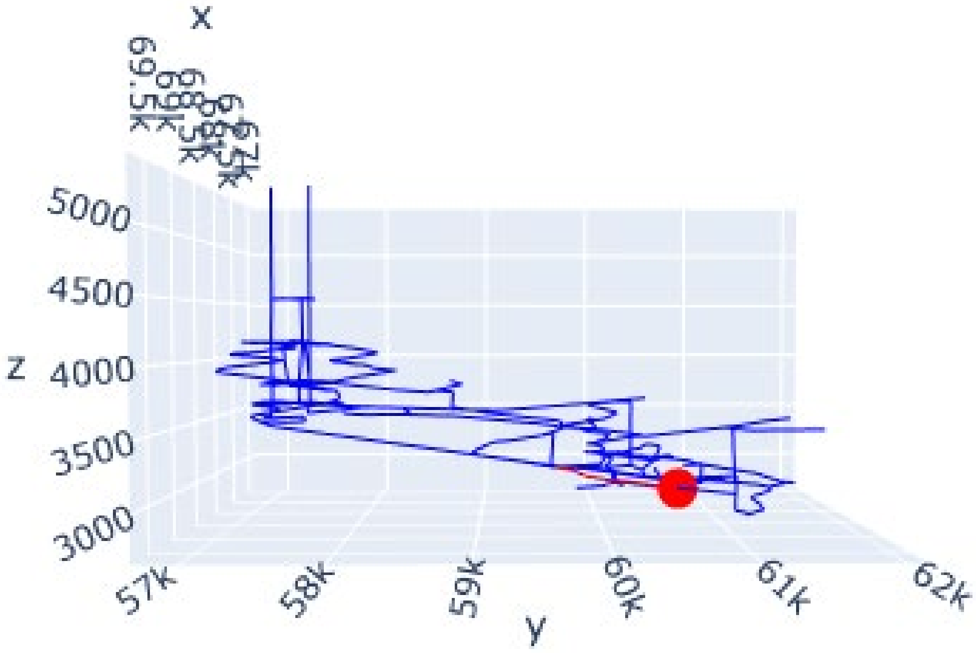

Figure 15: Route for Miner X in scenario 1, side view.

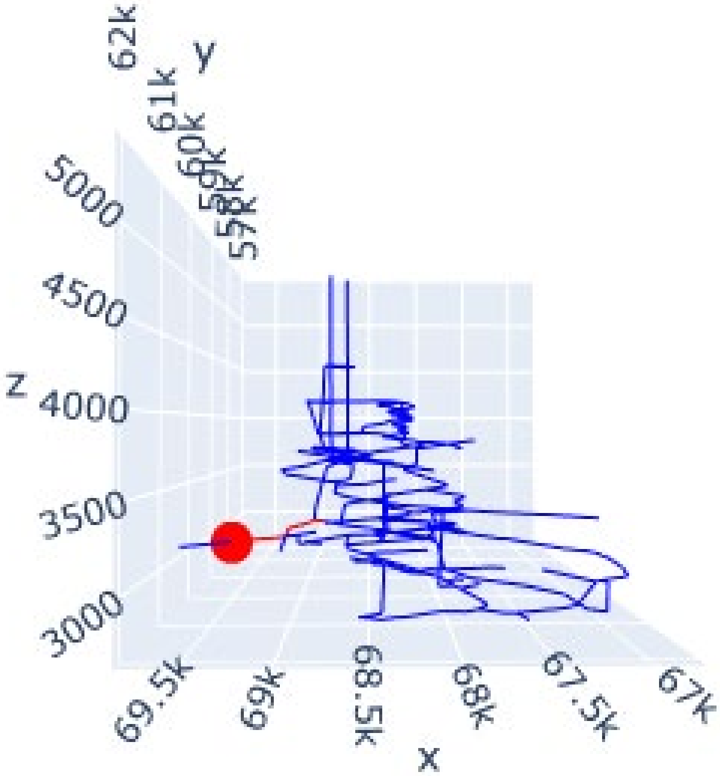

Figure 16: Route for Miner X in scenario 1, front view.

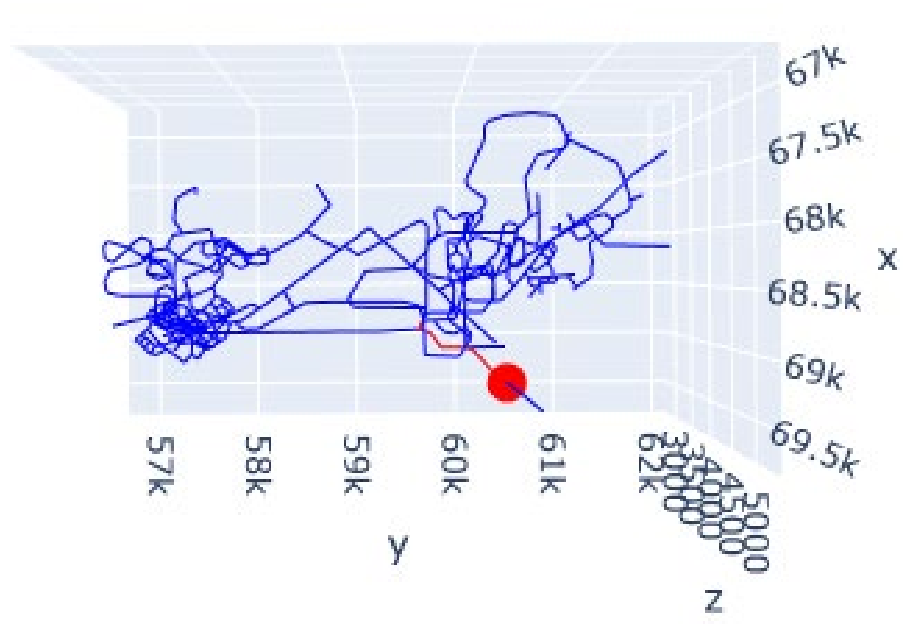

Figure 17: Route for Miner X in scenario 1, top view.

No real conclusion can be drawn from the route of a single miner in a specific scenario. The different routes of Miner X will be analysed in the chapters where different scenarios are compared.

4.1.4 Running Times

The timing results for scenario 1 are given in Table 6 and are visualised in Figure 18.

Table 6: Running Times for Scenario 1

Number of miners / situation	1	2	3	4	5	Average	STD
1	9.41	9.27	9.56	9.64	9.54	9.49	0.13
5	9.85	9.64	9.85	9.65	9.59	9.72	0.11
10	9.72	9.24	9.99	9.36	9.29	9.52	0.29
50	10.56	9.60	9.70	9.57	9.39	9.76	0.41
100	10.21	9.86	9.62	9.62	9.86	9.83	0.21
200	10.30	10.51	10.00	10.02	10.05	10.18	0.20
500	10.95	11.01	12.79	10.74	11.37	11.37	0.74
1000	16.59	15.52	15.10	15.64	15.20	15.61	0.53

As can be seen in Figure 18, in scenario 1, the runtime grows only slightly between 1 and 100 miners. For the situations with 200 miners and more, the growth is sharper. In this scenario, the lowest runtime was found to be 9.24 seconds (for situation 2, with 10 miners present in the mine). The highest runtime was 15.64 seconds (for situation 4, with 1000 miners present in the mine). In general, it can be said that a larger number of miners increases the running time significantly. However, the situations with a thousand miners present in the mine at the same time are unrealistic (they were only ran to see how the algorithm would handle large numbers and the clogging up of refugee chambers). Thus, in reality this number will always be lower. Therefore, it can be said that (on the computer on which these simulations were run) in scenario 1, an escape solution can be generated within 16 seconds. This conclusion is confirmed by looking at Figure 18 where one can see that the running times for the different situations are relatively close to one another.

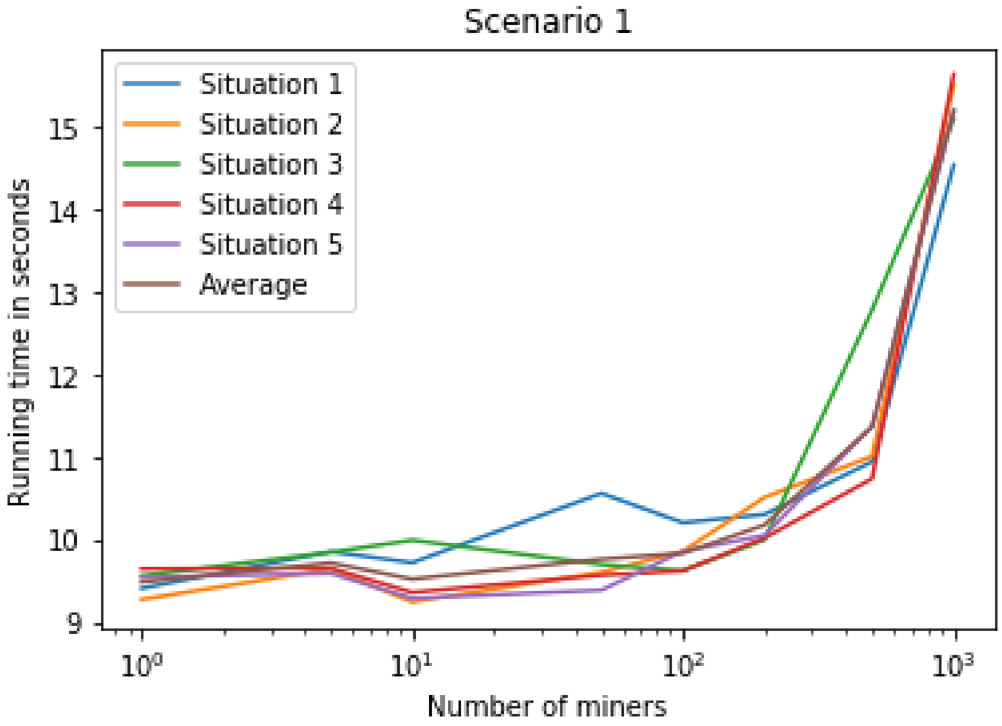

Figure 18: Running times scenario 1

4.2 Scenario 2

In scenario 2, for each situation, ten fires are started in the mine, making the pathways where the fire takes place inaccessible. The numbers of miners that are trapped in each different situation are given in Table 7. The stamina for all the miners is the same.

Table 7: Trapped Miners

Number of miners / situation	1	2	3	4	5
1	0	0	0	0	0
5	0	0	0	0	0
10	0	0	0	0	0
50	0	0	1	0	0
100	0	0	1	0	0
200	0	0	3	2	0
500	2	0	5	2	0
1000	4	0	5	4	0

4.2.1 Division Among Safe Havens.

The division of the miners among the safe havens for scenario 2 are given in Table 8 till Table 12.

Table 8: Defined destinations for Scenario 2, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	3	8	18	29	30	30
Chamber 150	0	0	0	3	6	16	30	30
Chamber 300	0	0	0	3	8	21	30	30
Shaft 200	0	2	4	24	45	96	247	492
Shaft 250	1	2	3	12	23	38	161	414
Total	1	5	10	50	100	200	498	996

Table 9: Defined destinations for Scenario 2, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	1	19	30	30	30	30
Chamber 150	0	0	1	3	19	30	30	30
Chamber 300	0	0	1	4	7	30	30	30
Shaft 200	1	3	6	23	39	84	232	469
Shaft 250	0	1	1	1	5	26	178	441
Total	1	5	10	50	100	200	500	1000

Table 10: Defined destinations for Scenario 2, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	2	3	9	18	30	30	30
Chamber 150	0	0	0	4	11	21	30	30
Chamber 300	0	0	0	3	8	24	30	30
Shaft 200	0	0	4	22	44	87	242	503
Shaft 250	1	3	3	11	18	35	163	402
Total	1	5	10	49	99	197	495	995

Table 11: Defined destinations for Scenario 2, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	10	16	30	30	30
Chamber 150	0	0	0	1	7	23	30	30
Chamber 300	0	0	1	5	11	16	30	30
Shaft 200	1	4	5	18	41	86	216	469
Shaft 250	0	1	4	16	25	43	192	437
Total	1	5	10	50	100	198	498	996

Table 12: Defined destinations for Scenario 2, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	5	15	26	30	30
Chamber 150	0	0	0	7	15	29	30	30
Chamber 300	1	1	2	6	7	9	30	30
Shaft 200	0	3	7	23	46	88	242	497
Shaft 250	0	1	1	9	17	48	168	413
Total	1	5	10	50	100	200	500	1000

Again, the divisions are quite different for up till two-hundred miners, and become more similar from five-hundred miners and up. This is for the same reasons as in scenario 1. A difference is that the number of miners in safe havens is sometimes not equal to the total number of miners. This is because some miners are trapped, and can therefore not reach safety.

4.2.2 Total Distance Travelled

The total distance travelled by the miners in scenario 2 is given in Figure 19. As can be seen, the distances are quite different for lower numbers of miners. For the medium levels, the data converges. After this, the distances start to diverge. The reason the numbers are different in the beginning, is the same as in scenario 1: the differences are more outspoken as regression towards the mean has not taken place. This regression can be seen around one-hundred miners. The reason the distances diverge after this is that some miners are trapped. These trapped miners do not move, and therefore their distance travelled is zero. These 'missing' distances are visible in the situations with more miners, as more of the workers will be trapped.

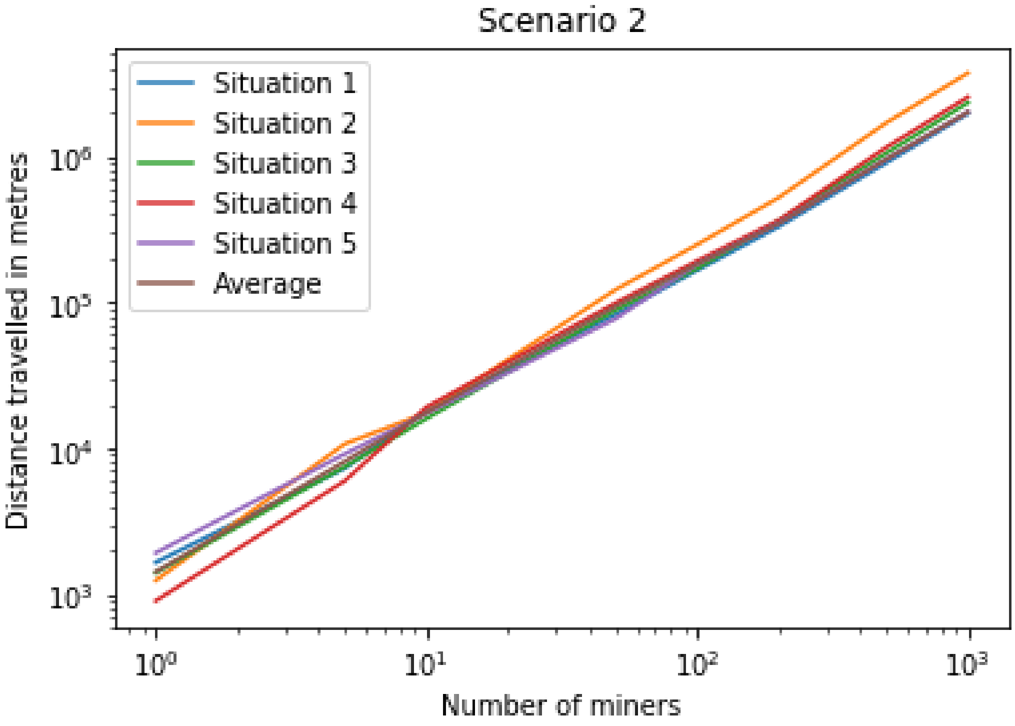

Figure 19: Total distances travelled for scenario 2

4.2.3 Miner X

The total distance travelled by Miner X in scenario 2 is 2502.7 metres, while heading to the refugee chamber at node 150. This is the same route as in scenario 1. Therefore, his route can be found in Figure 15, Figure 16, and Figure 17.

4.2.4 Running Times

Again, for each situation the time for the algorithm to come up with a solution was kept. The running times are given in Table 13 and Figure 20.

Table 13: Running Times Scenario 2

Number of miners / situation	1	2	3	4	5	Average	STD
1	9.62	9.32	9.79	9.41	9.83	9.59	0.20
5	9.69	9.41	9.15	9.33	9.66	9.45	0.20
10	9.56	9.62	9.35	9.75	9.84	9.63	0.17
50	9.85	9.65	10.64	9.68	9.98	9.96	0.36
100	10.30	9.81	10.55	9.52	10.26	10.09	0.37
200	9.96	10.13	10.65	10.73	10.81	10.45	0.34
500	11.99	11.57	11.64	11.58	12.35	11.83	0.31
1000	14.74	15.19	14.59	13.88	15.36	14.75	0.52

As can be seen in Figure 20, the growth is light for the lower numbers of miners, and starts growing sharper as the factor of increase becomes bigger (just as in scenario 1). The lowest runtime was 9.15 seconds (for situation 3, with 5 miners present in the mine). The highest runtime was 15.36 seconds (for situation 5, with 1000 miners present in the mine). As mentioned, the mine will never contain more than 1000 miners and it can be said that a solution can be created in under 16 seconds in this scenario (on the computer that was used to run the simulations). This is enforced, just as in scenario 1, by running times that are relatively close to one another for the different situations.

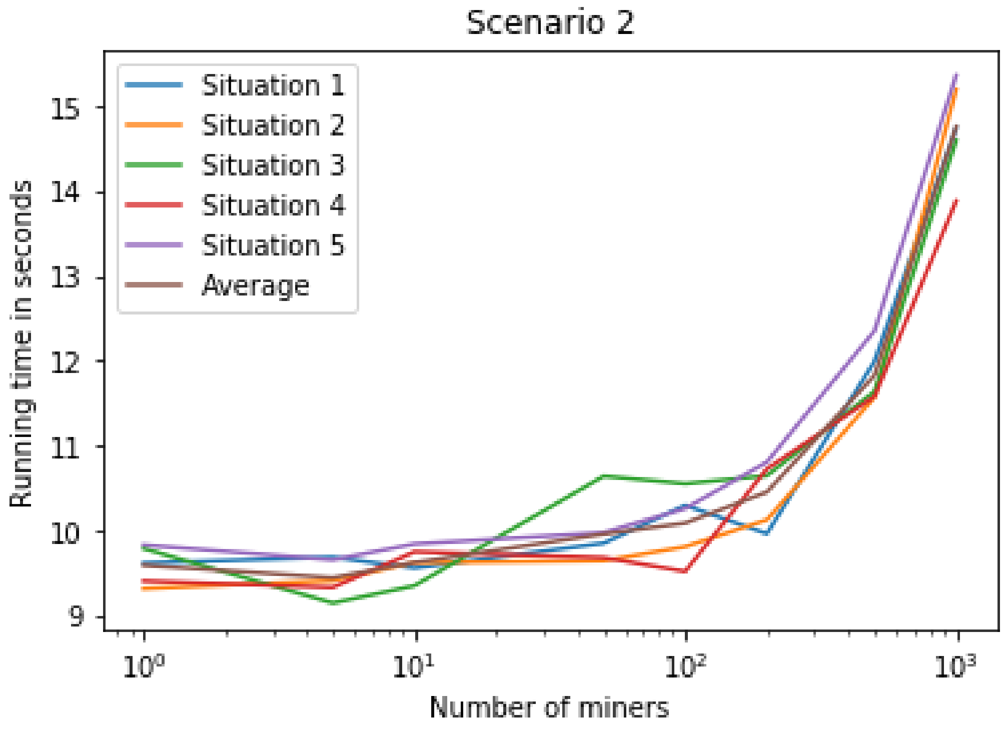

Figure 20: Running Times Scenario 2

4.3 Scenario 3

In scenario 3, miners are divided up into stamina categories and there are no fires in the mine.

4.3.1 Division Among Safe Havens

The division of miners among the safe havens for scenario 3 are given in Table 14 till Table 18.

Table 14: Defined destinations for Scenario 3, Situation 1

Refugee / Amount of Miners	**1**	**5**	**10**	**50**	**100**	**200**	**500**	**1000**
Chamber 120	0	1	3	8	18	29	30	30
Chamber 150	0	0	0	3	6	16	30	30
Chamber 300	0	0	0	3	8	21	30	30
Shaft 200	0	2	4	24	45	96	247	492
Shaft 250	1	2	3	12	23	38	163	418
Total	1	5	10	50	100	200	500	1000

Table 15: Defined destinations for Scenario 3, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	4	12	28	30	30
Chamber 150	0	0	1	3	12	26	30	30
Chamber 300	0	2	3	7	10	16	30	30
Shaft 200	1	2	5	22	38	73	217	454
Shaft 250	0	1	1	14	28	57	193	456
Total	1	5	10	50	100	200	500	1000

Table 16: Defined destinations for Scenario 3, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	2	3	10	22	30	30	30
Chamber 150	0	0	0	4	11	30	30	30
Chamber 300	0	0	0	2	5	16	30	30
Shaft 200	0	0	4	22	42	85	224	475
Shaft 250	1	3	3	12	20	39	186	435
Total	1	5	10	50	100	200	500	1000

Table 17: Defined destinations for Scenario 3, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	9	13	28	30	30
Chamber 150	0	0	0	1	7	21	30	30
Chamber 300	0	0	1	4	11	16	30	30
Shaft 200	1	4	5	19	42	88	223	479
Shaft 250	0	1	4	17	27	47	187	431
Total	1	5	10	50	100	200	500	1000

Table 18: Defined destinations for Scenario 3, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	5	15	26	30	30
Chamber 150	0	0	0	7	15	29	30	30
Chamber 300	1	1	2	7	9	13	30	30
Shaft 200	0	3	7	22	44	84	241	492
Shaft 250	0	1	1	9	17	48	169	418
Total	1	5	10	50	100	200	500	1000

The results are similar to those of scenario 1. Again, the cautious conclusion can be drawn that as there are more miners underground, the chance of the refugee chambers clogging up increases, which may lead to some miners having to travel further. A difference is that in this case, miners with better stamina will be the ones that have to run longer distances, while their weaker colleagues will be send to safe havens closer by.

4.3.2 Total Distance Travelled

The total distances travelled by all miners for this scenario are given in Figure 21. The same trend as in scenario 1 can be seen. The distances in the different scenarios converge for larger numbers of miners. This is due to regression to the mean.

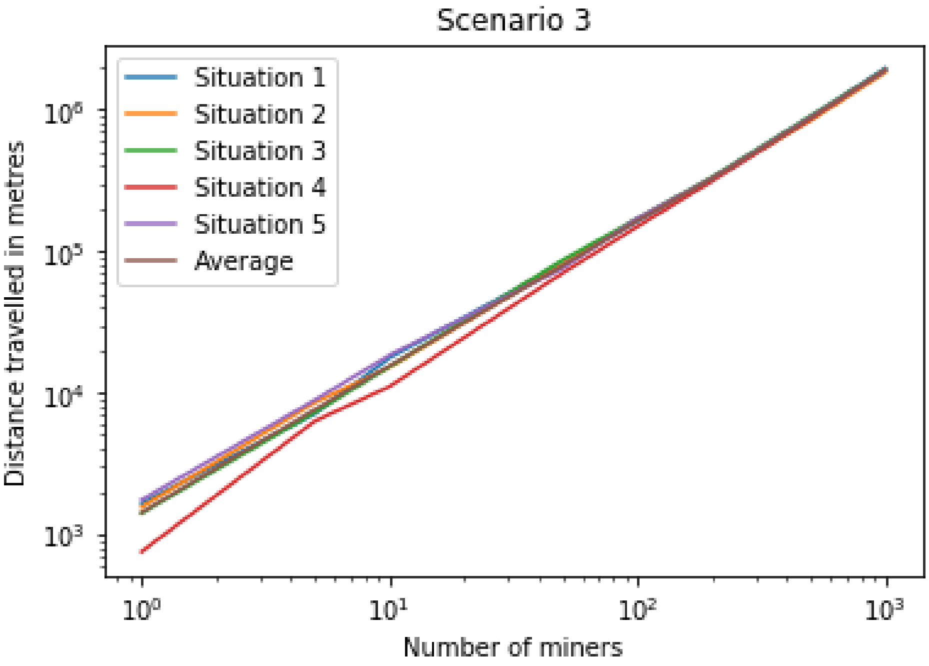

Figure 21: Distances travelled scenario 3

4.3.3 Miner X

In scenario 3, Miner X has to travel a total of 4285.1 metres to the shaft at node 250. His route is depicted in Figure 22, Figure 23, and Figure 24.

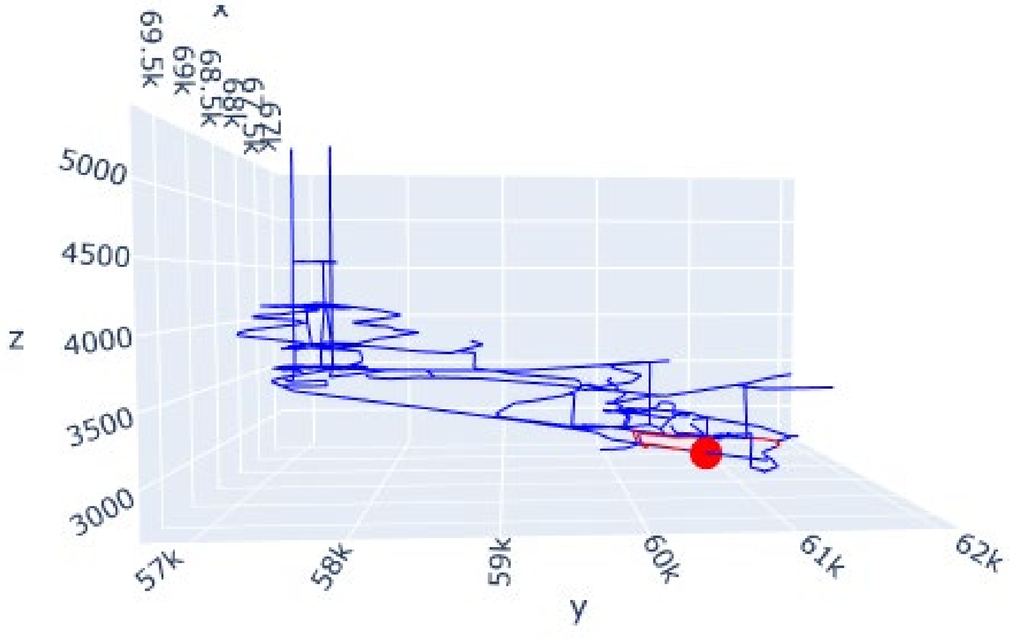

Figure 22: Route for Miner X in scenario 3, side view

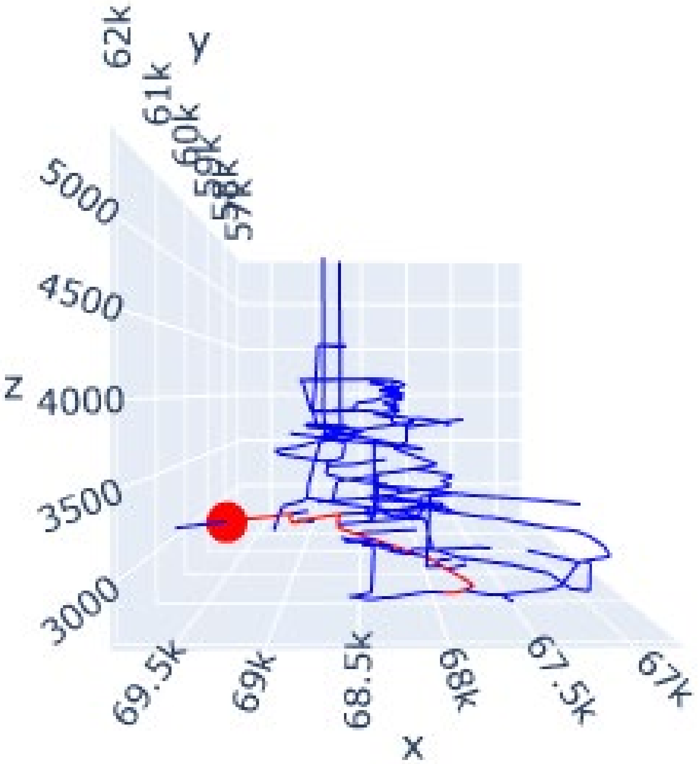

Figure 23: Route for Miner X in scenario 3, front view

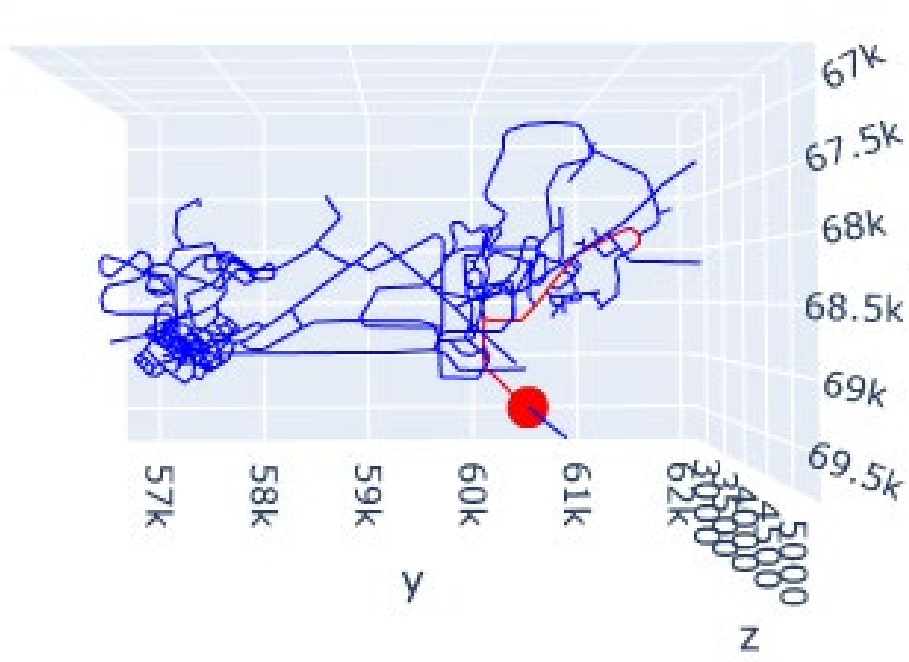

Figure 24: Route for Miner X in scenario 3, top view

4.3.4 Running Times

The running times for scenario 3 are given in Table 19 and Figure 25.

Table 19: Running times scenario 3

Number of miners / situation	1	2	3	4	5	Average	STD
1	10.36	10.28	10.15	10.11	10.23	10.22	0.09
5	10.61	10.01	9.93	10.15	10.49	10.24	0.27
10	10.55	10.31	10.01	10.38	10.12	10.28	0.19
50	10.54	10.05	10.33	10.64	10.17	10.35	0.22
100	11.12	10.07	10.14	10.70	10.36	10.48	0.39
200	11.68	11.21	11.22	11.58	10.96	11.33	0.26
500	14.70	13.68	13.65	13.86	13.61	13.90	0.41
1000	21.20	20.28	20.26	20.28	20.69	20.54	0.37

Again, a low growth can be seen between one and one-hundred miners, after which the running time starts to rise more sharply (as the amount of miners also rises more sharply). The minimum running time was 9.93 seconds (for situation 3, with five miners in the mine). The maximum running time was 21.20 seconds (for situation 1, with a thousand miners in the mine). As the numbers, again, lie relatively close to one another (and the amount of people in the mine will always be under a thousand), it can be said that, for this scenario, a solution can be created in under 21.5 seconds.

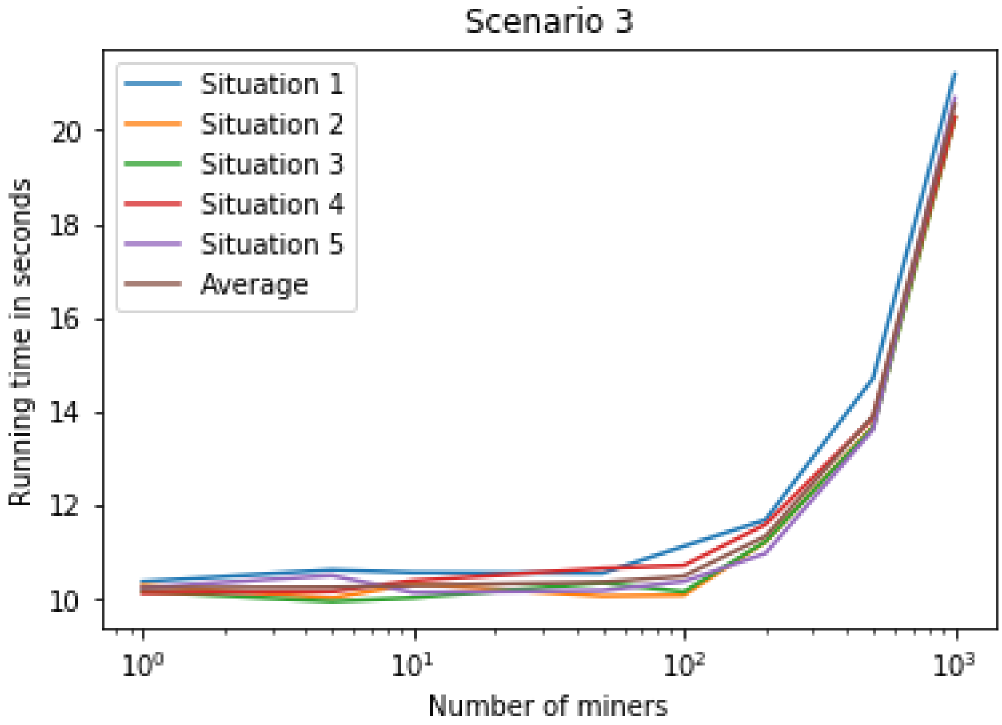

Figure 25: Running times scenario 3

4.4 Scenario 4

In scenario 4, there are ten fires in the mine and the miners are divided up into stamina categories. The entrapment of miners is the same as in scenario 2 (the specific numbers can be found in Table 7).

4.4.1 Division Among Safe Havens

The division of the miners among the safe havens for scenario 4 are depicted in Table 20 till Table 24.

Table 20: Defined destinations for Scenario 4, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	3	8	18	29	30	30
Chamber 150	0	0	0	3	6	16	30	30
Chamber 300	0	0	0	3	8	21	30	30
Shaft 200	0	2	4	24	45	96	247	490
Shaft 250	1	2	3	12	23	38	161	416
Total	1	5	10	50	100	200	498	996

Table 21: Defined destinations for Scenario 4, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	1	19	30	30	30	30
Chamber 150	0	0	1	3	19	30	30	30
Chamber 300	0	0	1	4	7	30	30	30
Shaft 200	1	3	6	23	39	84	233	470
Shaft 250	0	1	1	1	5	26	177	440
Total	1	5	10	50	100	200	500	1000

Table 22: Defined destinations for Scenario 4, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	2	3	9	18	30	30	30
Chamber 150	0	0	0	4	11	21	30	30
Chamber 300	0	0	0	3	8	24	30	30
Shaft 200	0	0	4	22	44	87	243	502
Shaft 250	1	3	3	11	18	35	162	403
Total	1	5	10	49	99	197	495	995

Table 23: Defined destinations for Scenario 4, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	10	16	30	30	30
Chamber 150	0	0	0	1	7	23	30	30
Chamber 300	0	0	1	5	11	16	30	30
Shaft 200	1	4	5	18	41	86	219	462
Shaft 250	0	1	4	16	25	43	189	444
Total	1	5	10	50	100	198	498	996

Table 24: Defined destinations for Scenario 4, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	5	15	26	30	30
Chamber 150	0	0	0	7	15	29	30	30
Chamber 300	1	1	2	6	7	9	30	30
Shaft 200	0	3	7	23	46	88	241	483
Shaft 250	0	1	1	9	17	48	169	427
Total	1	5	10	50	100	200	500	1000

The results are similar to scenario 2, which means that due to entrapment not all miners can find a safe haven and that larger amount of numbers can lead to clogging of the refugee chambers. Also, as in scenario 3, if the refugee chambers are at capacity, miners with better stamina may be send to safe havens farther away.

4.4.2 Total Distance Travelled

The total distance travelled by the miners in the different situations for scenario 4 is given in Figure 26. The same trend as in scenario 2 can be seen. Firstly, a convergence is visible, after which the distances slightly diverge. This is for the same reasons as in scenario 2. Firstly regression towards the mean takes place. As more miners are present, more may get trapped, which means they do not move, leading to a lower total distance than in situations where all miners can escape.

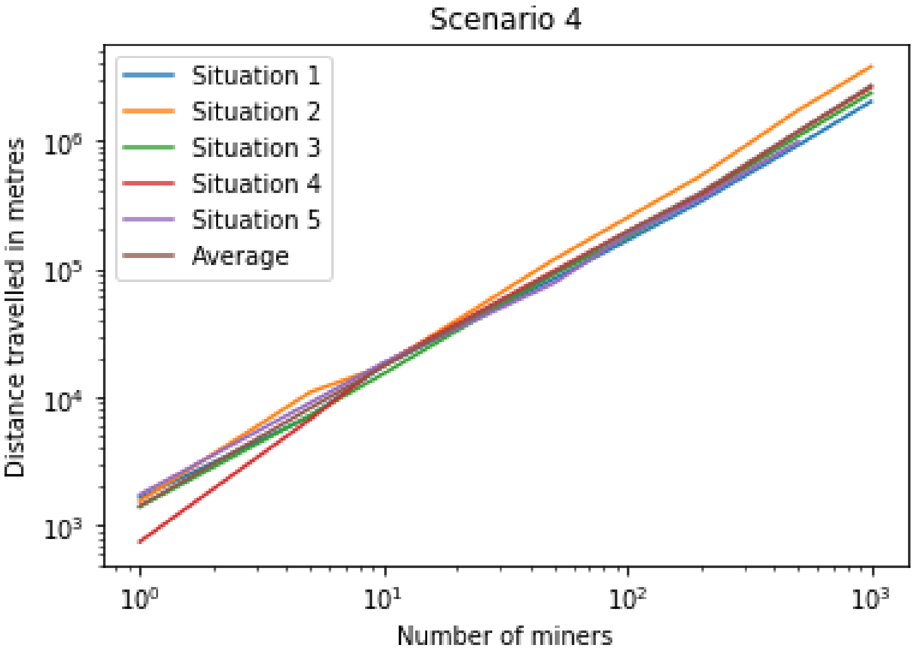

Figure 26: Distances travelled scenario 4

4.4.3 Miner X

In scenario 4, Miner X travels a total distance of 6821.1 metres towards the shaft at node 250. His route is depicted in Figure 27, Figure 28, and Figure 29.

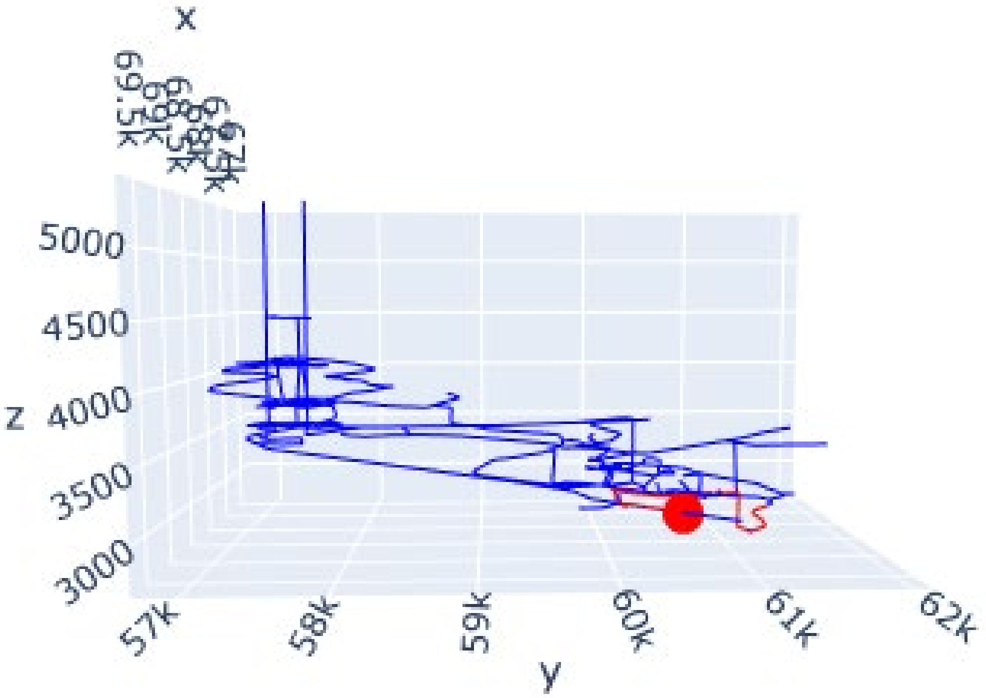

Figure 27: Route for Miner X in scenario 4, side view

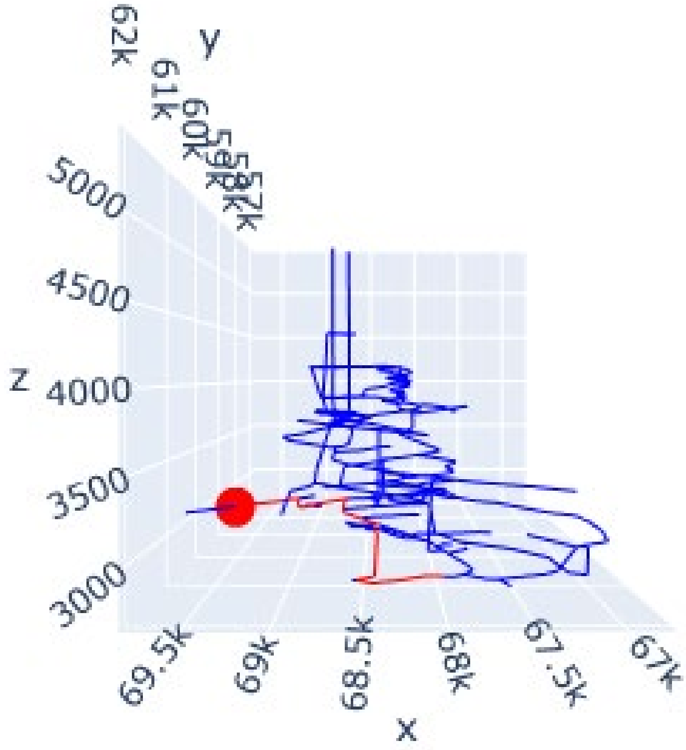

Figure 28: Route for Miner X in scenario 4, front view

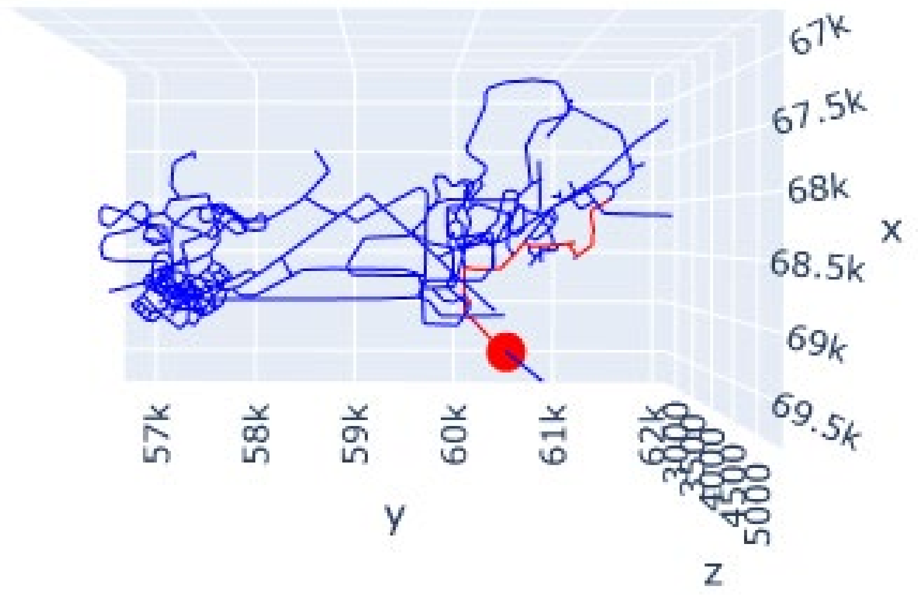

Figure 29: Route for Miner X in scenario 4, top view

4.4.4 Running Times

The running times for scenario 4 are depicted in Table 25 and Figure 30.

Table 25: Running times scenario 4

Number of miners / situation	**1**	**2**	**3**	**4**	**5**	**Average**	**STD**
1	10.40	9.93	9.99	9.96	9.58	9.97	0.26
5	10.13	10.07	10.15	10.12	10.02	10.10	0.05
10	10.43	9.65	9.70	10.07	10.85	10.14	0.45
50	10.59	9.87	10.55	9.89	10.09	10.20	0.31
100	10.32	10.60	11.26	9.92	10.41	10.50	0.44
200	11.22	11.08	11.65	11.61	11.24	11.36	0.23
500	14.58	13.55	14.55	14.31	13.58	14.11	0.46
1000	20.55	20.29	21.18	21.41	20.59	20.81	0.42

Again, the growth is light between one and two-hundred miners, and becomes more aggressive as the intervals get bigger. The minimum running time was 9.58 seconds (for situation 5, with 1 miner underground) while the longest running time was 21.41 seconds (for situation 3, with 1000 miners underground). Just as in the previous scenarios, the running times lie relatively close together. Therefore, for the reasons stated previously, it can be expected that a solution for this scenario can be generated in under 21.5 seconds.

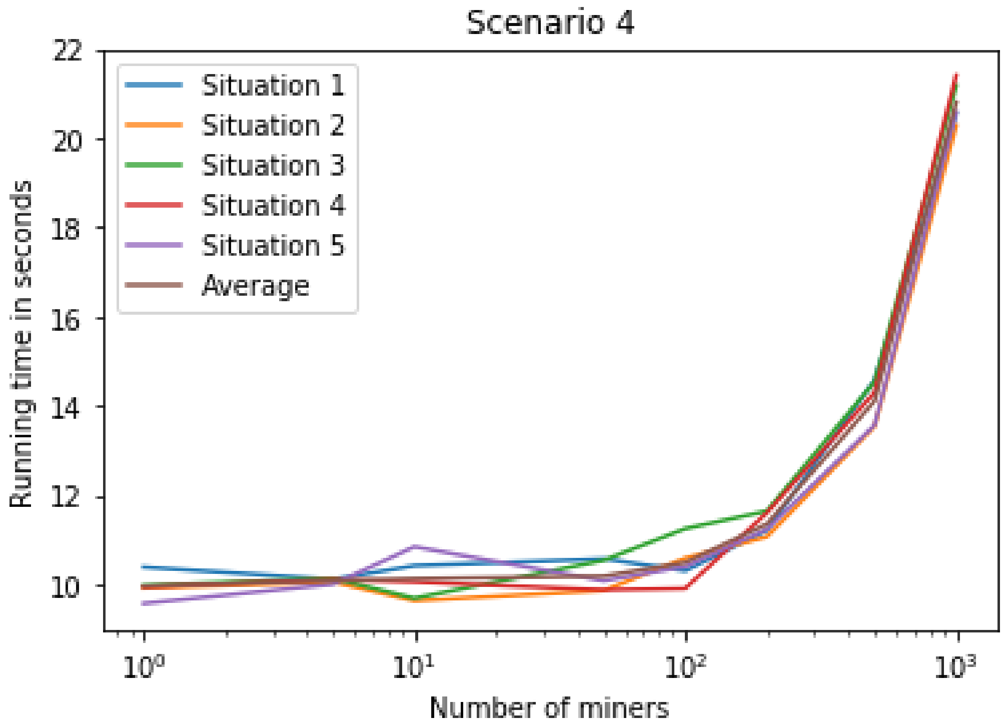

Figure 30: Running times scenario 4

4.5 Comparison: Scenario 1 vs. Scenario 2.

In this paragraph, scenario 1 will be compared to scenario 2. This is done to see what the effect of trapped miners is on the results produced by algorithm 1.

4.5.1 Division Among Safe Havens

Firstly, the differences in the division of the number of miners in a safe haven will be looked at. This is done by taking the absolute difference of the number of miners in a safe haven between the different situations for the two scenarios. The purpose of this is to see if closed drifts have significant impact on the routes the miners take in case of an evacuation. The values can be found in Table 26 till Table 30.

Table 26: Difference in number of miners in safe haven between Scenario 1 and 2, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	5
Shaft 250	0	0	0	0	0	0	1	1

Table 27: Difference in number of miners in safe haven between Scenario 1 and 2, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	1	15	18	2	0	0
Chamber 150	0	0	0	0	7	4	0	0
Chamber 300	0	2	2	3	3	14	0	0
Shaft 200	0	1	1	1	1	11	16	12
Shaft 250	0	0	0	13	23	31	16	12

Table 28: Difference in number of miners in safe haven between Scenario 1 and 2, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	1	4	0	0	0
Chamber 150	0	0	0	0	0	9	0	0
Chamber 300	0	0	0	1	3	8	0	0
Shaft 200	0	0	0	0	2	2	19	21
Shaft 250	0	0	0	1	2	4	24	26

Table 29: Difference in number of miners in safe haven between Scenario 1 and 2, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	1	3	2	0	0
Chamber 150	0	0	0	0	0	2	0	0
Chamber 300	0	0	0	1	0	0	0	0
Shaft 200	0	0	0	1	1	2	8	17
Shaft 250	0	0	0	1	2	4	6	13

Table 30: Difference in number of miners in safe haven between Scenario 1 and 2, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	1	2	4	0	0
Shaft 200	0	0	0	1	2	4	0	9
Shaft 250	0	0	0	0	0	0	0	9

One can see a significant difference in the safe havens where miners are headed between the two scenarios. There are two reasons for this. The first, and most important, is that the shortest route to a safe haven can be blocked by the fires. This means an alternative route has to be calculated. On this alternative route, the safe haven that was closest by before may now be farther away. Moreover, it may be entirely blocked for some miners. This means they have to go to an alternative safe haven. A second, and less important, reason for the differences is that in some situations miners get trapped. This means they will not reach a safe haven, which is visible in the numbers.

4.5.2 Total Distance Travelled

The averages for the total distances travelled in scenario 1 and 2 can be found in Figure 31. As can be seen, in scenario 2 the miners travel relatively larger distances than in scenario 1. This is expected, as due to unavailable pathways the miners in scenario 2 have to take detours, which adds to their path length. Moreover, the difference is artificially low, as trapped miners are not included in the data regarding distance. The actual difference in path length between miners from scenario 1 and miners from scenario 2 is therefore more prominent in reality.

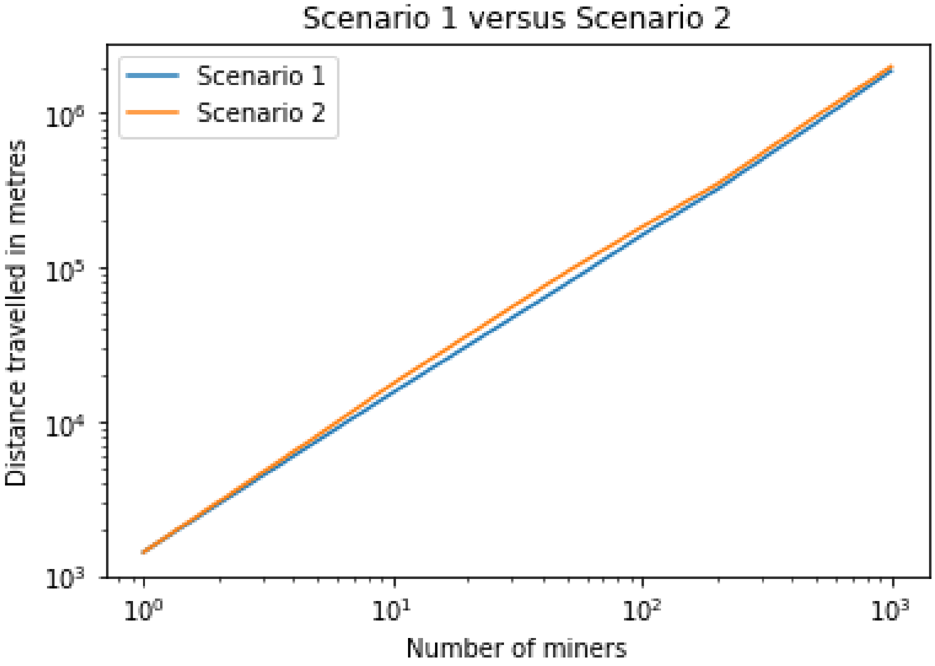

Figure 31: Distance travelled Scenario 1 vs. Scenario 2

4.5.3 Miner X

As described before, in both scenarios Miner X travels 2502.7 metres towards the refugee chamber at node 150. The fact that these values are identical, means that his path was unobstructed by fire, leading to the same escape strategy.

4.5.4 Running Times

In Figure 32 one can find the average timing results for both scenarios. As can be seen, the running times lie relatively close to each other. It seems as if trapped miners have no significant influence on the running time of the algorithm. In order to confirm this idea, the results need to be inspected in more detail. This will be done by looking at the results for simulations with 500 and 1000 miners. These quantities of miners were chosen as they, in general, have the largest amount of trapped miners. Therefore, if trapped miners have an effect on the results, it should be visible around these quantities of miners. The results are compared in Figure 33 and Figure 34.

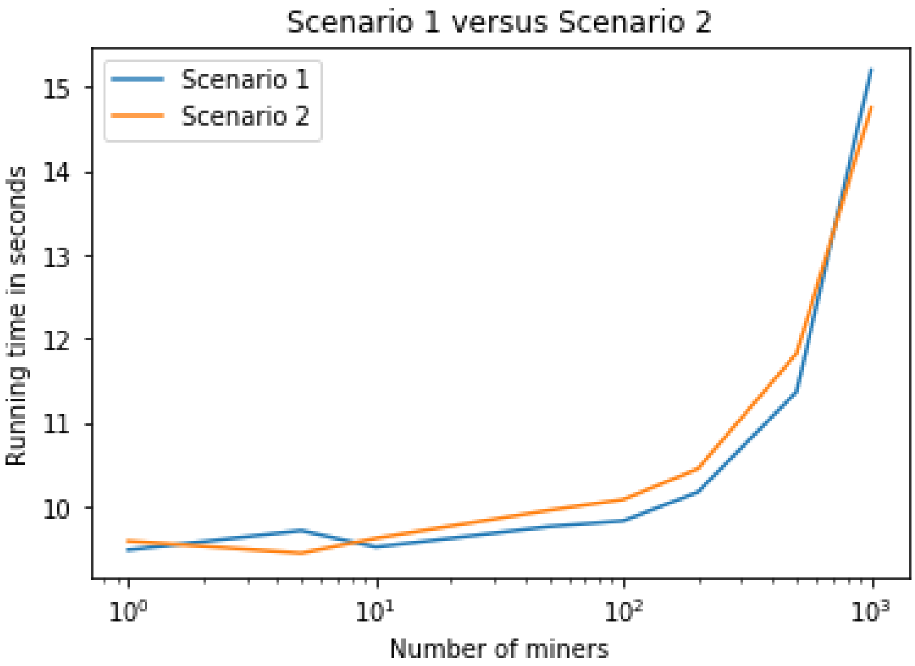

Figure 32: Average running times scenario 1 and 2

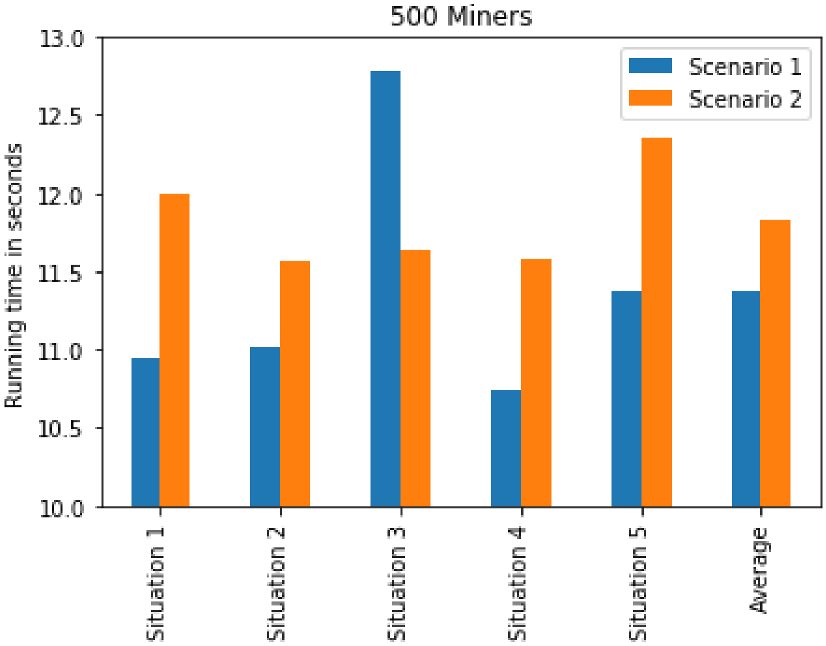

Figure 33: Comparison of running times for 500 miners in scenario 1 and 2

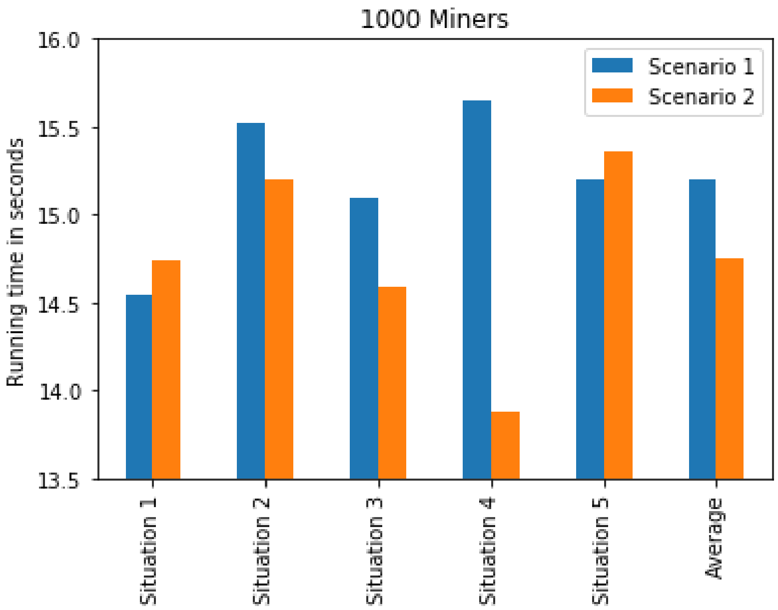

Figure 34: Comparison of running times for 1000 miners in scenario 1 and 2

Looking at Figure 33, one can see that the average difference in running time between scenario 1 and scenario 2 is about half a second. However, in four out of the five situations, scenario 2 has the longer running time, with a maximum difference of one second. That said, in situation 4 scenario 1 ran over 1.5 seconds longer than scenario 2. This is part of the reason why the average distance between both scenarios is relatively low. In Figure 34, the average difference is about 0.3 seconds. For this figure, in general, scenario 1 has longer running times, with the maximum difference being about 1.7 seconds (in situation 4). In all other situations, the difference is relatively low.

The results are quite unexpected. This is especially true for the simulations with a thousand miners, where scenario 1 in most situations has (marginally) longer running times than scenario 2. This while the latter scenario has more Python code that needs to be executed. It is worthwhile to compare situation 1, 3 and 4 to situation 2 and 5. This as in the first three situations miners are trapped in scenario 2, while in the latter two this is not the case. In Figure 33, however, no real difference between the situations with trapped miners and the ones without (apart for the longer running time of scenario 1 in situation 3, which is assumed to be an outlier in the data). In Figure 34, one can see that in two out of the three situations with trapped miners, scenario 2 has a longer running time, although marginally. A cautious conclusion can be that trapped miners only have a small influence on the running time of the algorithm where stamina is not considered. However, outliers, for whatever reason, can easily diminish this effect.

4.6 Comparison: Scenario 3 vs. Scenario 4

In this paragraph scenario 3 will be compared to scenario 4. This is done to see what the effect of trapped miners is on the results generated by algorithm 2.

4.6.1 Division Among Safe Havens

Again, the differences in the number of miners in safe havens will be presented, to see how the escape routes are influenced by blocked pathways. The results can be found in Table 31till Table 35.

Table 31: Difference in number of miners in safe haven between Scenario 3 and 4, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	0	2
Shaft 250	0	0	0	0	0	0	2	2

Table 32: Difference in number of miners in safe haven between Scenario 3 and 4, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	1	1	15	18	2	0	0
Chamber 150	0	0	0	0	7	4	0	0
Chamber 300	0	2	2	3	3	14	0	0
Shaft 200	0	1	1	1	1	11	16	16
Shaft 250	0	0	0	13	23	31	16	16

Table 33: Difference in number of miners in safe haven between Scenario 3 and 4, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	1	4	0	0	0
Chamber 150	0	0	0	0	0	9	0	0
Chamber 300	0	0	0	1	3	8	0	0
Shaft 200	0	0	0	0	2	2	19	27
Shaft 250	0	0	0	1	2	4	24	32

Table 34: Difference in number of miners in safe haven between Scenario 3 and 4, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	1	3	2	0	0
Chamber 150	0	0	0	0	0	2	0	0
Chamber 300	0	0	0	1	0	0	0	0
Shaft 200	0	0	0	1	1	2	4	17
Shaft 250	0	0	0	1	2	4	2	13

Table 35: Difference in number of miners in safe haven between Scenario 3 and 4, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	15
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	1	2	4	0	0
Shaft 200	0	0	0	1	2	4	0	9
Shaft 250	0	0	0	0	0	0	0	9

Again, significant differences can be seen in the amount of miners in a safe haven in a given situation. This is again mostly due to blocked pathways. Also, trapped miners can play a role in the differences.

4.6.2 Total Distance Travelled

In Figure 35 one can find the averages of the total distances travelled in scenario 3 and 4. A diverging trend can be seen. This is because the miners in scenario 4 have to take detours, which results in a growing difference in the travelled distance between both scenarios. Again, the real difference is more prominent, as trapped miners do not travel. This artificially lowers the average for scenario 4.

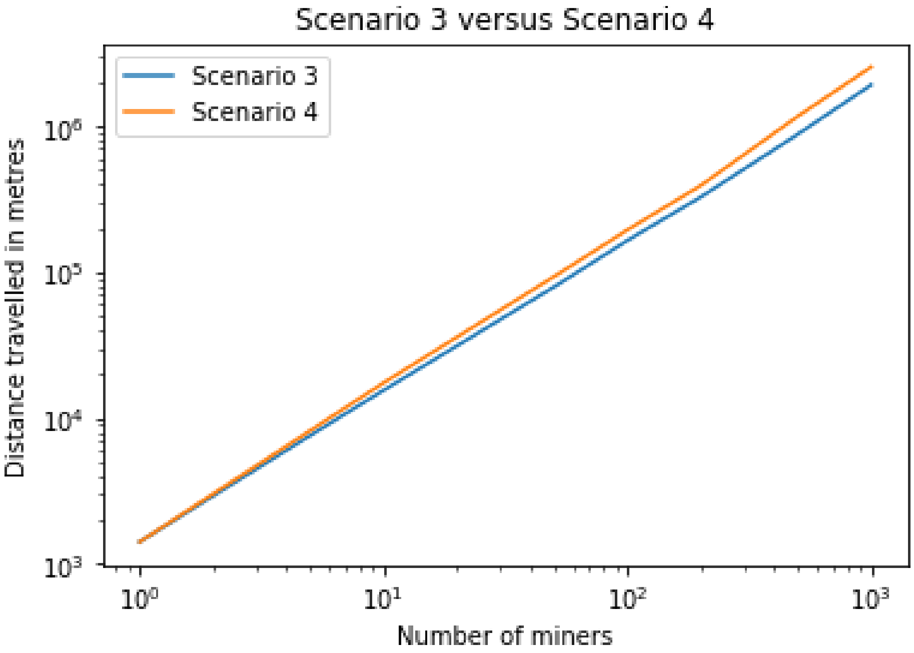

Figure 35: Distance travelled Scenario 3 vs. Scenario 4

4.6.3 Miner X

In scenario 3, Miner X had to travel 4285.1 meters to the shaft at node 250. In scenario 4, this is 6821.1 meters to the same location. This is due to blocked paths because of fire on the original route, which means Miner X has to take a detour.

4.6.4 Running Times

In Figure 36 one can find the average timing results for both scenarios. As can be seen, the running times are almost identical. This was not expected, as in scenario 4 more code has to be executed than in scenario 3. Again, the results for situations with 500 and 1000 miners will be inspected in more detail. This is to see if the results are as close as Figure 36 suggests, or if there are spikes in the data which evened out when the data was averaged. The comparison can be found in Figure 37 and Figure 38.

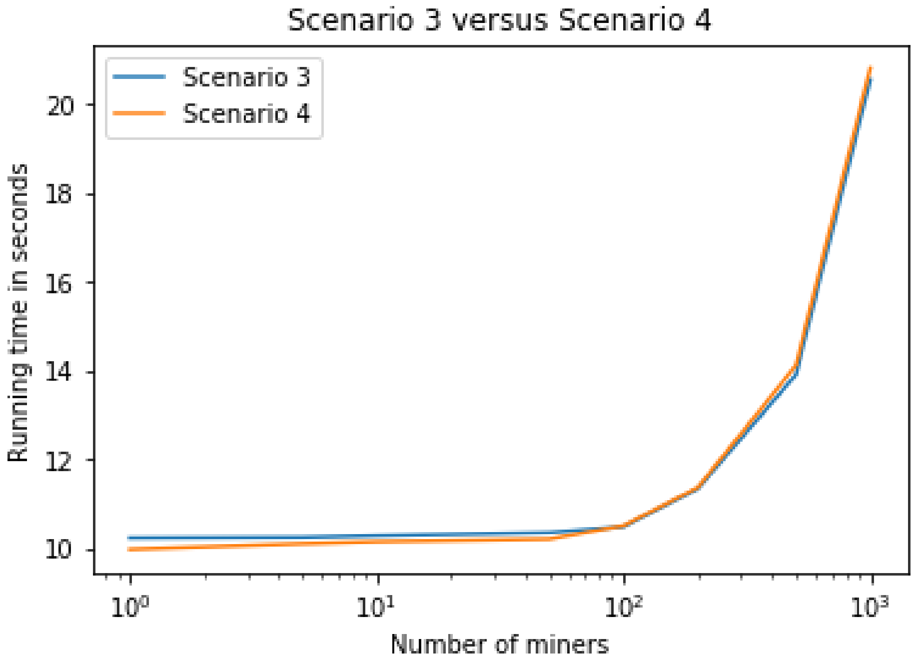

Figure 36: Average values for scenario 3 and scenario 4

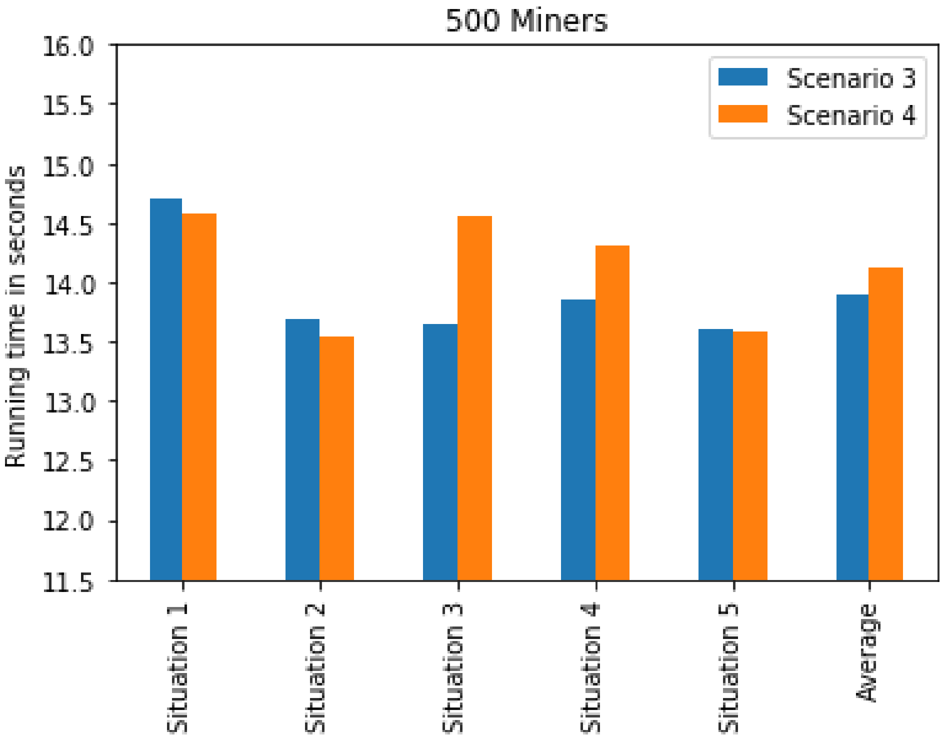

Figure 37: Comparison of situations for 500 miners in scenario 3 and 4

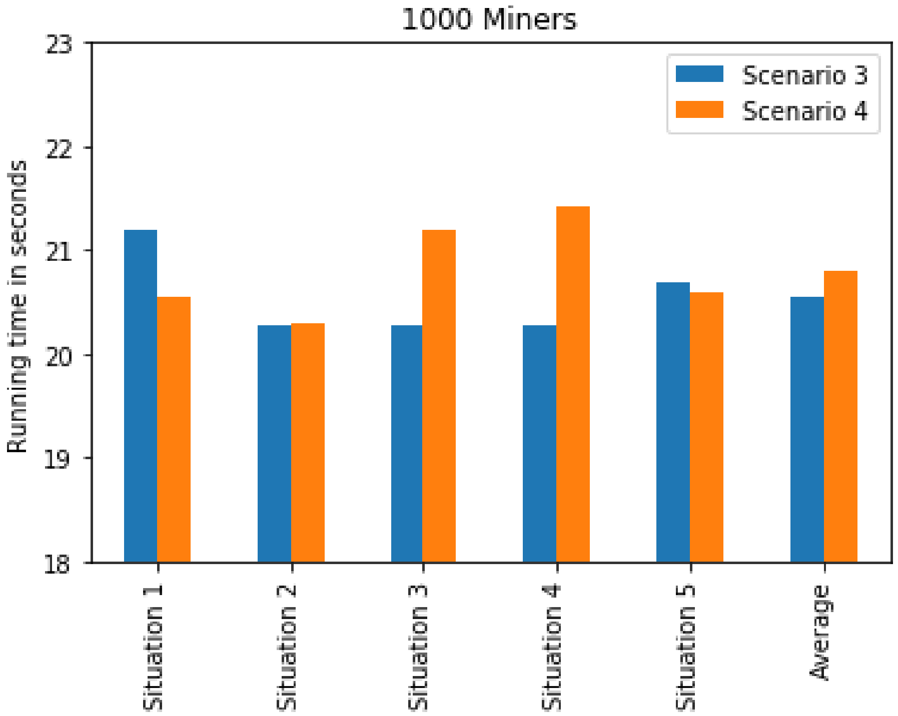

Figure 38: Comparison of situations for 1000 miners in scenario 3 and 4

Again, situation 1, 3 and 4 have to be compared to situation 2 and 5, as the first three contain trapped miners and the latter two don't (as was depicted in Table 7). In Figure 37, one can see that the running times in most situations lie relatively close together, with the maximum difference being a second (in situation 3). The same trend can be seen in Figure 38. As said, this is not expected (due to the fact that in scenario 4 more code has to be executed). However, no significant difference between both scenarios can be seen. It can be concluded, then, that the effect of locating trapped miners on the running time of the algorithm where stamina is considered is negligible.

4.7 Comparison: Scenario 1 vs. Scenario 3

In this sub-chapter, the effect of using stamina categories in cases where all pathways are available will be inspected in more detail.

4.7.1 Division Among Safe Havens

Again, the absolute difference in the division of miners among the safe havens will be reviewed. These can be found in Table 37 till Table 40.

Table 36: Difference in number of miners in safe haven between Scenario 1 and 3, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	5
Shaft 250	0	0	0	0	0	0	1	5

Table 37: Difference in number of miners in safe haven between Scenario 1 and 3, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	3
Shaft 250	0	0	0	0	0	0	1	3

Table 38: Difference in number of miners in safe haven between Scenario 1 and 3, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	7
Shaft 250	0	0	0	0	0	0	1	7

Table 39: Difference in number of miners in safe haven between Scenario 1 and 3, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	0	0
Shaft 250	0	0	0	0	0	0	0	0

Table 40: Difference in number of miners in safe haven between Scenario 1 and 3, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	14
Shaft 250	0	0	0	0	0	0	1	14

As can be seen, the only differences are visible at the two shafts in situations with five-hundred or a thousand miners. Why is this the case? Firstly, the algorithm where the stamina of miners is considered is only useful in situations where the refugee chambers lack capacity. If these chambers have enough room, people will be sent to the safe haven closest to them, no matter what their stamina category is. All distances are corrected with the same factor. Therefore, the safest haven closest by to a miner will not suddenly become farther away relative to any other escape node when the distances are corrected. Thus, if capacity is available, the results will not change by including stamina categories.

Why can some differences be seen at the higher numbers, but only around the shafts? This is because, when the refugee chambers are at capacity, miners in a lower stamina category will tend to be favoured for a spot in the refugee chamber (if this is relatively closer to them). For instance, Miner A is in a higher stamina category and will, if the distances are not corrected, be sent to a refugee chamber. Miner B is in a lower stamina category and is normally send to a shaft. In the situation without stamina categories this means that, in absolute terms, sending Miner A to the chamber minimizes the total distance travelled by all miners. In the situations with stamina categories, the distance towards the chamber becomes relative. This means that the total distance is minimized if Miner B is sent to the refugee chamber. Miner A therefore needs to find an alternative safe haven. However, the shaft closest to Miner A is not necessarily the one closest to Miner B, leading to the situation where Miner A is sent to a different safe haven than Miner B would have originally gone to. This is why some differences are visible for the situations with higher numbers, but only around the shafts.

4.7.2 Total Distance Travelled

In Figure 39, the total distances travelled in scenario 1 and 3 are compared. As can be seen, the total distances travelled are almost identical for scenario 1 and scenario 3. Apparently, the effect of correcting the distances according to the stamina category of a miner (when no pathways are closed) is negligible.

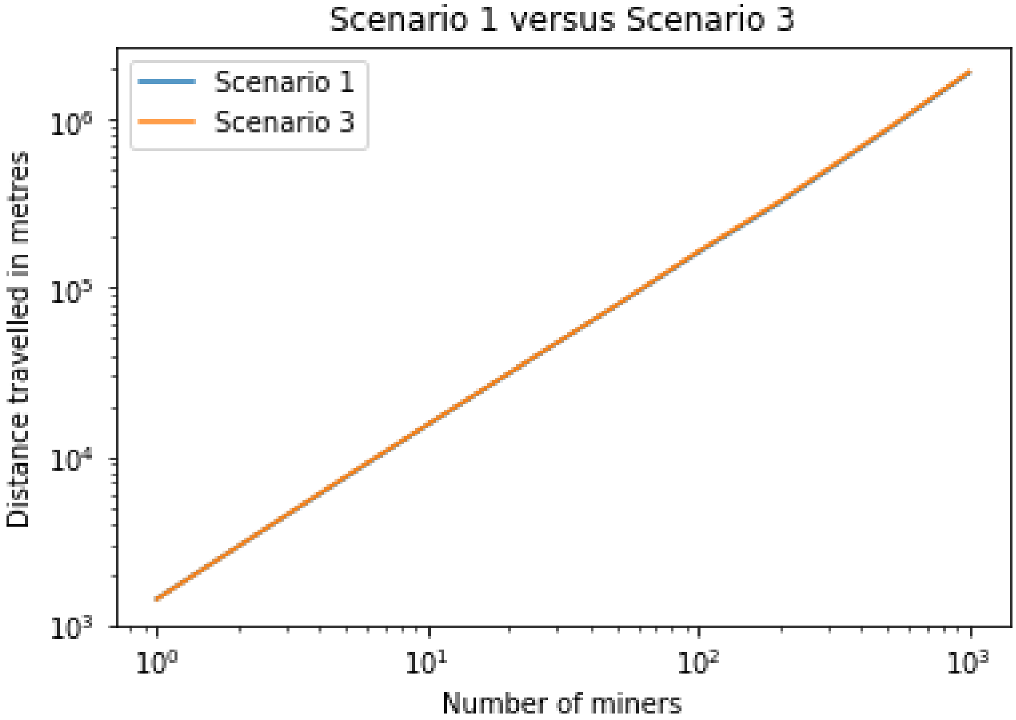

Figure 39: Distance travelled Scenario 1 vs. Scenario 3

4.7.3 Miner X

In scenario 1, Miner X travels 2502.7 metres to the refugee chamber at node 150, while in scenario 3 he travels 4285.1 metres to the shaft at node 250. This difference has the same explanation as given before: as Miner X has a high stamina, his relative distance to safe havens is closer by. This means that sending him to a safe haven farther away is relatively cheaper when solving the objective function than for a miner in a lower stamina category. A weaker miner is sent to the refugee chamber in his place.

4.7.4 Running Times

The average running time values for both scenarios can be found in Figure 40. One can immediately see scenario 3 has a significantly longer running time compared to scenario 1. Moreover, the difference becomes more outspoken as the number of miners increases. The minimum difference between the averages of both scenarios is 0.5 seconds (for five miners), while the maximum is 5.3 seconds (for a thousand miners). It is hard to draw conclusions from this, as the amount of miners present is not within the scope of this thesis. However, it will be more than five, and less than a thousand. Therefore, it can be expected that choosing algorithm 2 over 1 (with no blocked pathways), will take under 5.7 seconds longer. That said, a faster computer may give more efficient results. Concluding, it is up to the mine manager to decide whether he wants to add stamina categories to the evacuation algorithm the mine will be using. This is not only a technical consideration, as miners may be uncomfortable to be put in these types of categories. That said, it is technically feasible to include stamina categories when no paths are blocked, but there may be practical and social objections.

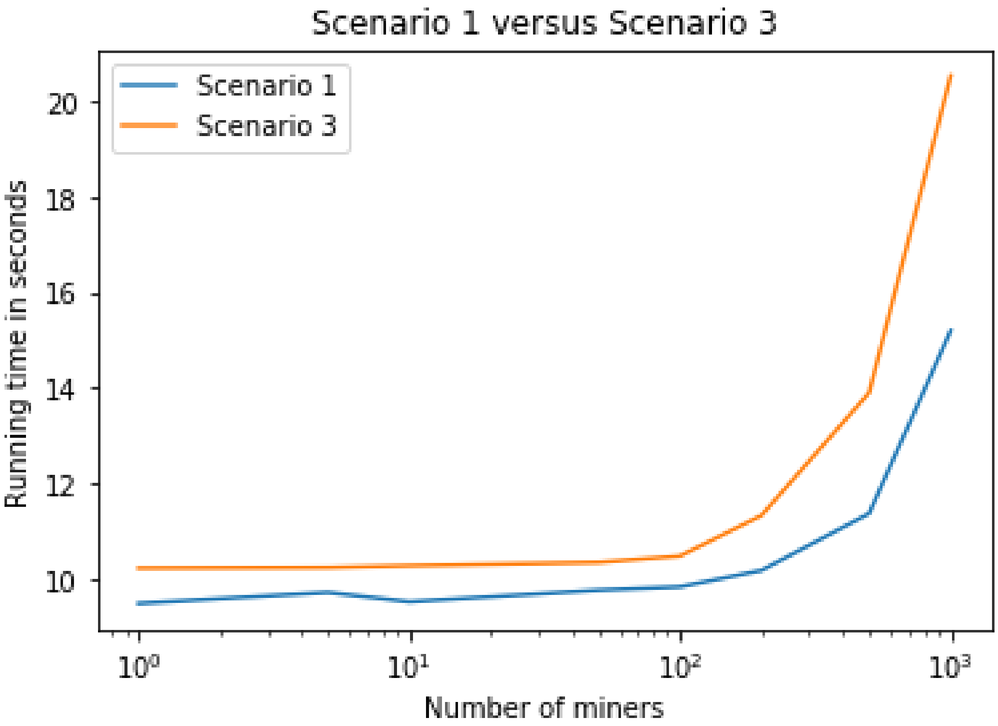

Figure 40: Average running time scenario 1 vs. scenario 3

4.8 Comparison: Scenario 2 vs. Scenario 4

In this sub-chapter, the effect of using stamina categories in cases where some paths are blocked will be inspected in more detail.

4.8.1 Division Among Safe Havens

The differences of the division of miners among the safe havens can be found in Table 41 till Table 45.

Table 41: Difference in number of miners in safe haven between Scenario 2 and 4, Situation 1

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	0	2
Shaft 250	0	0	0	0	0	0	0	2

Table 42: Difference in number of miners in safe haven between Scenario 2 and 4, Situation 2

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	1
Shaft 250	0	0	0	0	0	0	1	1

Table 43: Difference in number of miners in safe haven between Scenario 2 and 4, Situation 3

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	1
Shaft 250	0	0	0	0	0	0	1	1

Table 44: Difference in number of miners in safe haven between Scenario 2 and 4, Situation 4

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	3	7
Shaft 250	0	0	0	0	0	0	3	7

Table 45: Difference in number of miners in safe haven between Scenario 2 and 4, Situation 5

Refugee / Amount of Miners	1	5	10	50	100	200	500	1000
Chamber 120	0	0	0	0	0	0	0	0
Chamber 150	0	0	0	0	0	0	0	0
Chamber 300	0	0	0	0	0	0	0	0
Shaft 200	0	0	0	0	0	0	1	14
Shaft 250	0	0	0	0	0	0	1	14

Again, the only differences visible are in situations with higher numbers of miners and only around the shafts. This is, as explained in chapter 4.7.1, because when miners with higher stamina are send to a shaft instead of a refugee chamber, they don’t necessarily go to the same shaft as their colleagues who are send to the refugee chamber instead of them would have gone to.

4.8.2 Total Distance Travelled

In Figure 41 one can see the average distances travelled in scenario 2 and 4. As can be seen, the total distance travelled is almost equal for the lower numbers of miners, and starts to diverge slightly when the numbers increase. Including stamina when some pathways are closed, then, could lead to a less efficient solution of the objective function. This should be taken into account when considering using stamina categories in an evacuation algorithm. One could question whether it is ethical to increase the total path length (and therefore the time it takes to evacuate), in favour of miners with lower stamina.

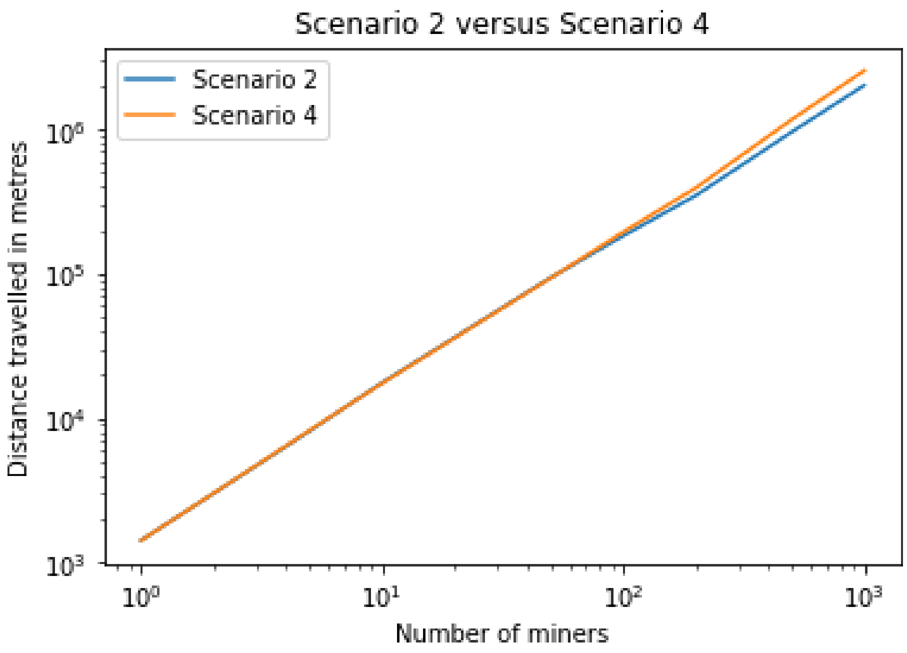

Figure 41: Distance travelled Scenario 2 vs. Scenario 4

4.8.3 Miner X

In scenario 2, Miner X hast to travel 2502.7 metres to the refugee chamber at node 150, while in scenario 4 he has to travel 6821.1 metres to the shaft at node 250. This means that, when using stamina categories, over four kilometres are added to the path of Miner X. This is partly because of his stamina, but also due to the fact that in scenario 2 he does not encounter blocked pathways, while he does in scenario 4. All in all, one could say that the increase in path length is highly significant.

4.8.4 Running Times

The average running times for scenario 2 and 4 can be found in Figure 42. Just like in chapter 4.7.4, it can be seen that using stamina categories adds significantly to the running times of the algorithm and that more miners means a bigger time difference. The minimum difference is 0.2 seconds (for fifty miners), while the maximum difference is 6.0 seconds (for a thousand miners). Again, as a situation with a thousand miners will not occur, it can be safely said that using stamina categories in an evacuation algorithm will only add a couple seconds to the running time. Therefore, in a situation where some of the pathways are blocked, using stamina categories is feasible.

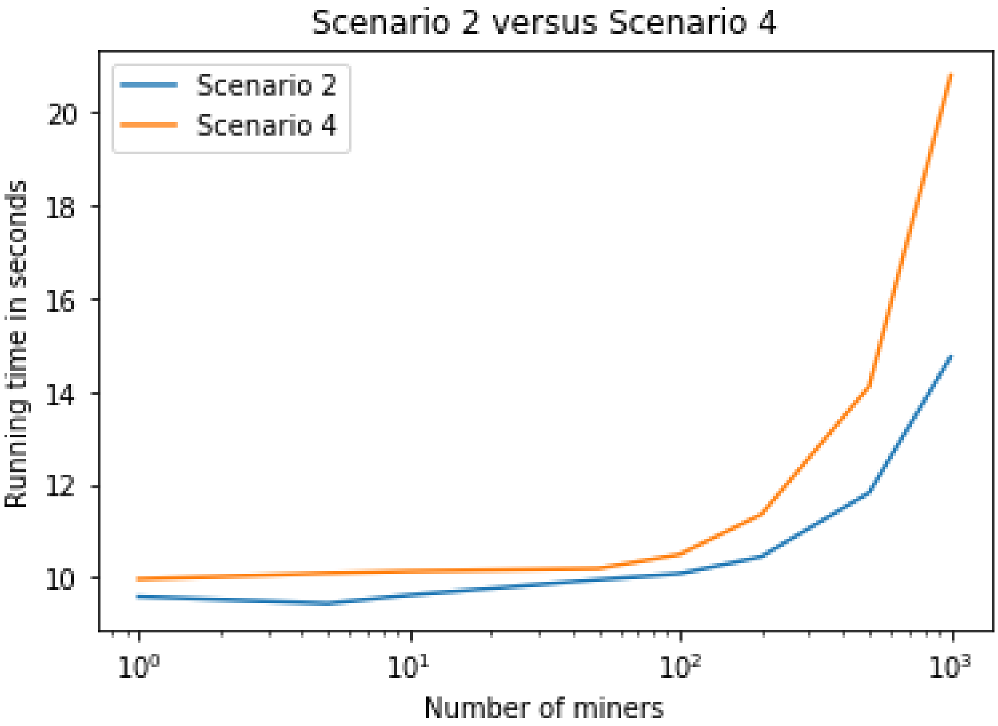

Figure 42: Average running time scenario 2 vs. scenario 4

4.9 Comparison: All Scenarios

To wrap up this chapter on results, a brief comparison of all scenarios will be done. Furthermore, this sub-chapter will be used to elaborate on the consequences of the differences between the scenarios.

4.9.1 Division among Safe Havens

As was shown in the previous chapters that compared the different scenarios, blocked pathways significantly change the way miners are divided among the safe havens. Adding stamina categories, on the other hand, only does so marginally. Moreover, the only differences in the latter case were seen in situations with (unrealistically) high numbers of miners. This raises the question whether using stamina categories has real added value. If the capacity of the refugee chambers is sufficient, the difference in the final result is non-existent. Therefore, when deciding to use stamina categories in an evacuation algorithm, one should make an elaborate analysis on how miners will usually be divided among safe havens, and whether using these categories will make an actual difference in the final results of this division.

4.9.2 Total Distance Travelled

In Figure 43, a recap of the distances travelled is given. As can be seen, the results for scenarios 1 and 3 are very similar. The total distance travelled in scenario 2 is somewhat higher, while in scenario 4 a more significant difference can be seen. It can be concluded, then, that blocked pathways add to the total distance travelled. This is, however, not a bad or disappointing result. Of course, in an actual evacuation, the more pathways are available the better. That said, it is even more beneficial if one does not encounter dangerous situations on his way to a safe haven. It is clear, then, that one should use a system that filters out the dangerous routes. This will lead to a safer, and therefore more efficient, evacuation.

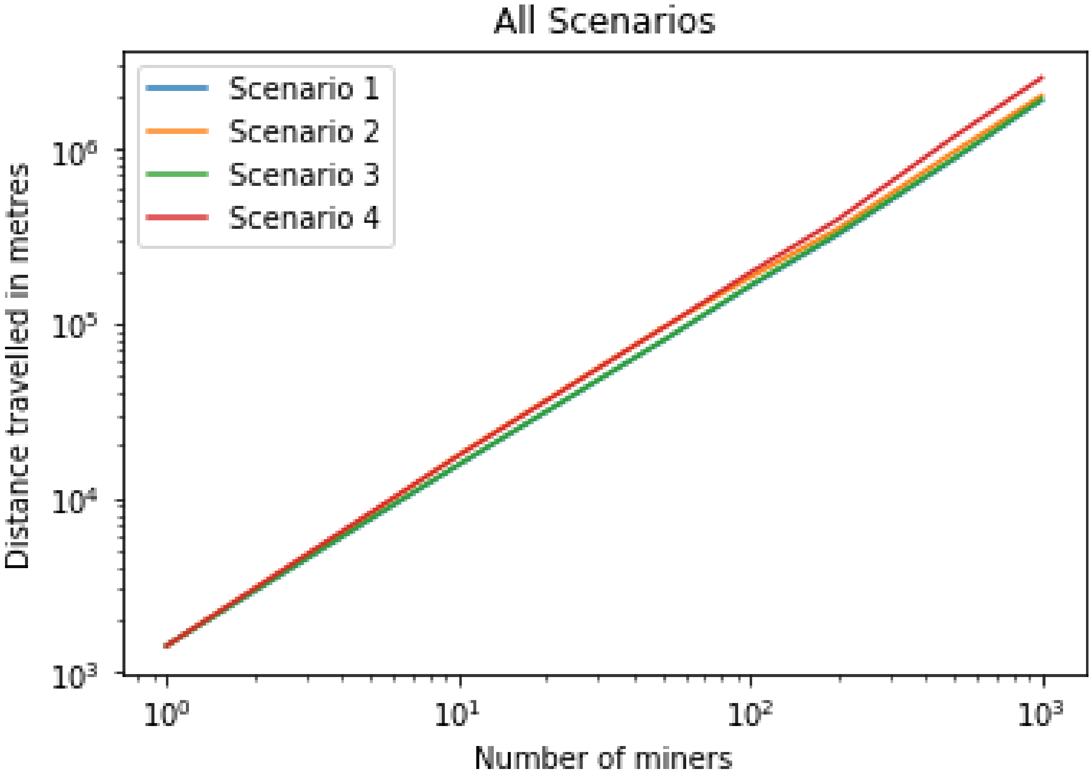

Figure 43: Distance Travelled All Scenarios

4.9.3 Miner X

In Table 46, a recap of the paths of Miner X is given.

Table 46: Destinations Miner X

Scenario	Distance in Metres	Final Destination Node
1	2502.7	150 (Refugee Chamber)
2	2502.7	150 (Refugee Chamber)
3	4285.1	250 (Shaft)
4	6821.1	250 (Shaft)

As mentioned before, using stamina categories can add over four kilometres to the path of Miner X. The question rises whether this is desirable. Can you expect a miner to travel these types of extra distances in case of an emergency, in favour of a weaker colleague? Would he be willing to? These are more philosophical than technical questions, and do not fall within the scope of this thesis. The conclusion that can be drawn here is that using stamina categories can have a big influence on the path an individual miner is given.

Readers with a background in mining engineering will notice that the path lengths for Miner X are way too long. Moreover, in a real emergency he would likely be killed. How can this be? The answer lies in the randomization that was used when determining the locations of miners and safe havens. Due to this randomization, miners may be located farther away from safe havens than would be desirable in real-life. The point of Miner X is to show how blocked drifts and stamina categories may add to path length of an individual miner. One can see that the influence of both may be more than significant. How can one avoid this problem in real-life? Clearly, in real-life the locations of workstations and safe havens are known. One could run the simulations with this data, filter out undesirable results (such as erroneous path lengths), and adjust the mine plan if necessary. These actions do not fall within the scope of this thesis, but are recommended for future research.

4.9.4 Running Times

A recap of the averages values for running times is given in Figure 44. As discussed before, the difference between scenario 1 and 2 is and scenario 3 and 4 is minimal. It is clear, then, that one should include closing dangerous pathways in the escape algorithm. Trapped miners can be localized, while their colleagues are sent on routes that avoid hazardous situations. This is a benefit of great value and, as there is no significant time penalty, comes without overly complicating the algorithm.

Adding stamina categories does add a time penalty, especially for larger numbers of miners. However, in the worst case, this penalty adds up to a couple of seconds. That said, as explained before, one can question whether these extra couple of seconds add significant value. The routes are only altered if the refugee chambers are at capacity, which, in a modern mine, should not be the case. Besides this it can be a significant strain on the miners with better stamina. This means that extra running time is added to the algorithm, while the benefit for the results is debatable. One could argue to save this time, although minimal, and choose the algorithm without stamina categories.

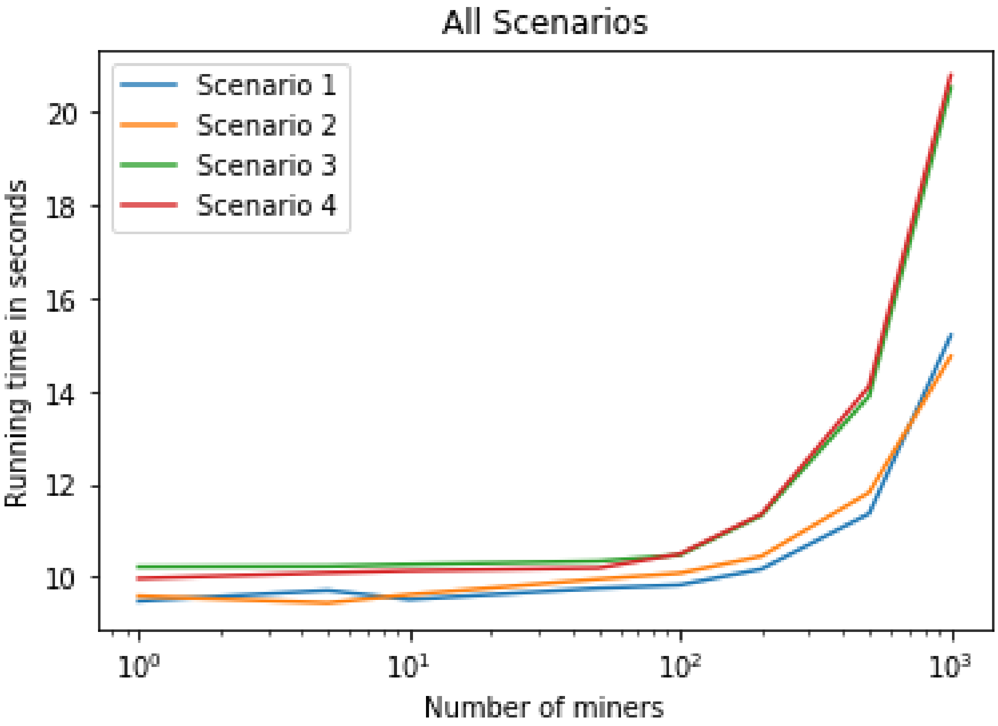

Figure 44: Average running time scenario all scenarios

4.9.5 Synthesis

Wrapping things up, it can be said that all four scenarios are feasible. However, as mentioned, it would be more than prudent to include a system that can locate trapped miners and that avoids sending their colleagues into hazardous situations. The choice, then, is between scenario 2 and scenario 4. As discussed, this is not only a technical decision, but also a social one. Using stamina categories can be beneficial, as the weaker miners will be directed to a safe haven closer by. The difference in computation time will be a couple of seconds, which most probably will not result in a matter of life and death. However, the difference in the results, for realistic numbers of miners, will be small to non-existent. That said, if the refugee chambers do clog up, the added path length for miners in a better stamina category may be unrealistic. Also, it may not be fair to have people with better stamina travel farther distances than their weaker colleagues. Furthermore, people may not want to be categorized according to their stamina. Therefore, the question whether one should use stamina categories in an escape algorithm is partly technical and partly philosophical. Technically, it is possible, although the final outcome will be the same as without these categories in cases with sufficient refugee capacity. If the capacity is insufficient, path lengths for miners with high stamina may become erratic. Philosophically, there are a number of objections. These, however, do not fall within the scope of this thesis.

CHAPTER 5 : CONCLUSION AND DISCUSSION

For this thesis, an evacuation algorithm for a drift and fill goldmine in Nevada was written. This algorithm was used to simulate different emergency scenarios in which miners need to be directed to safety as efficiently as possible. The evacuation was set as a ‘Minimum-Cost Network Flow Problem’, and solved using mathematical programming. For different scenarios, simulations with different amounts of miners were done to determine the outcomes and computational efficiency of the algorithm.

Mine evacuation algorithms have been reported before, but were based on shortest path algorithms such as Dijkstra’s algorithm, the Floyd-Warshall algorithm, or ant colony optimization. In mining engineering, setting an evacuation as a MCNFP has not been attempted before. The mathematical basis lies in an objective function, which connects weights to the different paths in the mine. These weights are determined by the length and the slope of the path. Also, the stamina of the miners may be used to determine the weights in the objective function. The objective function is subject to a number of constraints, which are linked to the nodes in the network. The nodes where miners are located are set to 1, which introduces them to the network of nodes and paths. The nodes where refugee chambers or shafts are located are set to a negative value, corresponding to their capacity. This way, a miner ‘disappears’ from the network once he reaches a node that contains a safe haven. All other nodes are set to zero. This means that if a miner reaches this node, he has to leave as well. Together, the objective function and the constraints make sure each miner reaches a safe haven, while the total distance travelled is minimized.

Two algorithms were written, which were used to test four different scenarios. The first algorithm assumes the weights in the objective function are the same for each miner. This algorithm was tested in cases where all paths were available and in cases where some paths were blocked, which could lead to miners becoming trapped. The second algorithm introduced stamina categories, which were used to correct the weights in the objective function according to the stamina category a miner is in. This algorithm was also tested in cases where all paths were open, and in cases where some paths were blocked.

The first result that was analysed for each scenario is the division of miners among the safe havens. It was found that up till two-hundred miners, the refugee chambers have sufficient capacity to harbour the miners closest to them. From five-hundred miners and up, the refugee chambers are at capacity, which leads to more miners being send to the shafts. When comparing the different scenarios to one another, it was found that the closure of pathways has significant influence on the division of miners. This is because blocked paths leads to miners having to take alternate routes. This, on its turn, can lead to a change in the safe haven that is closest by. Adding stamina categories only marginally changes the division of the workers and only occurs for situations with larger numbers of miners. This is because when refugee chambers are full, weaker miners will tend to be favoured for a spot in these chambers (if it is relatively close by). This leads to stronger miners, that would normally have a spot in the refugee chamber, being send to a shaft. The shaft they are send to, however, needn't be the same that their weaker colleague would have been send to. This leads to a difference in the division of miners among the shafts.

The second result that was analysed is the distance travelled by the miners in case of an emergency. It was found that blocked pathways add significantly to the total distance travelled. This is because, due to the blocked pathways, miners have to take detours, which adds to the total distance travelled. This isn't, however, a bad thing. It is important to keep the workers as safe as possible during an evacuation. This also means having them avoid hazardous situations on their way to a safe haven. It can be argued, then, that exchanging path length for safety is well worth the trade. It was also found that stamina categories can add to the total distance travelled. One can question whether this is desirable. Is protecting miners with lower stamina worth a less efficient solution? This is one of the philosophical/social questions this thesis raises.

Another result that was analysed are the paths of one specific miner, Miner X, in the different scenarios. It was found that using stamina categories can add up to over four kilometres to the escape route of Miner X. This means he has to travel to unrealistic distances to reach a safe haven. This is partly due to the randomization that was used when determining the location of miners and safe havens. That said, the fact the path length is increased by an erroneous amount is an indication that the use of stamina categories may be undesirable. Also, it raises philosophical/social questions. Would a miner be willing to travel an extra distance (under possibly hazardous situations) in favour of a weaker colleague? Can you expect this from him? Is this, in a wider sense, ethical? Although they do not fall within the scope of this thesis, these are important questions that should be considered when thinking about using stamina categories in an escape algorithm.

A final result that was analysed are the running times of the algorithms under different situations in the different scenarios. It was found that considering blocked pathways does not significantly add to the running time of the algorithms. This, again, is an indication that one should use this feature in escape algorithms. Trapped miners can easily be localized, while their colleagues are given routes that avoid dangerous situations. As there is no significant penalty in efficiency or otherwise for this feature, there is virtually no downside to using it. Stamina categories, on the other hand do add to the running time of the algorithm, especially when used for a larger number of miners. That said, the difference, in the worst case, is only a few seconds. It can be concluded, then, that, technically, using stamina categories is feasible. However, one can question whether it is worth the extra running time (although minimal). In situations with lower numbers of miners, where the refugee chambers have sufficient capacity, the final solution of both algorithms will be the same. Therefore, if an underground mine takes safety serious and facilitates enough escape capacity, using stamina categories has no added value. If the capacity is limited, the philosophical and social questions stated before must be considered.

Everything considered, this thesis has proven that mathematical programming can be used to write an escape algorithm for an underground mine. In all scenarios, for each individual in the mine, an escape solution was generated within a reasonable amount of time. Moreover, if the algorithm would be run on a more powerful computer, used specifically for escape route purposes, these running times could be lower. It is recommended to use the feature that considers blocked paths, as this has no real downsides and could save lives in case of an emergency. Whether it is a good idea to use stamina categories is debatable. It adds to the running time of the algorithm, while there may not be a difference in the final solution. Also, one could argue whether using these categories is ethical.

Although this thesis has proven that using mathematical programming to calculate escape paths for miners in case of an emergency is feasible, it lacks a certain degree of reality. This is due to a lack of data. For instance, it was not known what the locations of the refugee chambers are, how many miners are usually underground or what the locations of the workstations are. Therefore, to run the simulations, a lot of randomization was used. The location of shafts and refugee chambers were chosen by the author at random, while a pseudorandom generator was used to create the location of miners, their stamina and the location of inaccessible pathways. Therefore, the current code lacks applicability. It merely serves to show the possibilities of using MCNFP in case of an evacuation, but cannot, yet, be used to run an actual evacuation.

CHAPTER 6 : FUTURE RESEARCH

The first and foremost recommendation for future research is the introduction of more data. As mentioned, this thesis lacks data on the locations of the refugee chambers and shafts, the number of workers that are underground, and their locations. If this type data would be available, more specific simulations could be done, yielding results which will be closer to the ones that are needed in an actual emergency. For instance, if the mine normally has between 200 and 250 workers underground, simulations can be run within this interval. This way, one can create a realistic evacuation solution that can be used in emergency planning and training. Miners can be taught what the most likely evacuation routes are, depending on their location and the kind of emergency. This way, miners do not only get instructions for the route to a safe haven on their smart device if an emergency occurs, but also know what kind of routes they can expect.

A second thing one could consider for future research is using faster computers. The simulations in this thesis were run on an ordinary, everyday use laptop. In reality, however, most likely a computer will be used that has the sole purpose to run the code that calculates escape routes. Therefore, the running of the algorithms can be done faster and more efficiently. If one were to develop this code into a programme that can be used in actual emergency situations, he should use this type of computers to run the simulations. This way, a better expectation of the running times in case of an emergency can be created, which can be crucial when planning for one.

If one were to consider using stamina categories in the escape algorithm, a study should be done on the ethics of these types of solutions. These categories raise a number of questions that are not technical, but rather social or philosophical. This study, therefore, should not be done by an engineering division, but rather by someone who is trained in these types of questions.

A final recommendation is to use dynamic instead of static localization of miners. As described, there are many ways in which the location of miners in the underground mine can be tracked in real-time. Therefore, one could consider writing a code that uses this type of information instead of putting miners in fixed locations. This, in an actual emergency, will give more realistic instructions on how to get to a safe haven. However, one runs the risk of the algorithm becoming computationally expensive. That said, faster computers may have less problems with more complicated codes. Therefore, it should be investigated if real-time localization can be implemented efficiently into the escape algorithms.

APPENDIX: LINKS TO GITHUB

Algorithm without Stamina Categories:

https://github.com/RSHM1989/Thesis/blob/main/Main%20File%20without%20stamina%20FINAL%20(13-08-2020).ipynb

Algorithm with Stamina Categories

https://github.com/RSHM1989/Thesis/blob/main/Main%20File%20with%20stamina%20categories%20FINAL%20(13-08-2020).ipynb

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